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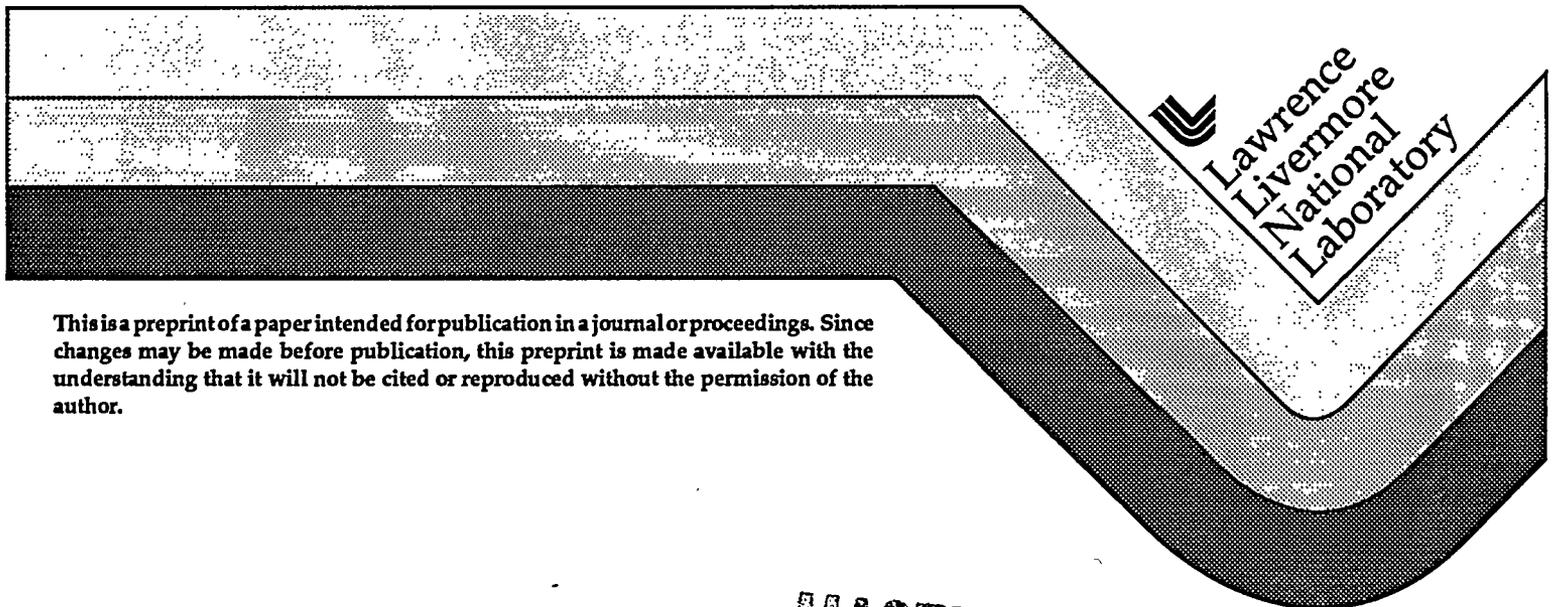
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High-Resolution Gamma-Ray Measurement Systems Using a Compact Electro-Mechanically Cooled Detector System and Intelligent Software

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HIGH-RESOLUTION GAMMA-RAY MEASUREMENT SYSTEMS USING A COMPACT ELECTRO-MECHANICALLY COOLED DETECTOR SYSTEM AND INTELLIGENT SOFTWARE

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ABSTRACT

Obtaining high-resolution gamma-ray measurements using high-purity germanium (HPGe) detectors in the field has been of limited practicality due to the need to use and maintain a supply of liquid nitrogen (LN₂). This same constraint limits high-resolution gamma measurements in unattended safeguards or treaty verification applications. We are developing detectors and software to greatly extend the applicability of high-resolution germanium-based measurements for these situations.

INTRODUCTION

The Safeguards Technology Program at the Lawrence Livermore National Laboratory is developing systems based on a compact electro-mechanically-cooled HPGe detector. This detector system broadens the practicality of performing high-resolution gamma-ray spectrometry in the field by not requiring LN₂ and having the capacity for continuous operation with a high-degree of reliability. The detector system is compact, lightweight and has a relatively short cool-down time. We are developing systems that address mobile applications calling for a high degree of portability and we are also developing systems for installation in facilities for unattended operation. The software to control these systems will be simple to operate or require no operator interactions. In either case, the system will check the counting conditions and sample characteristics to assure the analyzability of the data that is acquired. These systems extend the

applicability of high-resolution gamma-ray measurements in supporting safeguards inspections, unattended safeguards, treaty verification, and counter proliferation applications.

The other aspect to autonomous operation is analysis software that can adapt and respond to a wide variety of circumstances. The Safeguards Technology Program is developing isotopic analysis software that is constructed to be adaptable to a wide variety of applications and requirements. The MGA++ project will develop an analysis capability based on an architecture (Figure 2) consisting of a set of tools that can be configured by a software executive to perform a specific task. The software will detect and adapt to sampling conditions and unusual isotopics and change assumptions and methodology as required to successfully analyze a sample. It will provide an audit trail of its assumptions and decisions as an aid to analysts in interpreting results, as an aid to developers in extending the capability of the software to new circumstances, and to provide a measure of operational quality assurance. We will implement a flexible, configurable methodology applicable to perform plutonium, uranium, and general isotopic analysis depending on the situation. The MGA++ architecture also includes support for multiple absorber, sample and detector models to further extend the operational envelope of the software. The software development project is being performed under quality assurance, in anticipation of user requirements and to improve the maintainability of the software. We intend that MGA++ will improve isotopic measurement

capabilities for material control and accountability, treaty verification, complex reconfiguration and environmental clean-up applications. This software architecture will also allow us to respond quickly with highly specialized applications that address specific facility or transparency concerns.

The use of germanium detectors in applications requiring high-resolution x- or γ -ray spectrometry is widespread. There are a number of applications, growing in importance, for which high-resolution x- or γ -ray spectrometry would be very useful, but is not considered practical. This is primarily because the cooling requirements of the germanium detector create logistic and/or technical constraints that limit the applicability of germanium detectors in certain situations. Kenneth Neufeld and Wayne Ruhter of the Isotope Sciences Division at LLNL, with support from DOE's Office of Research and Development (NN-20), have developed an electro-mechanically cooled germanium detector that obviates most of those constraints. This opens a number of applications to solutions based on high-resolution x- or γ -ray spectrometry.

Gamma-ray spectrometry is a valuable tool in determining the presence of SNM in a sample. The technique is nondestructive and compliments other measurements such as neutron counting. MGA₂ is the LLNL developed analysis code that is used to determine relative isotopic abundances of primarily Pu isotopes. The code analyzes γ and X-ray spectra taken non-destructively from a sample and through a series of models and calculations determines the isotopic abundances without using external calibrations. Measurements of isotopic abundance can be combined with other non destructive techniques (i.e. calorimetry) to determine total amount for the various Pu isotopes. This combined technique is routinely used for material control and accountability (MC&A).

The current version of MGA works extremely well for samples that are homogeneous and do not contain unusual isotopics. The code has a long track record of providing high quality isotopic data analysis. We have been extending the capabilities of MGA and are presenting, in this paper, an architectural design for our current project.

The rationale for the project is focused on needs presented by new analysis problems and

deficiencies in MGA in the areas of maintainability, extendibility and adaptability.

MGA++ GENERAL DESCRIPTION

MGA++ is expected to perform the functions of MGA, perform them over a wider envelope of isotopics, interferences, sample matrices and counting conditions, and finally perform some analyses not currently performed by MGA. Thus MGA++ would have the capabilities of MGA, MGAU, for samples enriched in uranium isotopics, PU238, for samples enriched in ²³⁸Pu and mixed metal/oxide capabilities that do not currently exist.

MGA++ will be structured as a tool-box, where the individual modules can be used to form solutions to specific problems.

The performance requirements on MGA++ require reliability and accuracy using MGA as a baseline. They also require ease of modification and enhancement so that the system can address new problems in a timely manner.

One requirement for MGA++ is multiple modes of operation. The code can run in a very automatic mode for operators in the field or fully automatic for unattended applications. It can run in an interactive mode for analysts. It will also run in a highly interactive diagnostic mode for developers.

SYSTEMS DESIGN

Portable, unattended measurement systems have many common requirements. Size, weight, and power consumption are important to portable, most embedded and some unattended applications. Long lifetime and reliability are important to unattended and desirable for portable applications. Computer controlled multi-channel analyzer (MCA) and analog electronics are necessary for unattended systems and desirable for most others so that calibration can be automated and the system can adapt easily to changes in the samples or sampling environment.

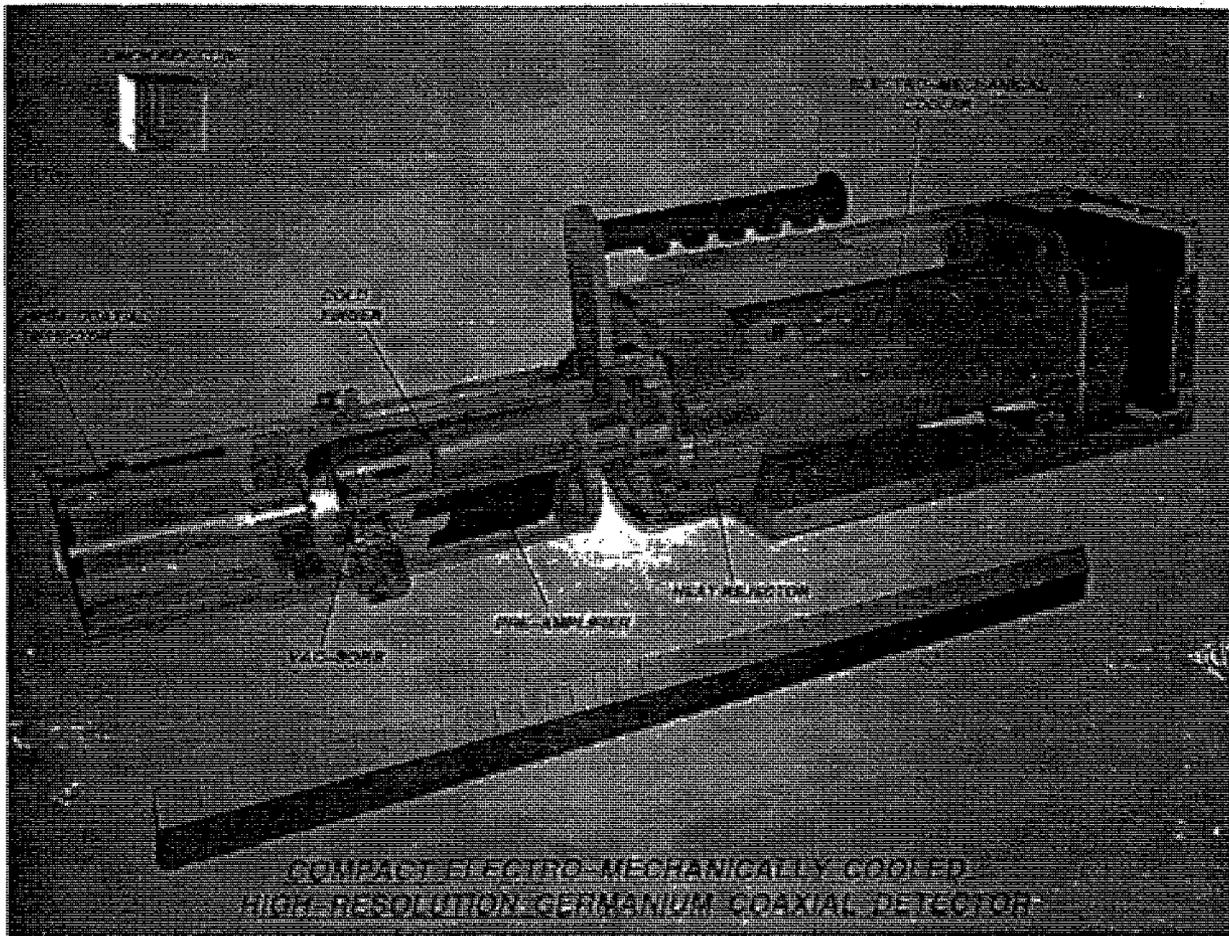


Figure 1

There is also considerable overlap in software requirements. Unattended and some portable systems require autonomous operation. Autonomous systems will not have a user interface, except perhaps for a diagnostic mode. They will make operational and analysis decisions based on external sensor values or analysis of the spectral data. They also need to be able to monitor their environment (power, temperature, detector performance, and facility, package or sensor integrity) to determine the viability of measurements.

Software for portable or unattended applications has some different requirements than data acquisition and analysis software designed for laboratory use by scientists. In the field, simplicity and ease of use and calibration are a high priority. Intelligent data acquisition, that quality assures the data in near real-time, and self-diagnosing analysis

software improve quick assessment of the adequacy of field measurements.

Because of distractions and other limitations of field measurements, operator attended systems need to have a simple and direct user interface and straightforward operation. They may have many of the decision-making capabilities of autonomous systems, but can express them as recommendations or notices to the operator. The instrument needs to assist the operator by automatically changing or suggesting changes to the measurement parameters, when possible, and displaying notifications or expert suggestions to the operator in an easy to understand form. This will decrease the setup time for data acquisition, reduce the need for operator training, and improve operation of the system for assurance of spectral data quality and results. The objective is to improve the quality of gamma-ray spectral data by using computer-controlled electronics and software that monitors the quality of

the data in real-time to automatically modify measurement parameters or to notify the operator to change the measurement conditions. These 'intelligent' features will enable operators to have portable instruments for field measurements that can obtain reliable and consistent information in a wide variety of conditions. All fielded systems benefit from fail-soft operation (no system hangs or application crashes without an automatic restart). This feature is essential for unattended systems.

Analysis software requirements vary with the application and transparency or other constraints. We are building an analysis architecture that can be adapted to a wide variety of analysis applications. MGA++_{1,3} is designed from a variety of modules or tools that can be assembled on the client-server model.

Some current MCA hardware that meets the above requirements include the *InSpector* from Canberra Nuclear Products Group, the *SpectrumMaster 92X*TM and *Nomad*TM from EG&G Ortec, and the *M³CA* from Aquila Technologies/LANL.

ELECTRO-MECHANICAL COOLING

There are several technologies that are alternatives to liquid cooling. High pressure gas systems share two of the limitations of liquid cooling in that a source of gas need to be available and they require venting. Conventional large-scale electro-mechanical coolers are bulky, microphonic and cannot be expected to run for more than a few months without maintenance. Stirling cycle cryo-coolers offer size and power consumption advantages, but are also microphonic and can only be expected to run for a few months.

Refrigeration advances, driven by infrared imaging applications, are available with small packages and longer anticipated lifetimes (~10 years). The microphonics are still an issue and have been addressed several different ways. Two passive techniques are employing additional mass to absorb the vibration or using complicated mounting schemes to decouple the vibration. One can also actively cancel the vibration. This is the technique we are using.

We are using a Sunpower cryo-cooler. The specific advantages of this cooler result primarily from the gas-bearing design of the cold-head which improves reliability, vibration and lifetime. This cooler has an

integrated counterbalance mass and electronics to perform high-speed vibration control using DSP (digital signal processing) technology (see Figure 2). We have achieved a significant reduction in vibration with overall acceleration levels reduced from greater than 1 g to ~1-10 mg. The most straightforward measure of the effectiveness of the vibration cancellation is the detector resolution. This shown in the performance section in Table 1.

DETECTOR SYSTEM SPECIFICATIONS

Size length 56 cm and diameter 13.7 cm (for LEGe)

Weight less than 6.8 kg (detector and cryo-cooler)

Power Requirements

consumes 37-97 watts

(8-12 hours of battery operation with 11.4 kg Ni₂Cd batteries)

Cooling Capability

4.25 watts of lift @ 77°K, cool-down for a LEGe ~3-4 hours and cool-down for a 50% HPGe ~ 6-8 hours

Durability

continuous operation, expected Mean-Time-To-Failure (MTTF) is 5-10 years

prototype system has operated more than 5000 hours, through more than 200 power and temperature cycles

Temperature Stability

± 0.5°K at 78°K

DETECTOR SYSTEM PERFORMANCE

LEGe Resolution, (eV)

Isotope	LN ₂ cooled (lab environment)	EM Cooled (lab environment)	EM Cooled (field environment)
²⁴¹ Am 59 keV	410	450	550
⁵⁷ Co 122 keV	523	570	720

[FWHM (eV) with amplifier shaping time of 4 μs]

Table 1.

COAX (50%) Resolution (keV)

Isotope	LN ₂ cooled (lab environment)	EM Cooled (lab environment)
⁵⁷ Co 122 keV	0.95	1.2
⁶⁰ Co 1332 keV	1.95	2.0

[FWHM (eV) with amplifier shaping time of 4 μs]

Table 2.

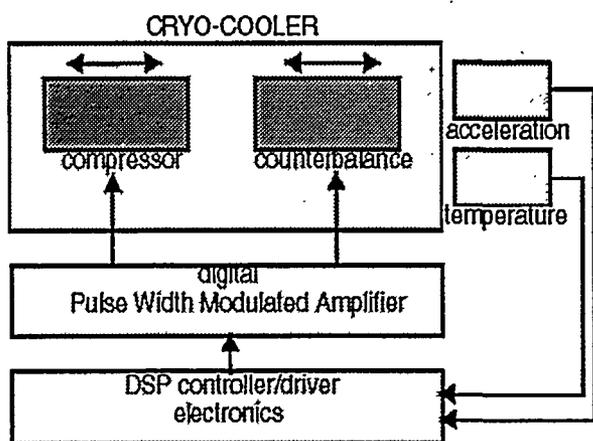


Figure 2. Active Vibration Control

Isotopic Measurement Performance,

	LEPS (FWHM 534 eV @ 122 keV)		LEGe_PCC (FWHM 723 eV @ 122keV)	
	Weight Percent	% Error	Weight Percent	% Error
²³⁸ Pu	0.1303	1.75	0.1235	1.49
²³⁹ Pu	75.46	0.29	75.51	0.23
²⁴⁰ Pu	21.56	0.91	21.57	0.71
²⁴¹ Pu	2.001	0.76	1.962	0.54
²⁴² Pu	0.8494	(10)	0.8334	(10)
²⁴¹ Am	1.872	0.98	1.848	0.71

Table 3.

Results of analysis of one hour measurement of PIDIE#5 reference standard using MGA₂ code. Data

was taken with a LN₂-cooled LEPS and portable electro-mechanically cooled LEGe detectors.

The results in the table above indicate that there is no significant impact on the isotopic analysis results from using the cryo-cooled detector.

CLIENT-SERVER ARCHITECTURE

The client-server architecture of MGA++ is a collection of cooperating processes. These processes might all be on the same computer or they might be distributed over a network. The architecture allows a very complex collection of modules and functions to be 'assembled' to address specific tasks quickly and relatively simply. This architecture also allows the individual parts to be simple and independent of other parts of the system.

This model requires support for multi-tasking. This eliminates MS-DOS™ and also Windows™ as operational computing environments. Windows 95™, Windows NT™, Unix™ and OS/2™ remain as options for small systems.

Referring to Figure 3, the executive is the controller and primary client. It will communicate with one or more of the other servers listed and can communicate, as well, with other instruments or systems.

The SpecView server implements the graphical user interface and is described elsewhere¹⁴. The executive will not use this server on unattended systems.

The instrument control server is relevant to fixed installations with doors, motors, sensors, and robots that require direction and control. It will not be discussed in detail here. The executive only requires this server if the sensors are present in the system.

The data collection server provides sample characterization and counting system characterization, in addition to spectral data collection. These two functions provide quality assurance for the data collection process. MGA++ can operate in an 'analysis only' mode that does not require this server.

All three of the above servers could be implemented completely independent of MGA++ for operation in existing proprietary environments.

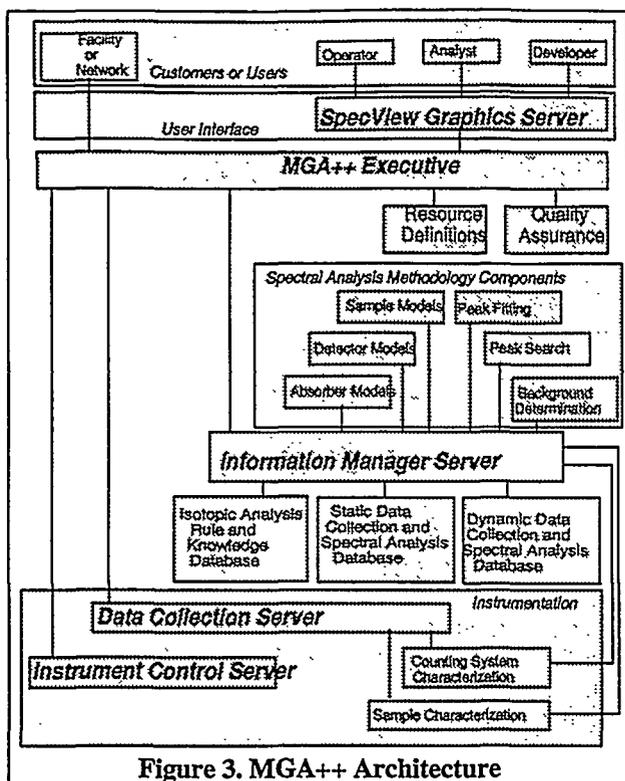


Figure 3. MGA++ Architecture

Software to guide the operator in collecting quality assured (analyzable) data has been developed in the *PRECHECK*, function for systems like the Intelligent Isotopic Analysis System (IAAS)₁₀. This function allows the operator to determine the suitability of data that will be collected during a short (~1 minute) count where various aspects of the spectra data are checked and an appropriate count time is calculated. The enhanced *PRECHECK* will include examination of dead-time, peak-ratios, resolution and peak shapes. This function can also be called throughout the data collection process to characterize the instrument and assure continued proper operation and analyzable data. In this mode, it would be calculating a dynamic figure-of-merit from the other *PRECHECK* parameters as a barometer of instrument performance.

EXECUTIVE

The MGA++ executive will serve as the controller of the isotopic analysis and manage all interprocess communications between itself and the various servers. It will operate as an inference engine with the rules and knowledge for how isotopic analysis is best performed under various conditions stored in a database of analysis rules and knowledge. If the executive is implemented using a commercial expert system shell, then the rule and knowledge

base will reside with that product. If the executive is implemented in a conventional programming language then the rule and knowledge databases will reside with the information manager.

The executive will be the basis for automated analysis under a wide variety of isotopic, sample and counting conditions. Its construction will make the analysis process auditable. This will also allow verification of correct operation of the code.

In its role for managing interprocess communications, it can require authentication and detect tampering of communications. It will use industry standard protocols implemented on flat files, shared memory, network messages or some combination.

Because the methods for performing isotopic analysis reside in the rule and knowledge base, it will be possible to extend MGA++ to solve a much more general class of isotopic analyses than actinide analysis. Applications in environmental monitoring and remediation, hazardous waste characterization and nonproliferation are anticipated.

INFORMATION MANAGER

The information manager will be a server that maintains, delivers and when necessary orders the generation information requested by clients in the MGA++ system.

The information manager will manage two distinct databases. The first is a static database that contains gamma-ray information including nuclide, energy, branching intensity and half-lives. It will also contain material absorption data. All data will include reference information so that we will be able to attribute all physical constants and data in the system. This data can not be modified by the information manager, although it can be directed to use a specific database. The second database will be a dynamic database populated with various data objects required for or generated by the specific analysis in progress.

When a request for information is received by the information manager, the database is checked for the presence and status of the data object. If the object is not present, the information manager looks up what is required to generate the data object, and calls the appropriate routines to perform that function. In a sense, the information manager controls the spectral analysis function of MGA++.

SPECTRAL ANALYSIS METHODOLOGY

The spectral analysis process determines the intensity and energies of the gamma ray photopeaks that have been measured by the detector. After various physical corrections have been applied, these quantities are used to determine the relative isotopic ratios of the radioactive components of the sample.

MGA currently uses predetermined windows near a peak or region to determine background. If the isotopics are significantly different than expected or there is an unanticipated interference, this background determination can be significantly in error. We have documented cases where this effect has distorted the results. To solve this problem, we are globally generating background.

An automated global background determination will not be dependent on assumptions of relative peak strength and interferences. This will remove one possible source of inaccuracy and potential instability from the analysis.

The background determination is made in three phases. First a global continuum is determined. Next the peak regions are located. Finally a background interpolation is performed in those regions.

The first stage in the spectral analysis process is the determination of the continuum portion of the spectrum. The continuum is primarily due to Compton scattered events from both the sample as well as naturally occurring background radiations. Most of the remainder of the spectrum consists of the individual photopeaks corresponding to each gamma ray energy detected. Determination of the continuum is extremely important, especially in the case of low intensity photopeaks as well under multiple peak groupings.

The global continuum is used to determine regions of potential photopeaks. Each region that contains data exceeding the global continuum are examined, as well as first and second derivatives to confirm that the region seems reasonable as a peak region.

Detailed continuum determination under the peak region is then performed, matching both value and first derivative at the splice points.

The composite continuum is then used for all subsequent analysis of the spectrum.

The process of determining peak regions also provides initial estimates of peak location and height. This information is used to make rough estimates of both isotopic identification and composition. For example, having both 376 keV and 414 keV photopeaks of roughly equal intensity is a reasonable clue that ^{239}Pu might be present in the sample. This would be confirmed by detailed examination of other peaks that should be visible in the spectrum.

Automated global peak search is desirable to mitigate the same limitations as 'local' background determination. These are isotopic and sample assumptions and unanticipated interferences.

We are currently modifying MGA's absorber model to provide a more analytic solution, again less dependent on assumptions.

We are also providing for multiple detector models so that MGA++ can be used in the analysis of spectra from CdTe, CdZnTe and other medium resolution detectors. Resolution and efficiency of these detector systems need to improve before a full isotopic analysis of plutonium is practical.

MGA++ peak fitting methodology will adapt to various peak shapes due to Doppler broadening (x-rays), recoil broadening (n,n', γ), and pile-up. The fitting process will use the Levenberg-Marquardt least-squares method and will be independent of the analytical model of the peak shape.

ONGOING WORK

To widen the practical domain of application for this technology, the cost of long-life expectancy electro-mechanical cryo-coolers and their supporting electronics must be reduced. This is being pursued through ongoing LLNL development and through commercialization efforts.

Development of different detector configurations are under development or being considered. Integration of the driver/controller electronics into the detector/cooler package is desirable but will require a VLSI implementation of the current electronics. Integration of the multi-channel analyzer into the detector/cooler package is also being pursued. Towards this end we are evaluating the LANL M³CA and have installed a M³CA into our control unit. From the experience in optimizing the active vibration control for the LEGe and the COAX HPGe, we believe there is substantial

engineering effort remaining in perfecting generalized electromechanically cooled germanium detectors.

As an interim product in our project, we are developing an MGA-hi code. This application will perform plutonium and uranium isotopics (including ^{238}Pu) using only spectral data above the 100 keV region. This code will not include an inference engine executive. It will use automatic global background determination and peak region identification. It will also use the physics portion of MGA for its absorbers, sample absorption and detector models. Our performance expectations are 5% accuracy for Pu isotopics and 10% accuracy for U isotopics.

Another interim deliverable is U235 which performs uranium isotopic determination using analysis of the peaks in the 100 keV region. By fitting the peaks in this region, rather than fitting a response function, we feel this code will be more stable and adaptable to interferences.

Because of our 'tool-box' approach, we will approach commercialization without transferring source code or co-developing software. We will provide an application programming interface (API) to vendors interested in licensing. They will provide the interface that integrates the MGA++ analysis software into their proprietary data collection and viewing environment. They would provide their own user interface to the operation of MGA++. This is being pursued through determining interest and generating memoranda of agreement with the interested vendors. This way we will retain control of the technology to simplify both enhancements and 'in-depth' technical support issues.

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