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On-Site Inspection RadioIsotopic Spectroscopy (OSIRIS) System Development

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Abstract

We have designed and tested hardware and software for the acquisition and analysis of high-resolution gamma-ray spectra during on-site inspections under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The On-Site Inspection RadioIsotopic Spectroscopy—OSIRIS—software filters the spectral data to display only radioisotopic information relevant to CTBT on-site inspections, e.g.,^{132}I. A set of over 100 fission-product spectra was employed for OSIRIS testing. These spectra were measured, where possible, or generated by modeling. The synthetic test spectral compositions include non-nuclear-explosion scenarios, e.g., a severe nuclear reactor accident, and nuclear-explosion scenarios such as a vented underground nuclear test. Comparing its computer-based analyses to expert visual analyses of the test spectra, OSIRIS correctly identifies CTBT-relevant fission product isotopes at the 95% level or better.

The OSIRIS gamma-ray spectrometer is a mechanically-cooled, battery-powered ORTEC Transpec-100, chosen to avoid the need for liquid nitrogen during on-site inspections. The spectrometer was used successfully during the recent 2014 CTBT Integrated Field Exercise in Jordan. The spectrometer is controlled and the spectral data analyzed by a Panasonic Toughbook notebook computer.

To date, software development has been the main focus of the OSIRIS project. In FY2016-17, we plan to modify the OSIRIS hardware, integrate the OSIRIS software and hardware, and conduct rigorous field tests to ensure that the OSIRIS system will function correctly during CTBT on-site inspections. The planned development will raise OSIRIS to technology readiness level TRL-8; transfer the OSIRIS technology to a commercial manufacturer, and demonstrate OSIRIS to potential CTBT on-site inspectors.

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1. Introduction

Many arms-control agreements have failed to control arms; the 1899 Hague Declaration concerning the Prohibition of the Use of Projectiles with the Sole Object to Spread Asphyxiating Poisonous Gases [1] is an object lesson. During World War I, fourteen years after the Hague Declaration entered into force, France, Germany, Russia, the United Kingdom, and later, the United States, conducted chemical warfare on a scale unequalled to this day. The Hague Declaration on chemical warfare was a failure, and often this has been the fate of treaties with no provision for compliance monitoring.

Toward the end of the twentieth century, a series of arms-limitation treaties have been negotiated, all with provisions for monitoring and inspections. These include the Intermediate-Range Nuclear Forces (INF) Treaty [2], the Chemical Weapons Convention (CWC) [3], and the Comprehensive Nuclear-Test-Ban Treaty (CTBT) [4]. The INF, CWC, and CTBT have all required the development of special technologies for monitoring.

Initially, most of the technical work to monitor CTBT compliance focused on global seismic, infrasound, hydro-acoustic, and radionuclide measurements, and a world-wide network of sensors called the International Monitoring System [5] is the result. However, on-site inspections are explicitly allowed under certain instances spelled out in the CTBT text and may be required to resolve anomalies, especially for allegations of low-yield underground testing. By measuring closer to the source and minimizing delay from the time of the explosion, on-site inspections can sometimes detect short-lived (prompt) radioxenon isotopes with much greater sensitivity than distant monitoring stations. If an underground test has vented, an on-site inspection may detect a rich set of long-lived (β-delayed) fission products as particulates [6, 7], and it may help localize the underground testing site. [8]

The On-Site RadioIsotopic Spectroscopy (OSIRIS) system, a gamma-ray spectroscopy system for on-site inspections under the CTBT, is the subject of this report.

1.1 CTBT On-Site Inspection

Each State Party under the CTBT has the right to request an on-site inspection in accordance with the provisions of the CTBT. The treaty and its Protocol allow the use of gamma-ray spectroscopy during the conduct of an on-site inspection, and they also allow for measurement restrictions as a managed access tool by the Inspected State Party. [9]

1.2 Restrictions on Radionuclide Data

An underground nuclear explosion releases noble gases like the radioxenons by diffusion through cracks in the rocks, and specialized instruments for on-site noble gas collection and analysis have been developed. [10] In addition, if a test vents, other radioisotopes may be deposited on the ground as particulate matter, and these isotopes are best identified by gamma-ray spectroscopy.

Paragraph 89(b) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) Protocol limits the radiation measurements to those isotopes and energies relevant to the determination that a nuclear explosion has occurred so as not to disclose irrelevant and potentially sensitive information. [11] To minimize the intrusiveness of gamma-ray spectral measurements during on-site inspections, the CTBT Working Group B has agreed to restrict gamma-ray spectral measurements to these seventeen activation and fission products: ^{140}Ba, ^{141}Ce, ^{144}Ce, ^{134}Cs, ^{137}Cs, ^{131}I, ^{132}I, ^{140}La, ^{99}Mo, ^{95}Nb, ^{147}Nd, ^{144}Pr, ^{106}Rh, ^{103}Ru, ^{99m}Tc, ^{132}Te, ^{95}Zr. [12]

1.3 OSIRIS Design Choices

An "off-the-shelf" commercial gamma-ray spectroscopy software package would have been sufficient for CTBT on-site gamma-ray spectroscopy, except it would reveal, when present in a spectrum, the gamma-ray peaks of other radioisotopes beyond the seventeen listed above.

Instead, we adopted and modified the data acquisition and analysis software of the Portable Isotopic Neutron Spectroscopy (PINS) prompt gamma-ray neutron activation analysis system [13] for OSIRIS. PINS was developed at Idaho National Laboratory for on-site inspections under the Chemical Weapons Convention. The PINS software can hide gamma-ray spectra from users, presenting only summary information. The PINS graphical user interface is shown in **Figure 1.**

The complexity of fission-product gamma-ray spectra requires the use of a high-purity germanium detector for on-site inspections under the CTBT. It is likely that on-site inspections under the CTBT will take place in remote locations, and access to liquid nitrogen and even electricity may be limited. Accordingly, we chose the mechanically-cooled ORTEC Transpec-100 gamma-ray spectrometer, shown in **Figure 2**. The Transpec-100 does not use liquid nitrogen, and with an external battery it can operate for 12 hours. Advanced versions of PINS also use the Transpec-100.

OSIRIS is controlled by a Panasonic Toughbook notebook computer, also seen in Figure 2. The Toughbook is a ruggedized computer, and its screen can be read in direct sunlight. PINS systems have used Panasonic Toughbook models since 2001.

1.4 Technology Readiness Levels

The commercially-available hardware and software components at the beginning of OSIRIS development were at Technology Readiness Level 9 (TRL-9), [14] and this level corresponds to equipment and software that has been used successfully in military field applications. OSIRIS technology readiness levels are discussed further in section 4.5 below.

1.5 Performance Metrics

The following metrics are used to evaluate OSIRIS system performance:

- Detection of the CTBT-relevant fission product isotopes actually present in a spectrum (high true-positive fraction).
- Non-detection of the CTBT-relevant fission-product isotopes not present in a spectrum (low false-positive fraction).
- Correct areas for the CTBT-relevant peaks truly present in the spectrum. The radioactivity, in becquerels or curies, of an isotope is directly proportional to its gamma-ray peak area.
- Accurate spectrometer energy calibrations.
- Stable spectrometer electronic gain between energy calibrations.

2. OSIRIS Software

The OSIRIS software has been designed to collect, measure, analyze, and filter gamma-ray spectra so that only treaty relevant information is revealed. The gamma-ray spectra are not visible to the operator; instead, the information displayed is limited to radioisotopes relevant to CTBT on-site inspections. OSIRIS also provides information to the operator on natural background isotopes and energy-calibration check sources to assure operators the system is performing correctly.

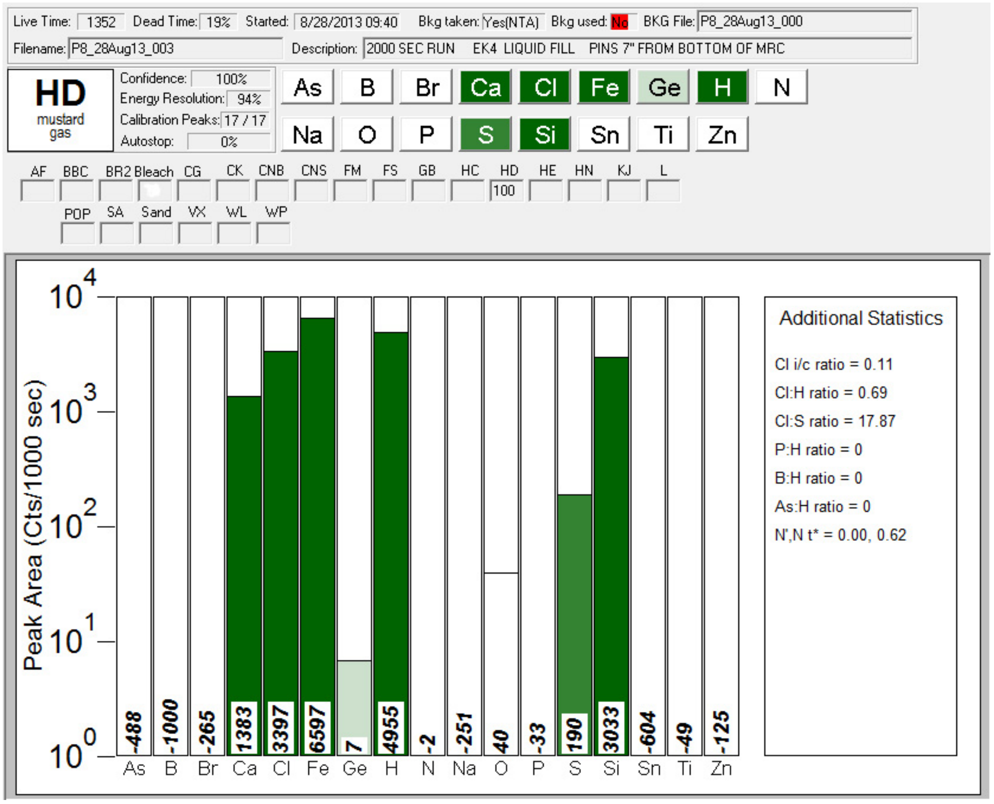

Figure 1: *PINS graphical user interface*

Figure 2: *ORTEC Transpec-100 gamma-ray spectrometer and Panasonic Toughbook notebook computer*

As noted above the OSIRIS software was refactored from PINS software, eliminating any reference to chemical warfare agents, changing isotope libraries to reflect the CTBT-related radioisotopes, selecting different gamma-ray energies for calibration and gain setting, and revising the calibration methods. The analysis and post-processing of the peak-fit data were optimized for fission-product gamma-ray spectra.

2.1 Data Acquisition

The OSIRIS data acquisition software controls the ORTEC Transpec-100 gamma-ray spectrometer, and reads out the spectra for analysis.

At startup, OSIRIS guides the operator with a checklist set of instructions shown in **Figure 3**. The initialization routine enters the multichannel-analyzer parameters, enables the detector high voltage, performs a pole-zero cancellation, and using a check gamma-ray check source, it sets the electronic gain to approximately 3.0-MeV full scale.

Next, the operator is instructed to perform an energy and peak-width calibration, again using a gamma-ray check source, like ^{152}Eu. During energy calibration, a separate window appears, displaying the calibration peaks as they grow, as shown in **Figure 4**. Peaks from other isotopes that may be present in the spectrum are not displayed in the calibration window, nor is the Compton continuum below the calibration peaks. The calibration procedure can be repeated at any time between spectral measurements.

Prior to spectral data collection, the operator presets the measurement live time.[1] Controls are provided to start and stop data collection, and to extend measurement live time. At the end of a measurement, the spectral data are saved to disk. During data acquisition, the spectrum is analyzed and the display is updated every ten seconds. Only limited radioisotopic data are revealed to the operator, as explained below in sections 2.2 and 2.3.

The instrument is shut down via another checklist, similar to that in **Figure 3**. The spectrometer cooler must remain in operation during shutdown, if the instrument is to be used the next day.

[1] *Most radiation-counting instruments can process only one pulse at a time. During pulse processing, the instrument is effectively "dead" to incoming radiation. When pulse processing has been completed, the instrument resets, and it is now said to be "live". Most multichannel analyzers (MCAs), including the OSIRIS MCA, contain two clocks: a real-time clock that runs continuously like a wall clock, and a live-time clock, that is stopped whenever the multichannel analyzer is busy processing a gamma-ray pulse. Real time is the sum of live time and dead time, and dead time increases with counting rate. At low counting rates, live time is close to real time, but at high counting rates, live time can significantly lag real time, due to higher dead-time. To accurately compare a weak radioactive source to a strong source, the MCA counting interval must be measured in live time, not real time, to correct for dead-time counting losses with the strong source.*

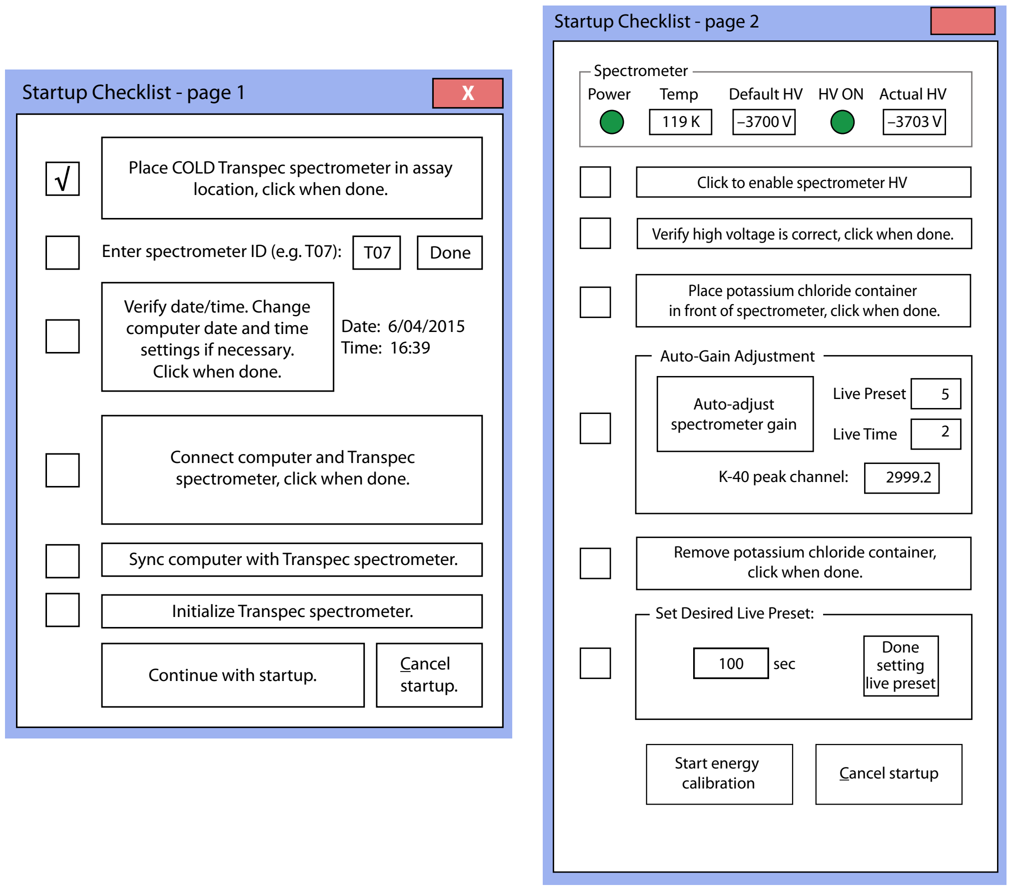

Figure 3: *Startup checklist instructions*

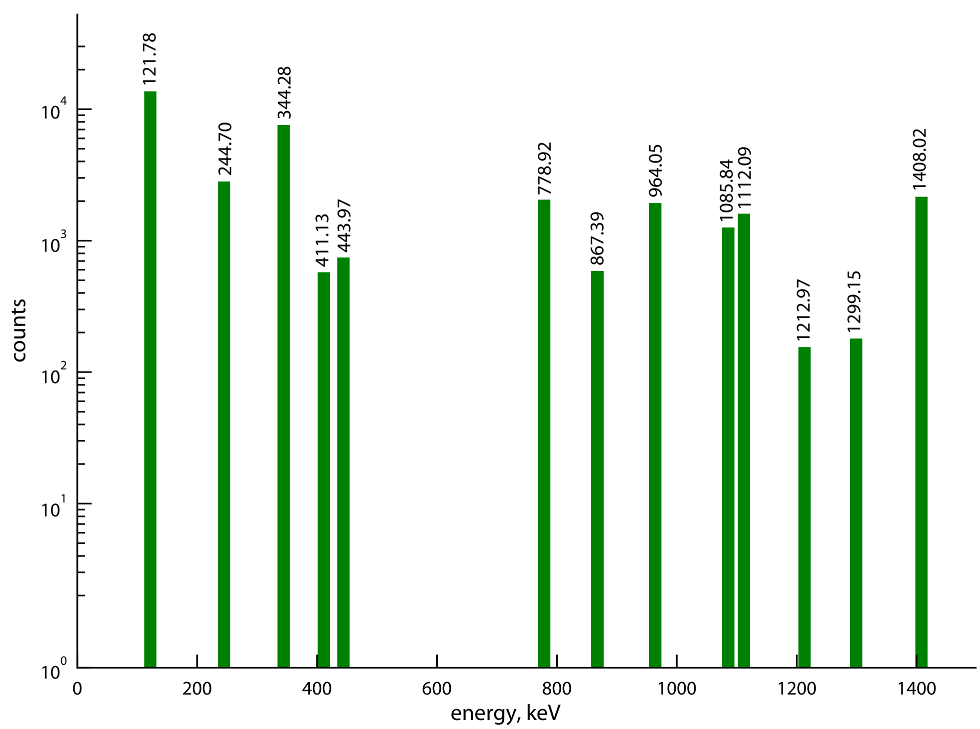

Figure 4: *Energy calibration window*

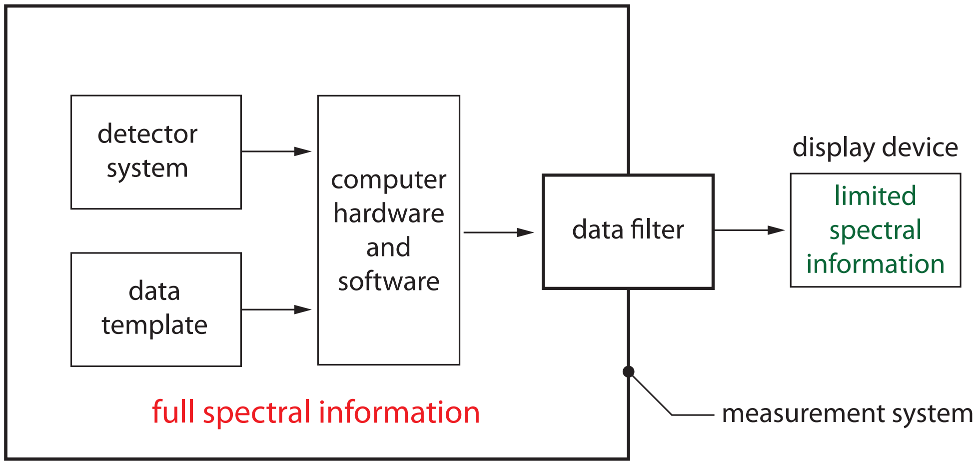

Figure 5: *Data filter concept*

2.2 Data Filter

The OSIRIS software represents a prototype information filter of spectral information measured during an on-site inspection so that only information related to certain isotopes deemed relevant to the purpose of the inspection ("CTBT-relevant radionuclides") is revealed to the user.

A notional spectroscopic measurement data filter, termed by others an "information barrier" [15], is depicted in **Figure 5**. The data filter hardware and software hide full spectral information from users, revealing only treaty-relevant information on its display device. Radiation measurement data filters have been designed for nuclear arms-limitation treaty-related purposes, including the Brookhaven National Laboratory CIVET system [16]; the Oak Ridge National Laboratory NMIS instrument [17]; and the Sandia National Laboratories TRADS instrument [18]. OSIRIS uses an enhanced version of the data filter in the Idaho National Laboratory PINS Chemical Assay System, developed for the Chemical Weapons Convention.

The OSIRIS data filter is implemented entirely in software; future developments will include hardware and procedural safeguards for the measured spectra, plus means for assuring users and inspected parties that the spectroscopic results are correct. While OSIRIS software measures the gamma-ray peaks from natural background isotopes, other fission products not deemed relevant, and other radioisotopes, it only presents users with information on treaty-relevant fission-product gamma-ray peaks, calibration peaks, and a few natural background peaks to increase user confidence in correct operation.

2.3 OSIRIS Graphical User Interface

The fission-product spectrum measured from an experimental reactor fuel sample is shown in **Figure 6**. OSIRIS limits information about this complex spectrum to the simple bar chart of **Figure 7**. For each of the seventeen treaty-relevant fission products, a vertical bar is drawn, and the bar height for each fission product is proportional to the area of that isotope's most-intense gamma-ray peak used by OSIRIS. The bar chart also includes information on three of the more-intense natural background gamma rays, corresponding to ^{40}K and the ^{238}U and ^{232}Th decay chains. During data acquisition, the bars grow in height, in real time, as the treaty-relevant fission-product peak areas grow.

Additionally, if a user clicks one of the buttons atop the bar display with the mouse pointer, summary data for that isotope is displayed. The ^{134}Cs-^{137}Cs information window for the reactor fuel sample spectrum is shown in **Figure 8**.

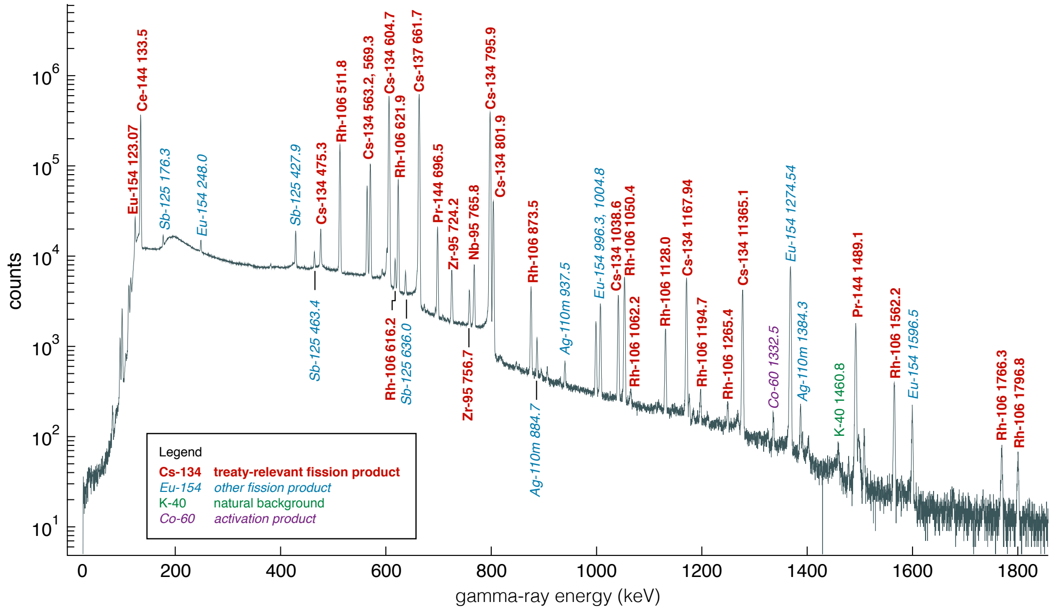

Figure 6: *Reactor fuel sample fission-product spectrum measured 24 months after irradiaton*

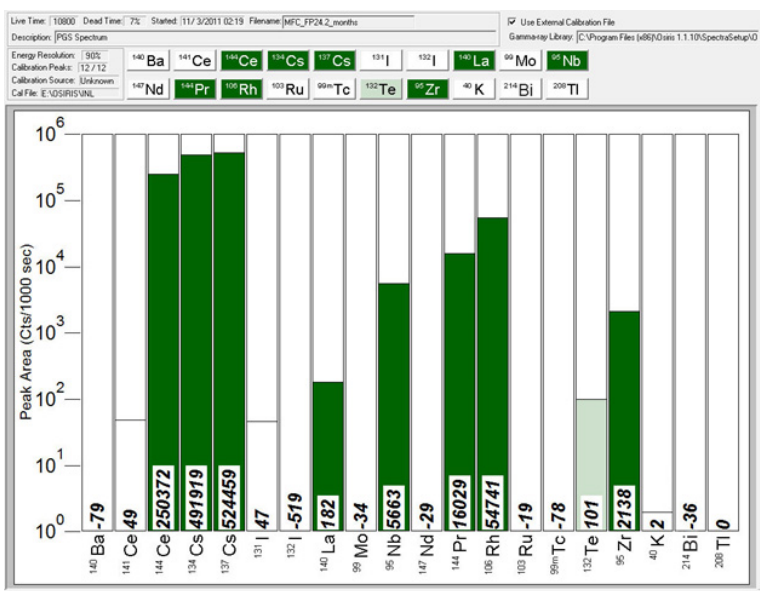

Figure 7: *OSIRIS bar-chart display of Figure 6 reactor fuel sample fission-product spectrum*

isotope	library energy	measured energy	net area	t*
Cs-134	569.31	569.18	874692.8	839.7
Cs-134	604.70	604.64	5312730.7	2251.9
Cs-134	795.85	796.19	3651670.9	1740.4
Cs-134	801.93	802.28	363554.6	539.8
Cs-137	661.66	661.59	5664162.0	2330.1

Cs-134/Cs-137 Ratio

ratio = (5312730.7/5664162.0) · (0.851/0.976) = 0.82

Figure 8: *Information window for ^{134}Cs and ^{137}Cs*

2.4 Spectrum Analysis

The OSIRIS spectral analysis supervisory logic is shown in **Figure 9**. Following initialization and energy calibration, a gamma-ray spectrum is acquired. Next a peak search is performed, and based on the detected and required peaks, the peak-fitting regions are determined. After region-by-region peak fits, the radioisotopes evident in the spectrum are identified by peak energy and the corresponding peak areas and peak area uncertainties noted. Finally, information on the treaty-relevant fission products is pushed across the data filter for display to the user.

Prior to use, the OSIRIS gamma-ray spectrometer must be calibrated with a gamma-ray check source, as described below in section 2.5.

2.4.1 Peak Search

OSIRIS conducts a peak search using Black's "zero-area square-wave" cross-correlation algorithm [19], similar to wavelet analysis methods. **Figure 10** depicts a zero-area square wave. Peaks found by the search routine are then compared to a "required peaks" list. If one of the required peaks in **Table 1** is not found within one half of the peak-width, i.e., FWHM/2, a directed peak fit is performed at the required peak energy.

2.4.2 Peak Region Definition

OSIRIS uses the peak-smoothing technique of Gunnink and Niday [20] to determine peak regions. Briefly, the measured spectrum is smoothed repeatedly, and the measured and smoothed spectra are then compared. Groups of spectral channels where the measured spectrum is significantly greater than the smoothed spectrum are chosen as peak-fit regions.

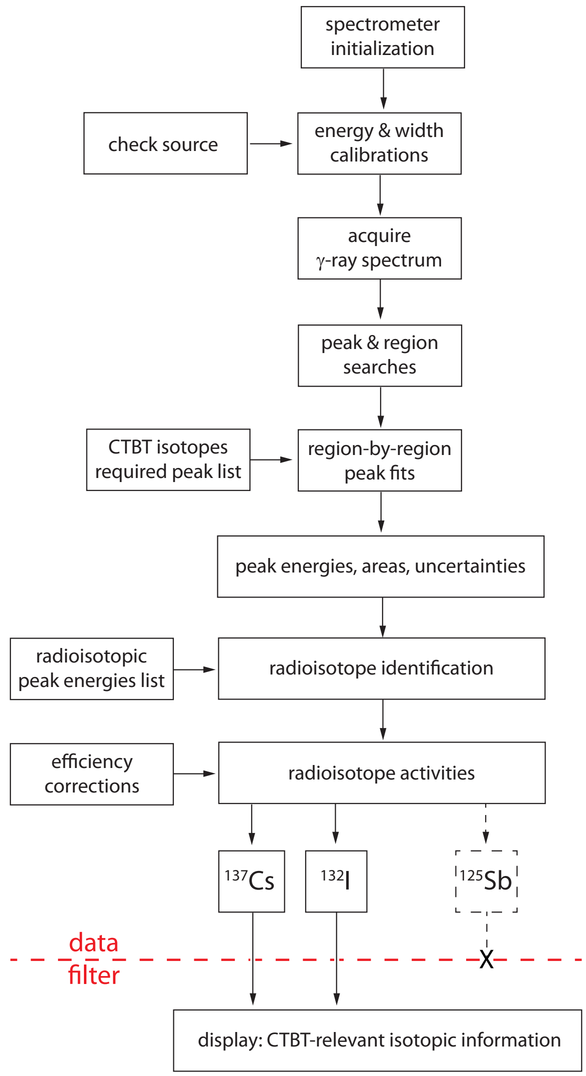

Figure 9: *Spectral analysis software supervisory logic*

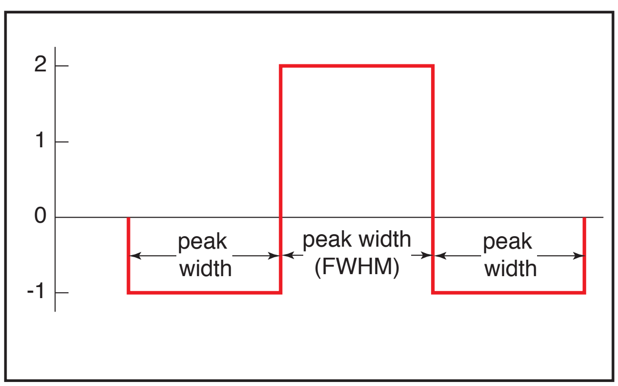

Figure 10: *Zero-area square wave*

2.4.3 Peak Fits

Peak region determination and peak fits are carried out with the Gauss gamma-ray spectrum analysis algorithms of Helmer, et al. [21] Similar spectrum analysis codes include GAMMAVISION [22], HYPERMET [23], and SAMPO [24].

GAUSS peak analyses use nonlinear least-squares fits, a method especially suitable for the analysis of complex fission-product spectra. **Figure 11** displays a GAUSS fit of overlapping peaks in the 650- to 680-keV region of the reactor fuel-sample spectrum. For peak detection, OSIRIS currently requires the peak area to exceed the peak background uncertainty by a factor of 3 or more.

2.4.4 Peak Selection

The CTBT-relevant fission-product isotopes and their four most-intense gamma rays are listed in **Table 1**. The peaks used by OSIRIS to characterize a fission-product spectrum are set in bold type. Common natural background gamma rays are listed in **Table 2**. The gamma-ray energies and branching ratios in both tables were taken from the *Table of Isotopes*. [25]

In complex spectra, it is important to avoid peak interferences. OSIRIS does not use peaks in the X-ray region, near Compton edges, or near coincidence sum peaks. Even then interferences can be difficult to avoid. For example, the highest intensity ^{106}Rh peak is found at 511.86 keV, and to avoid interference with the 511.00-keV annihilation peak, the second-highest intensity ^{106}Rh peak at 621.93-keV is used instead. But the 621.20-keV ^{132}I peak can interfere with the 621.93-keV ^{106}Rh peak, and additional program logic vetoes ^{106}Rh identification if strong ^{132}I peaks are present in the spectrum.

2.4.5 Radioactivities

The radioactivity *R* of an isotope is determined from its net peak area, the measurement live time, and the gamma-ray detector peak efficiency ε,

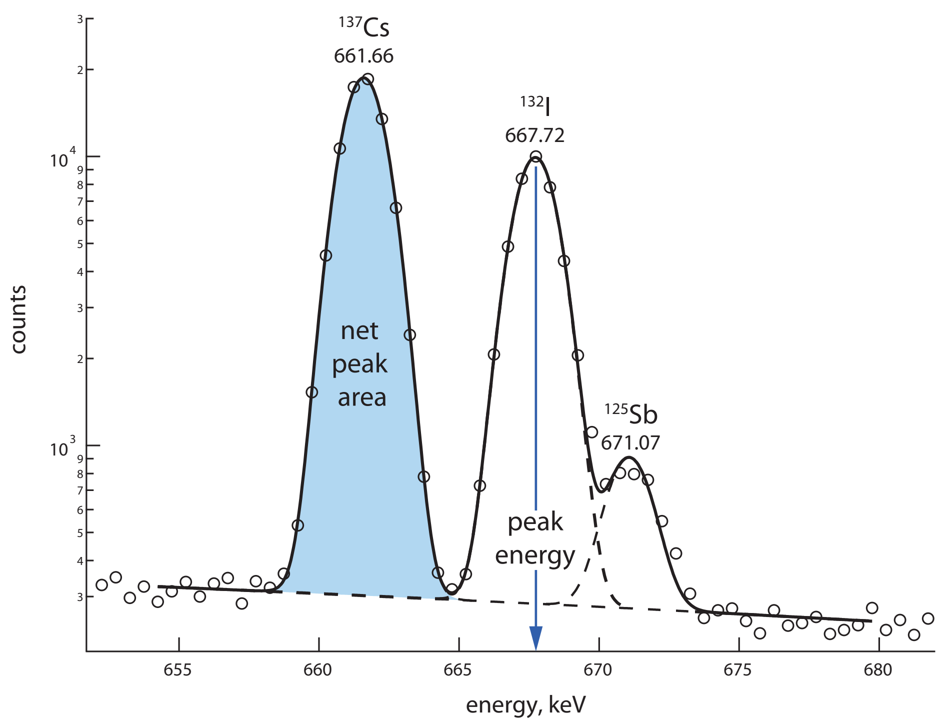

Figure 11: *GAUSS triplet peak fit*

Table 1: CTBT-relevant fission products and their major gamma-ray peaks. *The most-intense gamma-ray peak of each isotope is listed in the Peak 1 column, and the second-most-intense peak is described in the Peak 2 column. The peak used by* OSIRIS *to identify each of the CTBT-relevant fission-product isotopes is indicated in* ***bold*** *type. For best sensitivity,* OSIRIS *generally uses the most-intense peaks, however, second-intensity peaks are used for Nd-147 and Rh-106 to avoid interferences.*

Isotope	Peak 1		Peak 2		Exceptions
	energy, keV	branching ratio, %	energy, keV	branching ratio, %	
Ba-140	**537.3**	**24.4**	162.7	6.2	
Ce-141	**145.4**	**48.3**			
Ce-144	**133.5**	**11.1**	80.1	1.4	
Cs-134	**604.7**	**97.6**	795.9	83.4	
Cs-137	**661.7**	**85.1**			
I-131	**364.5**	**81.5**	637.0	7.2	
I-132	**667.7**	**98.7**	772.6	75.6	
La-140	**1596.2**	**95.4**	487.0	45.5	
Mo-99	**739.5**	**12.3**	181.1	6.2	
Nb-95	**765.8**	**99.8**			
Nd-147	91.1	28.1	**531.0**	**13.4**	Avoid possible X-ray interferences
Pr-144	**696.5**	**1.3**	2185.7	0.7	
Rh-106	511.9	20.6	**621.9**	**10.0**	Avoid 511.0-keV e^+e^- peak interference
Ru-103	**497.1**	**91.0**	610.3	5.8	
Tc-99m	**140.5**	**91.0**			
Te-132	**228.2**	**88.0**	49.7	15.0	
Zr-95	**756.7**	**54.4**	724.2	44.2	

$$R = \frac{N}{T\varepsilon} C_1 C_2 C_3 \ldots$$

where *N* is the number of counts in the gamma-ray photopeak, *T* is the measured live time, and the C_i are correction factors. [26]

Efficiencies must be provided for both horizontal sample counting geometries, and also for the vertical in-situ counting geometry. In general, the efficiency corrections are functions of both gamma-ray energy and source-detector distance.

2.5 Energy and Width Calibration

The spectrum analysis algorithms rely on accurate calibration of the spectrometer energy scale. OSIRIS energy calibrations must be sufficiently accurate to correctly identify the CTBT-relevant radioisotopes in complex spectra. For example, the fission product ^{137}Cs is identified by a peak in a gamma-ray spectrum at 661.7 keV; if the spectrometer energy calibration was just 0.9% too high, this peak would be mistakenly identified as the 667.7-keV ^{132}I fission-product gamma ray.

Table 2: *Strong natural background gamma rays*

Isotope	E gamma, keV	abs. branch, %	rank	remarks
Ac-228	911.16	26.6	1	
	968.97	16.2	2	
Bi-212	727.33	6.6	1	
Bi-214	609.31	44.8	1	
	1120.29	14.8	3	
	1764.49	15.3	2	
e^+e^-	511.0	200	1	positron annihilation
K-40	1460.83	10.7	1	
Pb-212	295.21	18.5	2	
	238.63	43.3	1	
Pb-214	351.92	35.8	1	
Ra-224	240.99	4.0	1	
Ra-226	186.10	3.5	1	possible interference: U-235 185.7
Tl-208	510.77	22.6	3	
	583.19	84.5	2	
	2614.53	99.2	1	

With care, it is routine to calibrate high-resolution gamma-ray spectrometer spectral energies to 0.1%. The accuracy and stability of OSIRIS energy calibrations under field conditions will be an important component of our work planned for FY2016-17.

Figure 11 on the previous page displays the ^{137}Cs and ^{132}I peaks, and the energies of both peaks are correctly identified.

Automatic Spectrometer Calibration

The OSIRIS spectrometer automatic energy-calibration algorithm can be divided into four steps, automatic gain adjustment, calibration source measurement, peak centroid determination, and correlation of peak centroids to peak energies using linear least-squares fitting. The linear fit determines the relation between spectrum channel number x to energy $E(x) = A + B \cdot x$, where A is the constant coefficient, also known as the "DC offset", and the linear coefficient B is often called the "conversion gain".

The calibration routine also determines the peak width equation $W(x) = \alpha + \beta \cdot x$. Here $W(x)$ is the peak full-width at half maximum (FWHM) at channel x. The area of a gamma-ray peak is proportional to the product of peak height and peak width, and hence, the peak width must be accurately known.

1. Automatic Gain Adjustment

A radioactive source is placed in front of the spectrometer. The initialization software sets the spectrometer fine gain so that the full-scale gamma-ray energy is 3000 keV, using a check source gamma-ray peak. For example, the 1460.83-keV ^{40}K peak is placed into channel 3989. Since the OSIRIS spectrometer uses 8192 channels, this adjustment sets the approximate conversion gain b_0 to

(3000 keV)/(8192 channels) = 0.366 keV/channel.

2. Calibration Source Measurement

Once the auto-gain adjustment is complete, a multiple gamma-ray source like ^{152}Eu or ^{228}Th is placed in front of the spectrometer and measured for a few minutes; 100 live seconds is often sufficient for microcurie-strength check sources.

3. Determination of Peak Centroids

The spectrum is searched for peaks at least 5σ above background, using Black's zero-area square-wave method. The peaks found by the search are fitted using Gauss algorithms, and their centroids are stored in a list as $C_1, C_2, \ldots, C_m$.

4. Correlation of Peak Centroids to Peak Energies

Energy calibration is straightforward once the calibration spectral peak centroids $C_1, C_2, C_3, \ldots$ are matched to the calibration source gamma-ray energies, $E_1, E_2, E_3, \ldots$. But this correlation is a challenge for spectrum-blind spectroscopy systems, since the operator cannot visually match peaks to the calibration source energies. Additionally, there may be other gamma-ray peaks in the spectrum from natural background isotopes, and the less-intense calibration source gamma-ray peaks may not be evident if the counting time is too short. A simplified block diagram of the overall energy-calibration algorithm is shown in **Figure 12**. The centroid-energy correlation process is illustrated in **Figure 13**.

For a given radioisotope, two strong peaks are chosen, one at the low-energy end of the spectrum, and another at the high end. Without loss of generality, call the energies of these peaks E_L and E_H. Ideally, E_L and E_H are the lowest- and highest-energy gamma rays emitted by the source, or nearly so. For Eu-152, we chose E_L = 121.78 keV, and E_H = 1408.02 keV. If a peak centroid C_L can be correctly matched to E_L and another peak centroid C_H correctly matched to E_H, the remaining peak centroid-energy correlations are automatic. C_L and C_H are called the "starting centroids".

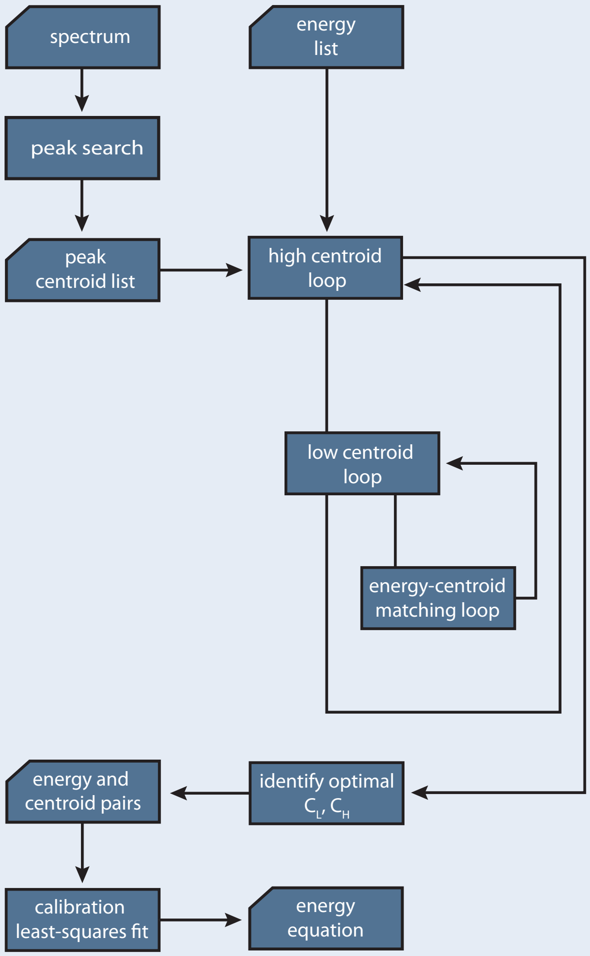

***Figure 12:** Energy calibration algorithm block diagram*

4.1. Outer Loops

The starting centroids are unknown at the beginning of the energy calibration process, and hence every centroid C_i is a candidate for the first starting centroid, and every centroid $C_j < C_i$ is a candidate for the second starting centroid.

The outermost loop steps through candidate centroids $C_1, C_2, \ldots, C_m$ to pair with the energy E_H in the calibration library. By assuming a DC offset of zero, and performing a linear calibration, an approximate initial calibration curve, $E(x) = b_1 \cdot x$ is constructed. Since the auto gain adjustment has produced an approximate conversion gain (energy-equation slope) of 0.366 keV/channel, a centroid producing that conversion gain within tolerance is accepted as a candidate starting centroid C_H.

A second outer loop steps through candidate centroids $C_1, C_2, \ldots, C_m$ to pair with the energy E_L in the calibration library. By performing a linear calibration with the first and second centroid-energy pairs, a calibration curve $E(x) = a_2 + b_2 \cdot x$ is constructed. Again, knowing the approximate conversion gain, a second centroid producing a calibration curve within the conversion gain and DC offset tolerances will be accepted as a candidate for the second starting centroid.

4.2. Inner Loop

The inner loop starts with a candidate linear calibration $E(x) = a_2 + b_2 \cdot x$ obtained from the two "starting" gamma-ray peak centroid-energy pairs expected from the gamma-ray check source. For each choice of starting centroid-energy pairs, the inner loop is executed once.

4.2.1. Third Centroid-Energy Pair

The third energy E_3 in the calibration library is compared to the centroid list $C_1, C_2, \ldots C_m$ obtained from the peak search. The number of centroids may be less than, equal, or greater than the number of library energies. By inverting the approximate channel-energy relation, one can determine the approximate position of the peak corresponding to E_3, if present; $x_3 = (E_3 - a_2)/b_2$. If one of the centroids C_i lies within tolerance of x_3, it is paired with E_3.

Next, a line is drawn through the three points by a linear least-squares fit. If C_i and E_3 indeed correspond to the same gamma-ray peak, the three points should be collinear or nearly so, and the linear fit χ_2 should be small. But if $\chi^2 > 50$, or if $\chi^2 > 2$ and χ^2 is at least 5 times greater than its previous value, the centroid does not match E_3, and E_3 is skipped.

Assuming a good match between C_i and E_3, a new and likely better energy equation is generated by the fit: $E(x) = a_3 + b_3 \cdot x$.

4.2.2. Successive Centroid-Energy Pairs

In turn, the algorithm attempts to find a peak centroid C_j matching E_4, and fits a line through the existing centroid-energy pairs and the new (C_j, E_4) pair. If the fit χ^2 is small, the new pair is accepted, and the new energy equation $E(x) = a_4 + b_4 \cdot x$ is used to find the peak centroid corresponding to E_5. The process repeats until centroids are produced (or rejected) for all of the library energies through E_n. At each step, a new linear fit is performed, producing a new energy equation for each centroid-energy match.

4.3 Choose Optimal Starting Centroids

The choice of starting centroids that produce the greatest number of centroid-energy matches, as tallied in the inner loop, is chosen as optimal, and the energy calibration corresponding to that choice of starting energies is used for calibration. If there is a tie, the starting centroids choice that produces the lowest fit χ^2 is chosen.

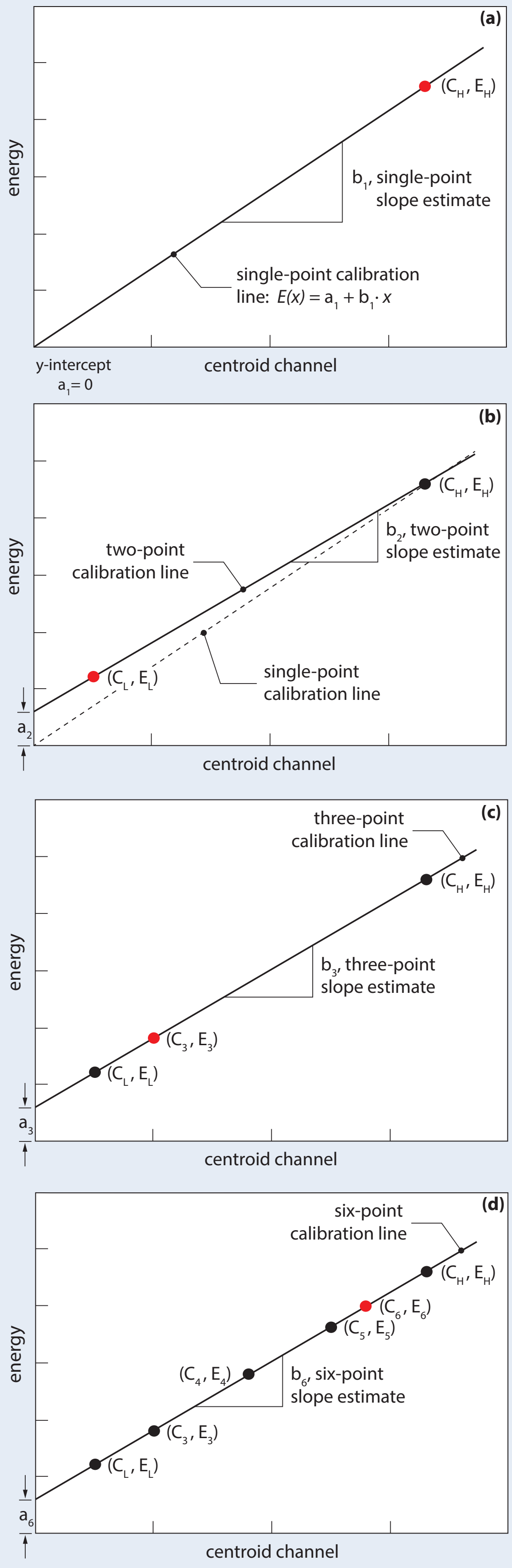

Figure 13: *Automatic energy-calibration progression: (a) The low-channel centroid-energy pair determines an approximate calibration line. (b) The high-channel centroid-energy pair refines the calibration line. (c) Addition of a third centroid-energy pair improves the calibration line estimate. (d) As many additional centroid-energy pairs as possible are added to the energy calibration line, to further refine the least-squares fit.*

4.4. Energy Calibration Example

Table 3 below presents OSIRIS spectrometer calibration performance following a 100-live-second measurement of an ^{152}Eu check source. Besides twelve ^{152}Eu gamma rays, the calibration also used the 2614.53-keV ^{208}Tl natural background gamma ray. The peak energies determined by the calibration agree with the library energies to 0.1 keV or less in most cases, and they agree to better than 0.1% in all cases.

4.5. Peak Width Calibration

The peaks from the centroid-energy pair list are fit using Gauss algorithms, while allowing the peak width to vary. The resulting width from each peak fit is paired with its centroid to create a centroid-width pair, and then the list of pairs is linearly fit to produce the spectrometer width equation,

$W(x) = \alpha + \beta \cdot x.$

The width equation determined during the calibration described in **Table 3** is

$W(x) = 3.898 + 0.000749 \cdot x.$

Table 3: *Eu-152 energy calibration of the OSIRIS spectrometer. ΔE is the difference between a library energy and an energy from the least-squares fit. The library energies are from K. Debertin and R.G. Helmer,* Gamma-Ray Spectrometry with Semiconductor Detectors *(Amsterdam: Elsevier, 1988) page 360.*

Peak Centroid	Library Energy	Fit Energy	ΔE	ΔE/E	ΔE/E, %
(channel)	(keV)	(keV)	(keV)		
332.58	121.78	121.74	-0.04	-3.28E-04	0.033%
668.78	244.70	244.55	-0.15	-6.13E-04	0.061%
941.77	344.28	344.27	-0.01	-2.90E-05	0.003%
1124.96	411.13	411.18	0.05	1.22E-04	0.012%
1214.85	443.97	444.02	0.05	1.13E-04	0.011%
2131.75	778.92	778.95	0.03	3.85E-05	0.004%
2374.00	867.39	867.43	0.04	4.61E-05	0.005%
2638.30	964.06	963.98	-0.08	-8.30E-05	0.008%
3043.68	1112.09	1112.05	-0.04	-3.60E-05	0.004%
3320.25	1212.97	1213	0.03	2.47E-05	0.002%
3556.25	1299.15	1299.29	0.14	1.08E-04	0.011%
3853.79	1408.02	1407.97	-0.05	-3.55E-05	0.004%
7156.71	2614.53	2614.46	-0.07	-2.68E-05	0.003%

OSIRIS spectrum T6_09Jun15_001.chn

Figure 14: *Transpec-100 in Jordan during IFE14*

3. Osiris Hardware

The Osiris hardware includes an ORTEC Transpec-100 mechanically-cooled high-purity germanium (HPGe) gamma-ray spectrometer, [27] and a Panasonic Toughbook notebook computer [28] that serves as the instrument's control panel and data display.

3.1 ORTEC Transpec-100 Gamma-Ray Spectrometer

The ORTEC Transpec-100 gamma-ray spectrometer was selected because of its proven reliability, freedom from liquid nitrogen supplies, battery operation, and 40% relative-efficiency Ge detector. The Transpec and the nearly identical ORTEC Detective [29] gamma-ray spectrometers have been used in U.S. military applications since 2005. The Transpec-100 Ge crystal is cooled to about 100 Kelvin (–173 °C, –279 °F.) by an electrically-powered Stirling-cycle refrigerator. The Transpec-100 lithium-ion battery can power the instrument for 12 hours. The Transpec-100 also includes a built-in 8192-channel digital-signal-processing multichannel analyzer.

The gamma-ray spectrometer was used at the Comprehensive Nuclear-Test-Ban Treaty Organization Integrated Field Exercise (IFE14) conducted in Jordan during November-December 2014. [30] The spectrometer was used in the *in-situ* tripod-mounted counting geometry during IFE14, as shown in **Figure 14**.

3.2 Panasonic CF-31 Toughbook Notebook Computer

The Panasonic Toughbook is a ruggedized computer with a daylight-visible screen; Toughbooks have been standard in PINS systems since 2001. This notebook runs under Windows 7, and besides controlling and reading out the Transpec-100 spectrometer, it reanalyzes the current gamma-ray spectrum every ten seconds for the duration of the measurement.

3.3 Future Data Security Modifications

While OSIRIS software hides spectra and spectral information irrelevant to CTBT on-site inspections, the current OSIRIS hardware presents several data security issues. In particular, a small personal-digital-assistant-like (PDA-like) computer atop the Transpec-100 includes a small display screen, and this screen can display gamma-ray spectra. **Figure 15** shows the Transpec-100 PDA and display screen. The PDA also stores spectra from the Transpec-100 on a removable SD card, another potential data security risk.

Figure 15: *Transpec-100, rear view showing the PDA*

Future data security modifications will include removal of the PDA computer and its display, and encryption of spectral files stored on the notebook computer hard drive.

4. Software Testing and Evaluation

4.1 OSIRIS Spectral Analysis Testing

The OSIRIS software has been tested with both measured and synthetic fission-product spectra.

In all cases, the spectra were analyzed twice, once by a spectroscopist using the GAUSS XI interactive gamma-ray spectral analysis program, and once by the OSIRIS automated software. The two analyses were compared and scored by a custom computer program.

4.2 Test Spectra

Our first fission-product test spectra were measured from irradiated reactor fuel samples. An additional 100 test spectra were synthesized at Lawrence Livermore National Laboratory (LLNL) and Pacific Northwest National Laboratory (PNNL).

4.2.1 Reactor Fuel Sample Spectra

We started by analyzing fission product spectra measured from experimental uranium nuclear reactor fuel samples irradiated in the Idaho National Laboratory (INL) Advanced Test Reactor. In these spectra, the fission-product peaks are quite intense, and since the spectrometer was shielded and tightly collimated, most of the natural background lines are not evident.

Seven reactor fuel sample spectra were measured, and the cooling times after irradiation prior to measurement varied from 6 to 24 months.

4.2.2 Synthetic Test Spectra

We defined nine on-site inspection scenarios to design a set of synthetic gamma-ray spectra for data filter assessment. The scenarios include the following:

1. Nuclear explosion – strong underground release including particulates, assayed weeks after explosion
2. Nuclear explosion – weak activity with limited particulate release, assayed 1-2 weeks after explosion
3. Nuclear explosion – weak activity with limited particulate release assayed 1-2 years after explosion
4. Nuclear explosion – Gas-only release with subsequent decay-daughter particulate deposition, assayed weeks after explosion
5. Legacy testing debris assayed decades after explosion, "Nevada Test Site" aboveground surface/shallowly buried or similar
6. Reactor accident – Predominantly volatile release, "Fukushima"
7. Reactor accident – Core release with refractories & volatiles, "Chernobyl"
8. Spent-fuel reprocessing waste site
9. Industrial/medical isotope production waste site

Of these, the first four scenarios are not compliant with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) while the latter five are treaty-compliant.

The synthetic spectra were based on actual measured spectra, to the extent possible, but often computer simulations were necessary to combine the fission-product signal with a natural background gamma-ray spectrum. In total, the test set of contains 130 individual synthetic spectra.

These test spectra were limited to HPGe detectors. As the "gold standard" (in terms of energy resolution) on-site inspection spectroscopic detector, it is most prone to requiring a data filter to prevent revealing the presence of non-relevant radionuclides, but also the most amenable to successful implementation of a data filter.

4.3 Spectral Analysis Testing

The OSIRIS spectral analysis software has been tested on the fission-product gamma-ray spectra described above in section 4.2. Each spectrum contained fission-product peaks, natural-background isotope peaks, or both, and each spectrum was analyzed twice. The first analysis was performed visually by an experienced spectroscopist. Each spectrum was then analyzed by the OSIRIS software. Finally, a computer program compared the visual and OSIRIS spectral analyses.

4.3.1 Visual Analysis

Visual analysis of the test spectra was carried out using the INL GAUSS XI interactive gamma-ray spectral analysis program. [31] It should be noted that OSIRIS and GAUSS XI share the same peak search, region definition, and nonlinear least-squares peak fitting software, the Gauss algorithms.

An example GAUSS XI analysis report for the reactor-fuel sample spectrum of **Figure 6** is shown in **Table 4**. For brevity, the table is limited to gamma rays in the energy range 120 – 700 keV.

4.3.2 OSIRIS Analyses

In File View mode, OSIRIS provides automatic analysis of a gamma-ray spectrum by simply clicking on a file name, or by choosing an entire file directory. For each spectrum, a text file containing energy and width calibration information must be provided. The energy and width calibration files were generated during visual spectrum analysis with GAUSS XI.

A similar OSIRIS analysis report for the reactor-fuel sample spectrum of **Figure 6** is shown in **Table 5**. Like **Table 4**, the OSIRIS analysis table is also limited to gamma rays in the energy range 120 – 700 keV.

Table 4: *GAUSS XI analysis of MFC reactor-fuel sample spectrum 107 (over energy range 120 - 700 keV).*

isotope	centroid E (keV)	σ-cent E (keV)	library E (keV)	library ΔE (keV)	net area (counts)	σ-area (counts)	net area/σ-area
Eu-154	123.19	0.00	123.07	0.12	115262.3	864.2	133.4
Ce-144	133.60	0.00	133.51	0.09	2707587.6	1803.2	1501.5
Sb-125	176.35	0.01	176.33	0.02	28451.2	592.7	48.0
Eu-154	247.88	0.01	247.97	0.09	29393.7	579.8	50.7
Sb-125	380.24	0.07	380.43	0.19	4937.1	466.9	10.6
Ba-140	423.53	0.05	423.72	0.19	7273.2	355.2	20.5
Sb-125	427.65	0.01	427.87	0.22	100361.1	538.2	186.5
Sb-125	463.13	0.01	463.39	0.26	29658.8	627.5	47.3
Cs-134	475.14	0.01	475.35	0.21	107073.5	590.0	181.5
Rh-106	511.61	0.00	511.84	0.23	1442217.3	1285.5	1121.9
Cs-134	563.06	0.00	563.23	0.17	481743.2	797.1	604.4
Cs-134	569.15	0.00	569.32	0.17	878080.0	1050.2	836.1
Eu-154	591.73	0.03	591.81	0.08	10780.8	331.2	32.6
Sb-125	600.38	0.01	600.56	0.18	58043.2	484.9	119.7
Sb-124	602.59	0.04	602.74	0.15	51774.3	1735.0	29.8
Cs-134	604.62	0.00	604.69	0.07	5281583.2	3084.1	1712.5
Rh-106	616.15	0.01	616.17	0.02	43734.2	371.8	117.6
Rh-106	621.96	0.00	621.93	0.02	592921.2	934.0	634.8
Sb-125	635.92	0.01	635.89	0.03	25053.2	378.3	66.2
Ag-110m	658.48	0.01	657.76	0.72	39616.7	389.8	101.6
Cs-137	661.67	0.00	661.66	0.01	5660275.8	2425.1	2334.0
Sb-125	671.50	0.05	671.41	0.09	3173.0	326.1	9.7
Ag-110m	677.56	0.19	677.62	0.07	869.7	207.8	4.2
Eu-154	692.70	0.05	692.42	0.28	4216.9	212.9	19.8

Table 5: *OSIRIS analysis of MFC reactor-fuel sample spectrum 107 (over energy range 120 - 700 keV).*

isotope	centroid E (keV)	net area (counts)	σ-area (counts)	net area/σ-area	isotope type	peak intensity rank
Eu-154	123.22	114594.8	613.8	186.7	OFP	1
Ce-144	133.58	2704027	1779.4	1519.7	TFP	1
Sb-125	176.37	34487.8	1842.1	18.7	OFP	5
Cs-136	188.25	3241.2	479.8	6.8	OFP	14
Pb-214	242.41	1984.2	411.6	4.8	NB	3
Eu-154	247.84	30520.5	464.1	65.8	OFP	7
Cs-136	340.55	1640.4	343.3	4.8	OFP	3
Sb-125	380.66	4310.1	389.8	11.1	OFP	9
Ba-140	423.72	4695.8	374.5	12.5	TFP	5
Sb-125	427.66	95750.9	695.8	137.6	OFP	1
Ac-228	463.15	29706.5	385.5	77.1	NB	5
Cs-134	475.14	101830.4	548.3	185.7	TFP	7
Cs-134	563.08	475917.8	826.6	575.7	NB	4
Cs-134	569.18	874692.8	1041.7	839.7	TFP	3
Tl-208	582.00	1303.9	304.0	4.3	NB	2
Eu-154	591.62	9733.6	331.1	29.4	OFP	8
Sb-125	600.56	62816.2	419.8	149.6	OFP	2
Cs-134	604.64	5312731	2359.2	2251.9	TFP	1
Rh-106	616.17	41929.5	395.2	106.1	TFP	4
Rh-106	621.98	591204.3	864.6	683.8	TFP	2
Sb-125	635.95	25387.6	395.9	64.1	OFP	3
Ag-110m	657.76	28293.8	359.7	78.7	OFP	1
Cs-137	661.69	5664162.0	2430.9	2330.1	TFP	1
I-132	671.40	1660.0	252.4	6.6	TFP	10
Eu-154	692.42	3989.6	225.6	17.7	OFP	10
Pr-144	696.64	173119.1	474.3	365	TFP	1

4.3.3 Spectral Analysis Comparison Software

The OSIRIS test tool was developed to assist in the comparison of the analysis of a spectrum by the OSIRIS software to the analysis of a spectrum as performed by an expert. It provides a tally of treaty fission product detection (true positives and true negatives), as well as a check of the peak area fidelity of each detected peak. For the set of test spectra provided, each spectrum was analyzed by both the OSIRIS software and by an expert using the GAUSS XI software program. Then the OSIRIS test tool was used to compare analyses and tally the comparisons. The tally was used in various papers and reports.

The OSIRIS test tool uses the analysis output files generated by an OSIRIS analysis along with the text files containing expert peak fit information as written by the GAUSS XI software program. For each spectrum, the test tool generates two reports: a full report comparing the OSIRIS and expert analysis results of each gamma-ray library peak, and a fast report limited to the CTBT-treaty relevant peaks only. If more than one spectrum is selected for comparison, the test tool generates a summary of the tallies of all the selected spectra.

An example full report for the spectrum of **Figure 6** is presented in **Tables 6a**, **6b**, and **6c**; for brevity, this report is limited to gamma rays between 120-700 keV. **Table 6a** compares peak energies and peak detection significances ($t^* > 3$) to determine if a peak has been identified by both GAUSS XI and OSIRIS.

If a peak has been identified by both programs, it is judged a true positive. If detected by neither program, it is a true negative. If detected by OSIRIS but not GAUSS XI, it is a false positive, and if it was detected by GAUSS XI but not OSIRIS, it is a false negative. **Table 6b** displays the treaty fission product isotope identification categorizations.

The test tool also compares the net peak areas computed by GAUSS XI and OSIRIS. If the peak areas agree to 5% or less, they are categorized as a match. **Table 6c** presents the peak area comparisons for the spectrum in **Figure 6**.

Table 6a: *Comparison of energies and peak detection significances (t*) of Gauss XI and Osiris Analyses of MFC Spectrum 107 (over energy range 120 - 700 keV).*

		Osiris	Osiris	Osiris	Osiris	Gauss XI	Gauss XI	Gauss XI	Gauss XI
Library E (kev)	**Isotope**	**Energy (keV)**	**Area (counts)**	**t***	**Detected**	**Energy (keV)**	**Area (counts)**	**t***	**Detected**
123.07	Eu-154	123.22	114594.8	186.7	true	123.193	115262.316	133.369	true
133.51	Ce-144	133.58	2704026.5	1519.7	true	133.596	2707587.645	1501.517	true
176.33	Sb-125	176.37	34487.8	18.7	true	176.351	28451.177	48.002	true
247.97	Eu-154	247.84	30520.5	65.8	true	247.88	29393.727	50.692	true
380.43	Sb-125	380.66	4310.1	11.1	true	380.241	4937.066	10.574	true
423.72	Ba-140	423.72	4695.8	12.5	true	423.529	7273.232	20.478	true
427.87	Sb-125	427.66	95750.9	137.6	true	427.651	100361.087	186.469	true
463.39	Sb-125				false	463.133	29658.81	47.267	true
475.35	Cs-134	475.14	101830.4	185.7	true	475.141	107073.468	181.476	true
511.84	Rh-106				false	511.61	1442217.291	1121.945	true
562.5	Ac-228	563.08	475917.8	575.7	true				false
563.23	Cs-134				false	563.059	481743.159	604.382	true
569.31	Cs-134	569.18	874692.8	839.7	true	569.154	878079.997	836.074	true
591.81	Eu-154	591.62	9733.6	29.4	true	591.729	10780.841	32.555	true
600.56	Sb-125	600.56	62816.2	149.6	true	600.38	58043.163	119.69	true
604.7	Cs-134	604.64	5312730.7	2251.9	true	604.619	5281583.164	1712.501	true
616.17	Rh-106	616.17	41929.5	106.1	true	616.153	43734.168	117.636	true
621.93	Rh-106	621.98	591204.3	683.8	true	621.956	592921.238	634.799	true
635.89	Sb-125	635.95	25387.6	64.1	true	635.922	25053.181	66.23	true
657.76	Ag-110m	657.76	28293.8	78.7	true	658.484	39616.747	101.626	true
661.66	Cs-137	661.69	5664162	2330.1	true	661.665	5660275.817	2334.001	true
671.4	I-132	671.4	1660	6.6	true	671.501	3173.005	9.729	true
692.42	Eu-154	692.42	3989.6	17.7	true	692.699	4216.916	19.807	true
696.51	Pr-144	696.64	173119.1	365	true	696.601	173566.515	332.935	true

Table 6b: *Treaty fission product isotope identification classifications of MFC Spectrum 107 (over energy range 120 - 700 keV).*

		Osiris	Osiris	Gauss XI	Gauss XI	Isotope Identification				
Library E (kev)	**Isotope**	**t***	**Detected**	**t***	**Detected**	**Type**	**true +**	**true -**	**false +**	**false -**
123.07	Eu-154	186.7	true	133.369	true	OFP	1	0	0	0
133.51	Ce-144	1519.7	true	1501.517	true	TFP	1	0	0	0
176.33	Sb-125	18.7	true	48.002	true	OFP	1	0	0	0
247.97	Eu-154	65.8	true	50.692	true	OFP	1	0	0	0
380.43	Sb-125	11.1	true	10.574	true	OFP	1	0	0	0
423.72	Ba-140	12.5	true	20.478	true	OFP	1	0	0	0
427.87	Sb-125	137.6	true	186.469	true	OFP	1	0	0	0
463.39	Sb-125		false	47.267	true	OFP	0	0	0	1
475.35	Cs-134	185.7	true	181.476	true	TFP	1	0	0	0
511.84	Rh-106		false	1121.945	true	TFP	0	0	0	1
562.5	Ac-228	575.7	true		false	TFP	0	0	0	1
563.23	Cs-134		false	604.382	true	TFP	0	0	0	1
569.31	Cs-134	839.7	true	836.074	true	OFP	1	0	0	0
591.81	Eu-154	29.4	true	32.555	true	OFP	1	0	0	0
600.56	Sb-125	149.6	true	119.69	true	TFP	1	0	0	0
604.7	Cs-134	2251.9	true	1712.501	true	TFP	1	0	0	0
616.17	Rh-106	106.1	true	117.636	true	TFP	1	0	0	0
621.93	Rh-106	683.8	true	634.799	true	OFP	1	0	0	0
635.89	Sb-125	64.1	true	66.23	true	OFP	1	0	0	0
657.76	Ag-110m	78.7	true	101.626	true	TFP	1	0	0	0
661.66	Cs-137	2330.1	true	2334.001	true	TFP	1	0	0	0
671.4	I-132	6.6	true	9.729	true	OFP	1	0	0	0
692.42	Eu-154	17.7	true	19.807	true	TFP	1	0	0	0
696.51	Pr-144	365	true	332.935	true	OFP	1	0	0	0

Table 6c: *Peak area comparisons of MFC Spectrum 107 (over energy range 475 - 700 keV).*

		Osiris	Gauss XI		Peak Area (A) Comprisons			
Library E (kev)	**Isotope**	**Area (counts)**	**Area (counts)**	**Type**	**Δ area**	**ΔA/A**	**ΔA/A, %**	**match**
475.35	Cs-134	101830.4	107073.468	TFP	-5243.1	0.049	4.9	yes
511.84	Rh-106		1442217.291	TFP				
562.5	Ac-228	475917.8	481743.159	TFP	-5825.4	0.012	1.2	yes
563.23	Cs-134	874692.8	878079.997	TFP				
569.31	Cs-134	9733.6	10780.841	OFP	-3387.2	0.004	0.4	yes
591.81	Eu-154	62816.2	58043.163	OFP				
600.56	Sb-125	5312730.7	5281583.164	TFP	31147.5	0.006	0.6	yes
604.7	Cs-134	41929.5	43734.168	TFP	-1804.7	0.041	4.1	yes
616.17	Rh-106	591204.3	592921.238	TFP	-1716.9	0.003	0.3	yes
621.93	Rh-106	25387.6	25053.181	OFP				
635.89	Sb-125	28293.8	39616.747	OFP				
657.76	Ag-110m	5664162	5660275.817	TFP	3886.2	0.001	0.1	yes
661.66	Cs-137	1660	3173.005	TFP	-1513.0	0.477	47.7	no
671.4	I-132	3989.6	4216.916	OFP				
692.42	Eu-154	173119.1	173566.515	TFP	-447.4	0.003	0.3	yes
696.51	Pr-144	114594.8	115262.316	OFP				

4.4 Spectral Analysis Test Results

The radioisotopes detected in the test spectra by Osiris are displayed in **Table 7**. Notably, all seventeen treaty-relevant fission products were represented in the test spectra and identified.

For each spectrum, the treaty-relevant fission-product true-positive and true-negative correct identification fractions are displayed in **Figure 16**.

Summed over all of the spectra, the Osiris isotope identification scores are presented in **Table 8**.

The test program also compared CTBT-relevant fission-product peak areas between Osiris and Gauss XI analyses, and the Osiris and Gauss XI peak areas agreed within error for 90.8% of the CTBT-relevant radioisotopic peaks. Peak areas had to agree within 5% to be scored as a match.

Table 7: Test spectral radioisotopes detected by OSIRIS

Type	Isotopes Detected
Treaty-relevant fission products	^{140}Ba, ^{141}Ce, ^{144}Ce, ^{134}Cs, ^{137}Cs, ^{131}I, ^{132}I, ^{140}La, ^{99}Mo, ^{95}Nb, ^{147}Nd, ^{144}Pr, ^{106}Rh, ^{103}Ru, ^{99m}Tc, ^{132}Te, ^{95}Zr
Other fission products	^{110m}Ag, ^{136}Cs, ^{152}Eu, ^{154}Eu, ^{125}Sb, ^{91}Y
Other radioisotopes	^{241}Am, ^{60}Co
Natural background isotopes	^{228}Ac, ^{212}Bi, ^{214}Bi, ^{40}K, ^{212}Pb, ^{214}Pb, ^{208}Tl

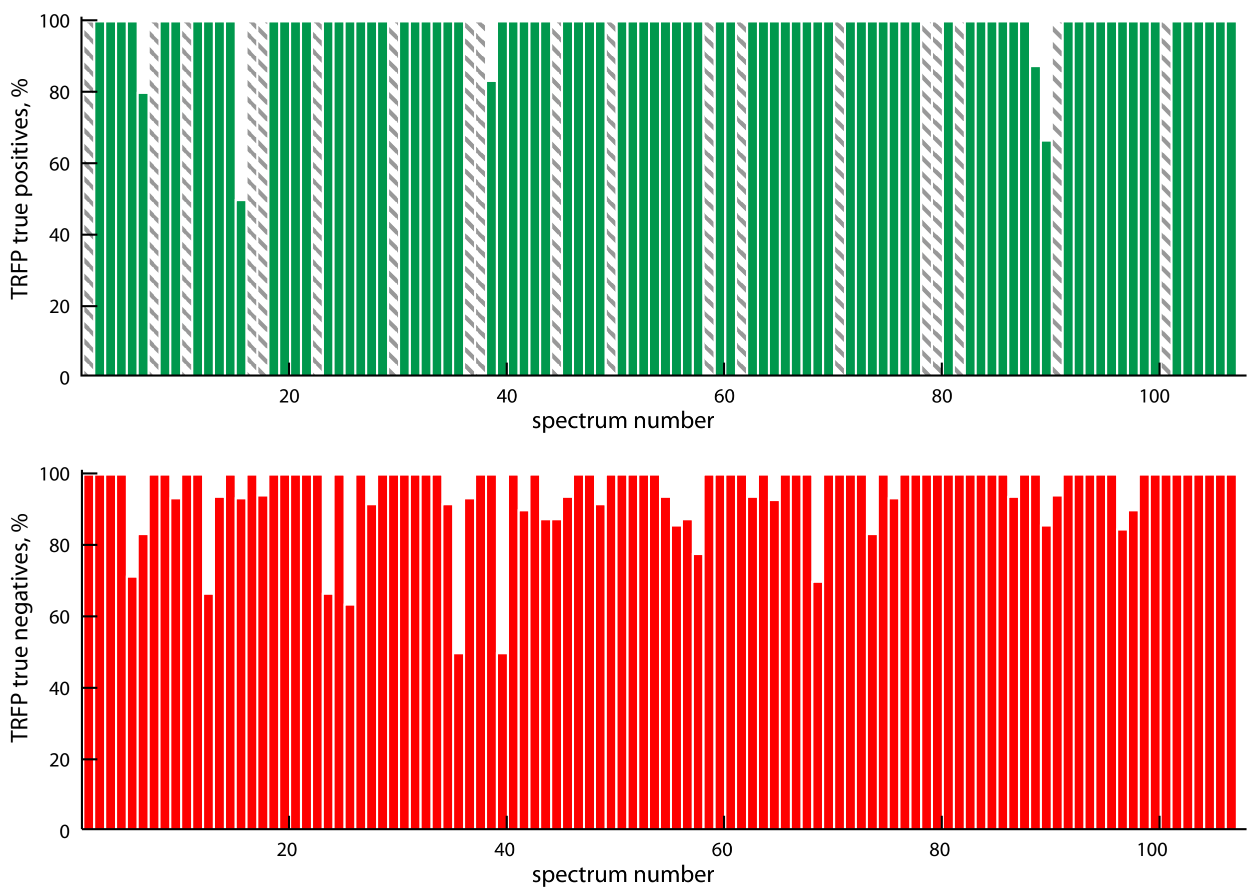

Figure 16: *True positive and true negative scores for treaty-relevant fission product (TRFP) isotopes*

Table 8: Overall OSIRIS correct and incorrect isotope identification scores

Isotope type	True positive fraction, %	True negative fraction, %	False positive fraction, %	False negative fraction, %
Treaty-relevant fission products	98.1	96.2	3.8	1.9
Other fission products	86.5	94.9	5.1	13.5
Other radioisotopes	95.0	96.8	3.2	5.0
Natural background isotopes	83.5	89.7	10.3	16.5

4.5 Technology Readiness Levels

Technology readiness levels characterize the maturity of and the risk associated with critical technologies. The U.S. Department of Energy/NA-22 Technology Readiness and Maturation Guide [32] defines a technology readiness level scale running from 1 to 9, as summarized in **Table 9**.

At the inception of the OSIRIS project, its ORTEC Transpec-100 gamma-ray spectrometer and Panasonic Toughbook CF-31 notebook computer were both "off-the-shelf" commercial products, and both had been used successfully in military field applications. Hence both hardware components qualify as TRL-9, per the definition in the Guide:

'**2.1.9 TRL-9 Actual system proven through successful mission operations**

> *"The technology is applied and operated in its final form and under real life conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last 'bug fixing' aspects of true system development. Examples include using the system under various real life conditions."'*

The OSIRIS software is based on PINS+ software, and the latter is also at TRL-9, since PINS is an ORTEC commercial project that has been used by the U.S. military in Afghanistan and Iraq. But since the OSIRIS software required significant modifications to the PINS data analysis code, its initial technology readiness would be rated no higher than TRL-4, as defined in the Guide:

'Appendix B.1.d TRL-4 Component and/or breadboard validation in laboratory environment

Software Description (Reference 4):

> *"Basic software components are integrated to establish that they will work together. Modules and/or subsystems are validated in a laboratory environment (e.g. software prototype development environment). They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation [is conducted] with current/legacy elements, as appropriate. Prototypes are developed to demonstrate different aspects of the eventual system."'*

Table 9: *Technology Readiness Levels*

Level	Definition
TRL-1	Basic principles observed and reported
TRL-2	Technology concept and/or application formulated
TRL-3	Analytical and experimental critical function and/or characteristic proof of concept
TRL-4	Component and/or breadboard validation in laboratory environment
TRL-5	Component and/or breadboard validation in relevant environment
TRL-6	System/subsystem model or prototype demonstration in relevant environment
TRL-7	System prototype demonstration in an operational environment
TRL-8	Actual system completed and qualified through test and demonstration
TRL-9	Actual system proven through successful mission operations

From these considerations, the OSIRIS overall technology readiness level at the start of the OSIRIS project in 2012 was TRL-4; the software was the limiting factor.

Currently, the OSIRIS hardware remains at TRL-9. The OSIRIS software is now operational and it is undergoing integration tests with the hardware. Since FY2014, the software has been tested with synthetic spectra generated at LLNL and PNNL, simulating both treaty-compliant and treaty-noncompliant operational scenarios.

We consider the OSIRIS software has now advanced to TRL-6, as defined in the Guide:

'**Software Description (Reference 4):**

> "*Level at which the engineering feasibility of a software technology is demonstrated. Modules and/or subsystems are validated in a relevant end-to-end environment. TRL 6 extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.*"'

Consequently, the current overall OSIRIS readiness level is TRL-6.

By the end of FY2016, we plan to advance OSIRIS to TRL-7 via rigorous field testing following hardware and software modifications to improve system security. In FY2017, we plan to complete development, and our planned end-state technology readiness level for the integrated OSIRIS system is TRL-8.

4.6 Future Development

We have planned a detailed set of system integration and field tests of OSIRIS for FY2016 and FY2017. [33]

4.6.1 System Integration

Initial system testing will be performed in an INL laboratory equipped with an environmental chamber. The Transpec-100 spectrometer will be cooled to -15° C (+5° F) and heated to 50° C (122° F) to study temperature effects on its electronic gain and its energy calibration.

INL will also obtain a sealed 5-microcurie (200-kilobecquerel) uranium fission-product source from Eckert and Ziegler and start measuring fission-product energy spectra as a function of time, as another OSIRIS system-integration test. This source will aid in the performance and proficiency of our gamma-ray spectral analyses. A similar fission-product source will be used in OSIRIS field tests.

4.6.2 Data Security Modifications

The Transpec-100 hardware will be modified by ORTEC to protect against surreptitious attempts to view or copy OSIRIS spectral data. For example, its PDA-like computer device with a built-in spectral display will be removed.

The OSIRIS software will be changed to automatically encrypt raw spectral data.

4.6.3. Software Modifications

In addition to spectral file encryption, a number of OSIRIS software modifications have been planned for FY2016.

4.6.3.1 Test Spectra Revisited

In early FY2016, we will re-analyze the set of 130 test spectra synthesized at LLNL and PNNL, with a goal of improving OSIRIS isotope identification and peak-area accuracies. We also plan to obtain approximately two dozen more test spectra, from calibrated fission-product sources.

4.6.3.2 Detector Efficiency and Isotopic Radioactivity Calculations

In the near future we will add efficiency-correction routines to calculate the activity of each CTBT-relevant isotope. As mentioned above in section 2.4.5, OSIRIS software will first read in tables of efficiency corrections for two distinct counting geometries, sample counting and in-situ counting. OSIRIS must also maintain a table of gamma-ray branching ratios for the 17 CTBT-relevant fission products. Then OSIRIS must calculate the activity of each isotope by applying the appropriate corrections, including detector efficiency, as a function of energy, distance, and counting geometry, the emission probability (branching ratio) for each gamma ray of interest, and sample self-absorption corrections, to the measured peak-area counting rates.

4.6.4.6 Post-Field Test Software Modifications

Later in FY2016, further software modifications may be needed, as suggested by field-testing experience. For example, it may become necessary to monitor the stability of the spectrometer energy calibration.

4.6.4 Field Testing

The OSIRIS field tests will study energy calibration accuracy, energy calibration stability, and fission-product measurement accuracy under outdoor conditions for three seasons of the year: winter, spring, and summer.

4.6.4.1 Fission-Product Measurements

The primary aim of field testing is to confirm that OSIRIS can accurately measure CTBT-related fission-product gamma rays outdoors, under variable weather conditions. The anticipated OSIRIS field testing schedule is listed in **Table 10**.

Table 10: *Planned OSIRIS Field Tests*

Start	Finish	Location	Test Goals
January 2016	June 2016	INL Reactor Site	Fission-product ID, E-Cal accuracy, Gain stability
July 2016	Sept. 2016	Hanford Site	Fission-product ID, E-Cal accuracy, Gain stability
Nov. 2016	Nov. 2016	NNSS* (former NTS**)	Fission-product ID in a contaminated test area
TBD, 2017	TBD, 2017	TBD	CTBTO on-site inspection training exercise

*NNSS: Nevada National Security Site **NTS: Nevada Test Site

4.6.4.2 Fission Product Half-Lives

On-site inspections under the CTBT could take place within a few weeks of a suspicious event, or perhaps as late as two years afterward. If the character of fission-product gamma-ray spectra remained constant in time after a fission event, field testing could be performed in a week or two. But fission-product isotopes decay and their daughter isotopes grow in, dramatically changing the gamma-ray spectra on time scales of a few months, during the first two years following a fission event. To see this, consider the half-lives of the CTBT-related fission-product isotopes displayed in **Table 11** below.

These half-lives vary from 2.7 days (Mo-99) to 30 years (Cs-137). In the first few months after a fission event, gamma-rays from I-131, I-132, Te-132, Ba-140, and La-140 dominate the fission-product spectrum. As those short-lived isotopes decay away, three or four months after a fission event, Zr-95, its daughter Nb-95, and Ce-141 become the dominant radioisotopes. A year or so after a fission event, gamma rays from Ce-144 and its Pr-144 daughter, Ru-106 and its Rh-106 daughter, and Cs-134 will produce the strongest spectral peaks. Longer term, Cs-134 and Cs-137 are the dominant isotopes.

Table 11: *The CTBT-relevant fission-product isotopes and their half-lives**

Isotope	Half-life	Parent
Ba-140	12.79 days	
Ce-141	32.52 days	
Ce-144	284.89 days	
Cs-134	2.062 years	
Cs-137	30.07 years	
I-131	8.02 days	
I-132	2.295 hours	3.204-day Te-132
La-140	1.678 days	12.79-day Ba-140
Mo-99	2.748 days	
Nb-95	34.97 days	64.0-day Zr-95
Nd-147	10.98 days	
Pr-144	17.28 minutes	284.89-day Ce-144
Rh-106	29.8 sec	373.6-day Ru-106
Ru-103	39.26 days	
Tc-99m	6.01 hours	2.748-day Mo-99
Te-132	3.204 days	
Zr-95	64.02 days	

*R.B. Firestone, Editor, Table of Isotopes, Eighth Edition (New York: Wiley, 1996)

We will measure a fission-product source repeatedly over nine months with Osiris in the field tests. The accuracy of the Osiris-measured fission-product activities will be compared to the activities calculated from the known decay and growth curves for these well-studied isotopes.

4.6.4.3 Osiris Energy Calibration Stability

Our second aim is to verify the stability of the Osiris energy calibration under field conditions.

A necessary condition for correct radioisotope identification is an accurate and stable energy calibration, and this condition is especially important for a spectrum-blind spectroscopy system like Osiris.

During the field tests, we will monitor the energy calibration of the Osiris system with a gamma-ray check source like Eu-152 at least three times per day. On field-test days focused on energy calibration, the energy calibration will be checked three times per hour for twelve hours.

The energy calibration test results will determine the frequency of energy calibrations by users, and help determine if spectrum stabilization is necessary. The Transpec-100 hardware has a built-in spectrum stabilizer.

4.6.4.4

The third aim of the field tests is to learn if the Osiris data filter reliably hides information on other radioisotopes, for example the actinides U-235 and Pu-239. We will also verify that natural background or actinide radiation sources will not interfere with Osiris identification of fission-product isotopes.

On the fission-product test days, we will introduce U-235 and Pu-239 check sources from time to time, and compare Osiris spectral analyses with and without the presence of those two actinides. At the Nevada National Security Site, we plan to conduct measurements at an uncontaminated site and at a site with residual contamination from a nuclear test.

4.6.4.5 System Ruggedness Evaluations

The fourth aim of field testing is to verify the Osiris hardware is sufficiently rugged to operate correctly outdoors, under battery power, during all four seasons. Field testing at INL is scheduled from January through June 2016, and it will continue at PNNL from July through September 2016. Any equipment failures will be noted and addressed.

5. Conclusions

5.1 Design Summary

We have designed hardware and software for the acquisition and analysis of high-resolution gamma-ray spectra during on-site inspections under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Our design is based on software used for over twenty years in U.S. military field operations, and on hardware used in the field for over ten years. The key software feature of the On-Site Inspection RadioIsotopic Spectroscopy—Osiris—system is a data filter that limits its display to only radionuclide information relevant to CTBT on-site inspections

5.2 Technology Readiness Level

In July 2015, an independent review committee deemed the current Osiris technology readiness level as TRL-6, and we concur.

5.3 Test Results

Initial tests of Osiris have been conducted with a set of 107 fission-product and/or natural-background spectra, and in these tests, the Osiris correct identification rate exceeded 95% for CTBT-relevant fission product isotopes.
The Osiris gamma-ray spectrometer was used successfully at the 2014 Integrated Field Exercise (IFE14) in Jordan.

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Sadly, we note the July 2014 passing of our PNNL colleague David Jordan. David performed much of the synthetic spectral modeling for OSIRIS.

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    "89. Pursuant to Article IV, paragraph 57 (b) and paragraph 88 (a) above, the inspected State Party shall have the right throughout the inspection area to take measures to protect sensitive installations and locations and to prevent disclosure of confidential information not related to the purpose of the inspection. Such measures may include, inter alia: (a) Shrouding of sensitive displays, stores, and equipment; (b) Restricting measurements of radionuclide activity and

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