COMPARABILITY OF ISOCS INSTRUMENT IN RADIONUCLIDE CHARACTERIZATION AT BROOKHAVEN NATIONAL LABORATORY

Paul Kalb
Brookhaven National Laboratory

Larry Luckett
URS Corporation

Kevin Miller, Carl Gogolak
DOE Environmental Measurements Laboratory

Larry Milian
Brookhaven National Laboratory

Brookhaven National Laboratory
Upton, New York   11973

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DISCLAIMER

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PAUL D. KALB
Brookhaven National Laboratory

LARRY W. LUCKETT
URS Corporation

KEVIN M. MILLER
Environmental Measurements
Laboratory

CARL V. GOGOLAK
Environmental Measurements
Laboratory

LAURENCE W. MILIAN
Brookhaven National Laboratory

ABSTRACT

This report describes a DOE Accelerated Site Technology Deployment project being conducted at Brookhaven National Laboratory to deploy innovative, radiological, *in situ* analytical techniques. The technologies are being deployed in support of efforts to characterize the Brookhaven Graphite Research Reactor (BGRR) facility, which is currently undergoing decontamination and decommissioning.

This report focuses on the deployment of the Canberra Industries *In Situ* Object Counting System (ISOCS) and assesses its data comparability to baseline methods of sampling and laboratory analysis. The battery-operated, field deployable gamma spectrometer provides traditional spectra of counts as a function of gamma energy. The spectra are then converted to radionuclide concentration by applying innovative efficiency calculations using monte carlo statistical methods and pre-defined geometry templates in the analysis software. Measurement of gamma emitting radionuclides has been accomplished during characterization of several BGRR components including the Pile Fan Sump, Above Ground Ducts, contaminated cooling fans, and graphite pile internals. Cs-137 is the predominant gamma-emitting radionuclide identified, with smaller quantities of Co-60 and Am-241 detected.

The Project used the *Multi-Agency Radiation Survey and Site Investigation Manual* guidance and the Data Quality Objectives process to provide direction for survey planning and data quality assessment. Analytical results have been used to calculate data quality indicators (DQI) for the ISOCS measurements. Among the DQIs assessed in the report are sensitivity, accuracy, precision, bias, and minimum detectable concentration. The assessment of the *in situ* data quality using the DQIs demonstrates that the ISOCS data quality can be comparable to definitive level laboratory analysis when the field instrument is supported by an appropriate Quality Assurance Project Plan. A discussion of the results obtained by ISOCS analysis of objects that could not be analyzed readily by conventional methods demonstrates a powerful application of the instrument. In conclusion, a comparison of costs associated with the analysis on the ISOCS instrument to the costs of conventional sampling and laboratory analysis is presented.

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ACRONYMS AND ABBREVIATIONS

AIF	Atomic Industrial Forum		keV	kilo electronVolts (energy)
ALARA	As Low As Reasonably Achievable		MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
ANSI	American National Standards Institute			
ASTD	Accelerated Site Technology Deployment		MCA	Multi-channel Analyzer
			MDA	minimum detectable activity
BEGe	Broad energy germanium [detector]		MDC	minimum detectable concentration
BGRR	Brookhaven Graphite Research Reactor		MCNP	Monte Carlo Nuclear particle
BNL	Brookhaven National Laboratory		NIST	US National Institute of Standards and Technology
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act		NRC	US Nuclear Regulatory Commission
D&D	Decontamination and Decommissioning		PARCC	QA parameters of precision, accuracy, representativeness, completeness and comparability
DOE	US Department of Energy			
DQA	Data Quality Assessment		PBMS	performance-based measurement system
DQI	Data Quality Indicator			
DQO	Data Quality Objective		PLF	Productivity Loss Factor
EML	US DOE Environmental Measurements Laboratory		PSSP	Project Specific Survey Plan
			QA	Quality Assurance
EPA	US Environmental Protection Agency		QC	Quality Control
ex situ	out of position, a sample removed and relocated for analysis		QAPP	Quality Assurance Project Plan
FOV	Field of View		RPD	Relative percent difference
HPGe	hyper-pure gemanium [detector]		RCRA	Resource Conservation and Recovery Act
in situ	in position, usually without disturbing or sampling the media		SOP	Standard operating procedure
ISOCS	In Situ Object Counting System		WAC	Waste Acceptance Criteria

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1.0 OVERVIEW

1.1   Introduction
This report describes a project sponsored by the DOE Office of Science and Technology (EM-50) under the Accelerated Site Technology Deployment (ASTD) initiative to deploy state-of-the-art techniques and equipment for improved characterization of nuclear facilities during characterization, decommissioning, and surveys for final status certification. Measurement of gamma emitting radionuclides is being accomplished using a field deployable gamma spectrometer *(In Situ* Object Counting System or ISOCS) manufactured by Canberra Industries, Inc. This report assesses the operational capabilities of the ISOCS instrument and the comparability of the field instrument results to results generated through the laboratory analysis of physical samples.

1.2   Description of ASTD Project
This Accelerated Site Technology Deployment (ASTD) project addresses some of the important issues of radioactive material characterization through deployment of an innovative *in situ* characterization technology. This project focuses on the characterization of the Brookhaven Graphite Research Reactor (BGRR), which is currently undergoing stabilization and near-term D&D. While the Environmental Management program of the U.S. Department of Energy (DOE) includes the D&D of many different types of nuclear facilities, the basic issues of characterization are universal and not dependent on site-specific dissimilarities.

The Brookhaven Graphite Research Reactor (BGRR) is a graphite-moderated, air-cooled, thermal neutron research reactor that operated at Brookhaven National Laboratory (BNL) from 1950 through 1968. Following shutdown, fuel was removed and the facility has been maintained in a safe shutdown mode since then. Many of the major BGRR sub-components are currently scheduled for near-term decontamination and decommissioning (D&D) including the Pile Fan Sump, above and below ground air ducts, and auxiliary buildings that house fans, filters, instruments, fuel transfer canal and water treatment systems.

Characterization of these facilities prior to, during, and after dismantlement is required to minimize worker exposure, plan for appropriate disposition of materials and remaining facilities, and demonstrate compliance with applicable environmental regulations. Due to the 30 years interval since shutdown, short-lived radionuclides have undergone considerable decay. Cs-137 is the predominant gamma-emitting radionuclide identified, with smaller quantities of Co-60, Eu-152, Eu-154, and Am-241 detected.

The project execution involved collaboration between BNL, the U.S. DOE Environmental Measurements Laboratory (EML), URS Corporation of Ronkonkoma, NY, Canberra Industries of Meriden, CT, and Cabrera Services. Inc of East Hartford, CT. Also participating in the plan was Bechtel Hanford Inc., which plans to deploy this approach for characterization of nuclear facilities at Hanford. Successful demonstration of comparability of the *in situ* technology provides an additional capability in nuclear characterization for DOE D&D undertakings. This deployment project also provides valuable experience and "lessons learned" that can be shared with facilities throughout the USDOE complex.

1.3   Report Format
This report describes the Canberra ISOCS instrument and the mathematical characterization (calibration) of the detector. Then a description of instrument response to field of view, depth of source, point source response and extended source response are described. This paper then discusses data quality indicators the basis for analytical comparability and demonstrates the comparability of the ISOCS instrument analysis to laboratory sample analysis. A discussion of the results obtained by ISOCS analysis of objects that could not be analyzed readily by conventional methods demonstrates a powerful application of the instrument. A comparison of costs associated with the analysis on the ISOCS instrument to the costs of conventional sampling and laboratory analysis is presented. Appendices to this report provide details of studies performed, project organization, cost assumptions, and a glossary of terms.

2.0 STUDY DESIGN AND METHODS

In situ gamma spectroscopy has been shown to be cost-effective in almost all applications where field sampling and laboratory analyses are the baseline technologies. Results can be obtained immediately following field acquisitions, thereby reducing the time delays incurred by physical sampling and laboratory analysis. *In situ* measurements can be performed on sealed systems (i.e., without breaching a containment barrier) or remotely (i.e., at a distance from an external radiation source), reducing personnel exposures and/or work hazards. When analysis by an independent laboratory is required by the project regulator prior to free release of materials, *in situ* measurements serve as a screening technique, eliminating the unnecessary analysis of samples above the derived concentration guideline level (DCGL). Large areas or volumes can be assayed with a large field of view to reduce errors arising from non-homogeneity, providing a more accurate estimate of average radionuclide concentrations. These advantages make *in situ* spectroscopy an attractive tool for many characterization applications.

2.1 Recent *In Situ* Studies

a. The DOE Fernald Area Office performed a study of comparability of traditional *in situ* gamma spectroscopy to the results of laboratory analysis of samples [ref 14]. The study was performed to demonstrate the comparable decision on disposition of remediated land parcels derived from either field or laboratory analysis. Due to heterogeneously contaminated surface soils and difficult to detect contaminants that also appeared in the background, the study was required to obtain as many as 15 samples from the field of view of the *in situ* spectrometer for correlation to the single *in situ* measurement. The study concluded that HPGe measurements of total uranium and thorium could meet certain of the QC acceptance criteria established by the project QAPP. Measurements of Ra-226 could only meet the QC criteria if corrected for disequilibrium caused by radon emanation.

b. The DOE Office of Science and Technology sponsored a demonstration of the ISOCS technology at the Argonne CP-5 Research Reactor [ref 15]. This demonstration, limited to performance over three days, determined that:

- The ISOCS can provide rapid, real time information on the type of radionuclides and the magnitude of the radiological hazard.
- As the ISOCS assay system is relatively new, it will be necessary to demonstrate the accuracy of the ISOCS system in relation to the standard baseline analysis.

It is this comparison of the ISOCS to baseline analysis technology that is addressed in this report.

2.2 ASTD Project Design

The ASTD project plan is built around the guidance contained in the *Multi-Agency Radiation Survey and Site Investigation Manual* (MARSSIM), published in December 1997 under the auspices of the U.S. Environmental Protection Agency (EPA) but compiled in collaboration with the USDOE, the U.S. Department of Defense, and the U.S. Nuclear Regulatory Agency [ref 13]. The MARSSIM was developed to provide a nationally-consistent consensus approach to conducting radiation surveys and investigations at potentially contaminated sites. The approach adopted in the MARSSIM is scientifically rigorous and yet flexible enough to be applied to a variety of site cleanup conditions. The MARSSIM provides information on planning, conducting, evaluating, and documenting environmental radiological surveys of surface soil and building surfaces for demonstrating compliance with regulations. Its focus is on the final status survey that is used in judging if a remediated site meets the applicable release criteria.

To date, the MARSSIM has been used primarily in determining the post-remediation status of a site or facility, not the condition prior to the initiation of remediation or decommissioning activities. However, the technical guidance contained within MARSSIM regarding the conduct of radiation surveys and site investigations has generic application, and has the potential for use in any situation involving radioactive contamination, whether or not a release criterion is to be applied. Using the MARSSIM to guide the characterization process in this project helped to optimize the survey design and to reduce or eliminate unnecessary samples, saving both time and money.

The Data Quality Objective (DQO) process is the basis for the performance-based guidance in planning MARSSIM surveys. Because the MARSSIM emphasizes the use of statistical planning and data analysis for demonstrating compliance with a final status survey, there are few examples of how to apply the DQO process for other types of surveys where such formal analyses are not necessary, or even appropriate. For example, data are collected during characterization surveys in order to determine the extent, but not necessarily the amount, of contamination. This does not

mean that the data do not meet the objectives of compliance demonstration, but it may mean that formal statistical tests would be of little or no value because the data have not been collected for that purpose. However, all analytical data should be of a quality, demonstrable through the DQO process, to support the determination or decision needed.

2.3   Baseline Analytical Methods

Conventional or baseline characterization in nuclear facility D&D requires the collection of thousands of surface smear, volumetric, and core samples, sending samples for on and off-site analysis, compiling the information in a database, and reviewing the data for quality assurance. Many of the areas requiring characterization are not readily accessible and/or are highly contaminated, further complicating the process. Thus, in addition to being time consuming and costly, the baseline characterization approach can result in excessive radiation exposures to personnel.

2.3.1 Conventional Gamma Spectrometry. The conventional laboratory gamma spectrometry system consists of a germanium detector connected to a dewar or cryostat of liquid nitrogen, a high voltage power supply, a spectroscopy grade amplifier, an analog to digital converter, and a multi-channel analyzer (MCA). When a gamma ray interacts with a germanium crystal, it produces electron-hole charge pairs which are collected rapidly. The total charge collected is proportional to the deposited energy.

The spectrometer system is energy calibrated using isotopes that emit at least two known gamma ray energies, so the MCA data channels are correlated to an energy equivalence. A curve of gamma ray energy versus counting efficiency is generated using known concentrations of mixed isotopes. The center of each gaussian-shaped peak corresponds to the gamma ray energy that produced it, the combination of peaks identifies each radionuclide, and the area under selected peaks is a measure of the amount of that radionuclide in the sample. Since the counting efficiency depends on the distance from the sample to the detector, each geometry must be given a separate efficiency calibration curve.

Samples are placed in containers and tare weighed. Standard practice is to dry solids and homogenize using a ball mill process prior to analysis. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. For environmental levels of contaminants, the sample and germanium detector are usually placed within a lead-shielded counting cavity, to lower interference from radionuclides in the surroundings. Counting times of 1000 seconds to 1000 minutes are typical. Each peak is identified manually or by gamma spectrometry analysis software. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope's decay scheme are factored together to calculate the concentration of radionuclide in the sample. The system accurately identifies and quantifies the concentrations of multiple gamma-emitting radionuclides in samples like soil, water, and air filters when a reference standard of known activity is available in a similar matrix and geometry [ref 13]. The availability of the reference standard requires preparation of a radioactive source that eventually must be disposed, thus increasing cost and generating secondary waste.

2.3.2 Conventional *In Situ* Analysis. The advantages of *in situ* measurements over traditional sampling methods have been known and appreciated for some time. These advantages include:
- reducing the potentially large errors associated with random sampling of non-homogeneous source distributions;
- reducing costs and improving safety by minimizing the sampling process; and
- essentially eliminating the delay time between sample collection and availability of nuclide-specific analysis results.

There have been many advances in gamma detection hardware and analysis software during the past 10 years, which now make it much more practical to perform *in situ* gamma spectroscopy. These advances include: large high-purity germanium detectors which provide the required resolution and sensitivity, rugged multi-attitude cryostats allowing the detector to be aimed in any direction and ensuring adequate liquid nitrogen holding times, laboratory-quality battery-powered portable MCAs, portable laptop-size computers with tremendous processing power and data storage capacity, and sophisticated and easy-to-use spectral analysis software.

In order to use the acquired pulse height spectrum for quantitative assessment of radioactivity, an efficiency calibration must be performed. This is normally done with the use of known quantities of radioactive materials in fixed distributions. Previous techniques used, involving uniform mixtures of radionuclides or large numbers of small sources in inert matrices, are very expensive. The user must purchase radioactive sources of the proper range of activity and energy,

distribute the source appropriately, and finally dispose of the source as radioactive waste.

For each new geometry, a new calibration standard and one to several hours of instrument calibration are required. This has limited *in situ* gamma spectrum analysis to simple geometries and contamination distributions. The mathematical detector characterization of the Canberra ISOCS is the innovative response to this problematic aspect of conventional *in situ* analysis.

2.4 ISOCS Description

ISOCS is a complete *In Situ* Object Counting System developed by Canberra for use in a wide variety of measurement applications [ref 2, ref 4]. The battery-operated system provides traditional spectra of counts as a function of gamma energy, which are then converted to radionuclide concentration by applying pre-defined geometry templates in the analysis software. The ISOCS software overcomes the limitations of traditional (tedious and expensive) efficiency calibration techniques, and allows practical modeling and accurate assay of almost any object in the workplace. Thus, complex contamination distributions (e.g., an inaccessible contaminated pipe within a wall) can be identified, and resulting quantification of the contamination therein can be performed.

2.4.1 Germanium Detector. The gamma radiation detector utilizes a high purity germanium crystal for high resolution and high efficiency gamma radiation detection. For the ASTD project, a Canberra Broad Energy Germanium (BEGe) detector was selected because it enhances the efficiency of gamma radiation detection below 100 keV while exhibiting increased transparency to high energy gammas, such as those from naturally occurring K-40. Typical energy response curves for the BEGe and the conventional Coaxial detectors are illustrated in Figure 2-1.

The wide, squat shape of the BEGe detector (active volume of 80 mm diameter by 30 mm thick) is optimized for analysis of objects in front of the detector. However, it has less sensitivity to a Marinelli beaker sample geometry than a traditional co-axial detector whose diameter is smaller than its thickness. The enhanced BEGe detector efficiency for low energy gammas (from 30-100 keV) provides a field capability for detection of Am-241 and low energy gammas associated with actinide alpha-emitters that greatly exceeds the capability of traditional detectors.

There is a drawback to using the BEGe detector. The ISOCS 30° field of view (FOV) collimator is designed for use with a standard narrow co-axial detector, and its
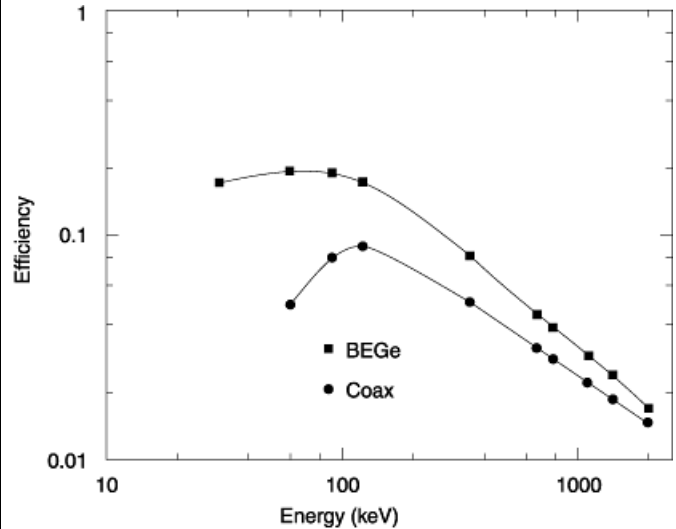
Figure 2-1. Comparison of BEGe detector response to coaxial germanium detector (Canberra, 1999)

use is impractical with the BEGe detector. The wide, flat shape of the BEGe results in the 30° FOV collimator shielding over 80% of the active BEGe detector region. This shielding decreases the sensitivity of the detector, which increases the time to acquire a spectrum with enough counts to provide minimal statistical uncertainty. This limitation could be rectified by the manufacturer producing a re-designed collimator for use with the BEGe detector.

2.4.2 Modular Shields and Cart. Mechanical components of the ISOCS system, including a field deployable mobile cart and a modular system of stainless-steel covered lead shields are shown in Figure 2-2. Annular side shields of either 19 mm (0.75 in) or 44 mm (1.75 in) lead thickness effectively reduce the detection of interfering radiation from items in the vicinity of the detector and from background radiation, resulting in improved system sensitivity. The detector's field of view can be further restricted, from 180° to 90° or 30°, by installing lead collimators on the cart's mounting rails, so that interference from items adjacent to the object of interest can be significantly reduced or eliminated from the analysis. In addition, a completely shielded sample chamber can be assembled by stacking the components of the two thickness annular shield systems to enable timely, low-background analysis of samples in the field.

2.4.3 ISOCS Detector Characterization. Previous attempts at simplified mathematical calibrations have had accuracy shortcomings due to assumptions that the detector was a point detector, and due to limitations in

sample shapes accommodated. With ISOCS, however, each individual detector has a unique set of characteristics that are used to generate the calibration data [Ref 2]. This process employs a two-phase, mathematical computation technique that includes detector-specific characteristics, accounts for collimators and/or shields, and models the physical object to be assayed. It uses a combination of Monte Carlo calculations and discrete ordinate attenuation computations to derive efficiency curves for quantitative spectral analysis.

Canberra uses the Monte Carlo Neutron-Particle (MCNP) code for the detector characterization phase of the process [Ref 1]. To accurately represent the Ge detector response, the MCNP model must be rather complex, and typically requires approximately 25 different physical elements. Even with fast 64 bit 300 MHz computers, and special biasing procedures, these efficiencies can take days to compute. To ensure the maximum accuracy and to minimize subsequent analysis times, this phase of the detector characterization is performed on each detector by Canberra at the factory before it is delivered.

The output of the detector characterization process is a series of equations that defines the detector response (in terms of fraction of gammas emitted from the object that interact in the detector):
- at any distance from the end-cap, from 0 to 50 meter;
- at any energy from 3 - 7000 keV; and
- at any angle in all 4-pi directions.

The results of this individual detector characterization are incorporated as a part of the calibration software. Individual detector characterization is recalled by the user when quantifying an individual gamma spectrum.

2.4.4 Source Geometry Modeling. The user phase of the efficiency computation allows accurate efficiency calibrations to be performed rapidly for a wide variety of sample shapes, sizes, densities and distances between the sample and the detector. Objects are modeled from one of a set of generic sample shapes, such as boxes, cylinders, planes, spheres, pipes, etc. These basic geometry templates have many parameters that can be modified to create an accurate representation of the sample object and detector geometry.

Photon attenuation effects due to collimators and shielding components (if present) can be included in the efficiency calibration process. Attenuation effects due to the sample material itself, the container walls (if any), and the air between the sample and the detector are also

Figure 2-2. ISOCS cart with detector, cryostat and modular shield system

included in the calculations. For typical objects and energy ranges of interest, an experienced user can complete the entire efficiency calibration process in several minutes or less. Exposure parameters and efficiencies can be generated in a few minutes in the field and can be modified easily if needed.

At this point, the data is presented and stored just as it would be using the conventional process, that is as if the user had prepared a multiple energy calibration source in the appropriate geometry, counted it, analyzed the spectrum, and computed the efficiency based upon the data in the calibration source certificate file. The resulting ISOCS efficiency calibration functions can then be used to analyze acquired spectral data files with the standard spectrometry analysis software.

2.4.5 Analytical Software. The output of the ISOCS process is a set of energy/efficiency/error triplets. Upon exiting the ISOCS user interface, this data is converted into the energy-efficiency curve format and is displayed for the user as shown in Figure 2-3. The user can

manipulate Canberra's standard efficiency response curve interface to determine the best equation that represents the energy vs. efficiency function. After the calibration curve is accepted, it is stored as an efficiency file, and is available for re-analysis of previous spectra or for newly acquired spectra from sources that are described by the same geometry parameters.

2.4.6 Validation of the ISOCS Computation. Given the uniqueness of the ISOCS mathematical calibration, Canberra Industries has performed a series of internal consistency tests and efficiency validations of the ISOCS methodology [ref 3]. These evaluations were conducted by Canberra to ensure that the ISOCS version 3.0 software handles the physics correctly for different source shapes and sizes, and for different source-detector geometries. The following discussion summarizes the validation performed by Canberra as reported in the validation document.

2.4.6.1 Internal Consistency Tests. Internal consistency tests were designed to demonstrate that the ISOCS software treated source geometries in a consistent manner when defined using several of the available geometry templates. Eight shaped objects (point, sphere, box, etc) were modeled using from 4 to 11 geometry templates of equivalent geometrical shape. If a given source geometry can be configured using different templates, then ISOCS should give the same efficiency

values for different templates. The tests indicated that for the eight shapes, the percent difference in efficiency at a given energy value ranged:

- between 0.10% to 1.12% for energies below 150 keV; and
- between 0.05% to 0.56% for energies greater than 150 keV.

Thus the detector characterization and template definition scheme is internally consistent across the 11 geometry templates.

2.4.6.2 Validation Tests. Validation tests were performed by Canberra to demonstrate the accuracy of the ISOCS efficiency calibrations when compared to actual, physical sources. The tests involved 119 different, multi-energy sources in three categories of spectrum acquisition,

a. field counting geometries, involving large sources ($> 1 \text{ m}^3$ in volume) and/or large source-to-detector distances (> 1 m);

b. laboratory counting geometries, involving small volume sources located within 1 meter of the detector;

c. collimated geometries, similar to the field counting geometries, using annular shields and $180°$, $90°$, or $30°$ FOV collimators.
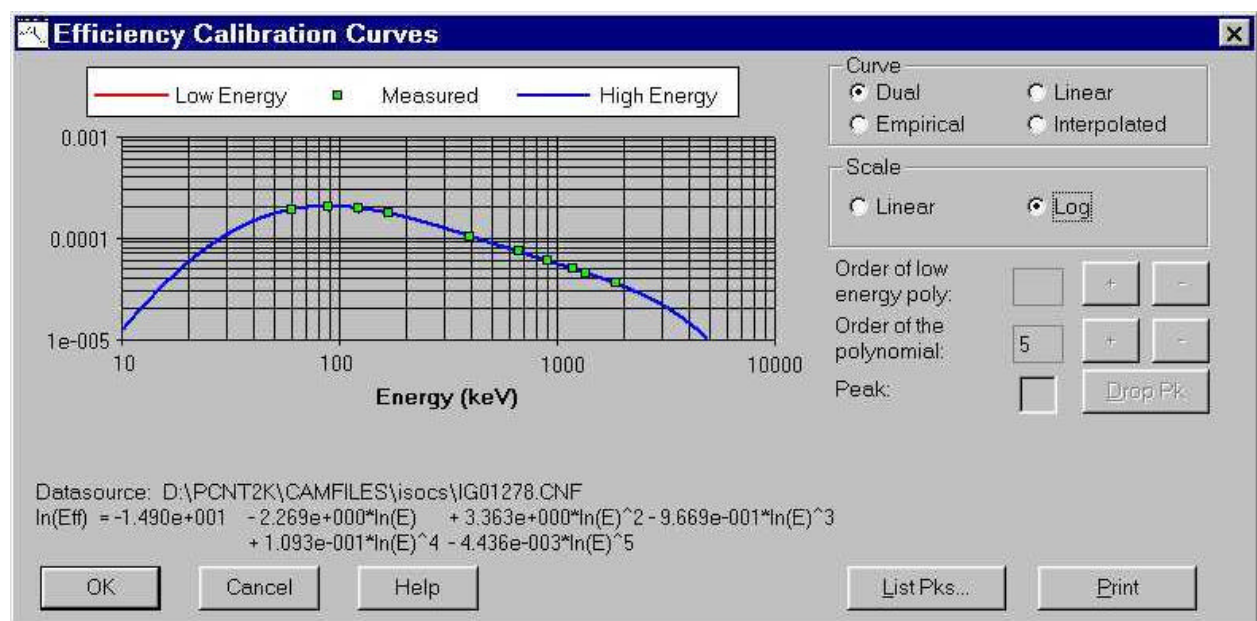
Figure 2-3. ISOCS efficiency response curve interface

The tests indicated that for the three conditions, the percent difference in efficiency at a given energy value ranged:

- between -1% to -2% for energies below 150 keV;
- between +0% to +6% for energies greater than 150 keV; and
- between +0% to +2% for all energies, pooled data.

The validation tests demonstrated that for all three categories, the average ISOCS calculated efficiency to true efficiency ratios were very close to unity. The greatest deviation (+6%) occurred for the higher energy gammas in the laboratory geometry.

2.4.6.3 Propagated Uncertainty. In concluding the software validation, Canberra presented the values in Table 2-1 for uncertainty in the efficiency calculation. These values are present as defaults in the analysis software code and are used with the counting uncertainty to develop a propagated total uncertainty for the measurement result.

The software allows these default values to be changed

Table 2-1. ISOCS Efficiency Uncertainties

Geometry Condition	Energy Range	Rel Std Dev (%)
Laboratory Sources	50 - 100 keV	7.1
	100 - 400 keV	6.0
	400 - 7000 keV	4.3
Field Sources and Collimated Geometry	50 - 100 keV	10.6
	100 - 400 keV	7.5
	400 - 7000 keV	4.4

by the analyst, when other sources of error are known or eliminated. For instance, Canberra recommends that under conditions of heavy attenuation (transmission less than 1% due to an absorber between the source and the detector), an additional multiplication of the error by a factor of 1.5 - 2.0 be applied.

3.0 BASIS FOR ASSESSING DATA QUALITY LEVEL

This ASTD Project is designed to demonstrate that *in situ* gamma spectrum analysis can be used in lieu of laboratory analysis in one or more of the following situations during the D&D process:

- Defining worker protection requirements in the design of work packages;
- Controlling work progress, excavation advancement and waste segregation;
- Waste characterization to demonstrate compliance with waste acceptance criteria; and
- Performing final status surveys for remediated facilities and land areas.

Since each of these phases uses the data for a different purpose, with different consequences for level of precision, accuracy and timely acquisition of results, the data quality requirements are not identical.

The Data Quality Objective (DQO) process has been developed to address the differing issues and requirements on the data use, in order to optimize the return of useful, relevant data for the collection and analytical efforts. The following discussion of data quality is distilled from federal agency guidance provided in EPA data quality documents [ref 10, ref 11, and ref 12] and in the *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)* [ref 13].

3.1 Data Quality Level

Despite a number of successful applications of *in situ* spectrometry over the years, issues have arisen regarding the level of data quality that is obtained with field measurement techniques for the purposes of demonstrating compliance with the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the Waste Acceptance Criteria (WAC) at disposal facilities, and other regulatory compliance mandates. In the past, EPA defined different levels of data quality, termed "analytical support levels," by the types of technology and documentation used, and the degree of analytical sophistication [ref 17]. Notwithstanding this intent, the actual titles provided to the analytical levels by the EPA guidance tended to associate the level of quality with the location of the analysis. The relevant levels are:

- Level IV – "Contract Laboratory Program Routine Analytical Services" – characterized by rigorous QA/QC protocols and documentation, providing qualitative and quantitative analytical data.
- Level II – "Field Analysis" – characterized by the use of portable analytical instruments which can be used on-site, or in mobile laboratories stationed near a site (close support labs). Depending on the types of contaminants, sample matrix, and

personnel skills, qualitative and quantitative data can be obtained.

- Level I – "Field Screening" – characterized by the use of portable instruments which can help provide real-time data to assist in the optimization of sampling point locations and in health and safety support.

Thus, field measurements, by definition and common usage, have been considered not to possess the quality control that needs to be established to match data quality from the laboratory.

The distinction between screening level and higher quality measurements is based on factors relating to data quality which should be demonstrable. In principle, the rigorous QA/QC protocols and documentation required for definitive analysis using EPA Contract Laboratory Program (CLP) procedures could be applied to radionuclide specific field measurements. Using field techniques at a higher analytical level is also in keeping with the latest EPA proposals for performance-based measurement systems (PBMS). PBMS is a process in which data quality needs, mandates, or limitations of a program or project are specified and serve as a criterion for selecting appropriate analytical methods. Under the PBMS framework, the performance of the method employed is emphasized rather than the specific technique or procedure [or location] used in the analysis. Equally stressed in this system is the requirement that the performance of the method be documented by the laboratory that appropriate QA/QC procedures have been conducted to verify the performance. PBMS applies to physical and chemical techniques of analysis performed in the field as well as in the laboratory [ref 11].

Thus, data quality is assured by adherence to a quality assurance program, regardless of whether analysis occurs in the field or in the laboratory. The quality assurance program establishes the required data quality indicators, procedures and operations. Data quality assessment determines the validity and performance of the data collection design, determines the adequacy of the data set for its intended use, and ultimately determines whether the *in situ* analysis can be used (is "comparable" or not).

From this discussion, it is evident that quality data may be generated in the field, as long as the project DQOs and QA/QC requirements are satisfied. It is the assessment of the total data quality, not the identification of which specific method or instrument was used, that establishes the confidence in the analysis and determines the data quality level.

Table 3-1. The Data Quality Objective Process

| STEP 1. STATE THE PROBLEM |
| STEP 2. IDENTIFY THE DECISION |
| STEP 3. IDENTIFY INPUTS TO THE DECISION |
| STEP 4. DEFINE THE STUDY BOUNDARIES |
| STEP 5. DEVELOP A DECISION RULE |
| STEP 6. SPECIFY LIMITS ON DECISION ERRORS |
| STEP 7. OPTIMIZE THE DESIGN FOR COLLECTING DATA |

3.2 *In Situ* Analysis Quality Assurance

The BNL-ASTD project used the DQO process as the basis for the performance-based guidance in planning characterization and final status surveys. The steps of the DQO process identified in the EPA guidance are shown in Table 3-1.

In the implementation of this project, the first four steps of the DQO process are common to both characterization and final status surveys. In the final three steps, there is significant difference in interpretation and application to the characterization survey.

The fifth step in the DQO process is the specification of a decision rule. For the final status survey Step 5 usually takes the form of a statistical hypothesis test. For a characterization survey such a highly structured rule will not generally be appropriate. However, in characterization surveys it should be possible to identify:
- a range of results that clearly indicates that there is no need for remediation in an area;
- a range of results that clearly indicates that there is need for remediation in an area; and
- an intermediate range of results that may indicate the need for more data before a decision is made.

Such a scheme is loosely patterned after sequential testing procedures, but is primarily intended to differentiate the easy decisions from the more difficult

ones so that more resources can be devoted to the areas that need it.

Specifying acceptable limits on decision errors is the sixth step in the DQO process. For final status surveys, Step 6 means specifying decision error rates for Type I (false positive or false rejection) errors and Type II (false negative or false acceptance) errors for statistical hypothesis tests. Again, such precision is usually neither desirable nor necessary in a characterization survey. In a final status survey, the decision errors are used to determine the number of samples it is necessary to collect. The same is true for the characterization survey, except that extensive use of professional judgement is made to balance the costs of additional measurements against the risk of drawing the wrong conclusion from the data.

Optimizing the design of a characterization survey (step seven of the DQO process), involves using all the information available, together with professional judgement, to assess the worth of the information to be gained from additional data in terms of increasing confidence in a remediation decision. This is where the width of the "gray region" expressed by choice (c) of Step 5 is used to separate, as efficiently as possible, the easy decisions from the difficult ones. The cost of data collected early in the characterization can be balanced against the possibility that new data will be needed. The consequence of incorrectly classifying an area as needing remediation when it does not should be balanced against the cost of discovering during a final status survey that an area thought to be clean actually is not. Remediation costs are also balanced against the cost of characterization measurements.

The seven specific elements of the overall DQO process, outlined above, are addressed by the ASTD project team through development of individual project-specific survey plans (PSSPs) in support of individual BGRR D&D campaigns. The PSSP considers the goals of the intermediate D&D objective, the baseline characterization elements, and the targeted components of the facility, to identify the scope and content of the *in situ* characterization efforts using the DQO process. The PSSP provides details on field of view, shielding, and detection levels necessary for the *in situ* evaluations and identifies sample number designations for items and views of items for tracking and reporting purposes.

3.3   Project Quality Assurance
Continuity of spectrum analysis and interpretation among the PSSPs is assured by compliance with the ASTD Project *In Situ* Analysis Quality Assurance Project Plan (QAPP). This QAPP provides a description of the individuals, organizational responsibilities, and control measures necessary to achieve, verify and demonstrate compliance with both federal and industry quality assurance requirements. This QAPP has been developed using the guidance in EPA QA/G-5 [ref 11] to ensure that appropriate requirements for project data quality have been adequately addressed. The incorporation of EPA QAPP guidance into the ASTD Project QAPP is demonstrated in Table 3-2.

In addition to the Project QAPP, instrument operations and spectrum analysis were standardized by the use of written procedures. These procedures included:

- SOP - DAT1, *Standard Operating Procedure for Gamma Spectrum Acquisition Using Canberra ISOCS System*, version 1, August 19, 1999. This procedure is used to acquire a gamma radiation spectrum for determining <u>qualitatively</u>, the gamma emitting radionuclides *in situ* and in samples. This procedure describes the steps necessary for routine operation of the Canberra gamma spectroscopy system, GENIE-2000 and ProCOUNT. Instructions are provided for identifying hardware components, proper equipment setup, routine instrument operation, in-field spectrum acquisition (sample counting), and spectrum file management.

- SOP - DAT2, *Analysis of Gamma Spectrum Files Using Canberra ISOCS System [Software ver 3.0]*, version 3, February 23, 2000. This procedure describes the steps necessary for <u>quantitative</u> gamma spectrum analysis and reporting using version 3.0 of the Canberra In Situ Object Counting System (ISOCS) Software. Instructions are provided for software environment setup, routine spectrum analysis, software modifications for specific acquisition and analysis requirements, and spectrum file management. The procedure covers the computation steps following spectrum acquisition (accomplished using SOP-DAT1), the development of a quantitative result from the gamma radiation spectrum and acquisition geometry parameters.

- ERD-OPM-4.3, *Procedure for ASTD Sample Processing to Support BGRR Decommissioning Operations*, revision 0, July 12, 2000. This is a work flow procedure to ensure proper, safe, and consistent handling and processing of potentially contaminated samples by instrument operators.

Table 3-2. EPA Requirements to Project QAPP Crosswalk

QAPP ELEMENT (defined in EPA QA/R-5)	Location in ASTD Project QAPP
A. Project Management	
A-1 Title and Approval Sheet	Cover Page
A-2 Table of Contents	Page ii
A-3 Distribution List	Page i
A-4 Project/Task Organization	§ 2.1
A-5 Problem Definition/Background	§ 1.1
A-6 Project/Task Description	§ 1.2
A-7 Quality Objectives and Criteria for Measurement	§ 3.1
A-8 Special Training Requirements / Certifications	§ 2.3
A-9 Documentation and Records	§ 6
B. Measurement / Data Acquisition	
B-1 Sampling Process Design	§ 3.2
B-2 Sampling Methods Requirements	§ 3.3, SOP-DAT1
B-3 Sample Handling and Custody Requirements	§ 3.4
B-4 Analytical Methods Requirements	§ 3.5, SOP-DAT2
B-5 Quality Control Requirements	§ 4.1
B-6 Instrument/Equipment Testing, Inspection and Maintenance Requirements	§ 4.2
B-7 Instrument Calibration and Frequency	§ 4.3
B-8 Inspection/Acceptance Requirements for Supplies and Consumables	§ 5
B-9 Data Acquisition Requirements (Non-direct measurements)	§ 5
B-10 Data Management	§ 6
C. Assessment / Oversight	
C-1 Assessment and response Actions	§ 7.1
C-2 Reports to Management	§ 7.2
D. Data Validation and Usability	
D-1 Data Review, Validation and Verification Requirements	§ 8.1
D-2 Validation and Verification Methods	§ 8.2
D-3 Reconciliation with Data Quality Objectives	§ 8.3

Ref: U. S. EPA, *EPA Guidance for Quality Assurance Project Plans (EPA QA/G-5)*, EPA/600/R-98/018, U. S. Environmental Protection Agency, Washington, DC. February 1998.

3.4   Data Quality Indicators

Data Quality Indicators (DQIs) are qualitative and quantitative descriptors used in interpreting the degree of acceptability or utility of data. The principal DQIs are precision, bias, representativeness, comparability, and completeness.   Secondary DQIs include sensitivity, recovery, memory effects, limit of detection, repeatability, and reproducibility.   Establishing acceptance criteria for the DQIs sets quantitative goals for the quality of data generated in the analytical measurement process.   Quantitative DQIs will be discussed in Section 4, below. The non-quantitative aspects of DQIs are addressed here.

3.4.1 Representativeness. Representativeness refers to the degree to which a measurement reflects the condition at a location or whether a group of measurements reflects the conditions in a particular area.   Generally, one desires that measurements (or samples) provide an estimated value of a mean radionuclide concentration that in turn yields a dose estimate (and thus risk) to the average member of a critical group for a particular scenario.   In order to achieve representativeness, a number of samples or measurements in a given area would be required in order to achieve a given confidence level or power using a statistical test.

Representativeness is affected by the heterogeneity of the contaminants in the media under investigation. Perhaps more than any other factor, field and laboratory measurements may differ at any particular measurement location due to the effects of heterogeneity. Heterogeneity can exist in both the lateral and depth distribution of a contaminant and can take the form of changes in concentration across various distances:
•   a centimeter or less, as would result from hot particles;
•   meters, as might occur from dumping and localized spills; and
•   tens or hundreds of meters, as from up-wind airborne sources.

Survey designs incorporate techniques and sample/measurement densities to accommodate these variations.   The number of measurements and the standard deviation about the mean are fundamental parameters to judge whether the mean concentration that is measured is within a certain confidence limit. These parameters can be used to compute the "t" statistic or applied to other statistical tests.

Where variations in concentration occur on a scale of tens of meters or more, it can be expected that either field measurements or soil sampling will give similar results.

It is where variations on the scale of a few meters or less occur that agreement in the results between any pair of measurements (i.e., two soil sample results or a field measurement and a soil sample result) might suffer. However, if the mean concentration in an area must be determined, a sufficient number of measurements or samples can ultimately yield the same average result, regardless of where the measurements or samples are taken within the area under investigation.

Depending upon the objectives of a measurement program, a field method could inherently have an advantage over discrete sampling. If the viewing area of a field instrument is significantly larger than the area of a soil sample, a set of field measurement results would tend to show a smaller standard deviation as compared to a set of soil sample data in a heterogeneous area. The mean obtained for a given number of field instrument measurements would then be more representative of the true mean than the mean obtained from a similar number of discrete samples.   A wide measurement area represented by a field method could also be consistent with the assumptions of a dose model such as RESRAD, which uses the average concentration over a large contaminated area.

The *in situ* measurement might also be more representative of actual radioactivity concentrations. Since samples in the laboratory are often screened to remove rocks, sticks and non-soil matter and are almost always dried before analysis, the laboratory concentration result is consequently biased high. The *in situ* analysis measures the soil "as found", which is more representative of the actual conditions, but is usually lower in magnitude than the laboratory result.

Because the *in situ* field of view of the ISOCS is greater than the area of an individual sample, the ISOCS measurements will generally be more representative of the average contamination in an area than a single sample with much smaller support. In general, up to ten or more samples may be required to determine the average concentration comparable to a single ISOCS wide-area measurement.

3.4.2 Comparability. Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpretation [ref 11]. Comparability is one of the principal Data Quality Indicators (DQIs) identified by the US EPA. The DQIs are quantitative and qualitative descriptors used in interpreting the degree of acceptability or utility of data.

Comparability is a critical factor that readily establishes the validity of a field technique. It can be established by

performing a study where field measurement results are compared to those given by an independent technique such as sampling and lab analysis. In some situations, it may be possible to compare two different field techniques. Numerical criteria proposed to determine an analytical method data quality level [ref 9] are provided in Table 3-3.

In performing a direct comparison study, it is important to establish that the two techniques are measuring the same thing. For instance, a technique that measures a contaminant concentration in the surface soil may compare poorly to one that is integrating down to greater depths. This situation would result where there is a non-uniform concentration depth profile of the contaminant. Where comparisons are made to soil samples, core depths can be adjusted to better match the effective viewing depth of the field measurement. The lateral distribution of the contaminant concentration across the ground could also be a factor. In this situation, compositing samples may be required to yield a better average with which to compare a field technique.

Table 3-3. Criteria for Categorizing Data Quality Level

Data Quality Level	Coefficient of Variation	Relative Percent Difference
Definitive Level	$0.85 < R^2 < 1.0$	RPD < 10%
Quantitative Screening Level	$0.70 < R^2 < 1.0$	RPD < 20%
Qualitative Screening Level	$R^2 < 0.70$	20% < RPD; False Negative rate < 10%

ref: U. S. EPA, *EPA Environmental Technology Verification Report: Field Portable X-ray Fluorescence Analyzer*, EPA/600/R-97/150, Washington, DC. March 1998.

4.0   COMPARABILITY DEMONSTRATIONS

An objective of this ASTD project is to document the comparability and quality of the ISOCS system field measurements. However, data "quality" or "comparability" as a concept is meaningful only when it relates to the intended use of the data. Data quality indicators, yardsticks for judging whether or not the data set is adequate, are essential criteria for ensuring that data fulfill the overall DQOs for the project. The context of the use of the data set is the basis for establishing data quality indicators during the planning phase of the DQO process.

The data quality assessment process is the statistical and scientific evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use. The DQA process addresses two fundamental questions [ref 12]:
•   Can the decision (or estimate) be made with the desired confidence, given the quality of the data set?
•   How well can the sampling (in this case the *in situ* analysis) design be expected to perform over a wide range of possible outcomes?

Note that the first question does not require that data from two measurement methods produce the same numerical result. It is the decision drawn from the data that must be the same. During a characterization phase project, less correspondence in reported results may be acceptable, while for the determination of unrestricted release less variation in the data sets might be required. The degree of acceptable correspondence or variation required is established in the DQO process. The second question recognizes that the measurement method performance must be understood over a wide range, so that its application for various decisions may be evaluated in the DQO planning process.

In this section, the data quality indicators are assessed in the context of the second question: If the ISOCS *in situ* analysis is used in an environmental/D&D study, would the data be expected to support the intended use for various decisions and with what desired level of confidence?

Initially, the quantitative data quality indicators of sensitivity, precision, accuracy, and detection limit are assessed. Then the issue of comparability is addressed by reviewing the implementation of ISOCS analysis for two data sets:
•   ISOCS analysis of *ex situ* samples, in a field laboratory set-up; and

• ISOCS analysis of *in situ* surface soil, the most common use for *in situ* gamma spectrometry.

Finally a powerful use of the ISOCS system, for objects that cannot be evaluated by conventional methods, is discussed.

4.1 Benchmarking Data Quality Assessment

As part of the deployment of the ISOCS, the BNL ASTD Project needed to demonstrate that this system provides data of sufficient quality for their intended use, compared to the baseline technology of collecting samples for laboratory analysis. The demonstration of data quality involves the assessment of data quality indicators, indicators that provide quantitative and qualitative measures of the degree of acceptability or utility of the data.

One aspect of comparability of the ISOCS measurements relies on the validity and reproducibility of the ISOCS mathematical efficiency computation. Another aspect is the stability and precision of repeated measurements. The sensitivity of the measurement to the interaction between size of the *in situ* field of view (FOV) and the size of the object are important to understand. The assessment of these indicators of data quality form the basis for confidence in the comparability of the analysis method or system.

4.1.1 Assessment 1: Instrument Sensitivity to Source Width. For analysis performed in the laboratory, the sample is finite and well defined by the physical container dimension. For analysis performed *in situ*, it is necessary to identify the lateral boundaries of the detector FOV in order to define what "sample" is actually being analyzed. This can be easily accomplished with the ISOCS efficiency computation code by calculating the efficiency response to a series of virtual contamination sources.

To assess the influence of source diameter, the detector efficiency response was calculated under the following simulated geometry conditions:
• a circular contaminated soil layer, 1.6 g/cm^3 density, 15 cm (6 inches) thick, lying on the surface, centered on the detector axis,

• a uniformly mixed contaminated layer with normalized activity concentration of 1 pCi/g for gamma energies of 59.5 keV (Am-241), 661.6 keV (Cs-137), 1173.2 keV (Co-60), and 1460.8 keV (K-40),

• a BEGe detector oriented to look vertically downward from a distance of 1 meter (39.4 inches) above the soil surface, and

• detector shielded by 44 mm (1.7 in) lead annular side shields.

The source diameter was increased step-wise from 0.5 m (18.7 in), and the efficiency was re-calculated at each diameter until the difference in detector efficiency with a change in diameter varied less than ± 0.5%. The calculated efficiency was then normalized by dividing by the maximum calculated efficiency for that energy.

Calculations were performed for two cases:
• Without a collimator, providing a 180° or 2 pi FOV; and
• With the 90° FOV collimator.

The results of the simulation are shown in Figure 4-1 for the 180° FOV and in Figure 4-2 for the 90° FOV.

Many studies of *in situ* analysis of large areas assume an area of approximately 10 meters diameter is "seen" by an unshielded detector [ref 6, ref 14]. The use of the annular shields illustrates that 95% of the BEGe response is achieved from radionuclides in a diameter of approximately 6.4 m (21 ft) for 59.5 keV (Am-241) to 7.6 m (25 ft) for 1460 keV (K-40). The use of the annular shields reduces the influence of adjacent, interfering sources.

With the 90° FOV collimator, the area "seen" by the BEGe detector varies little with gamma ray energy, as shown in Figure 4-2. What should be noted for the 90° FOV is the penumbra effect of the collimator for all energies. For a "90° FOV", at 1 meter distance the field should have a 2 meter diameter. The curves in Figure 4-2 show that fully 22% to 27% of the instrument response comes from radioactive material beyond the assumed edge at 2.0 meters. The 95% response level occurs for a field diameter of approximately 2.75 meters, which corresponds to a "108° FOV."

The Canberra "30° FOV" collimator is designed for use with a standard "co-axial" HPGe detector, and it is incompatible with the BEGe detector. The flat shape of the BEGe results in the 30° FOV collimator shielding over 80% of the active BEGe detector region. This shielding decreases the sensitivity of the detector which increases the time to acquire a spectrum with enough counts to provide minimal statistical uncertainty. The collimator also increases the ISOCS efficiency calculation time dramatically.

Figure 4-1. ISOCS detector response to surface soil contamination layer diameter
at 1 meter with 180° FOV collimator and 44 mm annular shields

Figure 4-2. ISOCS detector response to surface soil contamination layer diameter
at 1 meter with 90° FOV collimator and 44 mm annular shields

When using any collimator to reduce interference from an adjacent radionuclide source, the effect of penumbra penetration should be considered. The "effective" diameter for the 90° FOV collimator with the BEGe detector is approximately 40% larger than would be expected by "sharp" geometry alone. While the software correctly handles the penumbra penetration effect, when positioning or aiming the detector, the operator should be aware that adjacent objects may influence the measurement when near the "edge" of the FOV.

There are "effective" source dimensions, based on parameters of source distribution and FOV collimators. The use of greater dimensions in the geometry model enables the exact mathematical solution, but contributes little to the effective activity measurement reported by the ISOCS calculation. The code run time necessary to determine the detector-geometry efficiency can be reduced by choosing "effective" source dimensions, with impact on the analytical results that is insignificant when compared to other uncertainties in the analysis.

4.1.2 Assessment 2: Instrument Sensitivity to Source Thickness. As with the diameter, for analyses performed *in situ* there is an uncertainty in the thickness of the radiation source that is being measured. For physical samples, the depth of the sample layer is usually well defined and recorded when the sample is collected. Gamma photons of different energies are attenuated differently for the same thickness of a medium, so the detector response would be expected to differ also. Thus to have confidence in the *in situ* analysis, it is necessary to assess the influence of the source thickness in order to define what "sample" is actually being analyzed. This can be easily accomplished with the ISOCS efficiency computation code by calculating the efficiency response to a series of virtual contamination sources.

The detector efficiency response was calculated under the following simulated geometry conditions:

- a circular contaminated soil layer, 1.6 g/cm^3 density, 10 m (394 inches) diameter, lying on the surface, centered on the detector axis;

- a uniformly mixed contaminated layer with normalized activity concentration of 1 pCi/g for gamma energies of 59.5 keV (Am-241), 661.6 keV (Cs-137), 1173.2 keV (Co-60), and 1460.8 keV (K-40);

- a BEGe detector oriented to look vertically downward from a distance of 1 meter (39.4 inches) above the soil surface; and

- detector shielded by 44 mm (1.7 in) lead annular side shields.

The source thickness was increased step-wise from 1.0 cm (0.4 inch), and the efficiency was re-calculated with each thickness until the difference in detector efficiency with a change in thickness varied less than ± 0.5%. The calculated efficiency was then normalized by dividing by the maximum calculated efficiency for that energy.

Calculations were performed for two cases:
- Without a collimator, providing a 180° or 2 pi FOV; and
- With the 90° FOV collimator.

The results of the simulation are shown in Figure 4-3 for the 180° FOV and in Figure 4-4 for the 90° FOV.

The results in Figure 4-3 and Figure 4-4 disclose that there is little difference in detector response with source thickness between the two FOVs evaluated. The figures do demonstrate the magnitude of the difference on response depending on the energy of the gamma ray. For many *in situ* applications, the depth of the field of view is assumed to be 10-15 cm (4-6 inches), usually with the wording like "...average thickness for medium to high energy gamma rays" [ref 6, ref 7, ref 14].

For low energy gammas like 59.5 keV(Am-241), 50% of the detector response is to radioactivity in the top 1.2 cm (0.5 inch) of soil and 95% of the response is from approximately 6.5 cm (2.5 inches). Conversely, for a high energy gamma emitter, such as 1173.2 keV (Co-60), 15% of the response is from activity deeper than 15 cm (6 inches).

As with the source diameter discussed in Section 4.1.1 above, there are "effective" source thicknesses, based on source parameters and FOV collimators. The use of greater dimensions in the model contributes to the exact mathematical calculation, but contributes little to the effective activity measurement of the ISOCS calculation. The code run time necessary to determine the detector-geometry efficiency can be reduced by choosing "effective" source dimensions, with insignificant impact on the analytical results.
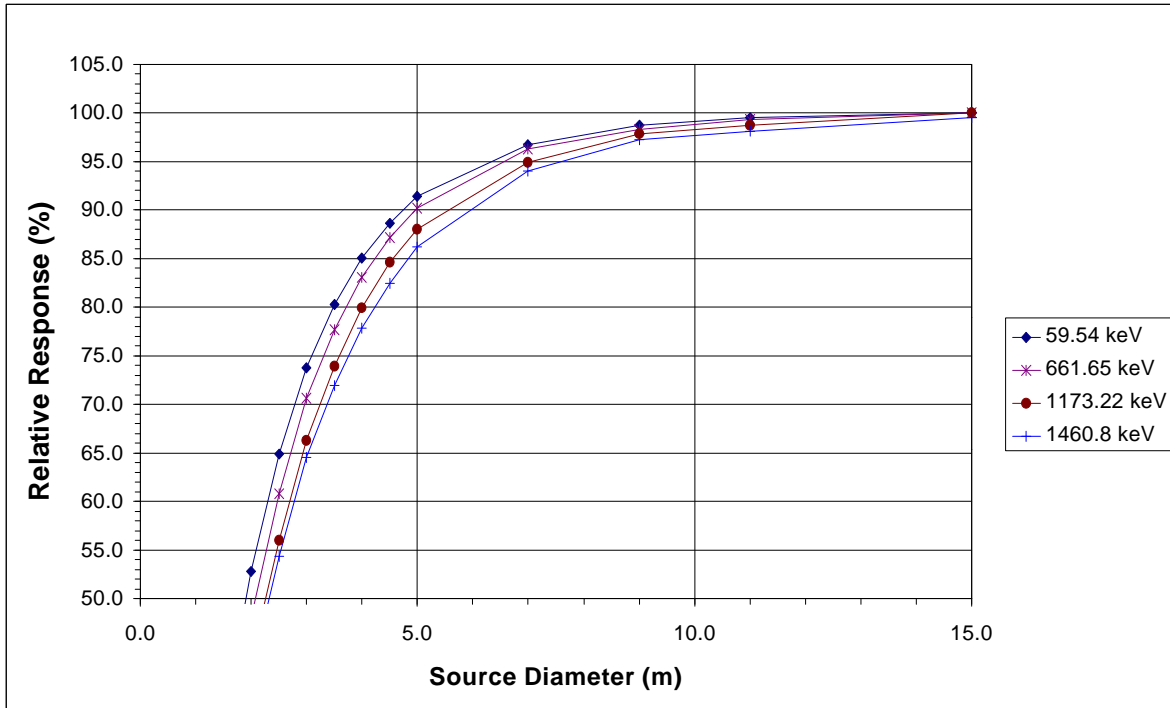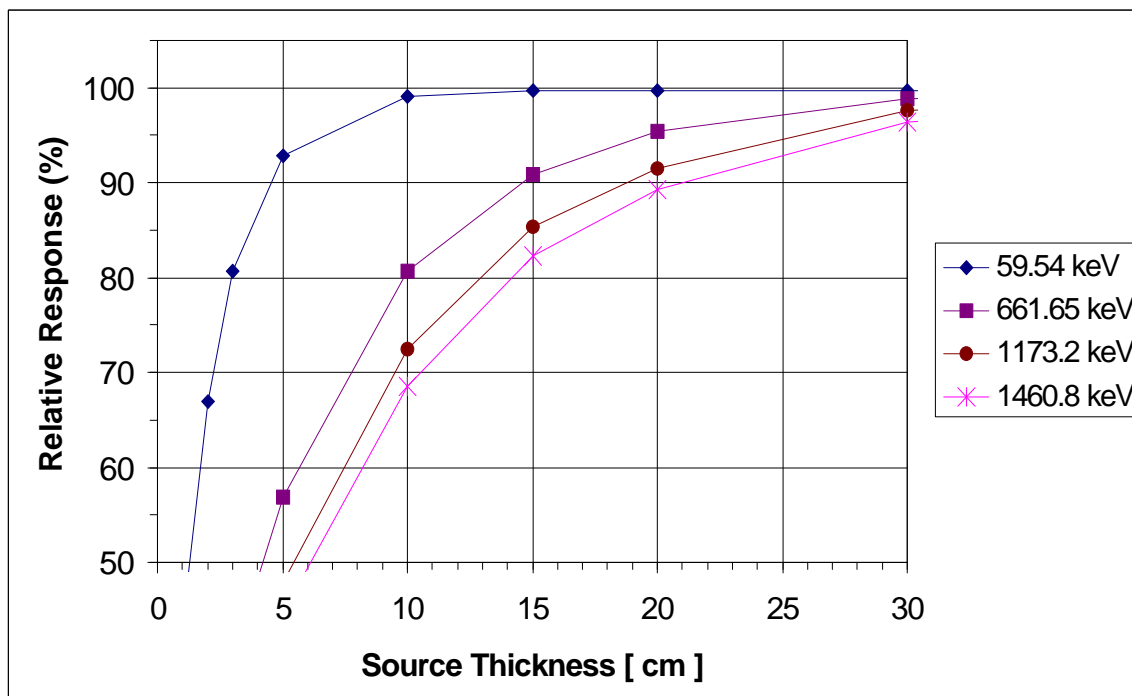
Figure 4-3. ISOCS detector response to surface soil contamination layer thickness
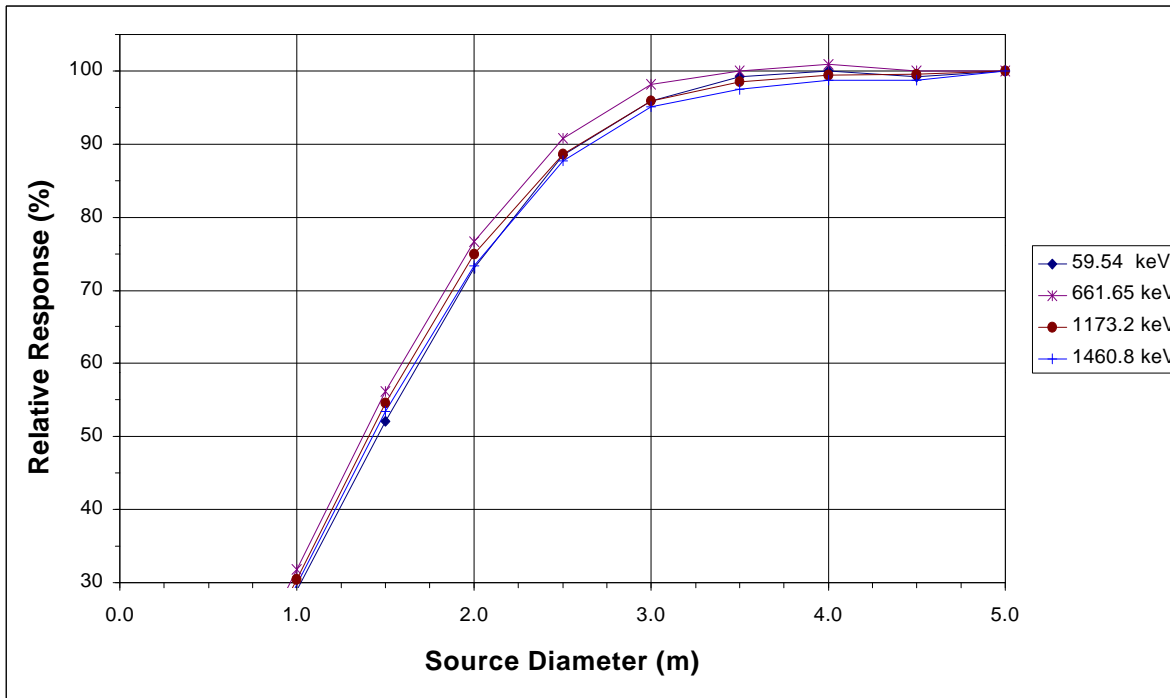at 1 meter with 180° FOV collimator and 44 mm annular shields
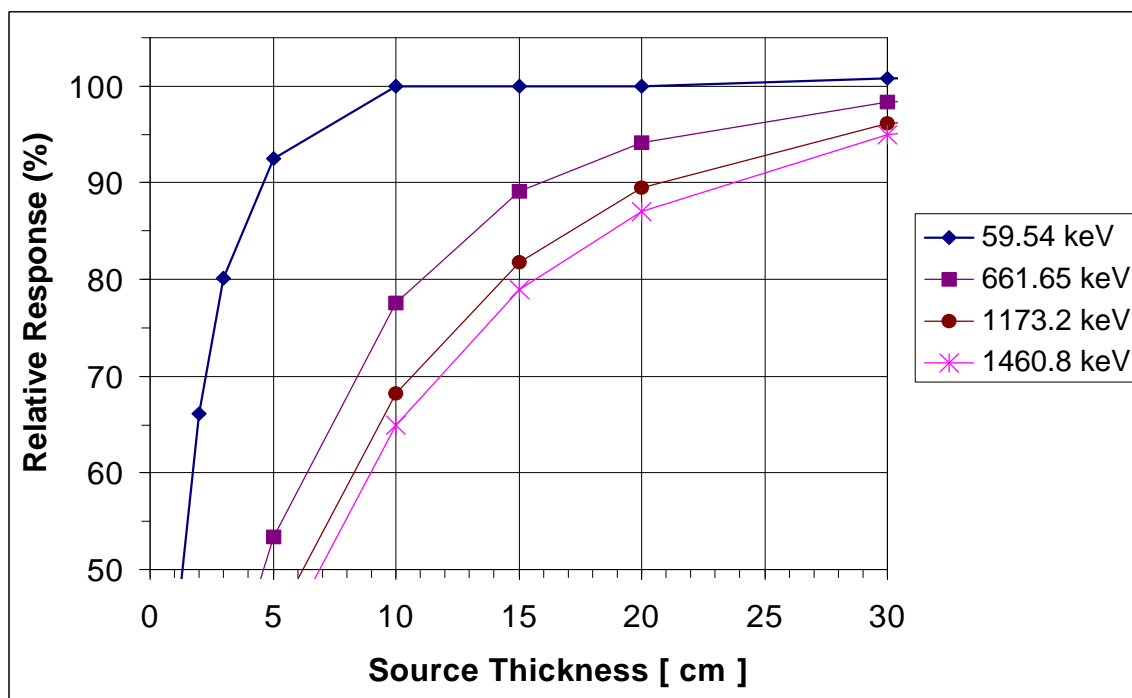
Figure 4-4. ISOCS detector response to surface soil contamination layer thickness
at 1 meter with 90° FOV collimator and 44 mm annular shields

4.1.3 Assessment 3: Analytical Accuracy to a Point Source. Analytical accuracy is an important, critical data quality indicator. The ISOCS code verification by Canberra Industries, discussed in Section 2.4.6 above, demonstrated internal consistency and accuracy of the analysis software itself. A benchmark for use of the system is that local operators should demonstrate the capability of interpreting and using the ISOCS computation methods to achieve accurate results.

For this assessment a spectrum of an NIST traceable Eu-152 source in a 0.5 mm capsule was acquired for 10 minutes. The source was positioned perpendicular and 30.5 cm away from the center of the detector end-cap, with the 47 mm annular shields around the detector. This geometry corresponds to the "laboratory counting" *in situ* geometry category identified in the Canberra Industries validation tests, a relatively high activity close to the detector (section 2.4.6.2 above). The quantification accuracy was calculated by using the simple cylinder ISOCS efficiency geometry model. An ambient background spectrum was accumulated with the source absent and demonstrated that Eu-152 was not present in the detector field of view. The results of the analysis are provided in the Table 4-1.

As shown in Table 4-1, the ISOCS system measurement is in excellent agreement with the manufacturer-specified source activity. Performance of this benchmark demonstrated the capability to use the ISOCS geometry templates to accurately model a physical exposure geometry and come up with accurate activity determinations.

4.1.4 Assessment 4: Analytical Accuracy to an Extended Source. For an assessment of analytical accuracy for the "field counting" *in situ* geometry category, *in situ* spectra were accumulated at an agricultural test pad at BNL. The accuracy of the *in situ* measurements is assessed by comparison to laboratory

Table 4-1. Assessment of Point Source Accuracy

Radio-nuclide	Point Source Activity (μCi)		Per cent Difference
	Manufacturer Specified	ISOCS Measured	
Eu-152	0.714 ± 0.036 [1]	0.699 ± 0.022 [2]	-2.1 %

(1)   Activity uncertainty of 5% at 99.7% confidence level, as specified by source manufacturer.

(2)   Measurement errors reported at the 95% confidence level and represent only counting error and ISOCS-generated efficiency errors.

analysis of soil samples collected from the same area. The area is the location designated "*Site X*", where EML conducted an *in situ* intercomparison study in the fall of 1997 [ref 7].

Site X, an approximately 100 m by 100 m area, has been used by EML as a field baseline study area. Gamma-ray-emitting radionuclides are present in the soil at ambient levels of naturally occurring radionuclides (background) and the nuclear weapons test fallout product Cs-137. The prior use of this site and the tilling operations that have taken place over the years make it a fairly homogenous area in terms of the lateral and depth distributions of the radionuclides. In the 1997 study at this site, six organizations participated in an *in situ* gamma ray spectrometer intercomparison, acquiring measurements at each apex of a regular hexagon of 5 m sides. After the *in situ* measurements, the EML collected 19 soil samples on a 5-m triangular grid overlying the hexagon for laboratory analysis to use in evaluating the *in situ* determinations.

The ASTD Project deployed to *Site X* in the fall of 1999 to acquire *in situ* spectra for comparison with the previous study results. Gamma ray spectra were accumulated *in situ* for 20 minutes at the six locations used in the prior study. The BEGe detector was mounted on the mobile cart and oriented to look vertically downward from a distance of 1 meter (39.4 inches) above the soil surface. The detector was shielded by 44 mm (1.7 in) lead annular side shields for a 180° FOV. Surface soil activity at each spectrum accumulation location was quantified using the uniform, circular plane geometry template, (contaminated layer 15 cm thick, 10 m diameter, with soil density of 1.6 g/cm^3). For data comparison, the ASTD ISOCS measurement results were corrected for radioactive decay occurring during the period between the original intercomparison in Fall 1997 and the ASTD measurements in Fall 1999. Results of the in situ measurements and the soil sample analysis are provided in Table 4-2.

In situ measurements with the ISOCS instrument were marginally lower than the results reported by the laboratory (percent difference of the means is 10 %). The low response of the ISOCS instrument can be partially explained by considering the following points that apply to any *in situ* measurement:

- The *in situ* result is for "as found" soil, which contains a non-uniform distribution of uncontaminated rocks and organic material. This material is removed from the sample before laboratory analysis. The extraneous material adds uncontaminated mass to the *in situ* soil that

decreases the reported radionuclide concentration (activity per gram).

- The *in situ* result is for "as found" soil, which contains a non-uniform moisture content, while a laboratory sample is dried before analysis. The uncontaminated moisture adds mass to the *in situ* soil that decreases the reported activity per gram.

For the intercomparison study, the soil activity concentration, reported in Table 4-2 above, was adjusted to account for soil moisture at the time of collection in 1997, i.e., the reported results are for moist soil, not dry. Since the ASTD readings were performed in 1999, some of the difference may be related to different soil moisture, but the values were close enough that further investigation of moisture effects were not deemed worthwhile.

4.1.5 Assessment 5: Analytical Accuracy through Intercomparison. One characteristic of quality sample analysis is the appropriate performance in an intercomparison program. For the baseline of laboratory analysis, intercomparison involves measuring blind samples of calibrated activity and submitting analytical results to the comparison organizer. Both the EPA and the EML coordinate a program of blind sample distribution and intercomparison of laboratory analysis results. For an *in situ* intercomparison, participants mobilize their portable instruments to a common site that has been characterized by the organizer. They then perform the indicated measurements, and submit analytical results for comparison with other participants.

The ASTD project participated in a modified intercomparison by performing measurements at a field site on BNL, where EML conducted an *in situ* intercomparison study in the fall of 1997 [ref 7]. The accuracy of the ASTD *in situ* measurements for the "field counting geometry" category was assessed by comparison to *in situ* measurements performed by other organizations in the same area. In the 1997 study at this site, measurements were performed on a 5 m triangular grid by different pairs of the six participants at each apex of a regular hexagon of 5 m sides. Thus each of the six positions had two reported analyses, a "higher" value and a "lower" value.

The ASTD project accumulated *in situ* spectra for 20 minutes at each of the six locations used in the prior study. The BEGe detector was mounted on the mobile cart and oriented to look vertically downward from a distance of 1 meter (39.4 inches) above the soil surface.

Table 4-2. Analytical Accuracy for a Large Area Source

Cs-137 Activity in Surface Soil (pCi/g)	ASTD Project *in situ* measurements at six locations	EML analysis of 19 soil samples
Mean	0.194	0.216
Median	0.188	0.211
Standard Deviation	0.026	0.027
Maximum Observed	0.243	0.281
Minimum Observed	0.174	0.181

Note: Laboratory analysis results from the EML study report [ref 7].

The detector was shielded by 44 mm (1.7 in) lead annular side shields for a 180° FOV. Surface soil activity at each spectrum accumulation location was quantified using the uniform, circular plane geometry template, (contaminated layer 15 cm thick, 10 m diameter, with soil density of 1.6 g/cm^3). For data comparison, the ASTD ISOCS measurements were corrected for decay during the time elapsed between the original intercomparison study in Fall 1997 and the ASTD measurements in Fall 1999. Figure 4-5 displays for each of the six positions, the BNL ISOCS measurement as well as the two measurements reported by the EML study.

The BNL-ASTD results were greater than the higher measurement at one position, between the two measurements for three positions, and less than the lower measurement for two positions. For the area as a whole, the ASTD *in situ* measurements determined a mean concentration (and 2 sigma uncertainty) of 0.19 ± 0.05 pCi/g, while the intercomparison participants average concentration (and 2 sigma uncertainty) was 0.20 ± 0.04 pCi/g. The 5% lower response of the ASTD measurement could be due to differences in the soil moisture due to the time elapsed between measurements. The ASTD performance is in line with other participants performance and demonstrates the capability to perform *in situ* analysis of a large source geometry.

Comparison of Cs-137 Analysis
in situ Analysis vs *in situ* Analysis
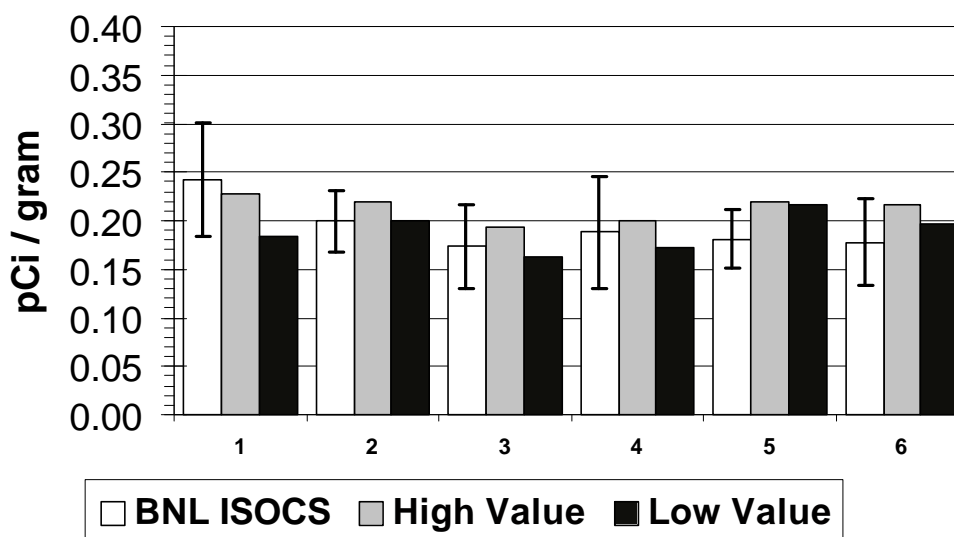
Figure 4-5. Comparison of ISOCS *in situ* analysis to inter-comparison study

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4.1.6 Assessment 6: Analytical Precision Over an Extended Period. An important QC indicator of data quality is analytical precision over an extended time period. Often referred to as "reproducibility", this aspect of precision evaluates the day-to-day stability of the instrument and/or the analysis method for periods of months to years. The data is often graphed as a control chart with bounds indicated for awareness and intervention.

To assess ISOCS system stability the spectrum from a nominal 1 microCurie source of Eu-152 is acquired in a fixed geometry each day of operation. The DQIs tracked and the limits on each are identified in the QAPP [ref 8] and are listed in Table 4-3.   The energy calibration and detector resolution elements track the electronic stability. The detector efficiency element is a higher order indicator that includes the analysis software operation, as well as electronic stability of the instrument.   An electronic control chart for each of the QC elements is produced following the daily QC procedure, and is reviewed on line at the laptop computer. An example of a typical control chart is provided in Figure 4-6.

The control chart in Figure 4-6 illustrates the stability and precision of the ISOCS system.   The chart shows response in a narrow band (average = 1.117 μCi,

standard deviation = 0.008 μCi) and an absence of trends. The outliers are few and occur randomly, and were usually corrected by repeating the QC check. Note that the ± 3 sigma intervention limit is only a $\pm 2.1\%$ variation in the activity measurement, indicating that the ISOCS system response is very stable.

Table 4-3. *In Situ* Quality Control Indicators and Limits

QC Element	Investigation Limit	Action Limit
Energy Calibration Low – 122 keV	± 1 keV	± 2 keV
Energy Calibration High – 1408 keV	± 1 keV	± 2 keV
Detector Resolution Low – 122 keV	± 1 keV	± 2 keV
Detector Resolution High – 1408 keV	± 1 keV	± 2 keV
Detector Efficiency Low – 122 keV	± 2 sigma	± 3 sigma
Detector Efficiency High – 1408 keV	± 2 sigma	± 3 sigma

Control Chart on Determination of Activity
Eu-152 at 121.8 keV
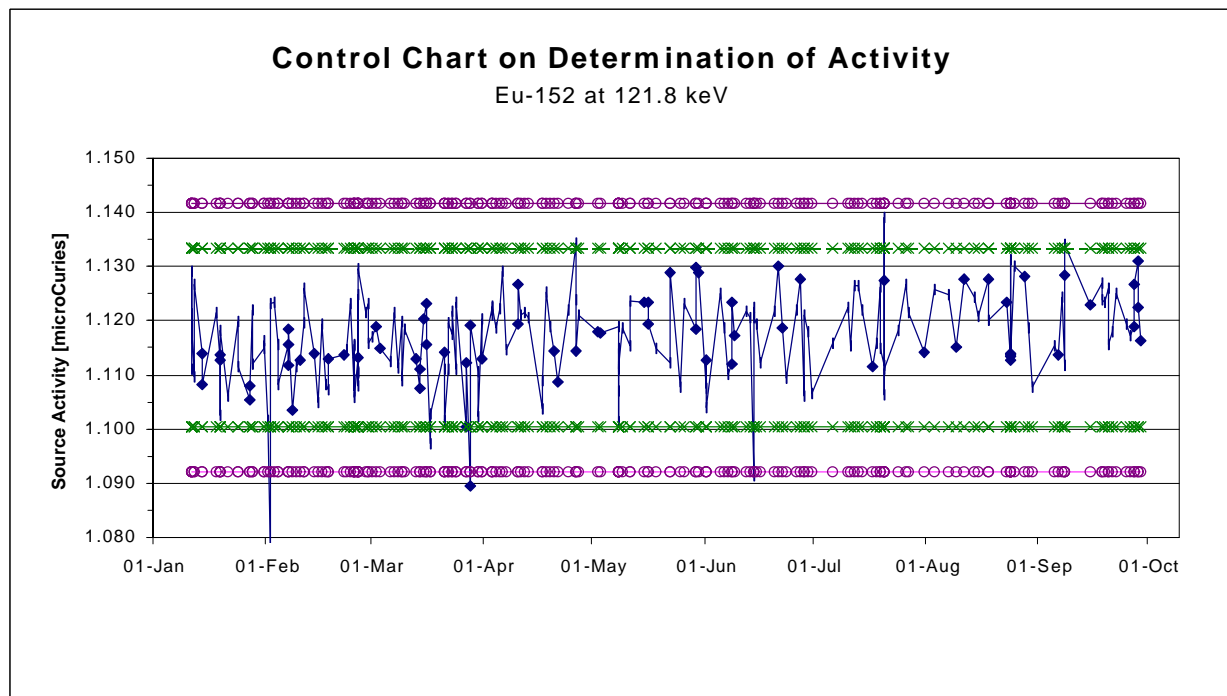
Figure 4-6. ISOCS analytical precision over extended time period

4.1.7 Assessment 7: Analytical Precision in Duplicate Analyses. Precision is a measure of agreement among replicate measurements of the same property, under prescribed similar conditions. Intralaboratory precision represents the agreement expected when a single laboratory uses the same method to make repeated measurements of the same sample. The precision may be expressed as a percentage of the mean of the measurements, the relative percent difference (RPD) [ref 12]. The BNL-ASTD Project QAPP stipulates a repeat analysis at least once per every 20 scans, with the QC action level of an RPD greater than 20%.

The analytical precision of the ISOCS instrument is illustrated by the results of repeat analyses performed during a remedial excavation of a contaminated sump. The ISOCS system deployed to the excavation site and provided rapid analysis on soil contamination, allowing the excavation manager to make real-time decisions on advancing the excavation and on disposition of spoils. To expedite the excavation, samples of suspect soil in 1 liter bottles were analyzed adjacent to the construction site, rather than moving the instrument in and out of the active excavation zone. The samples were modeled prior to the operation using the simple cylinder geometry template for four sample sizes (1/4 ful. 2/4 full. 3/4 full and 4/4 full). Gamma spectra were acquired for 5 minutes, the proper model of bottle fullness selected, and

the activity concentration was calculated immediately, available on the screen and stored for later printout.

During the excavation support, 600 samples were analyzed of which 25 were QC repeat analyses. Of the 25 repeat samples, 9 were "Non Detect" on both measurements, one was borderline ("Non Detect" vs 0.3 ± 0.2 pCi/g), and 15 samples had measurable activity. The original and repeat measurements for the 15 samples are provided in Table 4-4.

The results in the table indicate that the ISOCS system is capable of measurements as precise as those performed in a laboratory situation. All values of RPD were within the criteria of the Project QAPP. The largest values of RPD occurred when the activity was small (5~6 pCi/g or less), otherwise the RPD was less than 10% for the sample set.

Table 4-4. Analytical Precision in Repeat Sample Analyses by ISOCS

ASTD Analysis ID	Measured Activity Concentration (pCi/gram) Cs-137		Relative percent difference
	Results	MDC	
SAM00181	93.0 ± 8.7	0.6	1.07%
SAM00202	94.0 ± 8.8	0.7	
SAM00183	19.9 ± 2.0	0.4	0.50%
SAM00203	19.8 ± 2.0	0.4	
SAM00185	3.5 ± 0.5	0.2	12.12%
SAM00201	3.1 ± 0.5	0.2	
SAM00328	204.7 ± 15.9	1.2	2.92%
SAM00335	198.8 ± 15.4	0.9	
SAM00336	50.2 ± 4.1	0.5	0.80%
SAM00358	49.8 ± 4.1	0.8	
SAM00356	2169 ± 165	3.8	0.23%
SAM00357	2164 ± 165	4.0	
SAM00368	5.7 ± 0.6	0.3	15.09%
SAM00391	4.9 ± 0.6	0.3	
SAM00548	356 ± 27.3	1.3	2.77%
SAM00561	366 ± 28.0	1.1	
SAM00563	33.9 ± 2.8	0.6	6.39%
SAM00577	31.8 ± 2.7	0.5	
SAM00562	325 ± 25	1.4	0.61%
SAM00578	327 ± 25	1.6	
SAM00605	75.1 ± 6.0	0.5	2.84%
SAM00608	73.0 ± 5.8	0.6	
SAM00619	0.5 ± 0.2	0.1	0.00%
SAM00625	0.5 ± 0.2	0.2	
SAM00645	0.5 ± 0.2	0.2	0.00%
SAM00646	0.5 ± 0.2	0.2	
SAM00715	14.1 ± 1.3	0.3	5.84%
SAM00716	13.3 ± 1.2	0.3	
SAM00680	88.8 ± 7.1	0.6	4.62%
SAM00684	93.0 ± 7.4	0.6	

4.1.8 Assessment 8: Analytical Minimum Detectable Concentration. An indicator that typically substantiates the data quality of a laboratory method is the limit of detection. The limit of detection is the minimum concentration of an analyte in a specific matrix that can be identified with high probability (usually 95%) when it is present at that concentration. The ISOCS software uses an algorithm based on the Currie method of determining minimum detectable activity (MDA). The Currie method is widely accepted and used as the basis

for much of the laboratory analysis software used in industry [ref 6, ref 4].

The Currie method is based on treating the number of counts, B, in the Compton continuum beneath a gamma radiation photo-peak as a Poisson random variable, and the standard deviation of this number is then the square root of B. The minimum number of counts above the Compton continuum which results in an interpretation of detected radioactivity is then a function of the standard deviation (typically about four times the square root of B). Applying the instrument efficiency calibration curve, for the matrix and geometry of the spectrum acquisition, to this minimum count produces the MDA or the minimum detectable concentration (MDC), depending on the definition of the efficiency calibration.

Typical MDCs for the ISOCS system are provided in Table 4-5. These values are for common ISOCS uses or geometries that occurred during the program duration. The tabulated values are the averages of MDCs reported from 5 different positions/samples in each category in which none of the four radionuclides was detected.

The results in the table are indicative of the detection limits of the ISOCS in typical *in situ* and sample counting geometries that occurred in the D&D project. The magnitude of the MDCs are small, and much less

Table 4-5. ISOCS Minimum Detectable Concentrations for Various Geometries

Spectrum Acquisition Conditions and Area or Volume Analyzed	MDC (pCi/g)			
	Co-60	Cs-137	Am-241	K-40
in situ, 90° FOV @ 0.5 m, 1200 sec 4.9 m² or 735 liters of surface soil	0.09	0.12	0.71	0.78
in situ, 180° FOV @ 1.0 m, 1200 sec 20 m² or 3000 liters of surface soil	0.04	0.07	0.30	0.40
in situ, 180° FOV @ 1.0 m, 600 sec 20 m² or 3000 liters of surface soil	0.04	0.08	0.36	1.5
sample in shielded cavity, 300 sec 1 liter of soil	0.30	0.30	0.40	2.0

than typical levels of clean-up goals. The MARSSIM recommends that measurement techniques should be capable of measuring levels below the established clean up goals, and 10-50% of the clean up goal should be the target [ref 13]. The results in the Table 4-5 illustrate that the ISOCS can achieve this target.

It should be noted that the MDC values in Table 4-5 are for samples that have no activity detected. Due to the incomplete interaction in the detector, scattered or partially absorbed high energy gamma rays are detected in the Compton continuum at lower energies, raising the Currie method detection limit for radionuclides with low energy gamma rays. For example, for a soil sample measured in a 1 liter bottle for 300 second acquisition, the MDC for Am-241 shifts from ~0.4 pCi/g when Cs-137 is "not detected" to ~1.0 pCi/g when Cs-137 is present at 100 pCi/g. This phenomena is common to any gamma spectrometer, both ISOCS and laboratory systems.

4.2   Assessment of Comparability

Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpretation. Comparability must be carefully evaluated to establish whether two data sets can be considered equivalent in regard to the measurement of a specific variable or groups of variables. In a laboratory analysis, the term comparability focuses on method type comparison, holding times, stability issues, and aspects of overall analytical quantitation.

There are a number of issues that can make two data sets comparable, and the presence of each of the following items enhances their comparability:

- two data sets should contain the same set of variables of interest;

- units in which these variables were measured should be convertible to a common metric;

- similar analytic procedures and quality assurance should be used to collect data for both data sets;

- time of measurements of certain characteristics (variables) should be similar for both data sets;

- measuring devices used for both data sets should have approximately similar detection levels;

- rules for excluding certain types of observations from both samples should be similar;

- samples within data sets should be selected in a similar manner;

- sampling frames from which the samples were selected should be similar; and

- number of observations in both data sets should be of the same order or magnitude.

These characteristics vary in importance depending on the final use of the data. The closer two data sets are with regard to these characteristics, the more appropriate it will be to compare them. Large differences between characteristics may be of only minor importance, depending on the decision that is to be made from the data.

Two data sets obtained during the performance of the BNL-ASTD Project can be used to demonstrate the assessment of comparability:

- ISOCS analysis of *ex situ* samples, in a field laboratory set-up; and

- ISOCS analysis of *in situ* surface soil, the most common use for *in situ* gamma spectrometry.

4.2.1 ISOCS Sample Analysis vs Laboratory Sample Analysis. A convenient use of the portable gamma spectrometer is in the on-site, *ex situ* measurement of radioactivity in physical samples. In many locations or areas of interest, an *in situ* measurement is impractical:

-- the material of interest is in an area with adjacent radiation sources that interfere with an *in situ* measurement,

-- the material of interest is from an area, such as an excavation or in a sump, where moving the *in situ* instrument requires strenuous efforts and/or impractical delays, or

-- the material of interest is in an area where *in situ* operators do not have the training, medical evaluation, or security clearance to enter.

In these situations, on site field laboratory analysis of *ex situ* samples provides a rapid, economical alternative to shipping to a remote or off-site laboratory. The ASTD project performed a direct comparison of on site field laboratory sample analysis to remote laboratory analysis to demonstrate comparability of the ISOCS system.

4.2.1.1   Sample Collection. A total of twenty-five samples of surface soil were collected from four contaminated locations on the BNL site. The locations were selected for historical knowledge of the wide range of contamination level in the soil. Each sample consisted of 2 liters of material from the surface layer (0-15 cm) which was sieved to remove organic material, rocks and items larger than 6 mm (1/4 in). Each sample component

of sieved soil was combined, thoroughly mixed together and used to fill a 1 liter container. The liter bottles of sample were analyzed on the ISOCS instrument and then packaged and sent off-site for analysis at an analytical laboratory.

4.2.1.2   ISOCS Sample Analysis. The analysis was performed by accumulating *in situ* a gamma radiation spectrum using an ISOCS BEGe detector attached to a computer-based, multi-channel gamma spectroscopy system. The detector, portable cryostat and lead shielding collimators were mounted on the mobile cart support, allowing consistent sample positioning in a vertically upward orientation. The detector was configured using 44 mm lead annular side shields around the detector and 19 mm annular shields above the detector, creating a low-background counting cavity for the 1 liter sample bottles. The sample analysis geometry is illustrated in Figure 4-7 . The gamma spectrum from each sample was evaluated using the ISOCS software, modeling the sample as a uniformly-contaminated, simple cylinder of soil, with density of 1.6 g/cm^3. Results were

Figure 4-7. ISOCS instrument configured for sample analysis

reported as picoCuries/gram (pCi/g).

4.2.1.3   Laboratory Analysis. Analysis of samples by the analytical laboratory was performed in a low-background   shielded cavity, with a Hyperpure germanium detector attached to a computer-based, multi-channel gamma spectroscopy system. Prior to analysis, samples were dried, tumbled with steel shot to homogenize the matrix, and a 150-gram aliquot was sealed in an aluminum/tin can to isolate contaminants and facilitate sample handling. Results were reported as picoCuries/gram (pCi/g).

4.2.1.4   Results. Analysis results for Cs-137 in the samples by the ISOCS instrument and the off site laboratory are provided in Table 4-6 . The only contaminant observed was Cs-137. A plot of the ISOCS results versus the laboratory results is provided in Figure 4-8.

4.2.1.6   Discussion. The graph in Figure 4-8 demonstrates the excellent agreement of BNL ISOCS sample analysis with the laboratory sample analysis results. Indicated on the graph of Figure 4-8 is the least-squares linear regression line with slope 1.00 and correlation coefficient of 0.99. The regression slope indicates that the ISOCS result is equivalent to the laboratory reported result (no bias), with a very strong correlation ($R^2 = 0.99 \approx 1.0$) reflecting little non-random error.
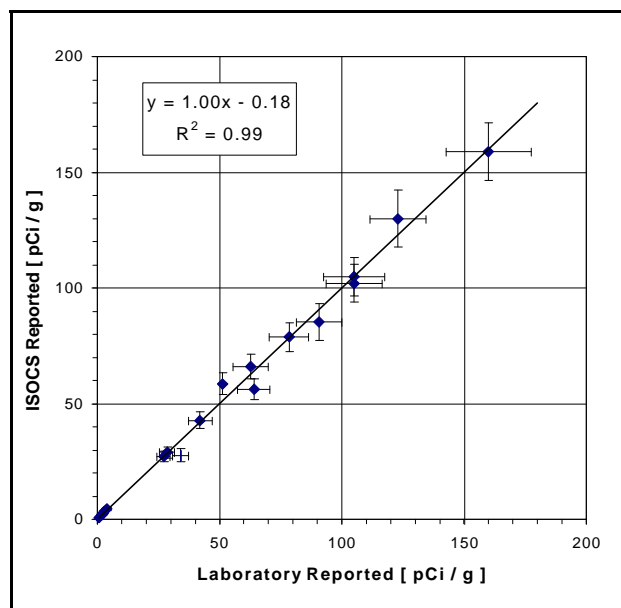
Figure 4-8. Correlation between ISOCS sample and laboratory sample analysis

The absence of bias reflects the conditioning of the samples before analysis:

- extraneous non-contaminated biomass was separated from the matrix by sieving in the field, so both systems analyzed only soil;

- Samples were surface soil from open fallow fields, collected in early March before spring rains, so moisture content was very low; soil drying at the remote lab did little to alter the mass of the sample from what was analyzed on site; and

- Ball milling by the remote laboratory was effective in homogenizing the soil.

4.2.2 ISOCS *In Situ* Analysis vs Laboratory Sample Analysis. An optimum use of the *in situ* technique is in

Table 4-6. Precision in Sample Analysis: ISOCS to Laboratory

Cs-137 Activity Concentration (pCi/g)				
Sample No.	ISOCS		Remote Lab		Percent Difference
	activity	2 sigma	activity	2 sigma	
1	0.65	0.4	0.76	0.09	-14.5 %
2	0.80	0.3	0.85	0.10	-5.7 %
3	1.8	0.3	1.73	0.23	4.0 %
4	2.4	0.4	1.99	0.20	20.6 %
5	3.3	0.5	2.69	0.29	22.7 %
6	4.5	0.6	4.01	0.41	12.2 %
7	27.1	2.3	27.2	2.68	-0.4 %
8	27.6	2.8	34.0	3.30	-18.8 %
9	28.9	2.5	28.6	3.08	1.0 %
10	42.8	3.6	42.1	4.70	1.7 %
11	56.2	4.6	64.0	6.67	-12.2 %
12	58.6	4.8	51.3	6.08	14.2 %
13	66.1	5.3	62.6	7.18	5.6 %
14	78.7	6.3	78.4	8.1	0.4 %
15	85.3	7.9	90.8	9.3	-6.1 %
16	102	8.1	105	11.4	-2.9 %
17	105	8.3	105	12.4	0.0 %
18	130	12.1	123	11.4	5.7 %
19	159	12.5	160	17.4	-0.6 %
20	256	19.7	317	30.8	-19.2 %
21	307	23.7	328	44.0	-6.4 %
22	324	29.8	270	26.4	20.0 %
23	457	41.9	418	39.2	9.3 %
24	494	38.0	441	47.6	11.9 %

the evaluation of large areas of surface soil, prior to or following remediation. Because of the field of view and ability to average heterogeneous distributions, the *in situ* technique provides a rapid, economical alternative to conventional sampling methods. The ASTD project performed a direct comparison of *in situ* analysis to laboratory analysis to demonstrate comparability.

4.2.2.1   Area Evaluated. A 90 m by 40 m irregular area of landscape soil adjacent to the BNL medical facility parking area known to be contaminated with Cs-137 was selected for the comparison. Ten positions were chosen to provide a variety of contamination levels across the range of interest, see Figure 4-9.

4.2.2.2   ISOCS Instrument. The analysis was performed by accumulating *in situ* a gamma radiation spectrum using an ISOCS BEGe detector attached to a computer-based, multi-channel gamma spectroscopy system. The detector, portable cryostat and lead shielding collimators were mounted on the mobile cart support, allowing consistent 1 meter distance and vertical orientation at each position. The detector was configured using 44 mm lead annular side shields and 180^0 field of view, with 5-20 minute accumulation. The gamma spectrum from each position was evaluated using the ISOCS software, modeling the surface as a uniformly-contaminated, circular plane of surface soil, 10 m diameter and 15 cm (6 in) thick. Results were reported as pCi/g.

4.2.2.3   Samples for Laboratory Analysis. At each *in situ* measurement position, soil samples were obtained from four locations: immediately below the ISOCS position and at three equidistant positions 2 meters out, see Figure 4-10. Each component sample consisted of ½ liter of soil from the surface layer (0-15 cm) which was sieved to remove organic material, rocks and items larger than 6 mm (1/4 in). The four components were combined, thoroughly mixed together and placed into a 1 liter container for shipment.

Analysis of samples by the analytical laboratory was performed in a low-background shielded cavity, with a HPGe detector attached to a computer-based, multi-channel gamma spectroscopy system. Prior to analysis, samples were dried, tumbled with steel shot to homogenize the matrix, and a 150-gram aliquot was sealed in an aluminum/tin can to isolate contaminants and facilitate sample handling during analysis. Results were reported as pCi/g.
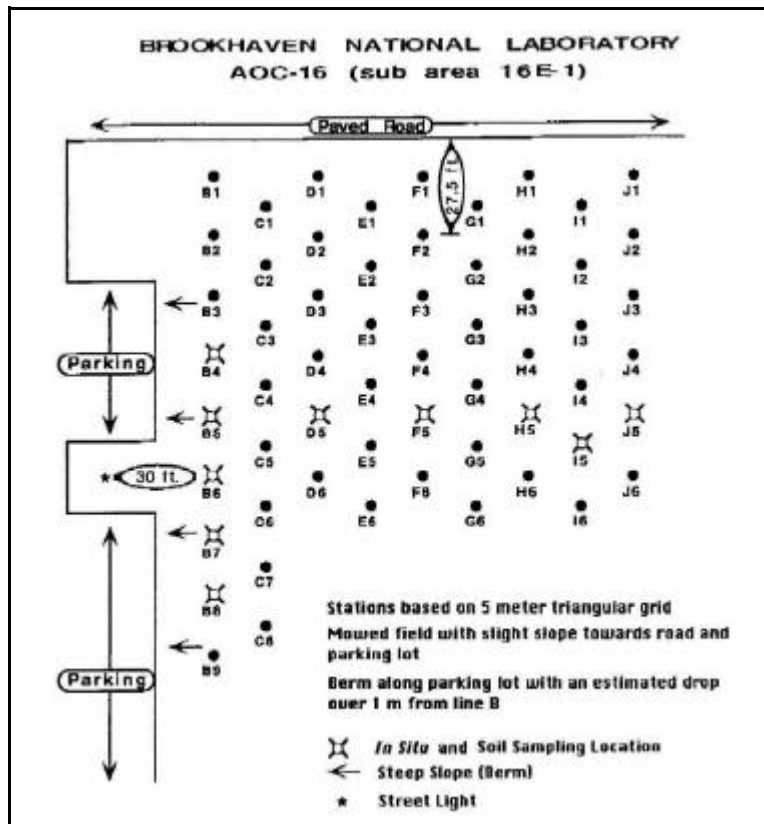
Figure 4-9. Analysis positions for *in situ* vs laboratory comparability
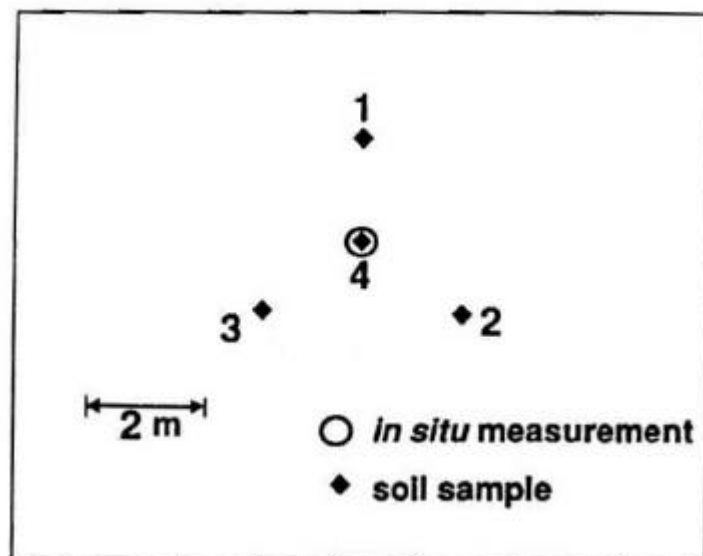
Figure 4-10. Locations of samples for composite at each analysis position

4.2.2.4   Results. A plot of the ISOCS results versus the laboratory results is provided in Figure 4-11. The only contaminant observed was Cs-137.

4.2.2.5   Discussion. *In situ* measurements with the ISOCS instrument were generally lower than the results reported by the laboratory.   Indicated on the graph of Figure 4-11 is the least-squares linear regression line with slope 0.70 and correlation coefficient of 0.98. The regression indicates that the ISOCS result is 70% of the laboratory reported result, with a very strong correlation ($R^2 = 0.98 \approx 1.0$) reflecting little non-random error. The low response bias of the ISOCS instrument can be partially explained by considering the following points that apply to any *in situ* measurement:

   a. The *in situ* result is for as found soil, which contains a non-uniform moisture content, while the laboratory sample is dried before analysis. The un-contaminated moisture adds mass to the *in situ* soil that decreases the reported activity per gram. For a typical range of soil moisture of 5-15 %, the *in situ* result would be 5-18 % lower than the concentration reported by the laboratory.

   b. The *in situ* result is for as found soil, which contains a non-uniform distribution of uncontaminated rocks and organic material. This material is removed from the sample before laboratory analysis.   The uncontaminated material adds mass to the *in situ* soil that decreases the reported activity per gram. For a typical range of non-soil components of 10-20 %, the *in situ* result would be 11-25 % lower than the concentration reported by the laboratory.

4.2.2.6   Conclusions. The ISOCS *in situ* analysis provides an analytical process that yields interpreted results rapidly to support remediation decisions. The *in situ* analysis is correlated directly to sampling and remote laboratory analysis. The *in situ* results are biased low, due to inclusion of moisture, rocks, and biomass that is removed prior to laboratory analysis.   The linear regression correlation provides a numerical coefficient that allows a prediction of laboratory results from the *in situ* results. This coefficient can be used to adjust *in situ* field data to be comparable to data that would result from conventional laboratory analysis.   While the *in situ* measurement more accurately reflects activity con-centrations as they exist in the field, prior reliance on and acceptance of the laboratory value may predicate adjustment of *in situ* data.
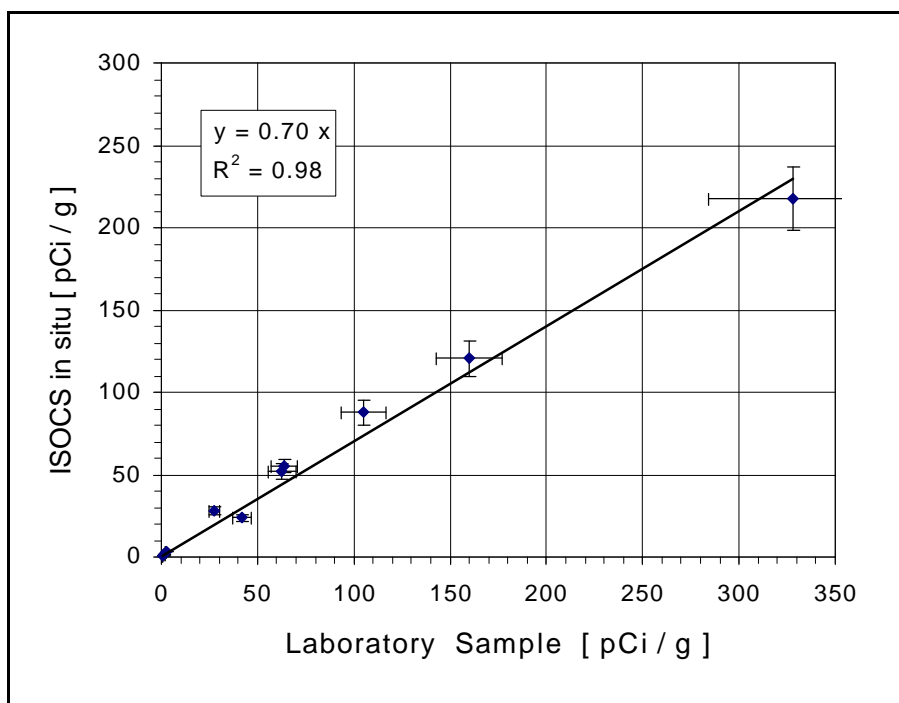
Figure 4-11. Correlation between ISOCS *in situ* and laboratory sample analysis

5.0 ANALYSIS OF DISTINCTIVE OBJECTS NOT EASILY EVALUATED BY CONVENTIONAL METHODS

One of the strengths of the ISOCS mathematical calibration and geometry templates is the capability to quantify objects of all shapes and sizes, without the expense of designing, fabricating and disposing calibration standards in the same geometry and matrix. This capability is demonstrated in the following discussion of analyses performed on distinctive objects during the D&D of the BGRR.

5.1   BGRR Fan House Fans

A typical ISOCS application can be illustrated by reviewing the characterization of core-cooling exhaust fans, prior to their removal, volume reduction, and shipment from the site. Each fan is a massive squirrel-cage type blower, nominally 8 ft x 10 ft x 12 ft, and 14,000 lbs. The fans became internally contaminated, likely as a result of fuel element failure, but the identity, extent, and quantity of radioactive material in the fan internals were unknown. External surveys revealed non-uniform internal deposition with highest readings in the vicinity of the fan volutes, where entrained dust particles would have had a higher probability of settling out due to eddies and dead spaces in air flow currents. Three of the five fans had been upgraded/replaced during the operating life of the reactor. Thus, physical configurations, dimensions, and radionuclide quantities were different from those in the other two fans.

The ISOCS was mobilized to the Fan House containing the five contaminated fans and *in situ* gamma spectra were acquired from Fan #5 (representative of Fans #5 and 4) and Fan #3 (representative of Fans #3, 2, and 1). Figure 5-1 is a photograph of the ISOCS deployed at the BGRR Fan House. Each fan housing was scanned using 44 mm annular shields and 90° field of view collimators to reduce interference as much as possible from adjacent contaminated structures. Because of the equipment layout, there was no position where gamma spectra could be acquired without structural components (concrete supports and carbon steel struts) shielding a portion of the field of view.

The ISOCS cart was positioned so that the detector was oriented diagonally downwards at the fan housing volute bottom, where surveys indicated an accumulation of radioactivity. Spectra were accumulated for 15 minutes each from two symmetric positions: NE of the housing facing SW and NW of the housing facing SE. Equipment setup, spectrum acquisition and equipment-breakdown required less than two hours, with only

minimal health and safety oversight and without breaching of contamination containment barriers.

Radioactivity in the fan housing was modeled as a layer of surface dust, uniformly covering the interior of the carbon steel fan volute (horizontal or diagonal rectangular plane). Due to the complex geometry with intervening structural members, several alternative geometry models were defined. The intervening structural members were adjusted in the models until the results from the symmetric scans were similar. The modeling and analysis of both fans required about six hours.

Figure 5-1. *In situ* measurement of Fan No. 3

Table 5-1. Results of *In Situ* Measurements at BGRR Fan House

Fan Unit	Measured Activity, µCi			
	Cs-137		Co-60	Am-241
	low estimate	high estimate		
Fan No 5	75 ± 3	600 ± 20	≤ 0.1	≤ 180
Fan No 3	114 ± 10	330 ± 30	4.8 ± 0.5	≤ 800

Note: The uncertainties in the table represent ±2ó counting error;
values expressed as "≤"represent an estimate of the bound on the activity and
indicate that the radionuclide was not detected.

The results of the analysis are provided in Table 5-1. The range in the value is representative of the uncertainty in the analysis, and is primarily associated with assumptions on unobserved inner structures of the fan.

The results in Table 5-1 demonstrates that even when using a BEGe detector with enhanced low-energy response, the detection level can still be high when the source is shielded by a highly attenuating medium such as this example, inside a carbon steel fan housing. With the use of the ISOCS modeling software, a quantitative estimate of the activity in the fan was provided in approximately eight hours, without fabricating a physical radioisotope calibration standard, without breaching contaminated barriers, and without handling and transporting contaminated samples.

5.2   Graphite Pile Internals
A complex *in situ* analysis application involved the characterization of the BGRR graphite pile internals to support the determination of pile disposition.   The characterization data was also needed for planning radioactive, hazardous, and mixed waste disposal, assessing potential health and safety hazards during stabilization D&D work, determining ALARA controls, and accurately scheduling the work. The analysis of experimental port penetrations illustrates the use of the ISOCS instrument in this survey, as well as some of the strengths and limitations of the application.

The pile is a 25-ft cube of refined graphite surrounded on all sides by a five-foot-thick, high-density concrete

biological shield. Between the shield and pile are air gaps to allow the flow of cooling air. The interior of the biological shield is faced with steel plates, 6 inches thick, providing structural support and thermal shielding, protecting the concrete from excessive dehydration due to the heat from the core and air. The graphite pile was de-fueled in 1968, with the final fuel shipment being made in 1972.

Access to the pile internals for collecting characterization data was through the penetration openings that exist on each face of the pile biological shield wall. The east and west faces are penetrated horizontally at 30 positions by 4.5-inch square ports for experimental access to the pile interior. Figure 5-2 is a view of the West face of the reactor, the location of several experimental ports visible by the dark, round port covers.

In situ experimental port measurements were performed by aiming the detector, aligned with and centered on the centerline of the experimental port, at each port opening located on the West face of the pile. The steel port covers and plugs were removed prior to each measurement, to minimize structural absorption of gamma rays along the analysis pathway. The resulting exposure condition   was analogous to a 4.5-inch diameter borehole through the concrete shielding into the pile interior.   Figure 5-3 is a photograph of an Experimental Port on the West Face (No. W-54) with the ISOCS instrument in place for spectrum acquisition.

Figure 5-2. West face of the BGRR showing access to experimental port locations

Physical restrictions near the pile face precluded the optimal geometry of a single, reproducible distance from the face at all ports. The *in situ* measurements were performed in conjunction with physical sampling and radiological surveys of the ports, so that radiological controls were in force during the spectrum acquisition. Instrument surveys along the experimental ports indicated maximum exposure rates at the position of the steel plate on the inside face of the biological shield.

The complex geometry of the spectrum acquisition necessitated several simplifying assumptions of the components scanned. The ISOCS geometry template method allowed the assumptions to be logically defined and consistently applied.

Assumptions concerning the geometry model included:

- The use of the thick, dense steel source and the intervening dense concrete absorber in the model causes an individual ISOCS efficiency calculation to take an extended amount of computer processing time, up to 200 minutes or more. Although the physical source resembles a slice of Swiss cheese (a 25 ft x 25 ft x 6 inch slab with 30, 4.5 inch holes), the source "seen" by the BEGe
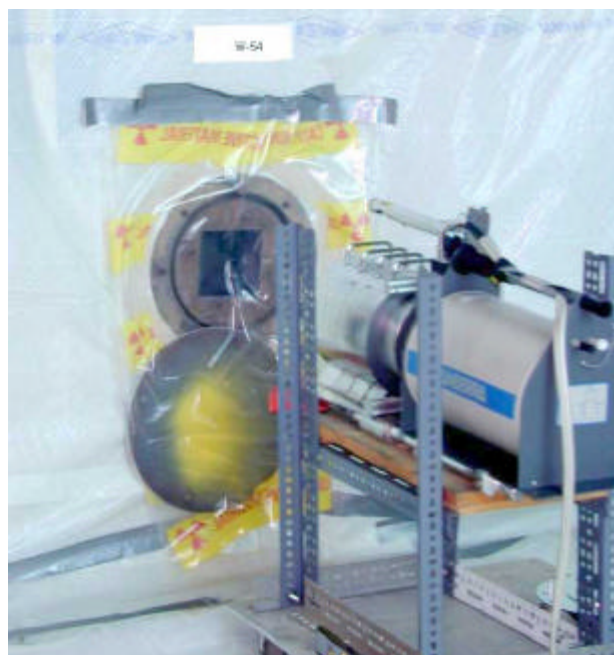
Figure 5-3. *In situ* measurement of pile internals at Experimental Port No W-54.

detector in a scan through an individual port is much less. As discussed in sections 4.1.1 and 4.1.2 above, there are "effective" source dimensions, based on source parameters and FOV collimators; greater dimensions contribute to the "exact" mathematical calculation, but contribute little to the effective activity measurement. Several alternative models of the geometry were performed to establish the "effective" source dimensions in order to reduce the analysis time for individual evaluations.

- The source activity was modeled as an activated, annular, carbon steel ring or pipe, with "effective" dimensions of an inside diameter of 4.5 inches (11.5 cm), a wall thickness of 2 inches (5.08 cm), and a length into the pile of 6 inches (15.24 cm). The steel ring is positioned at the end of the experimental port, 6 feet (183 cm) into the shield and flush to the concrete shielding around the port.

- The model assumes a homogenous distribution of activity throughout the steel source. Activity was calculated as concentration (pCi/g) in the steel to

enable extrapolation to the total activity in the entire steel liner.

- The intervening concrete biological shielding around the port was modeled as an external field of view collimator, 4.5 inches inner diameter, 9 inches (23 cm) outer diameter, and 6 feet (183 cm) in length. The ISOCS software allows the definition of external collimators, as well as two external absorbing layers.

The use of the "effective" dimensions for the steel source and the concrete collimator/absorber in the model reduced the individual ISOCS efficiency calculation times to between 20 and 40 minutes. Different acquisition distances necessitated individual efficiency calculations for each port evaluation. The initial evaluation of several alternative models of the geometry to establish the "effective" dimensions required 10-12 hours – 10-15 minutes of set-up time and 1.0-1.5 hours of computer run time per alternative. The modeling and analysis for 12 experimental ports averaged approximately 3 hours per port. Typical results of the analysis are illustrated in Table 5-2.

Table 5-2. *In situ* Analysis at West Face of BGRR Graphite Pile
Gamma Spectrum Analysis with the ISOCS Instrument

Experimental Port	W-51	W-54	W-56	W-30
ASTD Sample No	IG01231	IG01233	IG01229	IG01220
Radionuclide	Activity Concentration (pCi/g) *note 1*			
Am-241	ND [185,000]	ND [222,000]	ND [189,000]	243,000 ± 226,000 [370,000] *note 2*
Cs-137	ND [6,800]	ND [7,200]	ND [7,200]	1,200,000 ± 104,000 [20,500] *note 2*
Co-60	306,000 ± 12,500 [3,650]	413,000 ± 16,700 [4,300]	346,000 ± 14,200 [4,200]	960,000 ± 38,000 [7,650]
Eu-152	261,000 ± 10,400 [8,400]	316,000 ± 12,600 [9,300]	221,000 ± 10,200 [7,020]	153,000 ± 11,500 [11,100]
Eu-154	68,100 ± 4,700 [8,800]	108,600 ± 6,600 [12,800]	69,400 ± 5,000 [8,400]	30,300 ± 17,500 [39,200]

Notes: ND = Not Detected   [ ]   = Minimum Detectable Concentration in pCi/g
1. Uncertainties reported in the table are counting errors (1.96ó); additional uncertainties due to volume, mass, and density estimates could be approximately ± 50 % and should be added to the results shown.
2. Am-241 and Cs-137 activity on Port W-30 is more probably surface contamination than volume activation, as indicated in the table.

The results in Table 5-2 provide the measured activity for Ports W-51, W-54 and W-56, experimental ports that are vertically 8 feet (250 cm) above the pile centerline, and that run West to East from 8 feet South (No W-51) to 8 Feet North (No W-56) of the centerline. The relative locations of these experimental ports are illustrated in Figure 5-4. The radionuclides identified in the measurements are those expected in activated steel. Comparing the activities for Port W-51 and W-56, it is seen that the concentrations are symmetrical about the centerline. Note that the high detector response, due to the presence of large amounts of Co-60, has elevated the minimum detectable concentration of the low-energy radionuclide Am-241. This is due to scattered Co-60 gammas increasing the Compton continuum in the energy range of the 59.5 keV Am-241 gamma.

For Port W-30 which passes through the pile center, the results identify additional radionuclides and different activity ratios among the radionuclides. Historical operations and survey data indicated the presence of radioactive contamination in the Port infiltrated from failed fuel events in adjacent fuel channels. The analysis modeled the Cs-137 and Am-241 in the gamma spectrum as a volume activated source. To interpret the observed spectrum as surface activity would require that a different model be analyzed, with judgement applied to determine which portion of the spectrum belongs to which of the interpreted geometries. Since alternative methods were available to directly measure the removable contamination through a surface wipe, this effort was not considered necessary.

In situ analysis enabled the rapid evaluation of portions of the graphite pile and its internal components, without the expense and effort of core boring or dismantling the contaminated and activated pile. The modeling computation routine developed quantified estimates of internal activation. There were some ambiguities in the results, due to inconsistencies between the assumptions of the distribution of radionuclides and their physical location on or in the pile internal components.

Figure 5-4. Relative location of Experimental Ports 51-55, west face of BGRR

6.0 COST COMPARISON OF ISOCS AND BASELINE CHARACTERIZATION TECHNOLOGIES

This section provides a basis for comparing relative costs of the *In Situ* Object Counting System (ISOCS) deployed for characterizing gamma emitting radionuclides at the BNL BGRR with the conventional baseline approach of taking discrete physical samples for off-site analyses.

6.1 Categorization for Cost Comparison

Since the ISOCS system was deployed in numerous configurations and varying locations at BNL under this ASTD project, the cost analysis has been broken down into several broad categories to facilitate comparison.

- The first distinction for examining the cost breakdown is *in situ* vs. *ex situ*. The ISOCS system is well suited to conduct both *in situ* measurements of objects and areas requiring characterization and *ex situ* measurements of discrete samples when configured as an analytical field laboratory. *Ex situ* samples were further categorized as either soil or debris, sludge, and miscellaneous materials.

- The next distinction relates to the surface area being analyzed. *In situ* measurements were conducted on large areas (e.g., walls, floors, soil) and smaller unique samples (e.g., concrete cores, reactor components).

- The third and final category is related to the radiological conditions in which the samples were taken, i.e., whether the workers would be required to enter a radiologically controlled area in order to obtain the samples for analysis. One of the major advantages of the ISOCS system is the ability to conduct scans remotely, thus often avoiding the need to enter radiologically controlled areas. This reduces radiological exposure to workers, reduces cost, and reduces the time required to gather the analytical data. However, ISOCS analyses that would have required entry into radiologically controlled areas are identified to facilitate cost comparison with the baseline approach.

The ten general categories used for this cost comparison are summarized in Table 6-1.

All 920 of the *ex situ* samples analyzed for this deployment are summarized in Table A-1 of Appendix A. Of the total, 815 *ex situ* samples analyzed were soil and 105 were sludge, debris, or other materials. A total of 352 *in situ* measurements were conducted and are

Table 6-1. General Categories for BGRR ISOCS Characterization

	Description of Characterization Category
1	*Ex Situ* Sample Analysis of Soil
2	*Ex Situ* Sample Analysis of Debris, Sludge, and Miscellaneous Samples
3	*In Situ* Analysis of Large Uniform Areas (entry into Radiologically Controlled Area required for conventional sampling)
4	*In Situ* Analysis of Large Uniform Areas (**no entry** into Radiologically Controlled Area required for conventional sampling)
5	*In Situ* Analysis of Small Uniform Areas (entry into Radiologically Controlled Area required for conventional sampling)
6	*In Situ* Analysis of Small Uniform Areas (**no entry** into Radiologically Controlled Area required for conventional sampling)
7	*In Situ* Analysis of Large Heterogeneous Solid (entry into Radiologically Controlled Area required for conventional sampling)
8	*In Situ* Analysis of Large Heterogeneous Solid (**no entry** into Radiologically Controlled Area required for conventional sampling)
9	*In Situ* Analysis of Small Heterogeneous Solid (entry into Radiologically Controlled Area required for conventional sampling)
10	*In Situ* Analysis of Small Heterogeneous Solid (**no entry** into Radiologically Controlled Area required for conventional sampling)

summarized in Table A-2 of Appendix A, where they are further identified in terms of the categories described above. A total of 215 separate *in situ* scans were taken in which entry into radiologically controlled areas would have been required using the conventional baseline approach, and a total of 137 scans were taken in areas that would not require radiological controls for removal of characterization samples.

When comparing ISOCS with conventional analyses it is important to note that a single ISOCS measurement is not

necessarily equivalent to just one conventional analysis, so that a simple one-to-one comparison of ISOCS *in situ* measurements with conventional baseline samples is overly conservative. For example, a single *in situ* ISOCS measurement can potentially evaluate an area up to several square meters. In the case of heterogeneously contaminated solids, one ISOCS scan can provide an accurate report of average concentration values, whereas, numerous samples would be needed to derive a similar average value using the baseline approach. Thus, the overall savings associated with ISOCS is based on fewer samples to gather, prepare, ship, analyze, and evaluate.

In order to bracket a range of potential cost savings for this comparison, *in situ* measurements were categorized in terms of the approximate number of equivalent baseline analyses they potentially represent. *In situ* scans of large areas and objects were assumed to be equivalent to ten conventional samples and smaller areas and objects were assumed to be equivalent to five conventional samples.

Using this approach, 1760 baseline samples would be necessary to provide equivalent characterization data for samples in radiologically controlled areas and 1360 baseline samples in non-radiologically controlled areas. These represent the maximum estimated cost savings resulting from *in situ* characterization. Minimum cost savings are determined based on a 1:1 ratio for comparing baseline and *in situ* characterization analyses, i.e., 215 samples for radiologically controlled areas and 137 samples for non-radiologically controlled areas.

6.2   Methodology

Cost estimates were developed by preparing work breakdown structures (WBS) for *in situ* measurements and equivalent baseline measurements in a manner similar to the cost analysis prepared following the technology demonstration of the ISOCS at the Chicago Pile 5 Research Reactor [ref 15]. *In situ* sampling categories were grouped according to whether or not the work required sampling within radiologically controlled areas. The resulting WBS data sheets for the scenarios evaluated are identified in Table 6-2. The actual data tables are provided in Appendix C as Tables C-1 through C-10.

Estimates for the times required to conduct ISOCS measurements were based on actual deployment experience at the BNL BGRR. Times required to conduct the baseline activities were based on engineering estimates and information in the literature. Certain costs (e.g., capital equipment for innovative or baseline technologies, institutional overhead costs, training, project management) were not included to simplify the

Table 6-2. Identification of Cost Comparison Scenario Data Tables

Work Breakdown Structure Categories for Cost Comparison	Table Number
Baseline *Ex Situ* Sampling and Analyses Soil Samples	C-1
ISOCS *Ex Situ* Sampling and Analyses Soil Samples	C-2
Baseline *Ex Situ* Sampling and Analyses Debris, Sludge, Misc. Samples	C-3
ISOCS *Ex Situ* Sampling and Analyses Debris, Sludge, and Misc. Samples	C-4
Baseline Sampling and Analyses in place of *In Situ* ISOCS for All Radiologically Controlled Areas (Maximum Cost Savings Assumptions)	C-5
Baseline Sampling and Analyses in place of *In Situ* ISOCS for All Radiologically Controlled Areas (Minimum Cost Savings Assumptions)	C-6
In Situ ISOCS Sampling and Analyses of All Radiologically Controlled Areas	C-7
Baseline Sampling and Analyses in place of *In Situ* ISOCS for all Non-Radiologically Controlled Areas (Maximum Cost Savings Assumptions)	C-8
Baseline Sampling and Analyses in place of *In Situ* ISOCS for all Non-Radiologically Controlled Areas (Minimum Cost Savings Assumptions)	C-9
In Situ ISOCS Sampling and Analyses of All Non-Radiologically Controlled Areas	C-10

Note: Individual Cost data tables are provided in Appendix C of this report.

comparison and to facilitate comparison at other sites. It was assumed that these types of costs would be incurred regardless of the approach used and would be quickly amortized through future deployments.

Work conducted in radiologically controlled areas requires the use of personal protective equipment (PPE) with associated loss in productivity which is estimated by the Productivity Loss Factor (PLF). This factor is an historically based estimate of the non-productive portion

of the work day due to PPE changes, work rules based on As Low As Reasonably Achievable (ALARA) considerations, additional work breaks, etc. According to methodology developed by the Atomic Industrial Forum, tasks that are conducted within radiologically controlled areas are adjusted by a loss factor of 1.27, the product of factors of 1.15 to account for PPE and 1.10 to account for adjusted work-rest cycles [ref 16]. The additional costs associated with losses in productivity are calculated as the product of the amount of time required in radiologically controlled areas and the PLF. Other specific assumptions for each cost evaluation are provided as footnotes to the data tables.

6.3   Results and Conclusions

This cost comparison quantifies relative costs for ISOCS and baseline sampling/analysis at BNL's BGRR Decommissioning Project and related activities. Actual costs for baseline analyses are highly dependent on site-specific conditions and the types of analyses that are required. In order to make reasonable comparisons with the conventional baseline approach and establish a range of potential cost savings, assumptions were made about the number of baseline analyses that would be displaced. While there is considerable uncertainty in projecting the number of baseline samples equivalent to *in situ* characterization scans, this approach serves to bracket potential cost savings in terms of minimum and maximum levels. A summary of the cost comparison is presented in Table 6-3 and graphically in Figures 6-1 and 6-2. Based on the assumptions described above, the relative cost of ISOCS characterization at BNL was $81,769. Corresponding relative costs for baseline sampling/analysis ranged from a minimum of $292,065 to a maximum of $1,074,976. The resulting net cost savings of $210,296 to $993,207 represents savings ranging from 72% to 92% over the cost of the baseline technology. Average cost per sample for ISOCS characterization was $76 compared with $252 for baseline characterization.

While both the cost per sample and overall costs are significantly lower using ISOCS *in situ* and field laboratory characterization, perhaps the greatest cost savings associated with this innovative technology are "hidden" savings that are more difficult to quantify. These include savings associated with project schedule acceleration, the ability to characterize non-standard systems, and improved health and safety for D&D workers. Many engineering decisions during D&D

operations are dependent on radiological characterization of facilities and waste generated. For example, excavation of contaminated soils below the Pile Fan Sump and contaminated BNL Landscape Soils were greatly accelerated by the availability of near real-time analyses. Rapid analytical turn-around enabled project engineers to quickly determine when targeted clean-up levels were reached so that equipment and personnel could be efficiently staged. Net cost savings resulted from accelerated completion of the activities and minimization of non-productive use of resources. In addition, non-standard equipment and facilities were readily characterized using ISOCS, where no comparable technique was available using the baseline approach. For example, the large fan motors and plenums which contained inaccessible areas of contamination were evaluated through external *in situ* ISOCS scans and related modeling. Finally, numerous characterization activities of areas with significant levels of contamination were successfully completed without the necessity of extracting manual sub-samples, thereby avoiding radiological exposure to workers.

Both the documented cost savings and anticipated "hidden" cost savings demonstrated during this ASTD project were implemented over the course of about 1.5 years. Based on this success, use of ISOCS characterization has been integrated into the on-going D&D and environmental restoration activities at BNL and will continue to generate additional cost savings as these projects progress towards completion. For example, BNL's Environmental Restoration Division has successfully deployed ISOCS for final status surveys of the excavation of contaminated Landscape Soils. BGRR continues to support the use of ISOCS for numerous on-going characterization activities required during facility decommissioning. Investment in this technology has also been leveraged for a second ASTD initiative at BGRR beginning in FY01 in which contamination in subsurface soils will be characterized and modeled. If this approach can demonstrate that subsurface contamination is localized, some or all of the large below grade facilities (e.g., duct work) can be decontaminated and left in place, resulting in cost savings estimated to total over $3.4 million. Additional deployments planned at Hanford (Canyon Disposition Initiative) and Nevada Test Site (D&D of former nuclear Rocket Test Facility) promise to further increase return on investment for cleanup of DOE sites.

Table 6-3. Cost Comparison Summary

Minimum Savings over Baseline:

Characterization Description	Baseline Sampling Analysis		ISOCS		Savings	
	Total	Per Sample	Total	Per Sample	Total	Per Sample
Soil Samples, *Ex Situ*	$164,710	$202	$45,040	$55	$119,670	$146
Debris, Sludge, Misc. Samples, *Ex Situ*	$26,759	$255	$10,456	$100	$16,303	$155
Rad Controlled Areas (1:1 ratio of baseline: ISOCS)	$69,647	$324	$15,497	$72	$54,150	$252
Non Rad Controlled Areas (1:1 ratio of baseline: ISOCS)	$30,949	$226	$10,776	$79	$20,173	$147
Total	**$292,065**		**$81,769**		**$210,296**	
Average Cost/sample		**$252**		**$76**		**$175**

Maximum Savings over Baseline:

Characterization Description	Baseline Sampling Analysis		ISOCS		Savings	
	Total	Per Sample	Total	Per Sample	Total	Per Sample
Soil Samples, *Ex Situ*	$164,710	$202	$45,040	$55	$119,670	$146
Debris, Sludge, Misc. Samples, *Ex Situ*	$26,759	$255	$10,456	$100	$16,303	$155
Rad Controlled Areas (1:1 ratio of baseline: ISOCS)	$576,444	$328	$15,497	$72	$560,947	$256
Non Rad Controlled Areas (1:1 ratio of baseline: ISOCS)	$307,063	$226	$10,776	$79	$296,287	$147
Total	**$1,074,976**		**$81,769**		**$993,207**	
Average Cost/sample		**$253**		**$76**		**$176**
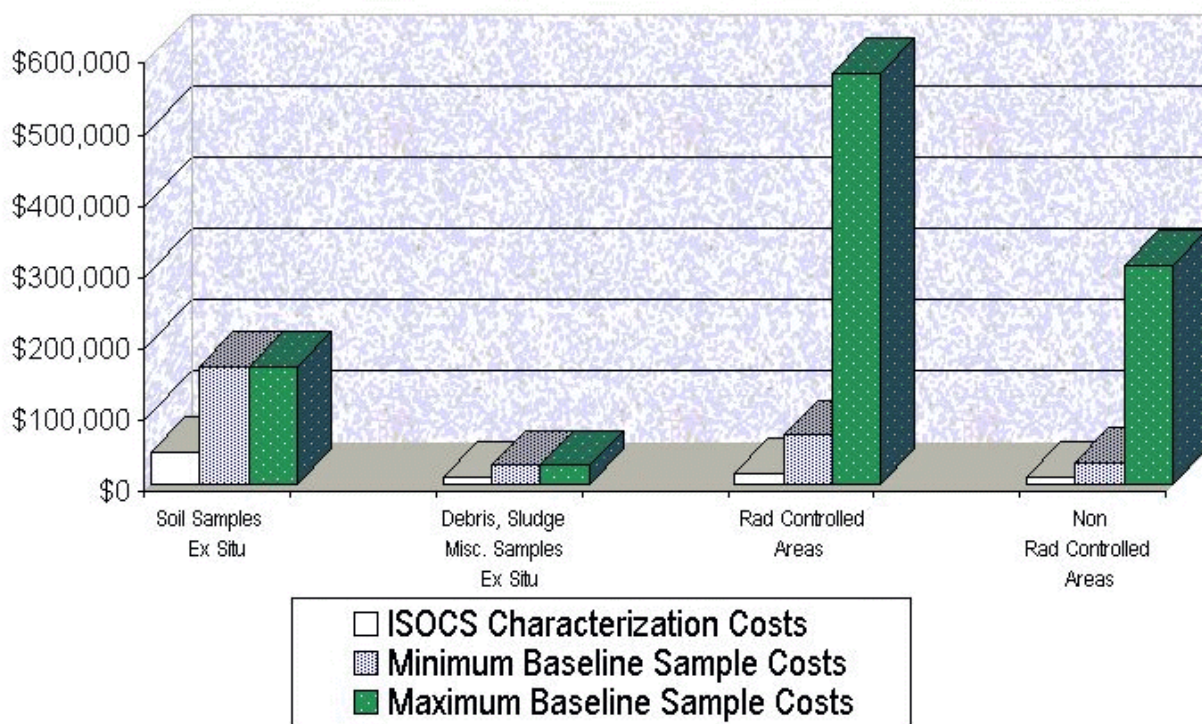
Figure 6-1. Comparison of ISOCS and baseline characterization costs by category
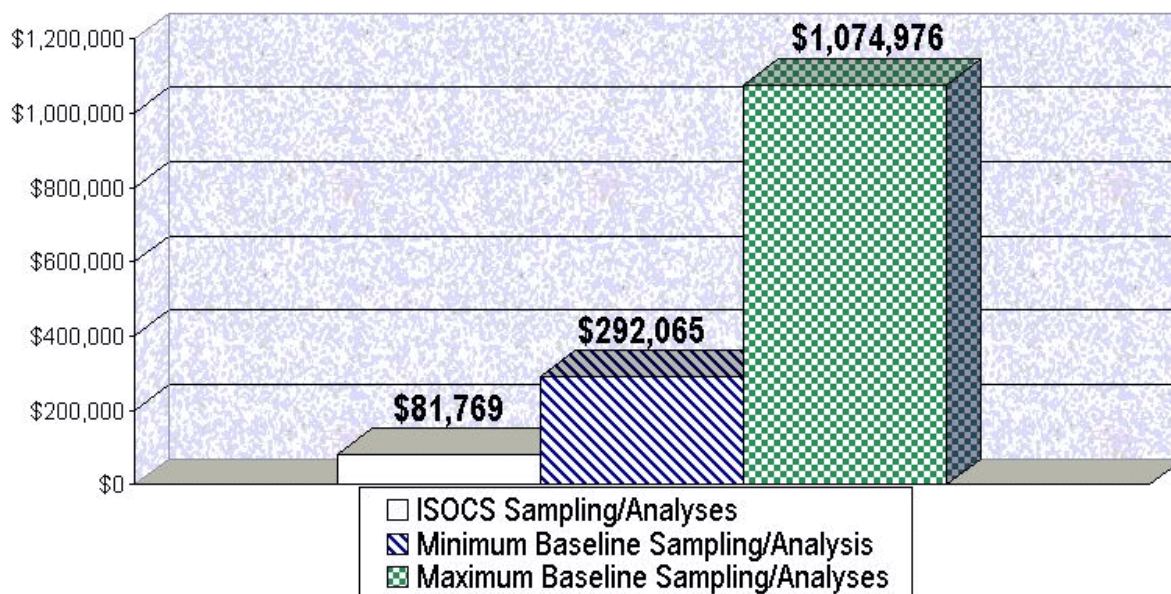
Figure 6-2. Comparison of total ISOCS and baseline characterization costs

7.0 SUMMARY

The versatility of the ISOCS system has been demonstrated in numerous situations during initial characterization and decommissioning efforts at the BGRR. Guidance from the MARSSIM and the Data Quality Objectives process provided direction for survey planning and data quality assessment. Surface soil detection sensitivities of less than 1 pCi/g have been attained with count times as short as 10 minutes for common gamma emitters such as Cs-137. Final results have been reported the same day, following data review and validation. Lower activities or more difficult to measure objects, such as enclosed systems, buried sources, and low-level surface contamination, can take longer to measure and evaluate. However, large surface areas or volumes with heterogeneous material distributions can be assayed with a single *in situ* measurement, thus saving time over other, more manual, methods, such as sampling and remote laboratory analysis.

7.1 Comparability Assessment

This assessment of the *in situ* data quality using the DQIs has demonstrated that the ISOCS data quality can be comparable to definitive level laboratory analysis when the field instrument is supported by an appropriate Quality Assurance Project Plan developed using the DQO process. Analytical results were used to calculate data quality indicators (DQI) were accuracy, precision, and bias.

a. The analytical accuracy of the BNL ISOCS instrument, expressed in terms of the percent difference (%D) was demonstrated in several modes:
- for a point source, the %D was -2.1%,
- for an extended source, the %D was -10.2%, and
- for an intercomparison to other *in situ* gamma spectrometers , the %D was -5.0%.

b. The periodic re-measurement of a single source demonstrated the precision of the instrument over an extended period. The relative standard deviation was only ± 0.7%, a variation in the activity measurement indicating that the ISOCS system response is very stable.

c. The analytical precision of the ISOCS instrument was illustrated by the results of repeat analyses performed on soil samples. For a series of paired original and repeat analyses on 25 samples, all values of the relative percent difference were within the criteria of the Project QAPP (RPD < 20%). The largest values of RPD occurred when the activity was small (5~6 pCi/g or less), otherwise the RPD was less than 10% for the sample set.

d. Very strong correlation was demonstrated between the ISOCS and laboratory results for *ex situ* ($R^2 = 0.99$) and *in situ* ($R^2 = 0.98$) analyses.

e. Analysis results for *in situ* surface soils were usually lower than the corresponding laboratory sample values. This low response "bias" is actually a demonstration that the instruments are analyzing different "samples": the *in situ* measurement looks at a wide area of soil in its native condition, while the laboratory analyzes a small aliquot, that is perturbed by preparation for analysis (drying and sieving). The bias in the laboratory values is usually very linear and can be adjusted to be more directly comparable to the *in situ* analysis, or vice versa.

7.2 Benefits

The successful implementation of this device provides many advantages over the traditional methodology, which is sampling followed by laboratory analysis.

a. Results are available nearly instantaneously, which allows better decisions to be made. The results can be used to guide the selection of the next measurement for a more complete survey without the necessity to re-mobilize the sampling crew. Or the results can be used to guide the conduct of a decontamination activity to know when to stop. The quick and reliable results are also very useful to advise interested members of the public and/or regulatory bodies on the extent of contamination and the effectiveness of the cleanup operation.

b. Most situations of radiological contamination do not result in uniform deposition of the offending material. Consequently, the selection of a small sample to send to the laboratory is a difficult and imprecise task. One solution is to take very large samples. And this is just what *in situ* measurement generally does. This large sample averages the non-homogeneity of the sample deposition over the entire object or area. Where the contamination on or in an object is not homogeneous, the ISOCS total activity results are probably more accurate than conventional samples, since a very large fraction of the sample is measured. *In situ* minimum detection limits are generally as low or lower than laboratory samples, since a very large sample size is used.

c. In many situations taking samples is difficult and/or presents health and safety hazards. Common examples are contaminated concrete, activated steel, radioactive liquids, corrosive or high temperature fluids,

dusts and powders, sludge on the bottom of a tank, tightly adhered surface contamination, gaseous samples, etc. In these cases once samples are successfully collected, they must be properly packaged and transported to the laboratory, where additional handling is required. *In situ* measurements can avoid this in many cases.

d. Conventional sampling and analysis is expensive. The cost comparison discussed in section 6, above, describes estimates of the cost of taking a sample, processing it, and laboratory spectroscopy. The same analysis is also provided for *in situ* gamma spectroscopy. The sampling/laboratory analysis process is approximately three times more expensive than *in situ* gamma spectroscopy, on a sample-to-sample basis. And, because of the non-uniform nature of the contamination in most cases, more samples must be taken than for *in situ* measurements.

7.3 Limitations

There are limitations on the implementation and use of the ISOCS system

a. The 30° FOV collimator can not be effectively used with the BEGe. The 30° FOV collimator is designed for use with a standard "co-axial" HPGe detector, and the wide, squat shape of the BEGe results in the 30° FOV collimator shielding over 80% of the active BEGe detector region. This limitation could be rectified by the manufacturer producing a re-designed collimator for use with the BEGe detector

b. Analysis results for *in situ* surface soils are usually lower than the corresponding laboratory sample values. The bias in the laboratory values is usually very linear and can be adjusted to be more directly comparable to the *in situ* analysis, or vice versa. Samples should be weighed before and after drying so that an adjustment for soil moisture can be made. In addition, the weight of any material, such as rocks or biomass, that are removed from

the sample should also be recorded so that a similar adjustment can be made. Without such adjustments, laboratory measurements are biased towards higher concentrations than actually exist at the sampling site. It is after all, the *in situ* concentration that is needed as input to a dose or risk model. The adjustment of laboratory results to be in line with physical site conditions is often ignored in an effort to be "conservative" in estimating risks. However, this practice should not be allowed to prejudice the comparison of *in situ* results to soil samples. Data Quality Objectives dictate that the measurement which is most closely related to risk should be preferred.

c. The use and application of the ISOCS geometry templates to generate instrument efficiency from the parameters of the spectrum acquisition can be daunting, especially for complex source objects. The system can be programmed to rapidly analyze recurring geometries, such as in the final status survey of remediated open fields. But when characterizing singular components, such as during a reactor decommissioning, the time to model individual pieces can add up quickly. In such cases it is the DQO process that can help to decrease the analysis setup time, by identifying less stringent precision or accuracy needs, allowing previous geometry models that are "close enough" to be used, without the necessity to refine the model to achieve unnecessary precision.

7.4 Conclusions

The ISOCS is an effective instrument for decontamination surveys, environmental measurements, operational radiation protection surveys, and waste assay measurements. This study demonstrated that *in situ* measurements can meet the QC acceptance criteria established by the project QAPP. Definitive level data may be generated by field instruments, as long as the project DQOs and QA/QC requirements are satisfied. The assessment of the total data quality in the study, and not just the instrument used in the analysis, will establish the confidence in the analysis and will determine the quality level of the data.

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APPENDICES

APPENDIX A.   Summary List of Project Measurements and Scans

Table A-1. ISOCS *Ex Situ* Sample Measurements

Sample Description	No. of Samples	Sample Description	No. of Samples
AGD Concrete dust from cutting down comers	3	AGD Concrete, Sludge, and Debris	22
AGD Cutting residuals	5	AGD North Duct Joint	6
AGD South Duct Joint	6	AGD Water from cutting down comers	3
Animal Tunnel East Debris	1	Background/Calibration/Source check	13
BGD and Cooler Drain Sludges	6	BGD Cooler Coils	3
BGD Filter Media	3	Canal Core Borehole Soil	78
Canal Debris	4	Canal House drill shavings	1
Canal Joint	1	Canal Sump	4
Canal Walk-way East	1	Canal Walk-way South	9
ERD Landscape Soil (pre-excavation surveys)	10	ERD Landscape Soil (post-excavation surveys)	51
ERD Soil from Sewage Treatment Plant	8	Fan House 1 Soil	1
Fuel Channel Extraction Tool	1	Graphite Plug stud section	1
PFS Asphalt (pre-excavation)	6	PFS Drainline Soil	7
PFS Drainline Soil and asphalt (post-excavation)	12	PFS Drainline Soil and asphalt (pre-excavation)	4
PFS Excavation Soil (during and post excavation)	606	PFS Soil (pre-excavation)	5
Soil for BetaScint Demo	30	Water Treatment House Debris	8
Water Treatment House Debris (west)	3		
TOTAL **922**		**NON-SOIL TOTAL** **105**	**SOIL TOTAL** **817**

Acronyms:
AGD = Above Ground Ducts   PFS = Pile Fan Sump
BGD = Below Ground Ducts   WMD = Waste Management Division
ERD = Environmental Restoration Division

Table A-2. ISOCS In Situ Scan Measurements

Scan Location	No. of Scans	Category	Sample Location	No. of Scans	Category
AGD (N&S hatch)	6	a-1	AGD Concrete Debris (from demob)	2	b-1
AGD (roof hatch)	3	a-1	Animal Tunnel East Debris	1	b-1
Canal House	1	a-1	Canal Sump Debris	3	b-1
ERD Waste Container	5	a-1	Canal walkway sludge	2	b-1
Experimental Port E23 (w cover)	2	a-1	ERD Chem Holes lead	1	b-1
Experimental Port W15 (w cover)	2	a-1	ERD C-magnets	11	b-1
Experimental Port E23	3	a-1	PFS cover closed	3	b-1
Experimental Port E30	2	a-1	PFS cover open	3	b-1
Experimental Port E24	3	a-1	Reactor sump cover	1	b-1
Experimental Port E26	3	a-1	**TOTAL Category b-1**	**27**	
Experimental Port N5	2	a-1	Canal Sump Debris (south bottom gate)	1	c-1
Experimental Port N6	2	a-1	Control Rod Guide Mechanism (SE)	2	c-1
Experimental Port N8	2	a-1	Control Rod Guide Mechanism (SW)	2	c-1
Experimental Port W12	1	a-1	Experimental Port W12 Graphite Debris	3	c-1
Experimental Port W12 (w cover)	1	a-1	Experimental Port W16 Debris	1	c-1
Experimental Port W15	1	a-1	Fan House 1	1	c-1
Experimental Port W16	1	a-1	Fan House 3	3	c-1
Experimental Port W30	1	a-1	Fan House 5	2	c-1
Experimental Port W31	2	a-1	Filter Bank media	4	c-1
Experimental Port W36	2	a-1	Glass block	1	c-1
Experimental Port W5	2	a-1	Graphite from Port 12	4	c-1
Experimental Port W51	2	a-1	Graphite from Port 30	5	c-1
Experimental Port W54	2	a-1	Graphite from Port 42	6	c-1
Experimental Port W56	3	a-1	Graphite from Ports 31 & 36	5	c-1
Northwest Side Scanner Slot	6	a-1	Rad Waste Bags (BLIP)	9	c-1
South Scanner Slot Samples (SE)	4	a-1	**TOTAL Category c-1**	**49**	
South Scanner Slot Samples (SW)	6	a-1	Excavated asphalt	11	c-2
Water Treatment House East	2	a-1	**TOTAL Category c-2**	**11**	
WMD Waste Box 1	4	a-1	AGD plug	1	d-1
WMD pig	9	a-1	AGD Sidewall Concrete Cores	4	d-1
WMD Waste Box 2 (bldg938)	3	a-1	Bioshield graphite plug	2	d-1
TOTAL Category a-1	**88**		Experimental Port W16 Graphite Powder	1	d-1
701 Parking lot	2	a-2	Fan House 3 dust	3	d-1
Agricultural Field Intercomparison Study	15	a-2	Fan House 5 dust	3	d-1
Bldg 703 floors	6	a-2	Instrument Tunnel East Debris	1	d-1
ERD Landscape soil	2	a-2	Interior Pile Debris (Port W32)	12	d-1
ERD lanscape soil (phyto)	8	a-2	Interior Pile Graphite Dust and Shavings	9	d-1
Fan House soils	27	a-2	North Scanner Slot Samples	14	d-1
PFS pipeline soil	59	a-2	PFS sludge	1	d-1
WMD Liquid Waste Tanker	5	a-2	**TOTAL Category d-1**	**51**	
TOTAL Category a-2	**124**		ERD Phyto plant	2	d-2
TOTAL Category b-2	**0**		**TOTAL Category d-2**	**2**	

ALL CATEGORIES TOTAL 352   RAD CON AREAS TOTAL 137   NON RAD CON AREAS TOTAL 215

a-1) large uniform area (homogeneity assumed).   Controlled area entry for baseline sampling
a-2) large uniform area (homogeneity assumed).   No controlled area entry for baseline sampling
b-1) small uniform area (homogeneity assumed).   Controlled area entry for baseline sampling
b-2) small uniform area (homogeneity assumed).   No controlled area entry for baseline sampling
c-1) large heterogeneous solid.   Controlled area entry for baseline sampling
c-2) large heterogeneous solid.   No controlled area entry for baseline sampling
d-1) small heterogeneous solid.   Controlled area entry for baseline sampling
d-2) small heterogeneous solid.   No controlled area entry for baseline sampling

APPENDIX B.   **Project Participants**

Accelerated Site Technology Deployment (ASTD) Project Organization Chart

DOE D&D Focus Area
Steven Bossart

DOE Chicago Operations
Miles Dionisio

DOE BGRR Oversight
James Goodenough (FY99)
Gail Penny (FY00)
DOE Brookhaven Group

ASTD Project Manager
Paul Kalb
BNL Environmental Sciences Dept

BGRR Liaison
Stephen Pulsford   Clyde Newson
BNL - BGRR

Stakeholder Involvement
William Gunther   BNL

Secondary Site Deployment
Kim Koegler   Bechtel Hanford

ISOCS Technical Assistance
Frazier Bronson
Canberra Industries, Inc

Analytical Physicist
Larry Luckett, CHP
URS-Dames & Moore

Survey Design and Data Assessment
Kevin Miller   Carl Gogolak
Peter Shebell
DOE EML

Data Acquisition Team
Larry Milian - BNL ESD
Dave Watters - Cabrera Services   Jay Adams - BNL ESD
Eric Barbour - Cabrera Services   Tom Roberts - BNL ESD
Dennis Ryan - URS-Dames&Moore   Rob Stone - URS-Dames&Moore

APPENDIX C.   **Cost Analysis Data Tables**

Table C-1
WBS for Baseline *Ex Situ* Sampling and Analyses
Soil Samples

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Transport equipment to work area	0.5	$45			$22.50	30	work days	$675	
Prepare equipment for use	0.5	$45			$22.50	30	work days	$675	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.1	$45			$4.50	817		$3,677	
Collect sample	0.1	$45			$4.50	817		$3,677	
Decon equip for next sampling	0.2	$45			$9.00	817		$7,353	
Package Sample	0.1	$45			$4.50	817		$3,677	
Prepare shipment for off-site analyses	0.25	$45			$11.25	817		$9,191	
Transport, Analyze, Dispose of samples	0	$0			$146	817		$119,282	(a)
Review/Evaluate Data	0.1	$75			$7.50	817		$6,128	(b)
Daily Project/Safety Briefing	0.5	$75			$37.50	30	work days	$1,125	
Containers	0	$0	817	$6			each	$4,902	
PPE	0		2	per day	$50	30	work days	$3,000	
Productivity Loss Factor (PLF)	0								(c)
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	30	work days	$675	
Transport equipment to storage area	0.5	$45			$22.50	30	work days	$675	

TOTAL:	$164,710
Cost/sample:	**$201.60**

Notes:
(a) Avg cost for off-site gamma analyses (14d turnaround) is $121 + $25 shipping/handling = $146
(b) One CHP evaluates 10 data sets/hr
(c) Adjusts for changes, breaks, respiratory protection, and ALARA
     (PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)

Table C-2
WBS for ISOCS *Ex Situ* Sampling and Analyses
Soil Samples

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Transport sampling equipment to work area	0.5	$45			$22.50	30	work days	$675	(a)
Prepare sampling equipment for use	0.5	$45			$22.50	30	work days	$675	
ISOCS Quality Assurance Procedures	0.5	$45			$22.50	30	work day	$675	(b)
Equipment Maintenance	0.5	$45			$22.50	6	week	$135	(c)
ISOCS Liquid Nitrogen				$0.90		30	work day	$27	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.1	$45			$4.50	817	each	$3,677	
Collect sample	0.1	$45			$4.50	817	each	$3,677	
Decon equip for next sampling	0.2	$45			$9.00	817	each	$7,353	
Package Sample	0.1	$45			$4.50	817	each	$3,677	(d)
Analyze samples at ISOCS field lab	0.13	$75			$9.75	817	each	$7,966	
Archive Files/Print Data	0.05	$75			$3.75	817	each	$3,064	(e)
Review/Evaluate Data	0.05	$75			$3.75	817	each	$3,064	
Daily Project/Safety Briefing	0.5	$75			$37.50	30	work days	$1,125	
Containers	0	$0	817	$6			each	$4,902	
PPE	0		2	per day	$50	30	work days	$3,000	(f)
Productivity Loss Factor (PLF)									
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	30	work days	$675	
Transport equipment to storage area	0.5	$45			$22.50	30	work days	$675	
							TOTAL:	$45,040	
							cost/sample:	$55.13	

Notes:
(a) Includes sampling costs - ISOCS assumed to be installed in field lab
(b) Daily calibration source and background check
(c) Fill cryostat with liquid nitrogen
(d) Assumes 5 min count time + 3 min set up
(e) One CHP evaluates 20 data sets/hr
(f) Adjusts for changes, breaks, respiratory protection, and ALARA
     PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)

Table C-3
WBS for Baseline *Ex Situ* Sampling and Analyses
Debris, Sludge, Misc. Samples

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Prepare area for sampling	0.5	$45			$22.50	10	work days	$225	(a)
Characterization									
Collect sample	0.25	$45			$11.25	105	each	$1,181	
Decon equip for next sampling	0.2	$45			$9.00	105	each	$945	
Package Sample	0.1	$45			$4.50	105	each	$473	
Prepare shipment for off-site analyses	0.25	$45			$11.25	105	each	$1,181	(b)
Transport, Analyze, Dispose of samples	0	$0			$146	105	each	$15,330	(c)
Review/Evaluate Data	0.1	$75			$7.50	105	each	$788	
Daily Project/Safety Briefing	0.5	$75			$37.50	10	work days	$375	
Containers	0	$0	105	$6			each	$630	
PPE	0		2	per day	$50	10	work days	$1,000	
Productivity Loss Factor (PLF)	0.885	$45			$39.83	105	each	$4,182	(d)
Demobilization									
Survey and Decon equipment	1	$45			$45.00	10	work days	$450	
							TOTAL:	$26,759	
							Cost/sample:	**$254.85**	

Notes:
(a) Prepare buffer area and assemble sampling equipment; assume 10 samples/day rate
(b) Avg cost for off-site gamma analyses (14d turnaround) is $121 + $25 shipping/handling = $146
(c) One CHP evaluates 10 data sets/hr
(d) Adjusts for changes, breaks, respiratory protection, and ALARA
    (PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)

Table C-4
WBS for ISOCS *Ex Situ* Sampling and Analyses
Debris, Sludge, and Misc. Samples

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Prepare area for sampling	0.5	$45			$22.50	10	work days	$225	(a)
ISOCS Quality Assurance Procedures	0.5	$45			$22.50	10	work day	$225	(b)
Equipment Maintenance	0.5	$45			$22.50	2	week	$45	(c)
ISOCS Liquid Nitrogen				$0.90		10	work day	$9	
Characterization									
Collect sample	0.25	$45			$11.25	105	each	$1,181	
Package Sample	0.1	$45			$4.50	105	each	$473	
Analyze samples at ISOCS field lab	0.13	$75			$9.75	105	each	$1,024	(d)
Archive Files/Print Data	0.05	$75			$3.75	105	each	$394	
Review/Evaluate Data	0.05	$75			$3.75	105	each	$394	(e)
Daily Project/Safety Briefing	0.5	$45			$22.50	10	work day	$225	
Containers	0	$0	105	$6			each	$630	
PPE	0		2	per day	$50	10	work days	$1,000	
Productivity Loss Factor (PLF)	0.885	$45			$39.83	105	each	$4,182	(f)
Demobilization									
Survey and Decon equipment	1	$45			$45.00	10	work days	$450	
							TOTAL:	**$10,456**	
							cost/sample:	**$99.58**	

Notes:
(a) Prepare buffer area and assemble sampling equipment;
      assume 10 samples/day rate
(b) Daily calibration source and background check
(c) Fill cryostat with liquid nitrogen
(d) Assumes 5 min count time + 3 min set up
(e) One CHP evaluates 20 data sets/hr
(f) Adjusts for changes, breaks, respiratory protection, and ALARA
       (PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)

Table C-5
WBS for Baseline Sampling and Analyses in place of *In Situ* ISOCS for All Radiologically Controlled Areas;
Maximum Cost Savings Assumptions
(Assuming 10:1 ratio of Baseline Sampling to ISOCS for Large Areas and 5:1 Ratio for Small Areas)

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Transport equipment to work area	0.5	$45			$22.50	440	work days	$9,900	(a)
Prepare equipment for use	0.5	$45			$22.50	440	work days	$9,900	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.25	$45			$11.25	1760	each	$19,800	(b)
Collect sample	0.25	$45			$11.25	1760	each	$19,800	
Decon equip for next sampling	0.2	$45			$9.00	1760	each	$15,840	
Package Sample	0.25	$45			$11.25	1760	each	$19,800	
Prepare shipment for off-site analyses	0.25	$45			$11.25	1760	each	$19,800	
Transport, Analyze, Dispose of samples	0	$0			$146	1760	each	$256,960	(c)
Review/Evaluate Data	0.1	$75			$7.50	1760	each	$13,200	(d)
Daily Project/Safety Briefing	0.5	$75			$37.50	440	work days	$16,500	
Containers	0	$0		$6		1760	each	$10,560	
PPE	0		2	per day	$50	440	work days	$44,000	
Productivity Loss Factor (PLF)	1.27	$45			$57.15	1760	each	$100,584	(e)
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	440	work days	$9,900	
Transport equipment to storage area	0.5	$45			$22.50	440	work days	$9,900	

Total: $576,444
Cost/sample: **$328**

Notes:
(a) With 4.5 hrs for set up, prep, PL factor, survey, decon & demob, Assume 4 samples/ day; 440 work days required
(b) Assuming 10 conventional baseline samples required for each ISOCS scan of large homogeneous areas; 5 conventional baseline samples required for each ISOCS scan of small homogeneous areas
(c) Avg cost for off-site gamma analyses (14d turnaround) is $121 + $25 shipping/handling = $146
(d) One CHP evaluates 10 data sets/hr
(e) Adjusts for changes, breaks, respiratory protection, and ALARA
(PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)
[This analysis assumes no compositing of analytical samples]

Table C-6
WBS for Baseline Sampling and Analyses in place of *In Situ* ISOCS for All Radiologically Controlled Areas;
Minimum Cost Savings Assumptions
(Assuming 1:1 ratio of Baseline Sampling to ISOCS for All Samples)

Mobilization	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Transport equipment to work area	0.5	$45			$22.50	54	work days	$1,215	(a)
Prepare equipment for use	0.5	$45			$22.50	54	work days	$1,215	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.25	$45			$11.25	215	each	$2,419	
Collect sample	0.25	$45			$11.25	215	each	$2,419	
Decon equip for next sampling	0.2	$45			$9.00	215	each	$1,935	
Package Sample	0.25	$45			$11.25	215	each	$2,419	
Prepare shipment for off-site analyses	0.25	$45			$11.25	215	each	$2,419	
Transport, Analyze, Dispose of samples	0	$0			$146	215	each	$31,390	(b)
Review/Evaluate Data	0.1	$75			$7.50	215	each	$1,613	(c)
Daily Project/Safety Briefing	0.5	$75			$37.50	54	work days	$2,025	
Containers	0	$0	77	$6		215	each	$462	
PPE	0		2	per day	$50	54	work days	$5,400	
Productivity Loss Factor (PLF)	1.27	$45			$57.15	215	each	$12,287	(d)
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	54	work days	$1,215	
Transport equipment to storage area	0.5	$45			$22.50	54	work days	$1,215	

Total: $69,647
Cost/sample: $324

Notes:
(a)   With 4.5 hrs for set up, prep, PL factor, survey, decon & demob, Assume 4 samples/ day; 54 work days required
(b)   Avg cost for off-site gamma analyses (14d turnaround) is $121 + $25 shipping/handling = $146
(c)   One CHP evaluates 10 data sets/hr
(d)   Adjusts for changes, breaks, respiratory protection, and ALARA
     (PLF is calculated by multiplying time spent applied to work within controlled areas by the adjustment factor of 27%)

Table C-7
WBS for *In Situ* ISOCS Sampling and Analyses of All Radiologically Controlled Areas

Mobilization	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Transport ISOCS equipment to work area	0.5	$45			$22.50	27	work day	$608	(a)
Prepare equipment for use	0.5	$45			$22.50	27	work day	$608	
Quality Assurance Procedures	0.5	$45			$22.50	27	work day	$608	(b)
Equipment Maintenance	0.5	$45			$22.50	6	week	$135	(c)
Liquid Nitrogen				$0.90		27	work day	$24	
Characterization									
Set up and move equipment (ISOCS)	0.1	$75			$7.50	215	each	$1,613	
Acquire data	0.25	$75			$18.75	215	each	$4,031	(d)
Model Data	0.25	$75			$18.75	215	each	$4,031	
Archive Files/Print Data	0.05	$75			$3.75	215	each	$806	
Review/Evaluate Data	0.05	$75			$3.75	215	each	$806	(e)
Daily Project/Safety Briefing	0.5	$75			$37.50	27	work day	$1,013	
PPE	0		0	per day	$50	0		$0	
Productivity Loss Factor (PLF)	0	$45			$0	0		$0	(f)
Demobilization									
Equipment Disassembly	0.5	$45			$22.50	27	work day	$608	
Transport equipment to storage area	0.5	$45			$22.50	27	work day	$608	

Total: $15,497
Cost/sample: $72

Notes:
(a)   With 2.5 hrs for set up, prep, & demob, Assume 8 samples/ day; 27 work days required
(b)   Daily calibration source and background check
(c)   Fill cryostat with liquid nitrogen
(d)   Assumes 15 min count time
(e)   One CHP evaluates 20 data sets/hr
(f)   Adjusts for changes, breaks, respiratory protection, and ALARA
     Assumes ISOCS data acquisition is conducted from outside controlled area

Table C-8
WBS for Baseline Sampling and Analyses in place of *In Situ* ISOCS for all Non-Radiologically Controlled Areas
Maximum Cost Savings Assumptions
(Assuming 10:1 ratio of Baseline Sampling to ISOCS for Large Areas and 5:1 Ratio for Small Areas)

Mobilization	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Transport equipment to work area	0.5	$45			$22.50	227	work days	$5,108	(a)
Prepare equipment for use	0.5	$45			$22.50	227	work days	$5,108	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.25	$45			$11.25	1360	each	$15,300	(b)
Collect sample	0.25	$45			$11.25	1360	each	$15,300	
Package Sample	0.25	$45			$11.25	1360	each	$15,300	
Prepare shipment for off-site analyses	0.25	$45			$11.25	1360	each	$15,300	
Transport, Analyze, Dispose of samples	0	$0			$146	1360	each	$198,560	
Review/Evaluate Data	0.1	$75			$7.50	1360	each	$10,200	(c)
Daily Project/Safety Briefing	0.5	$75			$37.50	227	work days	$8,513	
Containers	0	$0		$6		1360	each	$8,160	
PPE	0		0	per day	$50	0		$0	
Productivity Loss Factor (PLF)	0	$45			$0	0		$0	(d)
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	227	work days	$5,108	
Transport equipment to storage area	0.5	$45			$22.50	227	work days	$5,108	

Total:	$307,063
Cost/sample:	**$226**

Notes:
(a)   With 1.5 hrs for set up, prep, decon & demob, Assume 6 samples/ day; 227 work days required
(b)   Assuming 10 conventional baseline samples required for each ISOCS scan of large homogeneous areas;
      5 conventional baseline samples required for each ISOCS scan of small homogeneous areas
(c)   One CHP evaluates 10 data sets/hr
(d)   No Productivity Loss Factor for work in Non-Radiologically Controlled areas

Table C-9
WBS for Baseline Sampling and Analyses in place of *In Situ* ISOCS for all Non-Radiologically Controlled Areas
Minimum Cost Savings Assumptions
(Assuming 1:1 ratio of Baseline Sampling to ISOCS for All Samples)

Mobilization	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Transport equipment to work area	0.5	$45			$22.50	23	work days	$518	(a)
Prepare equipment for use	0.5	$45			$22.50	23	work days	$518	
Characterization									
Set up and move equipment (auger, geoprobe, etc)	0.25	$45			$11.25	137	each	$1,541	
Collect sample	0.25	$45			$11.25	137	each	$1,541	
Package Sample	0.25	$45			$11.25	137	each	$1,541	
Prepare shipment for off-site analyses	0.25	$45			$11.25	137	each	$1,541	
Transport, Analyze, Dispose of samples	0	$0			$146	137	each	$20,002	
Review/Evaluate Data	0.1	$75			$7.50	137	each	$1,028	(b)
Daily Project/Safety Briefing	0.5	$75			$37.50	23	work days	$863	
Containers	0	$0		$6		137	each	$822	
PPE	0		0	per day	$50	0		$0	
Productivity Loss Factor (PLF)	0	$45			$0	0		$0	(c)
Demobilization									
Survey and Decon equipment	0.5	$45			$22.50	23	work days	$518	
Transport equipment to storage area	0.5	$45			$22.50	23	work days	$518	

Total: $30,949
Cost/sample: $226

Notes:
(a)   With 1.5 hrs for set up, prep, decon & demob, Assume 6 samples/ day; 23 work days required
(b)   One CHP evaluates 10 data sets/hr
(c)   No Productivity Loss Factor for work in Non-Radiologically Controlled areas

Table C-10
WBS for *In Situ* ISOCS Sampling and Analyses of All Non-Radiologically Controlled Areas

	Labor Hours	Rate	Materials Quantity	Rate	Total Unit Cost	Total Quantity	Unit of Measure	Total Cost	Comment
Mobilization									
Transport ISOCS equipment to work area	0.5	$45			$22.50	23	work days	$518	(a)
Prepare equipment for use	0.5	$45			$22.50	23	work days	$518	
Quality Assurance Procedures	0.5	$45			$22.50	23	work days	$518	(b)
Equipment Maintenance	0.5	$45			$22.50	5	work week	$113	(c)
Liquid Nitrogen				$0.90		23	work days	$21	
Characterization									
Set up and move equipment (ISOCS)	0.1	$75			$7.50	137	each	$1,028	
Acquire data	0.25	$75			$18.75	137	each	$2,569	(d)
Model Data	0.25	$75			$18.75	137	each	$2,569	
Archive Files/Print Data	0.05	$75			$3.75	137	each	$514	
Review/Evaluate Data	0.05	$75			$3.75	137	each	$514	(e)
Daily Project/Safety Briefing	0.5	$75			$37.50	23	work days	$863	
PPE	0		0	per day	$50	0		$0	
Productivity Loss Factor (PLF)	0	$45			$0	0		$0	(f)
Demobilization									
Equipment Disassembly	0.5	$45			$22.50	23	work days	$518	
Transport equipment to storage area	0.5	$45			$22.50	23	work days	$518	

Total: $10,776
Cost/sample: **$79**

Notes:
a) With 3 hrs for set up, meeting, prep, & demob, Assume 6 samples/ day; 23 work days required
b) Daily calibration source and background check
c) Fill cryostat with liquid nitrogen
d) Assumes 15 min count time
e) One CHP evaluates 20 data sets/hr
f) Adjusts for changes, breaks, respiratory protection, and ALARA
   Assumes ISOCS data acquisition is conducted from outside controlled area

APPENDIX D. **GLOSSARY**

GLOSSARY

accuracy is a measure of the closeness of an individual measurement or the average of a number of measurements to the true value. Accuracy includes a combination of random error (precision) and systematic error (bias) components that result from sampling and analytical operations.

bias - the systematic or persistent distortion of a measurement process that causes errors in one direction (i.e., the expected sample measurement is different from the sample's true value).

boundaries - the spatial and temporal conditions and practical constraints under which environmental data are collected. Boundaries specify the area of volume (spatial boundary) and the time period (temporal boundary) to which a decision will apply.

comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Comparability must be carefully evaluated to establish whether two data sets can be considered equivalent in regard to the measurement of a specific variable or groups of variables.

completeness is a measure of the amount of valid data obtained from a measurement system, expressed as a percentage of the number of valid measurements that should have been collected (i.e., measurements that were planned to be collected).

data quality assessment (DQA) - a statistical and scientific evaluation of the data set to determine the validity and performance of the data collection design and statistical test, and to determine the adequacy of the data set for its intended use.

data quality objectives (DQOs) - qualitative and quantitative statements derived from the DQO Process that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

data quality objectives process is a systematic planning tool to facilitate the planning of environmental data collection activities. Data quality objectives are the qualitative and quantitative outputs from the DQO Process.

error is the difference between the true value and the measured value of a quantity or parameter.

false acceptance decision error - the error that occurs when a decision maker accepts the baseline condition when it is actually false. Statisticians usually refer to the limit on the

possibility of a false acceptance decision error as beta (ß) and it is related to the power of the statistical test used in decision making. An alternative name is false negative decision error.

false negative decision error - see false acceptance decision error.

false positive decision error - see false rejection decision error.

false rejection decision error - the error that occurs when a decision maker rejects the baseline condition (null hypothesis) when it actually is true. Statisticians usually refer to the limit on the possibility of a false rejection decision error as alpha, (á), the level of significance, or the size of the critical region, and it is expressed numerically as a probability. An alternative name is false positive decision error.

matrix is the predominant material of which the sample to be analyzed is composed. Matrix is not synonymous with phase (liquid or solid).

percent difference (%D) is used to compare two values; the percent difference indicates both the direction and the magnitude of the comparison, i.e., the percent difference may be either negative, positive, or zero. (In contrast, see relative percent difference.)

performance-based measurement system - a process in which the data quality needs or limitations of a program or project are specified and serve as a criterion for selecting appropriate analytical methods. Under the PBMS framework, the performance of the method employed is emphasized rather than the specific technique or procedure used in the analysis.

precision - a measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions expressed generally in terms of the standard deviation. It may also be expressed as a percentage of the mean of the measurements, such as relative range (RR) (for duplicates) or relative standard deviation (RSD).

productivity loss factor (PLF) is an historically based estimate of the non-productive portion of the work day due to PPE changes, work rules based on As Low As Reasonably Achievable considerations, additional work breaks, etc, when working in an area of radioactive contamination.

quality assurance (QA) - an integrated system of management activities involving planning, implementation, documentation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer.

QA Project Plan (QAPP) - a document describing in comprehensive detail the necessary quality assurance, quality control, and other technical activities that should be implemented to ensure that the results of the work performed will satisfy the stated performance criteria.

quality control (QC) - the overall system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer; operational techniques and activities that are used to fulfill requirements for quality.

random errors vary in a non-reproducible way around the limiting mean. These errors can be treated statistically by use of the laws of probability.

relative percent difference (RPD) - used to compare two values, the relative percent difference is based on the mean of the two values, and is reported as an absolute value, i.e., always expressed as a positive number or zero. In contrast, see percent difference.

representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point or for a process condition or environmental condition. Representativeness is a qualitative term that should be evaluated to determine whether *in situ* and other measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the media and phenomenon measured or studied.

support - the support of a physical sample is the volume from which an individual sample is drawn. For a grab sample the physical support is exactly equal to the size of the physical sample. Arises when assessing the representativeness of results for a heterogenous population or distribution.

systematic errors are errors that are reproducible and tend to bias a result in one direction. Their causes can be assigned, at least in principle, and they can have both constant and variable components. Generally, these errors cannot be treated statistically.

type I error - the statistical term for false rejection decision error.

type II error - the statistical term for false acceptance decision error.

uncertainty is the range of values within which the true value is estimated to lie. It is a best estimate of possible inaccuracy due to both random and systematic errors.