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COMPARISON OF RADIONUCLIDE DATA ANALYSIS RESULTS OF THE CTBTO/IDC AND THE FINNISH NDC

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ABSTRACT

The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is to operate a world-wide radionuclide monitoring network consisting of 80 measuring stations that transmit daily gamma-ray spectra measured from air filter samples to the International Data Centre (IDC). All spectra are analysed automatically and the results are reviewed interactively by an analyst. Quality of the automated analysis has a substantial impact on the reliability and efficiency of the analysis operation.

The Finnish National Data Centre (FiNDC) receives the analysis results and raw spectral data from the IDC and performs radionuclide analysis of the spectra using dedicated Finnish software packages.

This work evaluates the differences between the analysis results of the IDC and the FiNDC. The results are studied with respect to the spectrum peak finding, fitting and explaining performance. Furthermore, nuclides associated with the peaks are considered, and an effort is made to approximate the number of spurious nuclide identifications.

The material of this work consists of representative sets containing 500 to 1500 spectra and their respective analysis result pairs. The spectra were measured by the five certified radionuclide stations and three prototype stations that were operating between August 1, 2000 and March 26, 2001.

In the set of 1500 spectra from eight stations, the FiNDC analysis software package was found to detect 4.2 more peaks per spectrum and to explain 5.6 more peaks per spectrum than the IDC software package, which, in turn, left 1.4 more peaks per spectrum unexplained. The median peak explanation percentages of the FiNDC and IDC were 96.7 and 92.3, respectively.

The FiNDC analysis software package was found to report 0.7 more spurious nuclides than the IDC analysis software package. When only the CTBTO relevant nuclides were considered, the difference decreased to 0.05.

The throughput times involved with the IDC raw measuring data transfer and automatic analysis result data transfer were evaluated. 94 percent of the automated analysis results from the IDC were received at the FiNDC within 10 minutes after the end of the spectrum acquisition at the measuring station. This indicates a relatively high reliability of the system that is still in a building phase.

CONTENTS

1 INTRODUCTION

The Comprehensive Nuclear-Test-Ban Treaty (CTBT), adopted by the UN General Assembly and opened for signature in September 1996, has been signed by 160 states and ratified by 76 states as of May 2001. The Treaty bans all nuclear explosions in all environments.

The States Parties to the Treaty establish the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) that will run a global verification regime to monitor compliance with the Treaty. The International Monitoring System (IMS), which is part of the verification regime, utilises four techniques to monitor the earth for evidence of nuclear explosion. The technique based on detecting radionuclides in aerosol samples is the only technique that can distinguish between nuclear explosion and other types of explosion. Furthermore, the radionuclide detecting technique provides for backtracking capability. Certain isotopes and their activity ratios are measures of time and character of the nuclear test explosion.

When complete, the International Monitoring System will comprise 80 radionuclide measuring stations that send gamma-ray spectra to the International Data Centre (IDC) daily. The spectra go through an event screening process, in which each spectrum is analysed and categorised with respect to the radionuclides contained in the sample from which the spectrum was measured. The event screening process includes an automated analysis whose results are reviewed interactively by a human analyst. The analysis results and raw data are supplied as products for the National Data Centres of the States Signatories.

The Finnish National Data Centre (FiNDC) performs its own gamma-ray spectrum analysis and nuclide identification of IMS spectra using dedicated Finnish software packages. The automated radionuclide analysis pipeline installed at the FiNDC receives the raw spectral data from the IDC and performs the analysis and stores the results in a database. Interactive human review is also fully supported by the FiNDC analysis software package, but with limited resources, the aim is to make the automated analysis as reliable as possible.

Correct analysis of a gamma-ray spectrum measured from an air filter sample is a demanding task due to the uncertainties inherently present in the measurement process and the relatively large number of peaks in the spectrum. The Comprehensive Nuclear-Test-Ban Treaty requires that “the verification activities shall be based on objective information” [1, Article IV.2] and, accordingly, sets high quality standards for the automated gamma spectrum analysis. The success and efficiency of the IDC event screening for air filter spectra are highly dependent on the quality of the automated analysis. Correct automated identification of fission products is substantial in order not to rely on the human analyst observations only. Event timing, which is used to estimate the instant of the nuclear test explosion that released the fission and activation products, is based on the ratios of radionuclide concentrations and thus correct quantitative analysis results are of great importance. Furthermore, if the gamma spectra are to be interpreted exhaustively, every gamma peak that remains unidentified by the automated analysis has to be manually analysed, which is unfavourable for the event screening process throughput and cost efficiency.

The present work is result of project collaboration between the Laboratory of Advanced Energy Systems at Helsinki University of Technology and the Finnish National Data Centre. The objective of the project is to evaluate the radionuclide data analysis performance of the FiNDC by comparing its analysis reports to those of the IDC and finding explanations for possible differences in the

results. The FiNDC provided for the project funding and the work was carried out at the Helsinki University of Technology.

High quality of radionuclide data analysis implies correct identifications of source nuclides and accurate determination of their activities. This work presents a number of methods applied to assess the differences between the results of radionuclide data analysis of the IDC and FiNDC. All methods are based on comparisons of analysis results from a large set of spectra. The comparison objectives include the peak area calculation, number of found, explained, unexplained and missed peaks, peak explanation percentage, spurious nuclide identifications and spuriously explained peaks. In addition, the throughput time of the CTBTO spectrum data and automated radionuclide analysis results was examined.

The comparisons were performed under the Linux operating system using shell scripts and C language computer programs written for the purpose. All data transfer between Helsinki University of Technology and the Finnish National Data Centre exploited secure encrypted communications over the network.

2 COMPREHENSIVE NUCLEAR-TEST-BAN TREATY (CTBT)

2.1 Background

The era of nuclear explosions began 16 July 1945 when the first nuclear explosive test was conducted by the United States at Alamogordo, New Mexico. More than 50 nuclear explosions were registered prior to 1954.

In the early 1950s the radioactive fall-outs from atmospheric tests and the accelerated arms race invoked public concern accompanied by arms control advocates' campaigning for the adoption of a treaty banning all nuclear explosions. Prime Minister Nehru of India was the first to express the international concern at high level, when he proposed in 1954 the elimination of all nuclear test explosions worldwide. No agreement was found, though, largely because it was not believed that compliance with such an undertaking could be verified.

Two major steps towards nuclear weapon non-proliferation were taken in the 1960s. Partial Nuclear-Test-Ban Treaty (PTBT), signed in 1963, banned nuclear tests in the atmosphere, underwater and in outer space. The States Parties to the PTBT expressed their determination to seek to achieve the discontinuance of all nuclear weapon test explosions for all time and to continue negotiations to this end. The nuclear explosions were not discontinued, and neither France nor China, both nuclear weapon states, signed the PTBT.

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was opened for signature in 1968 and entered into force in 1970. In the NPT, the States Parties declare their intention to achieve at the earliest possible date the cessation of the nuclear arms race and to undertake effective measures in the direction of nuclear disarmament.

The NPT defines a nuclear-weapon State as one which has manufactured and exploded a nuclear weapon or other nuclear explosive prior to 1 January, 1967 (Article IX.3). According to this definition, the five recognised nuclear-weapon States are the USA, the UK, the Russian Federation, France and China. The nuclear-weapon States agree in the NPT not to act in any manner to enable, assist, encourage or induce any non-nuclear-weapon State to acquire nuclear weapons.

The non-nuclear-weapon States Parties agree to refrain from acquiring nuclear explosive devices and from seeking or receiving any assistance in the manufacture of nuclear explosive devices. Furthermore, each non-nuclear-weapon State Party to the NPT undertakes to accept a control regime, the IAEA safeguards, to be applied on all its nuclear material. The objective of safeguards is preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices.

2.2 Comprehensive Nuclear-Test-Ban Treaty

States Parties to the Partial Nuclear-Test-Ban Treaty held an amendment conference in 1991 to discuss converting the PTBT to an instrument banning all nuclear-weapon tests. With strong support from the UN General Assembly, negotiations for a comprehensive test-ban treaty began in 1993.

The Comprehensive Nuclear-Test-Ban Treaty was adopted by the UN General Assembly and opened for signature in September 1996. The Treaty has been signed by 160 states and ratified by 76 states as of May 2001.

The basic obligations of the CTBT States Parties are stated in the first Article of the Treaty. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such

nuclear explosion at any place under its jurisdiction or control. Each State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion [1].

The States Parties to the Treaty establish and are members of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). The CTBTO is established to achieve the object and purpose of the Treaty, and to implement an international verification of compliance with it. The CTBTO is, furthermore, to provide a forum for consultation and cooperation among the States Parties [1].

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO Preparatory Commission) was established in November 1996 by a resolution adopted by the meeting of States Signatories. The Preparatory Commission is to prepare for the Treaty's entry into force. The Treaty will enter into force 180 days after the ratification of the Treaty by 44 states listed in Annex 2 to the Treaty. These states were the members of the Conference on Disarmament as at June 18, 1996 which possess nuclear power reactors or nuclear research reactors.

The Preparatory Commission consists of two organs: A plenary body composed of all the States Signatories, and the Provisional Technical Secretariat (PTS). The Provisional Technical Secretariat governs the International Monitoring System and the International Data Centre [1,2].

2.3 International Monitoring System (IMS)

The Preparatory Commission for the CTBTO is responsible for establishing a global verification regime to monitor compliance with the Treaty. The regime is intended to be operational by the time the Treaty enters into force. The verification regime consists of the following four elements: The International Monitoring System, on-site inspections, confidence-building measures and, finally, consultation and clarification process.

The International Monitoring System is a global network of 321 monitoring stations and 16 radionuclide laboratories that monitor the earth for evidence of nuclear explosions in all environments. The system uses four distinct verification methods:

- seismic stations to monitor the underground environments
- hydroacoustic stations to monitor the underwater environments
- infrasound stations to monitor the atmosphere
- radionuclide stations to monitor the atmosphere.

In addition to the atmospheric explosions, the radionuclide stations can detect radioactive debris vented by underground or underwater nuclear explosions. Normal anthropogenic radioactive releases are as well regularly detected by the stations. These include, e.g., the fission and activation products released by nuclear power plants in normal operation and releases from accelerator facilities, hospitals and other users of radioactive materials. Resuspension of old fallouts from the atmospheric nuclear tests and the Chernobyl power plant accident also causes some fission and activation products to be present in samples measured by the stations.

The IMS stations are spread across the globe, often situated in remote and inaccessible locations posing various engineering challenges. The stations are established and certified to meet the quality requirements set by the Preparatory Commission after which they are operated by local institutions under contracts with the Technical Secretariat.

2.4 International Data Centre (IDC)

The IMS is supported by the International Data Centre, which resides at the CTBTO headquarters in Vienna. The purpose of the IDC is to receive and analyse the data measured by the IMS stations and to provide the States Parties with raw data and objective reporting products relevant to Treaty verification based on these analyses.

The data measured by the IMS stations are transmitted to the IDC for analysis. At present, over 100 stations are transmitting data to the IDC but not yet are all of these working continuously.

The data are processed automatedly at the IDC with resulting lists of seismoacoustic events and

radionuclides that have been detected by the stations. The automated analysis results are subjected to analyst review to produce the final analysis report.

The IMS data and the IDC reports are provided to States Signatories based on a secure signature account system which allows the States to access these data. In May 2001, roughly 50 States have established a secure signature account [1].

2.5 Radionuclide Monitoring Network

When complete, the radionuclide monitoring network will consist of 80 stations. At present, the number of stations in operation is remarkably smaller, and not all operating stations are yet certified as meeting the technical specifications.

According to the specifications, the stations should run in a short cycle operation mode. The short cycle operation mode includes 24 hours of air-filter sample collecting by filtering air with a specified flow rate of 500 to 1000 cubic meters in an hour, after which the sample decays for 4 to 24 hours. This decay time is needed for dealing with the complications caused by the daughters of Rn-220 and Rn-222 in air filter spectra.

After the sample decay time, the spectral data is acquired for 24 hours. The spectral data are measured using a high-purity germanium (HPGe) detector in a close geometry. The relatively long spectrum acquisition time of 24 hours is required because of the low activity and emission rates typical for an air filter sample, and the presence of Be-7 and Rn-220 and Rn-222 progenies in the filter causing a relatively strong gamma-ray background.

The air filter spectra contain information about the identity and amount of radionuclides and their relative abundances in the sample. This gives the radionuclide monitoring network the capability to distinguish between fall-outs of a nuclear reactor and a nuclear explosion. A list of radionuclides that can be considered relevant as evidence of a nuclear explosion is presented in Ref. 3.

In addition to the monitoring stations, the International Monitoring System comprises 16 Radionuclide Laboratories that analyse the samples suspected of containing radionuclides generated by a nuclear explosion. One of these Radionuclide Laboratories is situated in Helsinki at the Radiation and Nuclear Safety Authority (STUK).

3 GAMMA-RAY SPECTRUM ANALYSIS

3.1 General

Gamma-ray spectrometry using high-purity germanium (HPGe) detectors is a well-established discipline with many applications [4,5,6]. The advantage of the HPGe detectors relative to all other detector types is their excellent energy resolution which makes them optimal for measuring complicated spectra like the ones that can be produced by the IMS stations.

The gamma-ray spectrum analysis involves two distinct processes that can be described as the quantitative and the qualitative phases. In the quantitative phase the energies and emission rates of the gamma peaks in a spectrum are determined. In the qualitative phase an explanation is given to the gamma peaks in form of a combination of radionuclides and their activities in the radiation source that could have produced the measured spectrum. This process which is also known as radionuclide identification exploits a reference library of radionuclides containing information of radionuclide gamma energies and their emission probabilities [7].

3.2 Gamma spectrum analysis software at the FiNDC

The Finnish National Data Centre (FiNDC) uses a software package consisting of UniSampo spectrum analysis software [8] and expert system Shaman [9] for nuclide identification. UniSampo performs the quantitative phase of the analysis, i.e., the spectrum peak energy and intensity determinations. Shaman uses the results from the quantitative analysis together with a comprehensive nuclide library of 2616 radionuclides and 81 642 gamma lines to explain the spectrum with correct nuclides using various heuristic criteria. Shaman has been proved to be very reliable in finding the correct radionuclides and discarding the spurious ones [7].

The peak search algorithm used in UniSampo is based on the generalised second differences method [8]. The method locates peak candidates where minima of a particular peak search parameter reside. The parameter attempts to describe the discrete spectral data in a manner similar to that in which the second derivative describes a continuous function. The width of the spectral data region that is used to calculate the parameter is deduced from the shape (width) of peak. This information is provided by the peak shape calibration. A peak is considered found where the parameter value exceeds the search sensitivity threshold that can be adjusted freely in UniSampo software. At present, the search threshold used in UniSampo is considerably lower than that used in the IDC spectrum analysis software that uses a similar algorithm.

The detected peaks are fitted with a peak function consisting of a Gaussian center part and exponentially decreasing tails on the upper and lower energy side of the peak. The spectrum baseline is also fitted with a function to enable the peak area determination. The area of the fitted peak is calculated by integrating the peak shape function using fitted parameters. A statistical significance S of the form S=A/(3.29×sqrt(2×B)) is calculated for the fitted peak, where A is the peak area and B is the baseline area. The peaks whose significance is lower than a preset threshold are discarded.

Large, well-shaped single fitted peaks with known origin are used in the energy and shape calibration updates. Energy calibration update is needed to relate the spectrum channels to gamma-ray energy in a correct manner. Shape calibration is used to take into account that the gamma peaks in different regions of the spectrum have different

shape (they grow wider approximately as the square root of the channel number). Thus the correct width of the fitted peak function, given by the calibration function, can be used in all parts of the spectrum. This is particularly important in fitting small peaks and peak multiplets, i.e., close peaks that overlap significantly.

The efficiency of the detector in detecting the incident gamma rays has to be known in order to be able to deduce the source activity based on the detected gamma rays. The efficiency cannot be calculated from the sample spectrum. The efficiency of a particular detection instrumentation has to be measured separately at certain gamma energies. The results of these measurements, the efficiency calibration data, are fitted with a calibration function that yields the efficiency values throughout the energy range of spectrum.

The detector efficiency as a function of gamma energy exhibits behaviour that requires a high order (usually, the fourth or fifth order) function calibration. Functions of higher order are capable of following the data but they are very sensitive with respect to the quality of the data. This can be especially problematic when the efficiency values are obtained from the calibration function beyond the range covered by the original data, i.e., when extrapolation is needed. The efficiency values for the high-energy end of the spectrum are needed in Shaman, e.g., for activity corrections for true coincidence summing and for escape peak area estimation.

In energy calibration, UniSampo uses polynomials of the first or second degree (the order of the calibration functions is user-adjustable). Shape calibration utilises square root polynomials, and efficiency is calibrated using logarithmic polynomials.

3.3 The FiNDC radionuclide analysis pipeline

An analysis pipeline for data subscribed from the IDC is operated at the FiNDC by an automated script that categorises the incoming data according to their contents and runs the spectral data files through spectrum analysis. The analysis results are stored in a specifically designed directory tree, a “database”, together with the raw data and IDC analysis results (Figure 1). The IDC data and the analysis result files are stored in directory branches according to the measuring station, year and month [9].

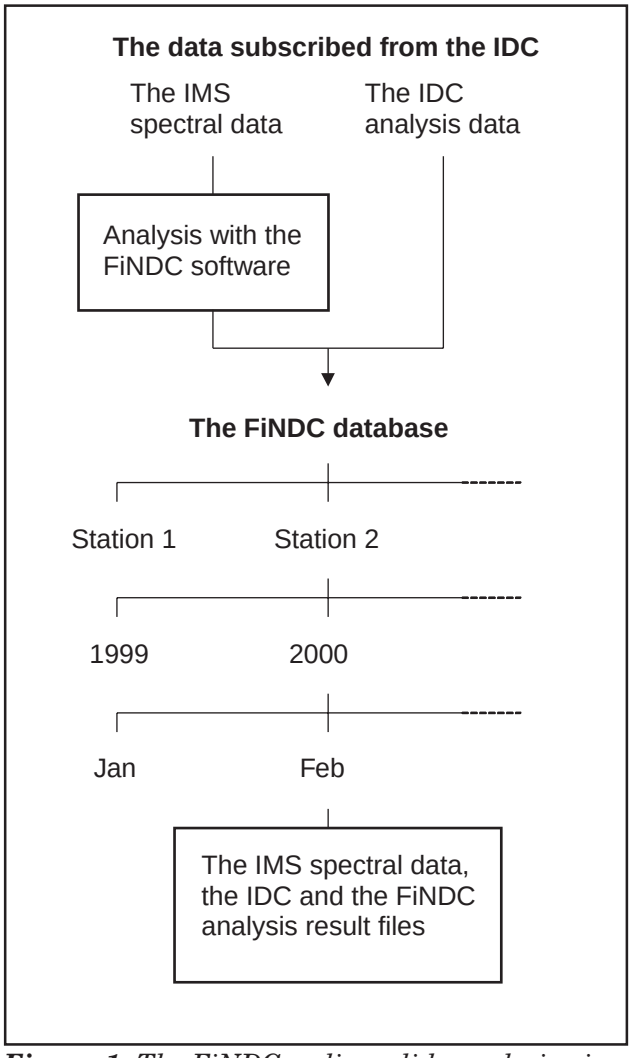

Figure 1. *The FiNDC radionuclide analysis pipeline.*

4 METHODS AND MATERIAL

4.1 General

Quality of automated gamma spectrum analysis results with known detection instrumentation can be assessed quite exhaustively in two conditions. First, if the gamma-ray emitting sources are known to full extent, the spectrum analysis quality assessment is a straightforward comparison. This is, however, only true with calibration sources or with synthesised spectra.

Second, a more attainable scheme for evaluating automated gamma spectrum analysis results is using human expertise in interactive spectrum analysis. An experienced analyst can confirm the validity of calibrations and approve the peak explanations and nuclide identifications suggested by analysis software.

The prospects for success of expert judgement depend on how complicated the spectrum is, and on the information supplied by the spectrum analysis software. For instance, when a spectrum peak can be explained equally well by more than one radionuclide, no reliable conclusion can be made about the activities of the nuclides contained in the sample. Therefore the explanation share of each explaining nuclide should be presented in connection with the peak with multiple alternative explanations.

Further, the extent to which a peak is being explained by the associated gamma sources should be presented, e.g., to be able to distinguish between peaks well explained and peaks with an insufficient explanation. This is not the case with the IDC analysis software where the **explanation shares** and **peak explanation percentages** of individual peaks are not reported. Thus all peaks associated with a gamma line energy have to be considered completely explained.

Interactive analysis can produce very reliable results that could in principle be used in benchmarking the auto-analysis results. In this study, however, methods for automated comparisons were developed and used because of the need to make comparisons without human interception between up to 1500 pairs of analysis result files.

Without the a priori knowledge of the gamma emitting sources the full statistical comparison of different software packages requires, at least, a knowledge of their precision and accuracy. If the analysis codes are not under statistical control, statistically correct statements of their performance cannot be made. This has not been done in this study. Instead, we restrict ourselves to comparisons between the analysis results without statements about the correctness of either software. Thus the comparisons should be considered qualitative and as test of consistency between the gamma spectrum analysis results of the two data centres.

4.2 Methods

4.2.1 General

The material of this study was composed of pairs of automated spectrum analysis results produced by the IDC and the FiNDC. The Automated Radionuclide Report (ARR) generated and supplied by the IDC is an ASCII file containing the summarised results of the automated spectrum analysis and radionuclide identification processes.

In order to facilitate the comparison, the nuclide identification software Shaman was tailored to produce a report named SAR that presents the analysis results in a similar format than that used in the ARR. The contents of the ARR that are essential for this study are presented in Section 4.2.2 and an example is presented in Appendix A. An example of a SAR report is presented in Appendix B.

The comparisons between the analysis results by the IDC and the FiNDC were performed by designated computer programs written in C language and operated under the Linux operating system. A script was written to find from the database the two corresponding results files which were read in by the comparison program.

4.2.2 The ARR report

The ARR contains information on the measuring station, the sample and the measuring times (Table I). Collection start and stop times refer to the times when the air filter sample collecting was started and finished. Acquisition start and stop times refer to the times when the spectral data acquisition with gamma-ray detection instrumentation was started and finished. Sampling time is the time interval between the collection start and collection stop times. Decay time is the time interval between the collection stop and acquisition start times.

Activation products and fission products that are identified are reported in their respective lists with the information presented in Table II. It should be noted that the activities of other identified nuclides are not reported. This makes the evaluation of the correctness of the identification very difficult.

The peaks that the automated peak search has found in spectrum are listed in the ARR with information presented in Table III.

The peak centroid channel is calculated using the peak search parameter values that the peak search algorithm calculates for each channel [10]. The peak search algorithms used in the IDC and the FiNDC software packages are closely related. The peak centroids reported by these software packages are always very close to each other except for the fact that the channels are numbered starting from 0 and 1 in the FiNDC and IDC software, respectively. This was taken into account in the comparison programs.

The peak energy is calculated from the peak centroid using the energy calibration function. The width reported in ARR refers to the peak fitting interval used by the IDC software. The full width at half maximum value (FWHM) is the width of the fitted Gaussian peak function at the level that corresponds to half of the height of the peak. The efficiency is calculated from the efficiency calibration function that has been fitted to the calibration data included in the spectrum file.

The peak area is calculated by subtracting the area under the fitted spectrum baseline function from the area under the fitted peak function. The width of the spectrum interval used in peak area calculation is typically 10–30 channels. The relative error of the calculated peak area is reported.

The calculated peak areas are used to determine the gamma-ray emission rates and the nuclide activities contained by the sample using the efficiency and decay corrections. Nuclide activities are further translated into corresponding air concentrations, which are reported for Be-7, Pb-212 and the fission and activation products.

In addition, four quantities about the number

Table I. *Sample information in ARR.*

Sample information	Unit
Station name	
Detector name	
Sample identification	
Collection start / stop	yy/mm/dd hh:mm
Acquisition start / stop	yy/mm/dd hh:mm
Sampling time	hours
Decay time	hours
Acquisition time	hours

Table II. *The information provided on activation and fission product identifications.*

Activation or fission product nuclide	Unit
Name	
Half-life	Y, D or H
Concentration	µBq in m^3 of air
Conc. error	%

Table III. *The spectrum peak information in ARR.*

Spectrum peak	Unit
Peak energy	keV
Peak centroid	channel
Peak fitting interval width	channel
FWHM	keV
Efficiency	%
Peak area	counts
Peak area error	%
Associated nuclide(s)	

of found and explained peaks in spectrum are reported.

1. Number of peaks found in spectrum by automated peak search.
2. Number of peaks associated with nuclides by automated processing.
3. Number of peaks not associated with nuclides by automated processing.
4. Percentage of the peaks that were associated with nuclides. The percentage is calculated as the ratio of the number of explained peaks to the number of found peaks multiplied with 100 and rounded to the nearest integer.

4.2.3 Comparison objectives

The criterion used to decide whether or not a peak was found by both software packages is based on the reported centroid channel of each peak. If a peak in the ARR file and a peak in the SAR file satisfy the condition $|c_A - c_S| < 3 + c_S/2000$, where c_A and c_S are the reported centroid channels in ARR and SAR, respectively, the peak is considered found by both software.

The studied spectra comprise either 4096 or 8192 channels with 1 keV energy interval corresponding to approximately 2 or 3 channels, respectively. Thus, the criterion based on channels is translated into different criteria in the two types of spectra when the peak distance is considered in energy units. Figure 2 presents the energy equivalent of the criterion in the two types of spectra and shows typical peak shape calibration data to illustrate the scale of the used criterion for the quantity $|c_A - c_S|$. Although they are presented together in Figure 2 for illustrative purposes, the criterion is not in any way used to interpolate or approximate the shape calibration data.

As a practical matter, the difference $|c_A - c_S|$ for a particular, well-shaped single peak is less than one channel at the lower energy region of the spectrum and less than two channels at the higher energy region of the spectrum. Hence if a peak is reported in both result files, this situation is most certainly identified by the comparison program. On the other hand, with the parameter setting used here there is a possibility that two peaks are incorrectly judged as the same peak. This error may occur if there is a close doublet (or multiplet) peak in the spectrum so that the peaks are fitted together with smaller centroid separation than the used criterion.

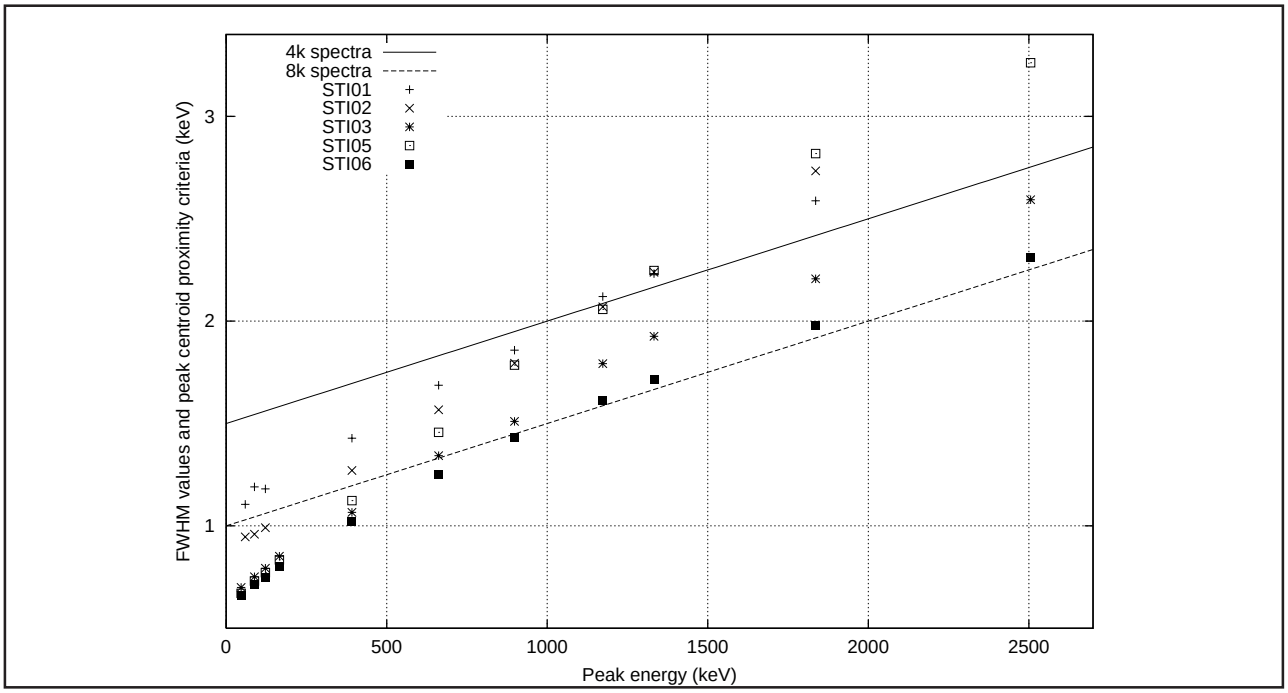

Figure 2. *The lines correspond to the criterion that was used to decide whether or not a peak in the ARR and a peak in the SAR represent the same spectrum peak. Since the criterion is based on channels its value expressed in energy units is different for spectra with 4096 and 8192 channels. Linear energy calibration is assumed here. The data points present the peak shape calibration data (the FWHM values) from the certified stations on March 3, 2001.*

Compromising is necessarily involved in setting the discrimination value for the quantity $|c_A - c_S|$. Too low a value would cause the program to fail to connect the correct peak identifications in the two results, and if the value is set too high, the program will connect peak identifications in the ARR and in the SAR that do not represent the same spectrum peak. The value used in this work was deduced and assessed by manual reviewing and it proved to operate as desired in most cases.

The peak areas and area errors reported by the two software packages were compared in order to find possible systematic differences. Only peaks that were found by both software packages in the energy region 110 keV…2700 keV were considered in order to exclude the peaks in the X-ray multiplet region that often constitute problems for the peak finding and fitting procedures of both software packages.

The differences between the reported peak finding and peak explaining results were explored using three different methods. The first method was to compare directly the reported numbers of found peaks, explained peaks and unexplained peaks. Second, the distributions of the reported peak explanation percentages were compared. Third, the peaks that were missed by either software package were taken under scrutiny.

The number of found peaks in a spectrum depends, among other things, on parameter settings, such as the peak search threshold and the selected energy region. The success of the peak fitting procedure also has an impact on the number of peaks reported as found in a spectrum.

The number of explained peaks in a spectrum is affected by several factors in addition to those that yield the number of found peaks. Most important of these factors are the utilised nuclide library and nuclide identification process. The difference between the reported numbers of explained peaks in a spectrum was used as a quantitative measure that describes in a non-spesific manner the general differences in the peak explaining capabilities.

The unexplained peaks in a spectrum are either spurious peaks, for which there are no correct explanations, or real peaks, in which case the fact that the peak remains unexplained is a consequence of a malfunction of the analysis software. The mere number of unexplained peaks does not distinguish between these possibilities. The peak search processes inevitably yield spurious peak detections (type I peaks) and there are one or two spurious peaks in most of the analysis results. In most cases, the nuclide identification process operates correctly if it does not explain these peaks. It is, of course, completely possible that the energy and emission rate calculated for a spurious peak are such that it is not possible to deduce whether the peak is spurious or real. In a situation like that the correct nuclide identification operation is to associate the spurious peak with a nuclide. Nevertheless, the number of unexplained peaks is typically larger than the number of type I errors produced by the peak search so that the difference between the two reported numbers of unexplained peaks can be interpreted as an indication of the peak explaining capability.

One method to describe the performance of the spectrum analysis process is to report the ratio of the number of explained peaks to the number of all found peaks. This figure, the **peak explanation percentage**, is not comparable between two analysis results unless both analyses have found the same peaks. Hence, instead of pairwise comparison, the peak explanation percentages were compared by studying the distributions of the two percentages in a large set of spectra.

When a spectrum is analysed by two software packages, there will usually be peaks in analysis results that are not present in the results of the other software package. These peaks, i.e., the peaks that have escaped detection by one software package while having been detected by the other, were examined with respect to their reported area, energy and explaining nuclides in order to find out possible trends in either group. The most obvious reasons for a peak to be missed by one software are different peak search methods and the utilised thresholds and energy ranges. A failure in shape calibration can also impair the peak search results, because the peak search filter width is based on the shape calibration.

Automated spectrum analysis and nuclide identification often yield spurious identifications: Certain nuclide, which is not present, is identified due to either spurious peaks or real peaks close to the gamma energies of the nuclide. In this work, a simplistic method was used to recognise the **spurious nuclide identifications**. All identifica-

tions of activation and fission products, with certain exceptions, were regarded spurious. Eight nuclides were taken as exceptions to this and regarded correctly identified.

The first four nuclides, Co-60, Tc-99M, I-131 and Cs-137, are anthropogenic nuclides that are typically present in air filter samples, according to the experience gained in the IMS network operation. Two nuclides that are produced by cosmic radiation in the atmosphere, Na-22 and Na-24, were always considered correctly identified. The last two nuclides, Ag-108M and Eu-152, are regularly identified in spectra measured with the USC1 detector at the STI08 station due to detector contamination. When reported as identified in these particular spectra, these nuclide identifications were regarded correct.

It is strongly emphasised here that **the described method of declaring activation and fission product identifications as spurious ones was used in awareness of its lack of general applicability**. However, it is very difficult to automatically evaluate the correctness of nuclide identifications within a large number of analysis results from air filter spectra, as there is no knowledge a priori of the radiation sources that originate the spectra. Furthermore, the procedure was applied equally to both analysis results and it served no other purpose than to evaluate the differences between these results.

The recognised spurious nuclide identifications were further divided into relevant nuclides and others according to the CTBTO decision [3,13]. The concept of relevant nuclide is introduced in the IDC event screening realm to only allow those nuclides that are relevant for the test ban treaty verification to have an impact on the spectrum characterisation (Figure 3). The spectra are characterised using five levels, and each category implies specific consequent operation at the IDC. The CTBT relevance of nuclides and how it affects the spectrum characterisation process are discussed in Ref. 3.

The peak explaining performances of the two

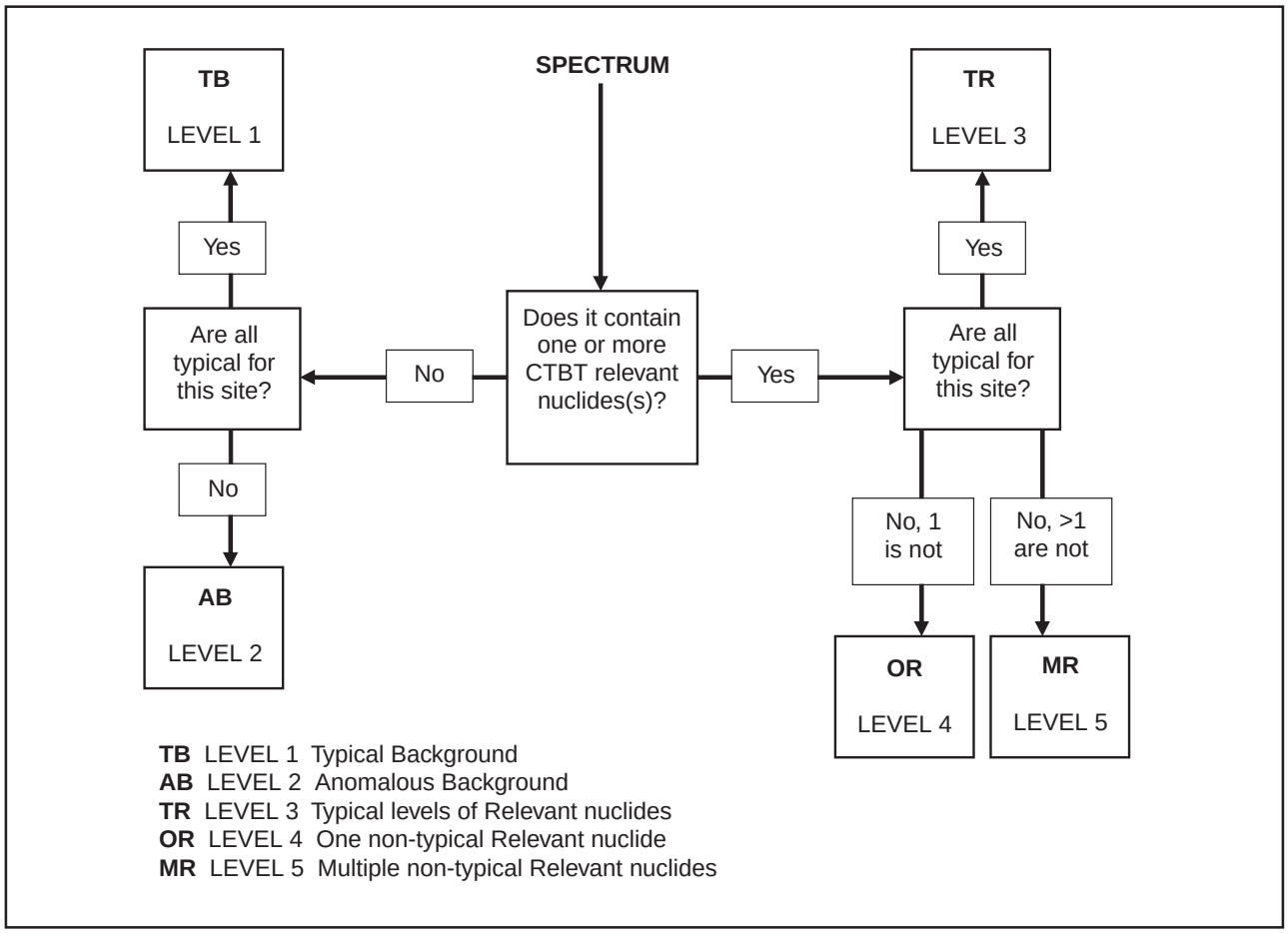

Figure 3. *The spectrum categorisation scheme used in the Release 2 software at the IDC. The figure is adopted from Ref. 3.*

software packages were further analysed with help of the information acquired from division of the explaining nuclides into spurious and real ones. The nuclides associated with each peak, i.e., the explaining nuclides, were reviewed and those peaks were counted whose all explaining nuclides were spurious. In this connection, no difference was made between the peaks with one associated nuclide only and those with many. The peaks found in this way will most probably be spurious peaks near the gamma energies of the defined spurious nuclides (given that the premise of absence of these nuclides holds, as it practically always does). This is one tool for estimating the number of spurious peaks in the spectra. A pairwise comparison of the number of spurious peaks that were found with this method was conducted.

4.3 Material

Eight radionuclide stations were submitting spectral data to the IDC at the time of the study (Table IV). Five out of these are certified IMS stations. The remaining three stations were included in order to increase the amount of data. These three stations work in the short-cycle operational mode, or sufficiently close to it, and send data regularly to the IDC.

The starting date of the time period from which the material was acquired, August 1, 2000, was chosen on the basis that the eight stations operated regularly from that date on and thus a representative set of material could be collected. March 26, 2001 was the last date from which material was included into the study.

All data submitted by the eight stations were not of high enough quality to be included in the comparison; automated analysis cannot be expected to perform at normal level with deficient data. The spectral data from the certified stations were satisfactory in form and content in the vast majority of cases. Only two incidents with deformed data were encountered. The efficiency calibration data submitted by the certified STI01 station for seventeen days starting January 1, 2001 were erroneous (Figure 4). However, these spectra were not discarded from the study in spite of the fact that the subsequent efficiency calibration failure by the UniSampo software reduces Shaman's ability to identify nuclides with several gamma lines.

Table IV. *The measuring stations and the number of spectra included from each station starting from August 1, 2000 until March 26, 2001.*

Station name	Number of spectra
STI01 *	226
STI02 *	193
STI03 *	228
STI04	65
STI05 *	235
STI06 *	229
STI07	154
STI08	188
	Tot. 1518

* certified station

Furthermore, the STI01 station sent a spectral data file with acquisition start on November 30, 2000, which was corrupted by inclusion of an inappropriate character (a question mark) leading to disqualification of the spectrum.

Quality problems were more common among the data from the non-certified stations. The STI08 station suffered from a large gain shift of detector amplifier during December 12, 2000 – January 1, 2001. Further, the spectrum with acquisition start dated on January 13, 2001 had

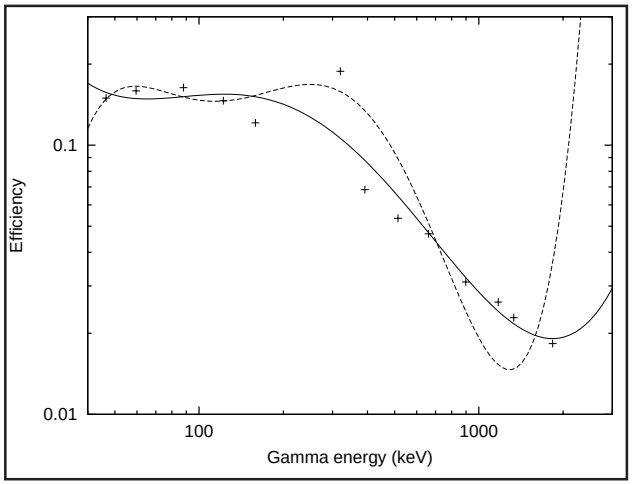

Figure 4. *An erroneous efficiency data point at 320 keV occurred in the data submitted by the certified station STI01 for seventeen days starting January 1, 2001. The UniSampo efficiency calibration function (dashed) is a logarithmic polynomial of fifth degree while the IDC software calibration function (solid) is of fourth degree. The fifth degree function was found optimal in Ref. 11, but severe distortions in the data, like the one presented here, are likely to cause calibration function fitting problems.*

abnormally few counts throughout the spectrum.

Only approximately half of the STI04 station spectra were measured in the short-cycle mode due to detector-related problems, and in 50 cases out of these, there were no ARR file available in the database. This was due to a processing error in the FiNDC analysis pipeline. Other than short-cycle spectra measured at this station were discarded from this study.

With the exceptions mentioned above, all spectra from the eight stations with the ARR file available and acquisition start between August 1, 2000 and March 26, 2001, were included, totalling 1518 spectra. However, **the number of spectra in individual comparisons vary depending on the particular date of the comparison**.

An exceptional set of spectra was utilised in one of the comparisons presented in Section 5.1. This set comprises 769 spectra from stations presented in Table V. There are two additional stations because these data were collected before the final stage of the work, on February 13, 2001, but the relative importance of the two additional stations in the whole is quite low. This set includes 7 spectra dated in 1999, 469 spectra dated in 2000 and 293 spectra dated in 2001.

Table V. *The measuring stations and the number of spectra included in one comparison dated February 13, 2001.*

Station name	Number of spectra
STI01	103
STI02	71
STI03	103
STI04	54
STI05	111
STI06	107
STI07	63
STI08	102
STI09	39
STI10	16
	Tot. 769

5 RESULTS

5.1 Peak area determination

Two selections of peaks, comprising of 25 517 peaks and 52 744 peaks, were used to observe the characteristics of the peak area determination of the two software packages. The peaks used here were selected from 769 and 1518 study material spectra with the following conditions:

- The spectrum peak is found, and, accordingly, reported by both software.
- The peak energy is above 110 keV to exclude X-ray peaks.

In Figure 5, the peaks are plotted according to their respective areas reported by the two software packages. Figure 6 shows the peak area determination by the IDC proportional to the peak area determination by the FiNDC. The distribution of the absolute difference between the two determined areas is shown in Figure 7.

A relatively good agreement was found between the determined peak areas. Concluding from the results, there are no phenomena causing large systematic deviations in the peak area determination of either software package. The apparent tendency of the peaks to be plotted on the diagonal in Figure 3 shows that on the average

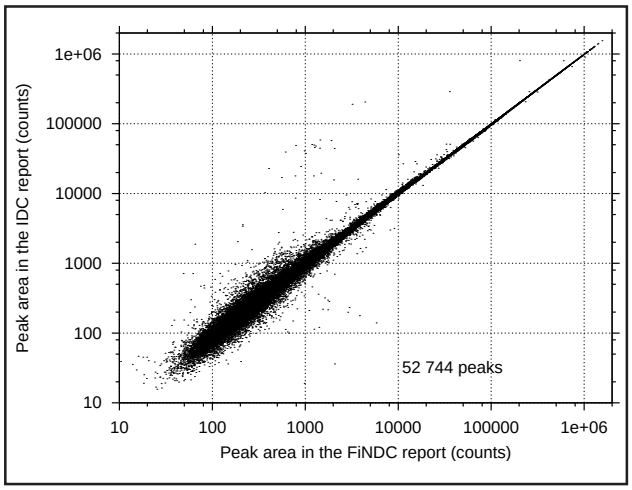

Figure 5. *Peak areas determined by the two software packages. A peak is plotted on the diagonal when both software packages have reported the same area for the peak.*

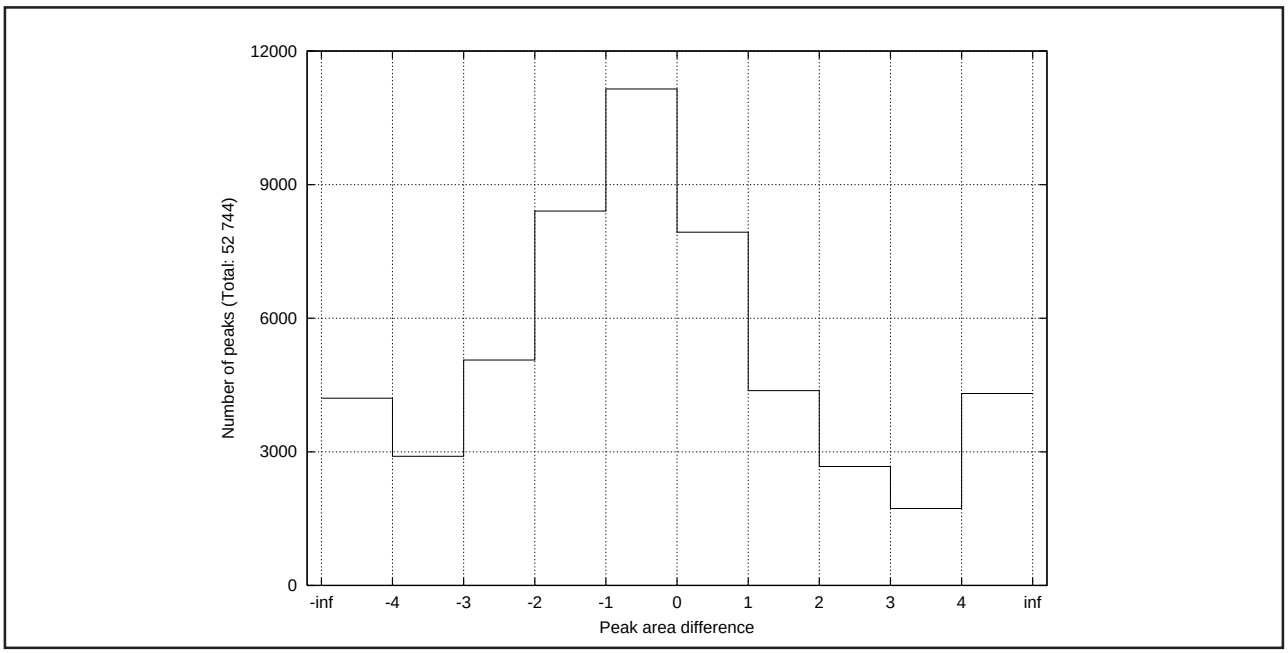

Figure 6. *The distribution of peak area reported by the IDC relative to peak area reported by the FiNDC. The difference (IDC-FiNDC) is measured in units equal to the square root of the area measured by the FiNDC.*

the areas tend to be the same. However, large deviations, which cannot be explained with statistics, can be observed, especially at small peaks.

There are 30 peaks in the upper left region of Figure 5 whose area reported by the IDC is more than nine times the area reported by the FiNDC. These peaks reside mostly at energies at which close peaks sometimes are fitted by the automated analysis (Table VI). Therefore, it is possible that these anomalities represent situations where there are, actually, two peaks within the channel interval defined by $|c_A - c_S| < 3 + c_S/2000$. In such an occasion the comparison program may or may not regard these close peaks as the same peak. It should also be noted that this kind of comparison error is more probable at small energies as can be seen from Figure 2.

The distribution in Figure 6 is calculated by subtracting the peak area reported by the FiNDC from the peak area reported by the IDC and relating the difference to the square root of the peak area reported by the FiNDC. The skewness of the distribution is apparent and it reveals that the expectation values of the two peak area determinations are not equal in this peak set. There are 31 722 peaks whose area reported by the FiNDC is larger than the area reported by the IDC. For 21 015 peaks the IDC reported a larger area than the IDC. Furthermore, from the distribution it can be seen that very large deviations in both directions measured with this method are approximately equally frequent.

Figure 6. The distribution of peak area reported by the IDC relative to peak area reported by the FiNDC. The difference (IDC-FiNDC) is measured in units equal to the square root of the area reported by the FiNDC.

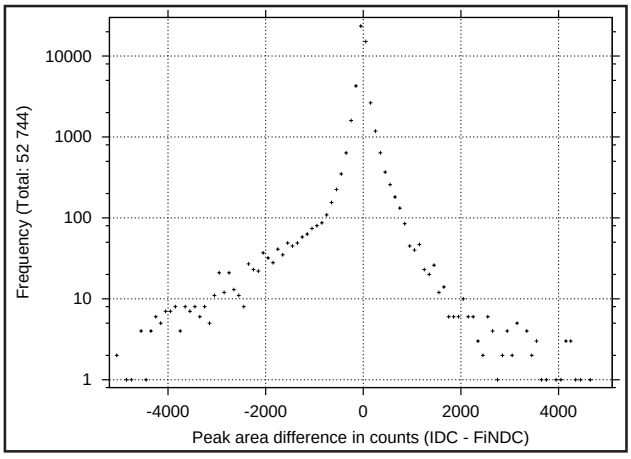

Figure 7. *The distribution of the absolute difference between the reported peak areas. Each data point represents an interval of 100 counts in the x-axis. The points are plotted at the center of the respective intervals.*

Table VI. *The most abundant peak energies among the total of 30 peaks whose area reported by the IDC is more than nine times the area reported by the FiNDC. In Figure 5, these peaks appear in the upper left region of the plot.*

Peak energy (keV)	Occurrences
476	8
725–726	8
511	4
237	2

Table VII. *The absolute difference between the peak area determinations. N = 52 085.*

Peak area difference (FiNDC-IDC)	
Average	Standard deviation
12800	63500

The absolute difference between the two peak area determinations is strongly peaked at the zero difference as seen in Figure 7. Due to the logarithmic y-scale, the skewness of the distribution is not as apparent in this presentation as in that shown in Figure 6. For 91.5 percent of the peaks, the difference is smaller than 300 counts. The average difference was calculated excluding the 659 peaks for which one software package reported an area larger than twice the area reported by the other software. The results are shown in Table VII.

The peak area uncertainty calculation methods differ so as to produce typically different area uncertainty estimates. This is demonstrated in Figure 8, where the peaks are plotted with respect to their reported area errors. The correlation presented by the plot arises from a constant ratio of the two area error estimates. The average value of this ratio (the area error reported by the IDC divided by the area error reported by the FINDC) for the 52 744 peaks is 1.68 and the standard deviation is 1.20. The distribution of the ratio is shown in Figure 9.

The separate peak accumulation in the upper right corner of Figure 8 consists of 170 peaks whose area error reported by the IDC is more than eight times as large as the area error reported by the FiNDC. Their origin was not studied here.

The behaviour of the peak area error as a function of the peak area was observed separately

for both software packages using the same set of 52 744 peaks as above. The results are shown in Figures 10 and 11 which, again, reveal the systematic difference between the error estimates. The FiNDC area error estimate imitates the standard Poisson statistics, where the uncertainty is equal to the square root of area. It would be depicted with a straight line going through the point (100,10) with the slope of –1/2. This behaviour is dominant at large peak areas. Generally, the IDC area error estimate behaves in quite a similar manner which is demonstrated by the equalities in the shape of the distributions. However, the IDC area error distribution is located higher in the error scale due to the systematically higher error estimates. This indicates that the FiNDC results are more precise, but this cannot be judged without knowing the accuracy also.

In the distributions in Figures 10 and 11, there are fragments consisting of peaks whose area error is c_i times as large as the minimum area error of the peaks of that size, where constant c_i > 1 and i = 1, 2, …, 8. These fragments are seen as accumulations of peaks about a straight line parallel to the main distribution. Only approximately five of these fragments are apparent in Figures 10 and 11 due to the used scale. The origin of this phenomenon was not studied here.

There is a group of 172 peaks in the upper left corner of Figure 11 with an area error larger than 150 percent reported by the IDC. The peak areas within this group are 70–700 counts. Among the peaks smaller than 500 counts there are also a few with abnormally low area errors reported by the IDC. These peaks are seen below the main distribution in the leftmost part of Figure 11.

The peak area errors reported by the two software packages were plotted as a function of

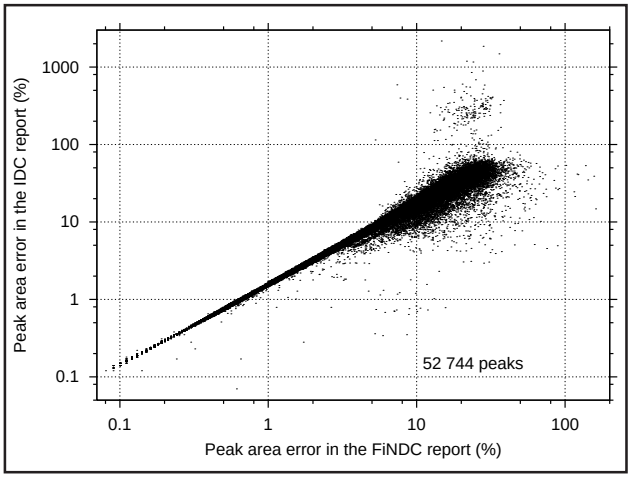

Figure 8. *The area error of each peak reported by the IDC against the area error reported by the FiNDC.*

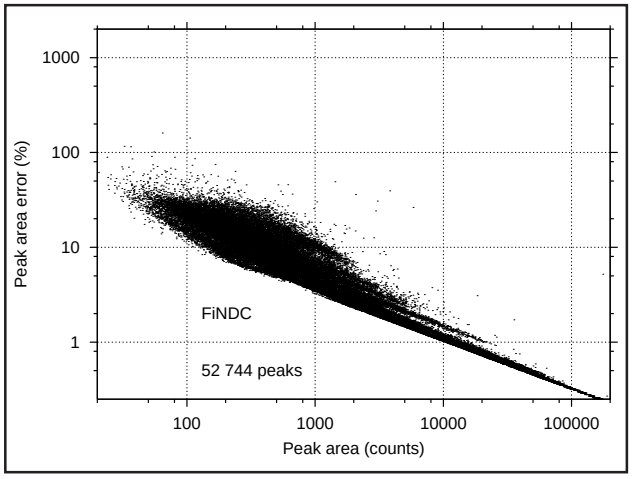

Figure 10. *The peak area error as a function of the peak area reported by the FiNDC.*

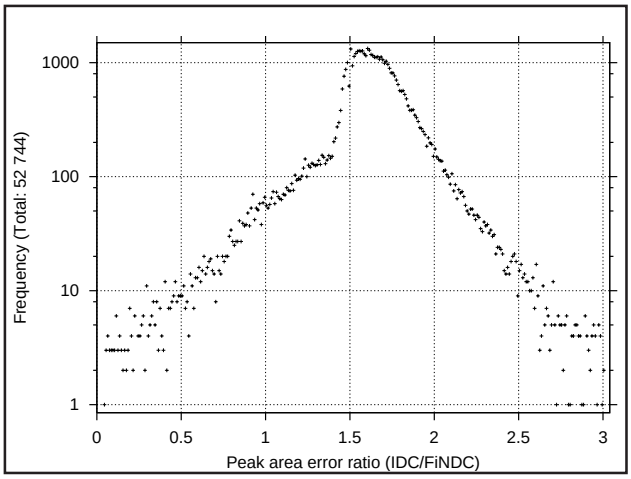

Figure 9. *The distribution of the ratio of the two reported area errors. Each data point represents an interval of 0.01 in the x-axis.*

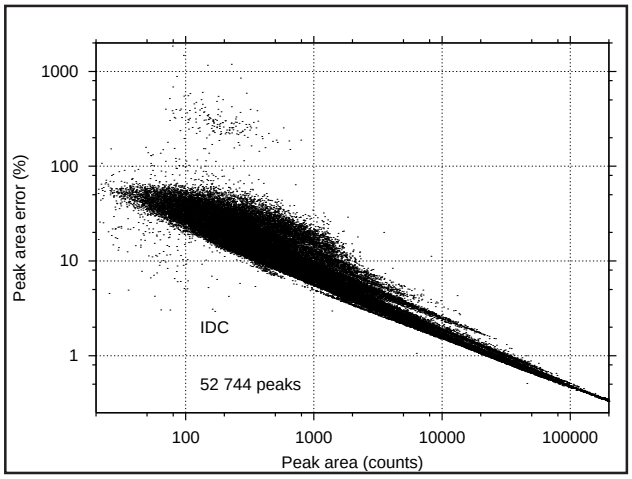

Figure 11. *The peak area error as a function of the peak area reported by the IDC.*

Table VIII. *Summarised differences presented for all stations together and separately.*

		Difference (FiNDC-IDC) in the number of					
		found peaks		explained peaks		unexplained peaks	
Station	**Spectra**	**mean**	**st.dev.**	**mean**	**st.dev.**	**mean**	**st.dev.**
All	1 518	4.2	3.3	5.6	4.4	–1.4	3.2
STI01	226	4.8	3.2	6.4	4.6	–1.8	2.3
STI02	193	6.4	3.2	9.0	2.5	–2.7	2.5
STI03	228	4.5	2.9	7.0	4.1	–2.5	3.9
STI05	235	3.0	3.3	3.7	3.8	–0.7	2.6
STI06	229	3.2	3.5	3.8	4.0	–0.6	2.6
STI04	65	3.3	3.0	4.8	3.0	–1.5	1.9
STI07	154	4.5	2.9	4.9	4.4	–0.4	3.3
STI08	188	3.8	3.0	4.7	4.7	–0.9	4.1

the peak energy using a set of 25 517 peaks of the 769 spectra of Table V. This set consists mostly of peaks that are present in the set of 52 744 peaks used earlier in this section. It can be observed from the results in Figure 12 that the divergence between the two area error estimates persists throughout the energy spectrum at the same level. Furthermore, the exceptionally large area errors reported by the IDC reside mostly in the lower energy region of the spectrum. The most abundant peaks among those with large area errors are at 152 keV, 177 keV, 233 keV and 295 keV. In this set of 25 517 peaks, there are 115 peaks with larger than 100 percent area error reported by the IDC, while the corresponding figure for the FiNDC is 3.

5.2 Peak finding and explaining performance

Three spectrum statistical quantities from each analysis report pair were compared to evaluate the peak finding and explaining performances in a quantitative manner. These quantities are

- The number of peaks reported as found in a spectrum.
- The number of peaks reported as explained in a spectrum.
- The number of peaks reported as unexplained in a spectrum.

The mutual difference in each of the three quantities was calculated by subtracting the value reported by the IDC from that reported by the FiNDC. The eight stations produce results with some individual variation but all results can be seen to follow the same general pattern. The results are summarised in Table VIII and the data are plotted in Figure 13 for all stations and in Figure 14 for each station separately.

In the set of 1518 spectra, the FiNDC software finds 4.2 more peaks in each spectrum on the average. Yet, the average number of explained peaks is 5.6 higher in the FiNDC results and the average number of unexplained peaks is 1.4 lower than in the IDC results.

The data in Table VIII and the distributions in Figures 13 and 14 demonstrate that the results

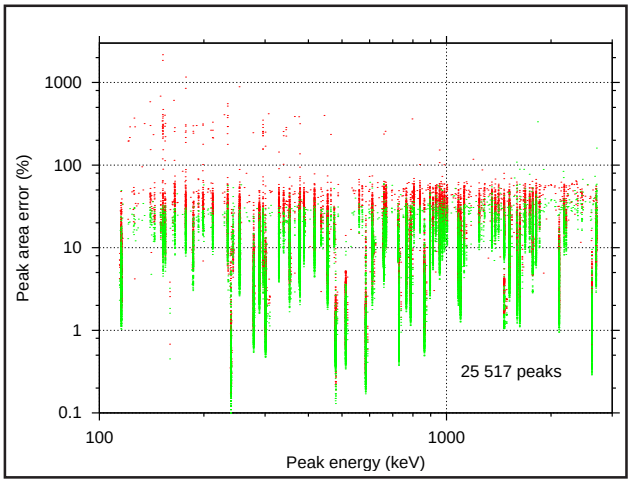

Figure 12. *Peak area error as a function of peak energy. The FiNDC results are in green and the IDC results in red.*

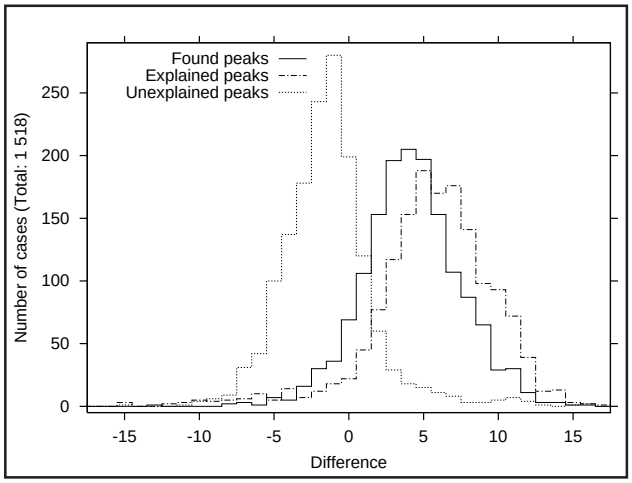

Figure 13. *The distributions of the differences (FiNDC-IDC) of the number of found, explained and unexplained peaks in the 1518 spectra from eight stations.*

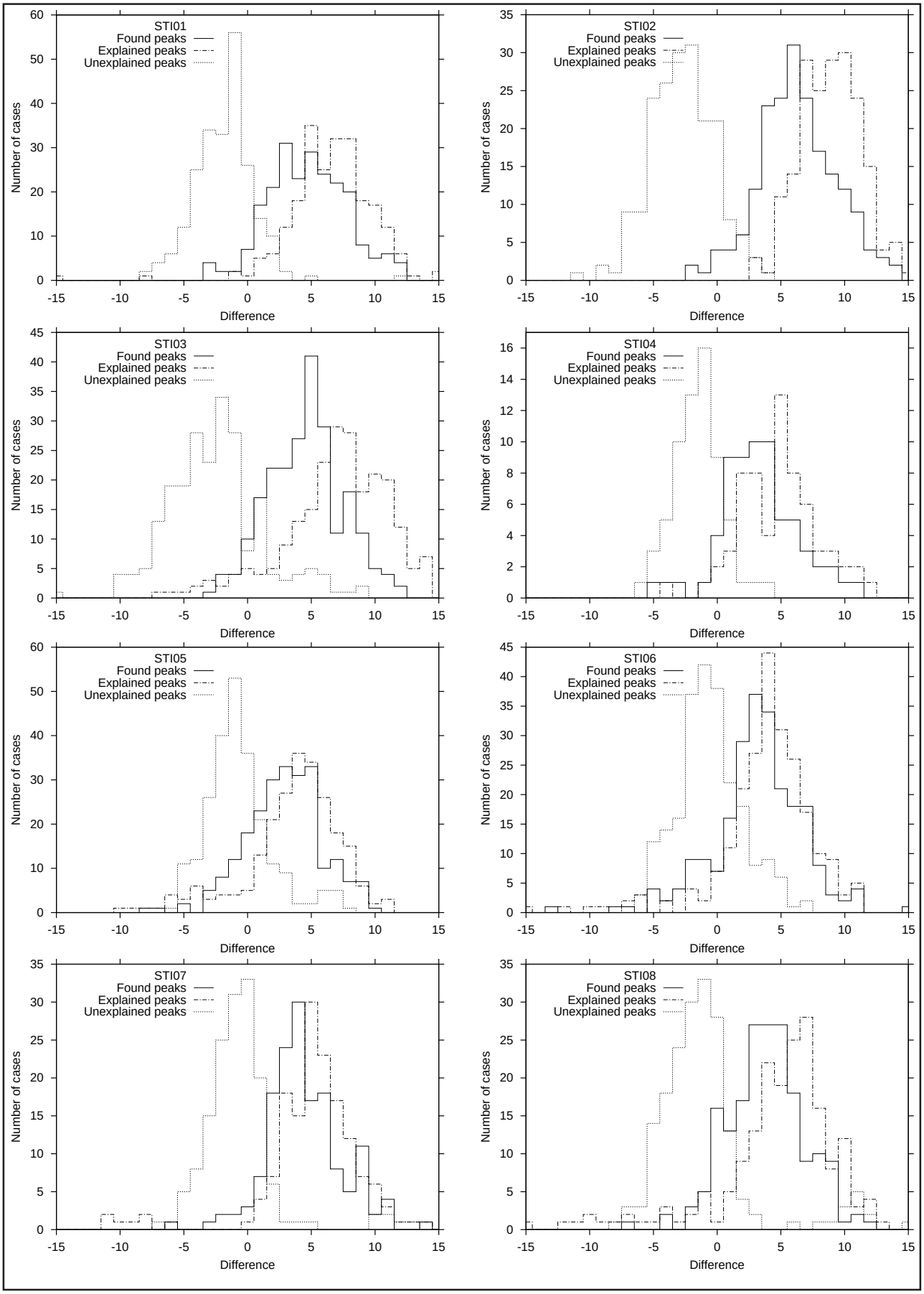

Figure 14. *The distributions of the differences (FiNDC-IDC) of the number of found, explained and unexplained peaks for each station.*

Table IX. *The numbers and areas of missed peaks for a set of 501 spectra.*

Peak category	Number of peaks	Peak area (counts)	
		mean	st.dev.
Category 1: Peaks missed by the FiNDC software	1420	933	10900
Category 2: Peaks missed by the IDC software	3179	1414	5500

from each station repeat the same general behaviour: More peaks are found by the FiNDC software, but nevertheless, more peaks remain unexplained by the IDC software.

The distribution of peak explanation percentages for both software packages were examined with 1438 spectra available in the database on March 16, 2001. The results are presented in Figure 15. Evidently, the FiNDC software tends to explain a larger portion of the peaks that it has found than the IDC software. By far the most often reported peak explanation percentage by the FiNDC is 100, while the corresponding mode value of the IDC percentage is 92. On the other hand, there is more deviation in the FiNDC peak explanation percentages. Out of the 1438 spectra represented in Figure 12, the FiNDC reported a peak explanation percentage of 80 or below in 72 spectra, while the corresponding figure for the IDC software is 11.

When these results are considered, two facts must be recognised. With equal peak explanation percentages, the FiNDC software generally explains more peaks as it tends to find more peaks

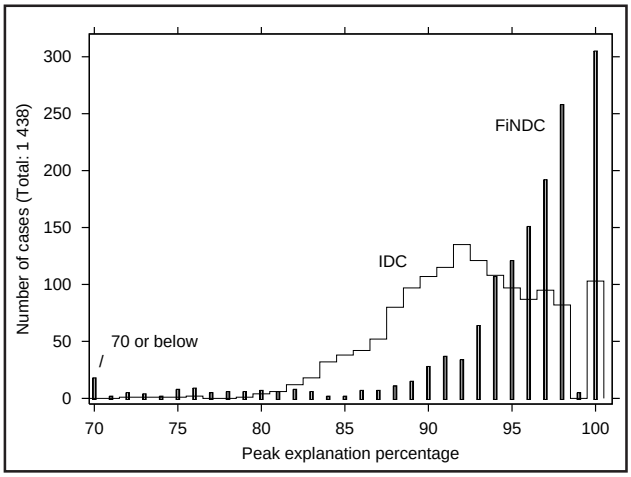

Figure 15. *The distributions of the peak explanation percentages. The reported percentages are rounded integers, hence the value of 99 percent is possible only for spectra with at least 67 peaks.*

in spectra. Furthermore, a frequent reason for low peak explanation percentages in the FiNDC results is an unsuccessful shape calibration. The calibration function used in UniSampo is prone to bad behaviour when there are too few calibration points. This is a typical condition in spectra from the stations STI05, STI06 and STI07. There is a good reason to assume that with a more robust shape calibration function in the FiNDC analysis pipeline, the share of low peak explanation percentages could be reduced significantly.

5.2.1 Peaks missed at the FiNDC or IDC

A set of 501 spectra and ARR reports available in the database on January 25, 2001 was used here to observe the peaks that are found by one analysis software package and missed by the other. The two groups of peaks collected using these criteria, referred to as Category 1 and Category 2 peaks for brevity, are presented in Table IX. The average number of missed peaks per spectrum is less than three for the FiNDC while for the IDC the reading is more than six.

The significance of the peaks of these categories would be of interest to the comparison, but since the IDC does not report peak significances, the comparison between these peak groups has to be made with respect to peak area. The area distributions of the peaks in both categories are presented in Figure 16.

The lower limit of the peak search energy range in the IDC software is set at such a value that the prominent 39.9 keV peak of Bi-212 is not detected. There is no reason to exclude this peak from the FiNDC analysis since the peak is usually well-shaped, successfully resolved and identified. Consequently, this peak is by far the most abundant peak in the Category 2. It appears 384 times with an average peak area of 8200 counts.

The contribution of this single peak to the Category 2 was studied by excluding the peaks

Table X. *Properties of Category 1 and 2 peaks when the peaks below 45 keV are excluded.*

Peak category	Number of peaks	Peak area (counts)	
		mean	st.dev.
Category 1: Peaks missed by the FiNDC software	1418	801	9700
Category 2: Peaks missed by the IDC software	2767	449	3600

whose energy is less than 45 keV. The results are shown in Table X and Figure 17. The most significant change is the reduction of the Category 2 mean peak area. It is worth noting that the fraction of the peaks smaller than 100 counts is still approximately twice as large in the Category 1

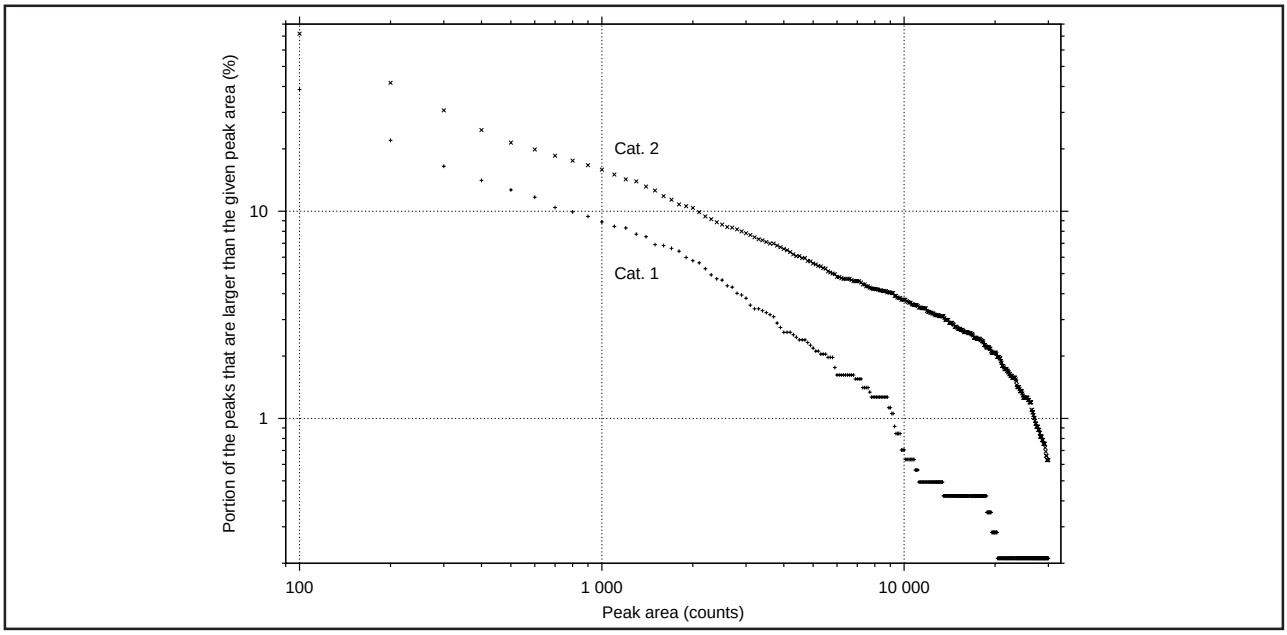

Figure 16. *The peak area distributions of the Category 1 and 2 peaks. Each data point represents the percentage of the missed peaks (y-axis) whose area is larger than the area given in the x-axis. The portion of the peaks larger than 100 counts is 38 % in Category 1 and 72 % in Category 2.*

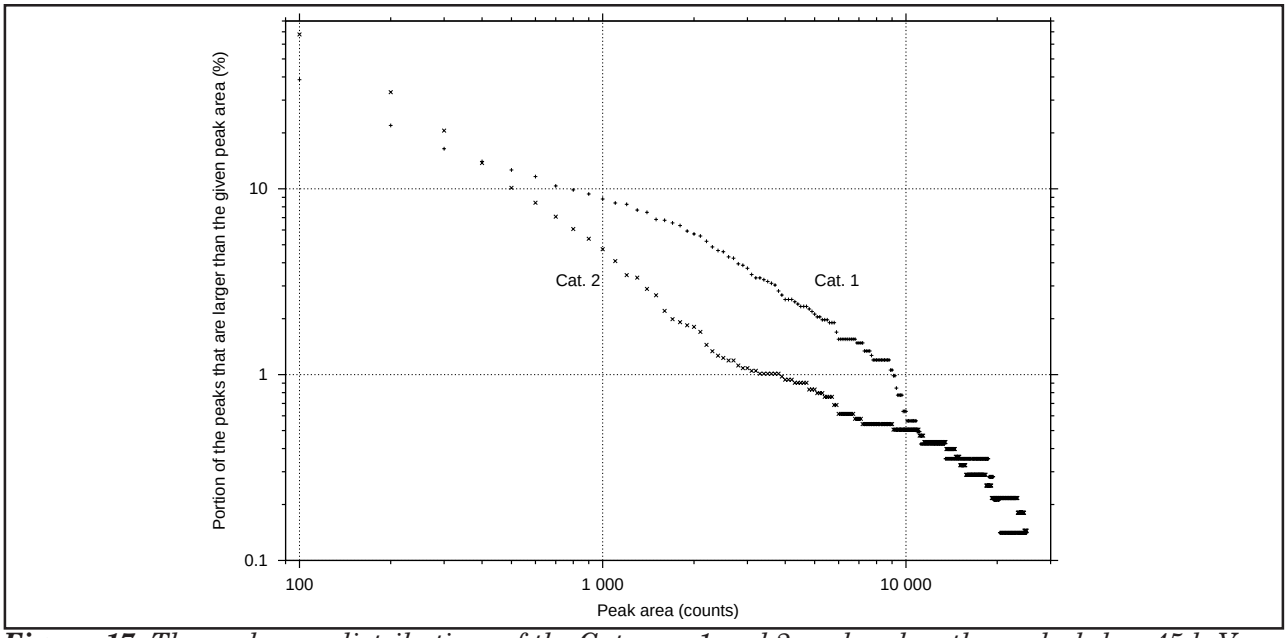

Figure 17. *The peak area distributions of the Category 1 and 2 peaks when the peaks below 45 keV are excluded.*

Table XI. *The most abundant peak energies within each category. The peak energies here denote an energy interval of 1 keV starting from the given energy. The energy cutoff is set so high in IDC analysis that the prominent 39.9 keV peak of Bi-212 is usually left undetected.*

Peak energy (keV)	Occurrences in Category 1	Occurrences in Category 2	Peak candidate
39–40	1	384	Bi-212
46	6	45	Pb-210
65	1	41	X-ray escape
67	11	69	X-ray escape
70	26	16	X-ray
78–79	41	5	X-ray
84	46	34	X-ray
139	11	16	Ge-75M / Tc-99M
154	4	35	X-ray sum
164	7	36	X-ray sum
198	13	42	Ge-71M
233	26	45	Tl-208
295	10	10	Pb-214
415	14	23	Pb-212
473	0	40	Bi-212
1 120	10	9	Bi-214
2 614	10	0	Tl-208
2 687	0	45	Tl-208 sum

as in the Category 2, as illustrated in Figure 17.

Excluding peaks below 45 keV also had an effect to the Category 1 mean peak area since there were two peaks in that category to be removed, the other of which was at 43 keV and reported with an area of 189 610 counts. This particular peak was not associated with any nuclide.

The energy distributions of the Category 1 and 2 peaks do not present any distinctive properties. The majority of the most abundant peaks in both categories are in fact relatively equally often present in the other category as well (Table XI). In absolute numbers, all of these peaks are equally or more common in the Category 2 than in the Category 1. This suggests that the existing peaks are more often left undetected by the IDC software than by the FINDC software.

5.3 Nuclide Identification Performance

5.3.1 General

The correctness of a result of nuclide identification by an automated analysis depends on several conditions at the consecutive phases of the process.

- Detecting instrumentation: Are the data correct?
- Storing and transmitting information: Are the data correct?
- Spectrum analysis: Are the energy, shape and efficiency calibrations correct?
- Spectrum analysis: Are the peak energies and emission rates correctly defined?
- Nuclide library: Does the library contain the required nuclides?
- Nuclide library: Are the energies and emission probabilities correct?
- Nuclide identification: Are the coincidence corrections made properly?
- Nuclide identification: How is the choice made between explanation alternatives?
- Nuclide identification: How probable is the given explanation?

The FiNDC analysis software provides estimates that facilitate evaluating analysis results: For each spectrum peak, a total explanation ratio is given that expresses the fraction of the area of the peak that is explained with the nuclides associated with it. Further, explanation share is given for each nuclide associated with a peak. This quantity expresses the portion of the particular peak that is explained by the nuclide at the calculated activity level.

This information on the individual peaks and their explaining nuclides are not provided by the IDC software. Thus, the comparison between the

radionuclides reported in the two analysis results could only be carried out in a simplistic manner, by comparing the explaining nuclides of each peak in the two reports. The different nuclide naming conventions [7] used in the software packages were taken into account in the comparison programs.

Figure 18 presents results of comparison of the associated nuclides in 1428 spectra available in the database on March 15, 2001. All peaks that were found by both software packages but explained by one software only were taken under scrutiny. These two peak groups were further divided into two groups. Explaining nuclides for peaks in groups A and C were identified by one software package only. For peaks in groups B and D, at least one of the explaining nuclides was identified by both software packages. The reader is encouraged to examine the peak categorisation in Figure 18.

The group A with 713 peaks has a major contribution, 407 peaks, from situations where the IDC software has associated Tl-208 with a peak. These situations have a common origin: The Un-

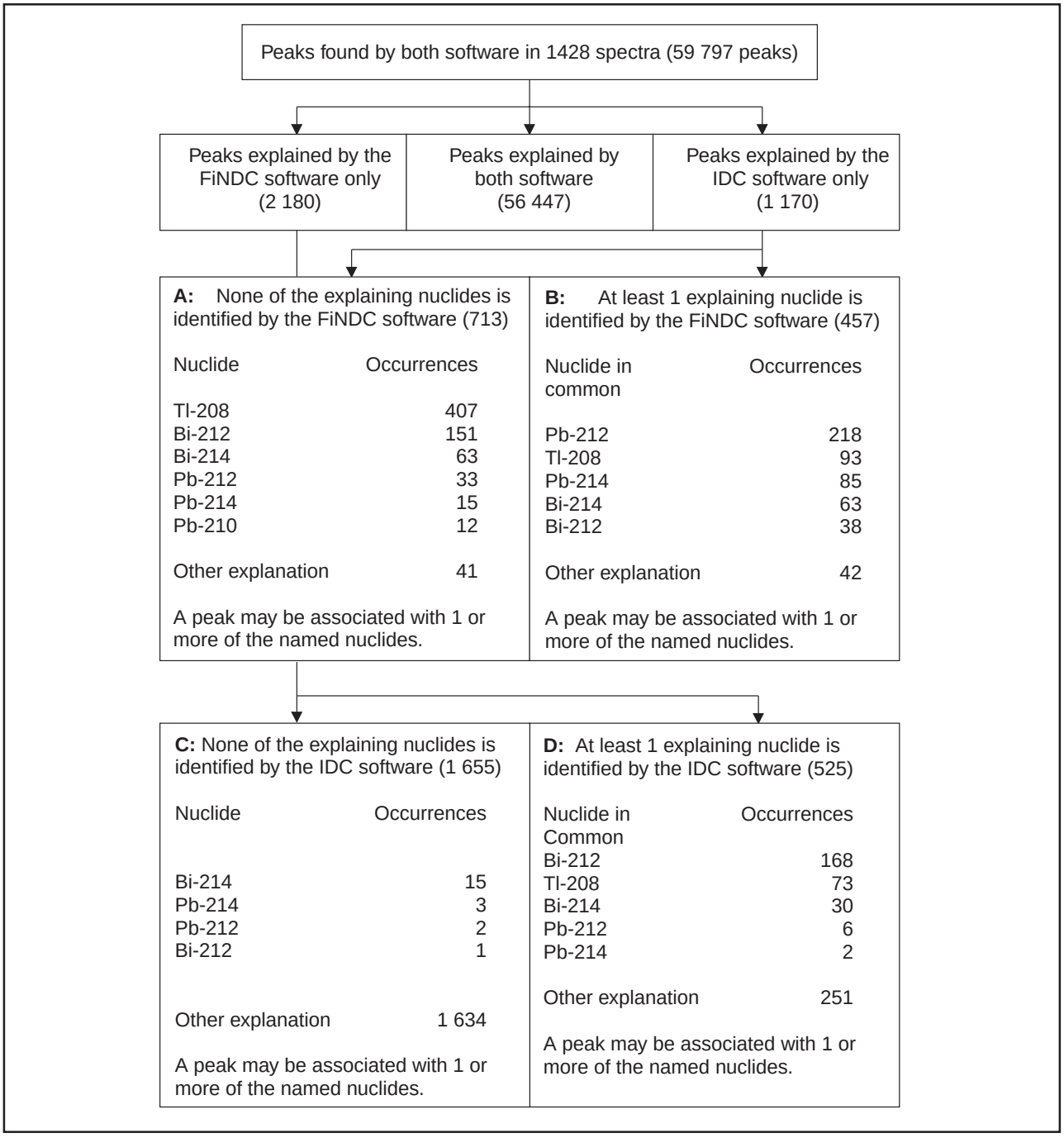

Figure 18. *Division of the peaks into groups A–D.*

iSampo spectrum analysis software used at the FiNDC fails to resolve an X-ray peak multiplet leading to erroneous discarding of Tl-208 in expert system Shaman that is used in nuclide identification in the FiNDC analysis pipeline. Consequently, 5–10 peaks of Tl-208 remain unexplained in these spectra.

A peak falls into group B if it is detected by both software, explained by the IDC software and not explained by the FiNDC software, and if at least one of the nuclides associated with the peak by the IDC software is associated with some other peak by the FiNDC software. The most likely reason for this is an erroneous identification of the IDC software. Because of its simplistic association rules, which ignore the relative emission rates of gamma lines, the IDC software package can associate extra nuclides with peaks that are already fully explained. However, since we have not elaborated these cases in detail, this assumption cannot be confirmed.

The peaks that are explained by the FiNDC software only are divided into groups C and D accordingly. It can be seen that the number of peaks explained by the FiNDC software only (groups C and D) is approximately twice the number of peaks explained by the IDC software only (groups A and B). The majority of peaks in groups C and D are sum peaks and escape peaks that the FiNDC software package can explain more comprehensively than the IDC software. The most frequent explanations given by the FiNDC software package to the group C peaks are listed in Table XII.

Table XII. *The most frequent peak explanations in group C.*

Nuclide or explanation	Occurrences in group C
Sum peak	986
Escape peak	205
Ag-108M	142
Ac-228	127
Th-234	37
W-185	17
K-40	10
Ag-105	8

Table XIII. *The number of spurious nuclides identified by the FiNDC and the IDC per spectrum. N = 1428.*

Number of spurious nuclides in a report	Average	Standard deviation
FiNDC	1.03	1.41
IDC	0.33	0.61

5.3.2 Spurious nuclide identifications

A recent study presented at CTBTO Evaluation workshop in April 2001 [12] emphasises the difficulty of the task of evaluating the correctness of spectrum analysis. In that study, based on five spectra measured on a data day and subjected to thorough review, 1 to 4 spurious peaks (type I errors) per spectrum were observed in the results of the IDC analyst review. The report includes useful discussion on the IDC practices with type I and II errors in connection with signals approaching detection limit, and on the peak search and significance testing plans within the IDC.

In the present study on spurious nuclide identifications, the comparisons were made for a large number of report pairs produced by automated analysis software without human interception. No human reasoning was applied on the comparison process, but the simplistic rules presented in Section 4.2.3 were applied to select the potentially spurious nuclide identifications in an automated manner. This method gives results that are sufficiently close to reality, but most importantly, it is unbiased and thus well suited for a comparison.

The frequency of occurrences of spurious nuclides was studied in a set of 1428 report pairs available in the database on March 15, 2001. The results are presented in Table XIII and Figure 19.

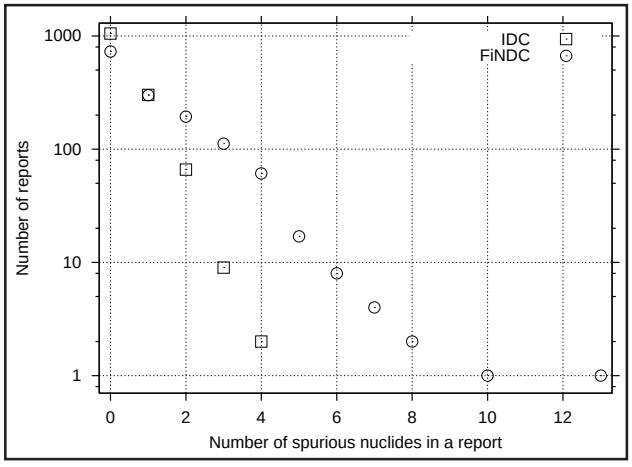

Figure 19. *The frequencies of spurious nuclide identifications in 1428 reports.*

Spurious nuclide identifications are more often reported by the FiNDC. The average difference of 0.7 more spurious nuclides per spectrum must be considered together with the fact that the the FiNDC nuclide library is 100 times larger than the IDC library. This inevitably leads to more spurious identifications as a side effect of the ability to identify more radionuclides.

The difference between the number of spurious nuclide identifications by the FiNDC and that of the IDC was calculated for each test spectrum. In 45 percent of the cases, both numbers were the same, and for 41 percent of the spectra the FiNDC reported more spurious nuclides than the IDC (Figure 20).

5.3.3 Spurious identifications of relevant nuclides

All fission and neutron activation product nuclides are not of interest for the test ban treaty verification regime. The nuclides relevant for the IDC event screening are restricted to those on the Recommended Standard List, comprising 42 fission products and 43 neutron activation products and residues from the nuclear fuel or added tracers. The list is presented in Appendix C. The relevance of the spurious nuclide identifications was studied using this list as a criterion [3,13].

When only relevant nuclides are considered, the difference between the number of spurious nuclide identifications by the FiNDC and the IDC reduces significantly. The following results concerning only relevant nuclides are produced by similar methods than those presented in Section 5.3.2. The differences are summarised in Table XIV and the frequencies of occurrences of the relevant spurious nuclides and their mutual differences are presented in Figures 21 and 22, respectively. Both software packages make the same number of relevant spurious nuclide identifications in 75 percent of the spectra as shown in Figure 22. In the rest of the spectra, these identifications are slightly more common in the FiNDC reports.

Table XIV. *The number of CTBTO relevant spurious nuclides identified by the FiNDC and the IDC per spectrum. N = 1429.*

Number of spurious nuclides in a report	Average	Standard deviation
FiNDC	0.20	0.49
IDC	0.15	0.39
Difference (FiNDC–IDC)	0.05	0.6

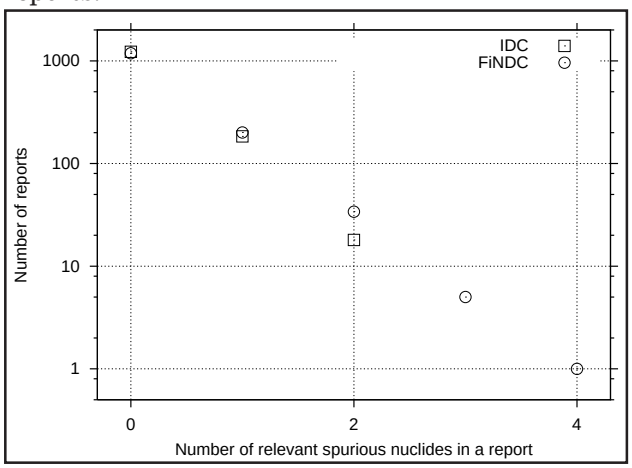

Figure 21. *The frequencies of CTBTO relevant spurious nuclide identifications in 1429 spectra.*

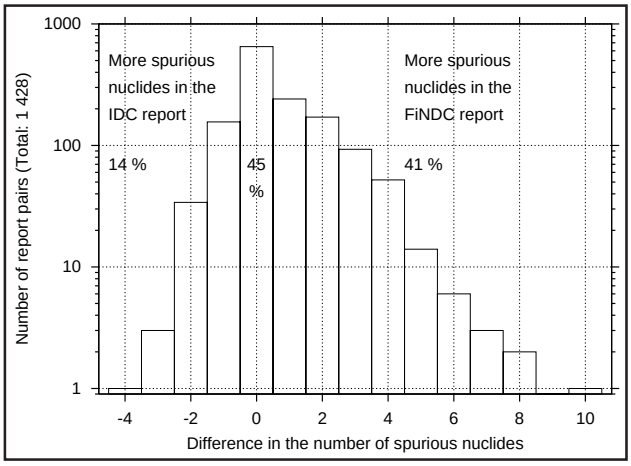

Figure 20. *The distribution of the difference between the number of spurious nuclide identifications for 1428 spectra.*

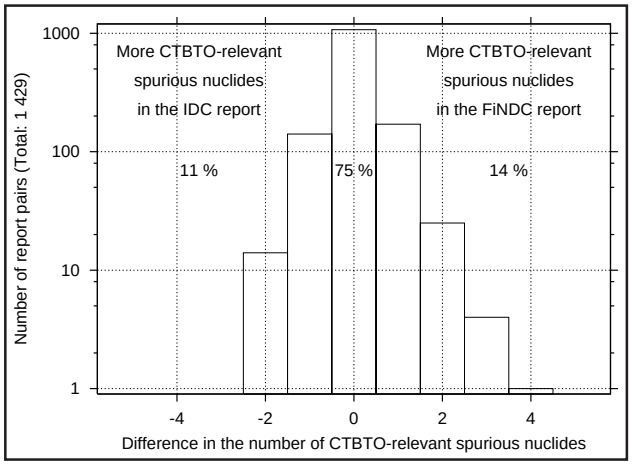

Figure 22. *The numbers of CTBTO relevant spurious nuclide identifications are equal in 75 percent of the spectra.*

Finally, the division of nuclide identifications into spurious and correct ones used in Section 5.3.2 was employed in a brief peak explanation assessment. One more simplistic assumption was made here. If a spectrum peak was associated with spurious nuclide(s) exclusively, the peak was flagged as spuriously explained. The occurrences of spuriously explained peaks defined in this way were gathered and compared within 1428 report pairs. The difference distribution thus gained is shown in Figure 23. In 60 percent of the spectra, both software packages reported the same number of spuriously explained peaks. The FiNDC software reported 0.19 more spuriously explained peaks on the average.

5.4 Assessment of throughput times of data transfer

A separate study was carried out in order to assess throughput times in CTBTO radionuclide data transfer. From an NDC point of view, the IDC should function almost like an e-mail forwarding service that introduces delays of the order of a few minutes or smaller to the data flow. According to our assessment, the IDC works very close to the ideal in this respect.

In order to enable a throughput time analysis, a C program was written to extract different time stamps from the spectral messages as well as IDC reports received by the FiNDC from the IDC via the automatic subscription mechanism. The program outputs the time stamps as well as differences between them, taking into account different complications like leap years and time zones.

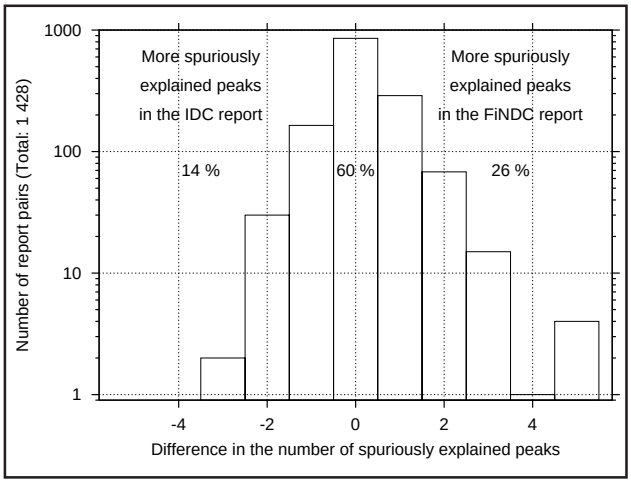

Figure 23. *The distribution of the difference between the numbers of spuriously explained peaks.*

Only data from the five certified stations can be used in these studies. Although the prototype stations STI04, STI07 and STI08 send relevant short-cycle spectra for analysis result studies, they do not attempt to obey the strict time constraints that the certified stations are supposed to obey. For example, the STI04 station sometimes sends spectra of many consequent days on one day.

A further limitation was that the FiNDC data subscriptions were started as late as November 2000. Only time stamps of data received in this way are relevant for this study, not those of spectra and reports received afterwards in bulk. Consequently, these analyses utilised spectra and reports from November 4, 2000 to April 15, 2001, a time period of 163 days.

Throughput time assessment results for ARR reports are presented below. The results for raw spectral data are very similar, so they are not presented here. On the other hand, the manual review introduces an additional delay of the order of one day to the reviewed ARMR reports that the FiNDC also subscribes to. Due to the random nature of this delay and the fact that the IDC is still in a development phase, the throughput time results for ARMR reports are not considered.

Figure 24 shows the throughput time in seconds between end of IDC spectrum analysis and end of spectrum acquisition at the station in the test set of 739 spectra. It can be seen that this time is less than 5 minutes in 95 percent of test cases. Some of the 38 anomalous cases above 5-minute delay seem to be random, but Figure 24 clearly reveals two special cases. First, the STI02 station seems to have had problems in delivering its spectra to the IDC round day 50, with delays up to 10 days. Second, there seem to have been analysis pipeline problems at the IDC between days 100 and 120, because data from all stations have been delayed by several days. As a whole, however, the performance can be considered very good.

Figure 25 shows the time between sending of the ARR reports and the end of IDC spectrum analysis. It can be seen that this time was typically below 2 minutes and only 3 cases out of 739 were delayed more than 5 minutes. The contribution of this delay to the total throughput time seems to be negligible, as could be expected.

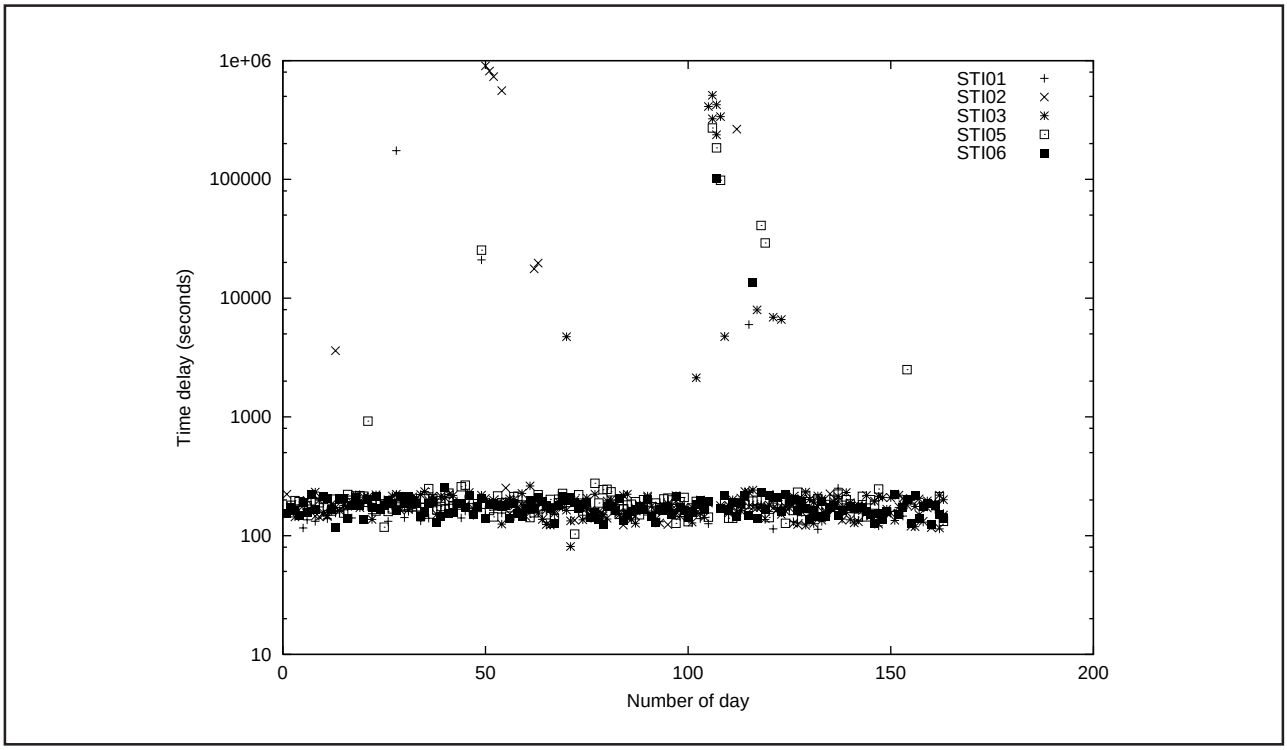

Figure 24. *The throughput time in seconds between end of IDC spectrum analysis and end of spectrum acquisition at the station according to ARR reports for spectra from five certified stations. Day 1 corresponds to Nov 4, 2000 (end of acquisition) and day 163 to Apr 15, 2001.*

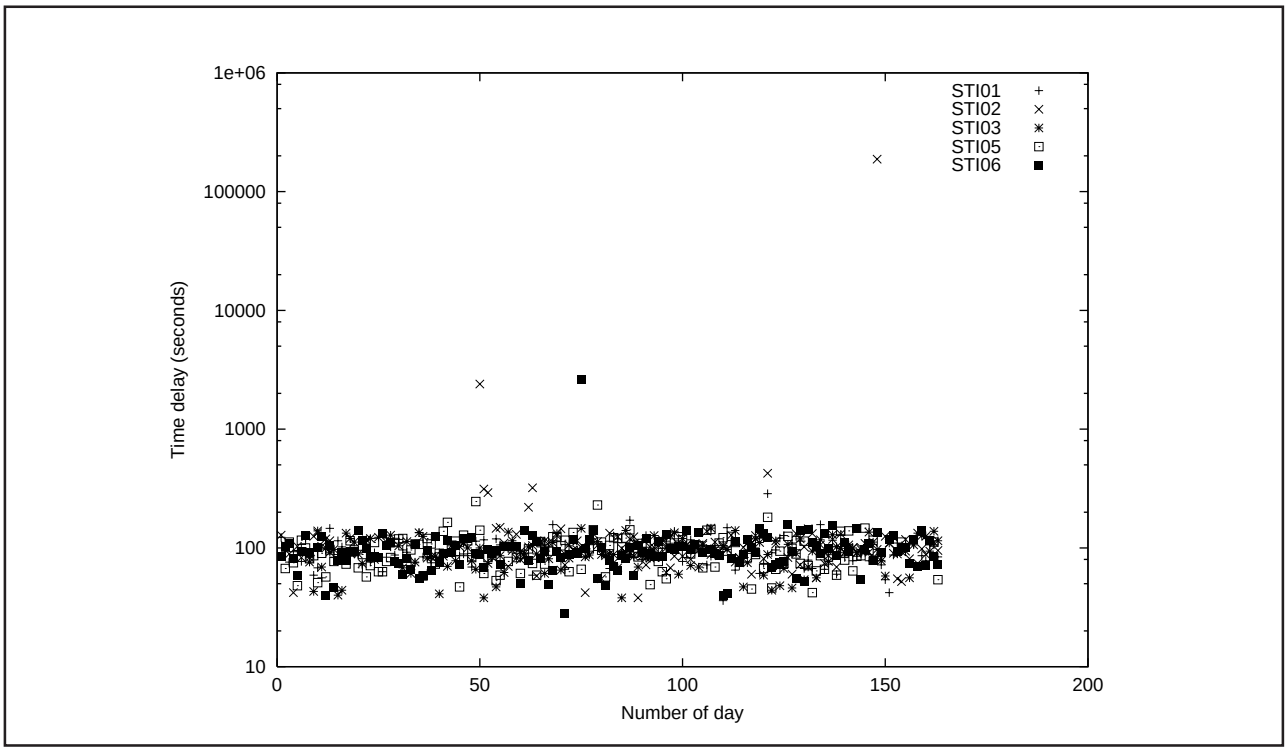

Figure 25. *The throughput time in seconds between sending of the ARR report to the FiNDC and end of IDC spectrum analysis according to ARR reports for spectra from five certified stations. Day 1 corresponds to Nov 4, 2000 (end of acquisition) and day 163 to Apr 15, 2001.*

Figure 26 presents the time between receipt of an ARR report at the FiNDC and sending from the IDC. The behaviour looks peculiar, but the explanation is simple: The clocks in the mail server of the IDC and that of the FiNDC are not synchronised and the clock of the FiNDC server is lagging and adjusted only at each boot by its hardware clock. The first fact explains the downward slopes of the seven linear parts and the second one the steps between them.

From Figure 26, it can be concluded that the transfer time is almost constant between days 40 and 160. The constant is of the order of one minute, but the exact value is impossible to specify because of the asynchronous clocks. There are only 6 cases out of 739 where the transfer time is significantly above 5 minutes, apparently due to problems in the Internet that is used as the transfer channel or in the mail server at the FiNDC.

Figure 27 presents the overall throughput time between ARR report receipt at the FiNDC and the end of acquisition at the station. Each point is the sum of the corresponding points in Figures 24–26. It can be seen that the data are transferred in less than 10 minutes in 94 percent of cases, which can be considered an excellent result for a system still in a building phase. Of course, the goal can be set even higher in the future when the system reaches maturity. The reason for the 46 cases where the overall throughput time is above 10 minutes is a combination of the factors discussed above.

This throughput time assessment emphasises the following issues.

1. It is recommended that all computers with CTBTO connections utilise the Coordinated Universal Time (UTC) as opposed to the local time zone. To our understanding, computers of the CTBTO already obey this recommendation.

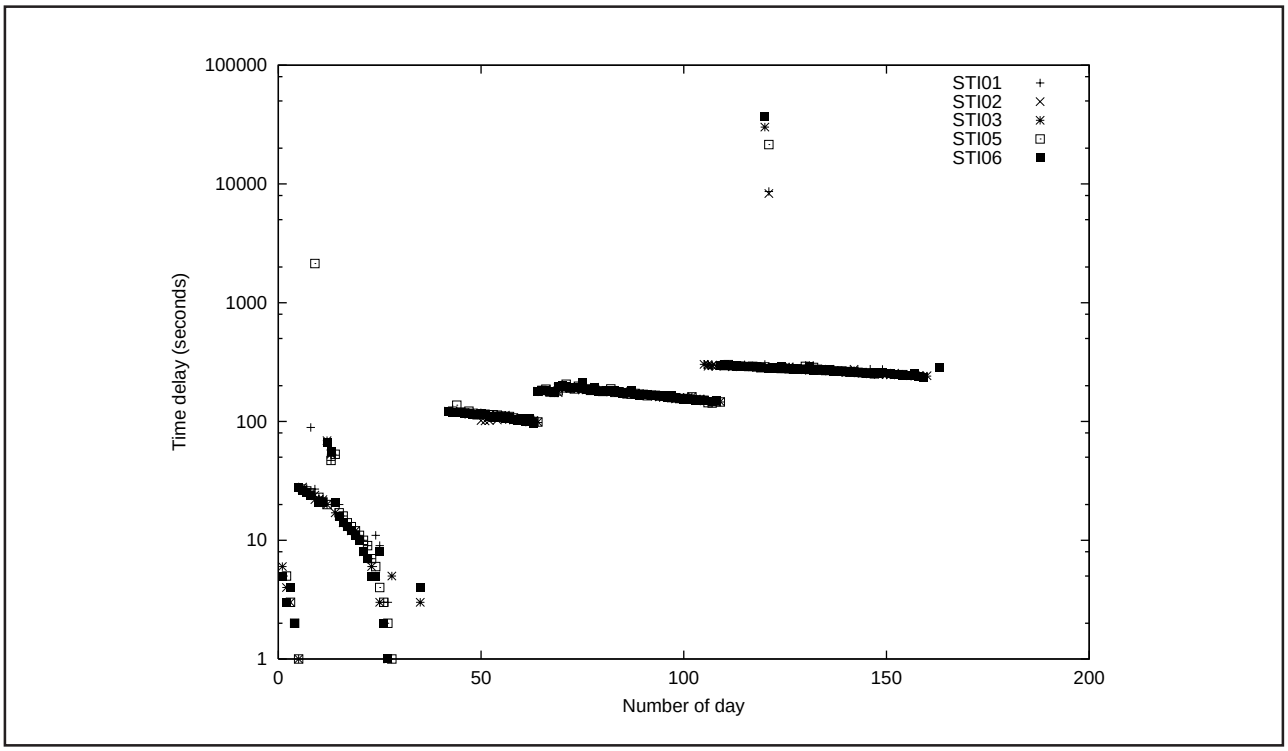

Figure 26. *The time in seconds between receipt of the ARR report at the FiNDC and sending from the IDC according to ARR reports for spectra from five certified stations. Day 1 corresponds to Nov 4, 2000 (end of acquisition) and day 163 to Apr 15, 2001.*

2. It is recommended that all computers with CTBTO connections synchronise their clocks using a common Network Time Provider (NTP) service. Computers of the CTBTO may already obey this recommendation.

3. The throughput times should be followed regularly in order to reveal problems at a station or anywhere between the station and the NDC. However, a tool like the Analyst Workarea used at the IDC is required to follow the throughput times in data transfer in daily work.

4. About 10 percent of ARR reports from the time period under scrutiny are missing from the FiNDC database. The problems in the FiNDC pipeline must be solved in order to see which of these reports, if any, have not been received byt the FiNDC at all. This kind of problems would be the most severe as they correspond to infinitely long throughput time.

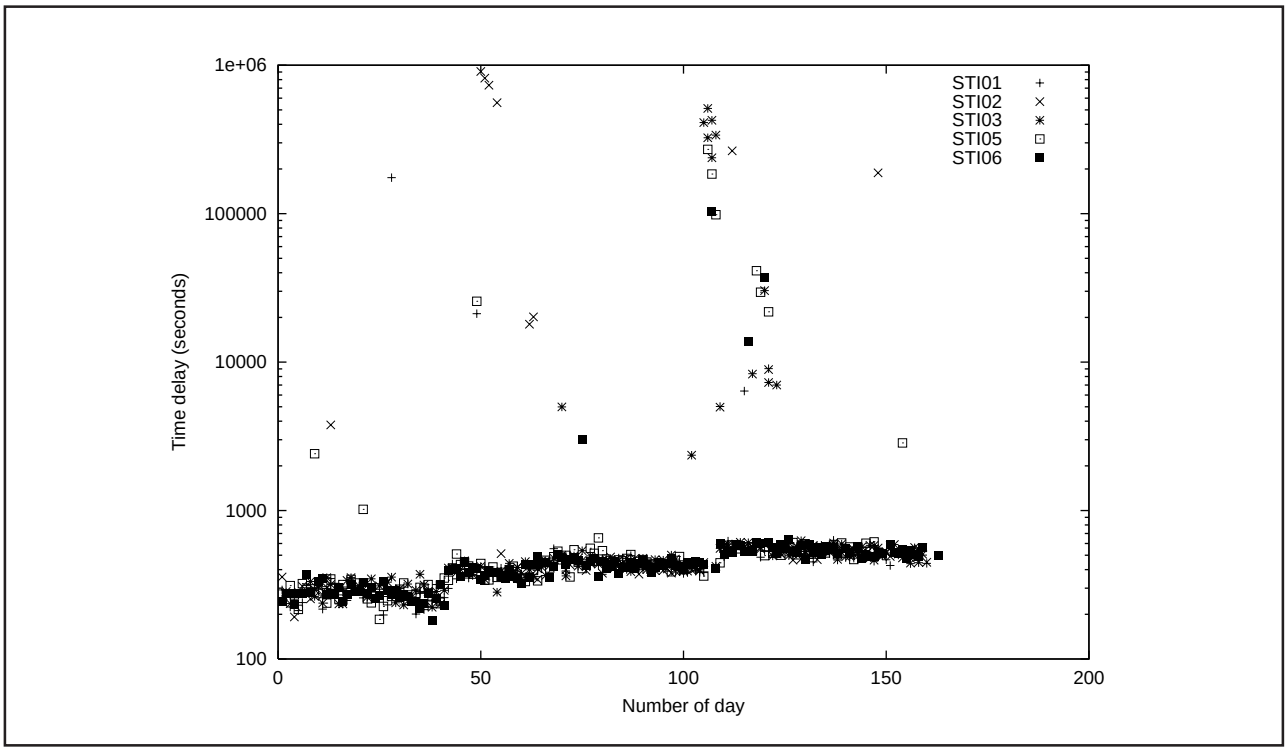

Figure 27. *The aggregate throughput time in seconds between receipt of the ARR report at the FiNDC and end of spectrum acquisition at the station according to ARR reports for spectra from five certified stations. Day 1 corresponds to Nov 4, 2000 (end of acquisition) and day 163 to Apr 15, 2001.*

6 CONCLUSIONS

The material used in this work consists of representative sets containing 500 to 1500 spectra and their respective analysis result pairs. The spectra were measured by the five certified radionuclide stations and three prototype stations that were operating between August 1, 2000 and March 26, 2001. The analysis results of the IDC and FiNDC were studied with respect to the peak finding, fitting and explaining performance and the nuclide identification performance.

Since the peak search algorithms utilised in the IDC and FiNDC software packages are closely related, the most significant difference in the number of found peaks is introduced by the different parameter settings. The very conservative peak search sensitivity threshold used in the IDC software (3.0 vs. 2.4 in the FiNDC software) makes it to deliberately ignore a multitude of real peaks. The FiNDC software package finds 4.2 more peaks in an average spectrum. Simultaneously, the peak significance test used in the FiNDC software following the peak search helps keeping the number of type I errors reasonably low.

Despite the lower peak search threshold and larger number of found peaks, the FiNDC software package leaves 1.4 fewer peaks unexplained than that of the IDC. In total, the FiNDC analysis provides explanations for 5.6 peaks per spectrum that the IDC analysis leaves undetected or unexplained.

These differences have two obvious reasons. First, the FiNDC reference library is remarkably larger than that of the IDC: the libraries include 80000 and 1000 gamma lines, respectively. Second, the FiNDC software uses more advanced nuclide identification methodology. In fact, the latter might be the more important one, since in the majority of air filter spectra there are no other nuclides present with detectable activities than the natural ones and few anthropogenic non-relevant nuclides. With an average of 9–10 identified nuclides in a spectrum [7, p. 33], the different size of libraries is by no means the most important factor in the difference between the number of unexplained peaks. However, the true value of the more comprehensive library is revealed if the sample contains anything out of the ordinary.

The brief examination of the reported peak areas shows that the FiNDC tends to report a slightly larger area for a peak than the IDC. Nevertheless, large relative differences appear to be frequent at small peak areas. This phenomenon should be investigated with synthesised spectra where the true peak areas are known.

The reported uncertainties of the peak areas appear to be calculated using different methods in the IDC and FiNDC software packages. This is demonstrated by the average ratio of 1.68 of the reported area errors (IDC/FiNDC). This indicates that the FiNDC results are more precise which, however, cannot be judged without knowing the accuracy also.

The median of the peak explanation percentage of the IDC analysis is 92.3 and the most often encountered value, the mode value, is 92. The peak explanation percentage of the FiNDC analysis exhibits a totally different distribution. Values above 95 percent are more frequent in the FiNDC analysis than in the IDC analysis. The median of the peak explanation percentage of the FiNDC analysis is 96.7 and the mode value is 100. We conclude that the peak explanation of the FiNDC is significantly better than that of the IDC, especially considering the larger number of found peaks to be explained.

The nuclide identifications made by the two analysis software packages could only be compared with simplistic methods due to lack of substantial information in the Automated Radionuclide Report of the IDC. The methods applied to assess the number of spurious nuclide identifications yielded results that are compatible with earlier evaluation results [7]. The FiNDC software package reports 0.7 more spurious nuclide identifications per spectrum on the average. This is a natural consequence of using a larger reference library. When only the CTBTO relevant nuclides are considered, however, the average difference decreases to 0.05.

The throughput times of the IDC raw measuring data transfer and automatic analysis result data transfer were generally found to be at a very good level. In 94 percent of cases, the automated analysis result from the IDC was received at the FiNDC no later than 10 minutes after the end of spectrum acquisition at the station.

All methods used in this work found real differences between the radionuclide data analysis results, which was to be expected considering the different implementations of many of the essential processes. The presented comparison methods were chosen to describe the features of the software packages in as many respects as allowed by the study material. The number of realisable comparison methods was restricted particularly by the brevity of the contents of the ARR report concerning the peaks and the nuclides associated with them. We suggest the following information to be added into the ARR report:

- peak emission rate and its propagated uncertainty where all sources of uncertainty are accounted for
- peak significance, i.e., how much the peak is above a detection limit
- explanation share of each nuclide, i.e., the share of the peak area that each associated nuclide explains at the calculated activity level.

With the suggested additional information contents of the analysis result report, the nuclide identifications could be assessed with a better judgement than the simplistic division to present or absent nuclides. A statistically sound measure for the goodness of the spectrum explanation could be derived and applied in the comparison.

Although the CTBTO is interested in the mere presence of certain nuclides, it has to be understood that a process like gamma spectrum analysis yields results with uncertainties. The uncertainties cannot be considered as separate items with secondary importance; in fact, the results of gamma spectrum analysis are meaningless if no uncertainties are attached to them.

In this work, many comparison results are presented mainly on a descriptive and qualitative level, mostly due to lack of uncertainty and other essential data in the analysis reports under scrutiny. A rigorous statistical study on the analysis result differences between the IDC and the FiNDC is recommended once the analysis report contents are upgraded.

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APPENDIX A AN EXAMPLE OF AN AUTOMATED RADIONUCLIDE REPORT ARR

```
                              IDC GENERATED REPORT
                               AUTOMATED RADIONUCLIDE REPORT
                               Particulate Version

SAMPLE INFORMATION ====================================================

Station ID:         ABC01              Detector ID:        ABC01_001
Station Type:                          Detector Type:      HPGe

Station Location:
Detector Description:

Sample ID:             0012345         Sample Geometry:    DISC70MMX5
Sample Quantity:      19000.00 m3      Sample Type:        Particulate


Collection Start:   2001/03/01 20:22    Sampling Time:        23.70 hours
Collection Stop:    2001/03/02 20:04    Decay Time:           25.15 hours
Acquisition Start:  2001/03/03 21:13    Acquisition Time:     22.83 hours
Acquisition Stop:   2001/03/04 20:02    Avg Flow Rate:       811.94 m3/hr

Collection Station Comments:
FilterMngr.exe Version 2.7.0.5 at 2001/03/04 20:03:14.055 UTC 2001/03/03
20:54:40 !ManualEntryWarning Air sampler record created for manually entered
air flow data.

IDC Analysis General Comments:
Analysis 2001/03/04 20:05:29


ACTIVITY SUMMARY ======================================================

NATURAL RADIOACTIVITY:

Nuclides Identified and not Quantified:

BI-212, K-40, PB-210, TL-208

Nuclides Quantified:

Nuclide            Half-Life           Conc(uBq/m3)       %RelErr        Notes

BE-7               53.3 D                 6.5E+03         4.66
PB-212             10.64 H                9.5E+03         5.39

ACTIVATION-PRODUCT RADIOACTIVITY:

None Found

FISSION-PRODUCT RADIOACTIVITY:

None Found
```

APPENDIX A AN EXAMPLE OF AN AUTOMATED RADIONUCLIDE REPORT ARR

MINIMUM DETECTABLE CONCENTRATION FOR KEY NUCLIDES ======================

Nuclide	Half-Life	MDC(uBq/m3)
BA-140	12.75 D	6.55
CE-143	1.4 D	11.38
CS-134	2.06135 Y	1.70
CS-136	13.16 D	2.18
CS-137	30.0197 Y	2.11
I-131	8.04 D	2.15
I-133	20.8 H	7.90
MO-99	65.94 H	25.50
NB-95	35.15 D	2.20
RU-103	39.26 D	1.60
TE-132	78.2 H	2.29
ZR-95	64.02 D	3.38
ZR-97	17 H	13.34

PEAK SEARCH RESULTS ==

34 peaks found in spectrum by automated peak search.
32 peaks associated with nuclides by automated processing.
2 peaks not associated with nuclides by automated processing.
94 percent of peaks were associated with nuclides.

Note: "*" indicates that a peak was a component of a multiplet.

Energy	Centroid	Width	FWHM	%Eff	Net Area	%RelErr	Nuclide	Nts
46.57	142.16	8	0.66	27.15	2178.72	4.58	PB-210	
72.87	222.17 *	22	0.73	29.18	1060.24	5.37	TL-208	
74.85	228.19 *	22	0.73	28.93	18213.89	0.97	PB-212	
74.85	228.19 *	22	0.73	28.93	18213.89	0.97	TL-208	
77.13	235.13 *	22	0.74	28.62	28469.47	0.84	PB-212	
84.81	258.50 *	24	0.98	27.48	553.38	9.20	TL-208	
87.22	265.84 *	24	0.99	27.10	10010.57	1.67	PB-212	
89.90	273.98 *	24	1.00	26.67	3126.88	2.61	PB-212	
115.22	350.99	10	0.74	22.85	684.94	11.30	PB-212	
238.58	726.23	12	0.87	13.12	44215.30	0.72	PB-212	
252.59	768.86	12	0.99	12.53	227.37	29.96	TL-208	
277.35	844.14	12	0.97	11.61	1640.07	5.68	TL-208	
288.04	876.67	10	0.80	11.25	302.67	22.72	BI-212	
300.08	913.29	13	0.90	10.88	1927.63	5.11	PB-212	
309.54	942.04	8	0.54	10.60	111.81	41.55		
374.89	1140.76 *	20	0.74	8.98	133.74	22.75	PB212XR1	
377.10	1147.49 *	20	0.74	8.93	214.59	18.70	PB212XR2	
452.78	1377.59	15	1.51	7.55	277.03	18.35	BI-212	
477.64	1453.17	15	1.09	7.17	73708.67	0.53	BE-7	
510.84	1554.11	15	1.39	6.71	3864.02	2.74	TL-208	
583.23	1774.18	16	1.19	5.85	10273.97	1.50	TL-208	
727.26	2211.97	17	1.32	4.58	2313.03	3.43	BI-212	
763.22	2321.26	11	1.33	4.33	151.11	22.00	TL-208	
785.33	2388.45	17	1.39	4.19	301.89	12.38	BI-212	
860.42	2616.66	18	1.41	3.75	1359.66	4.61	TL-208	
893.17	2716.18	15	1.26	3.59	110.66	24.74	BI-212	
1078.35	3278.86	17	1.36	2.84	76.07	33.25	BI-212	
1093.70	3325.50	17	1.53	2.79	299.45	11.38	TL-208	
1460.97	4441.29	39	1.89	1.96	208.43	14.22	K-40	
1513.11	4599.68	16	1.71	1.89	78.53	29.64	BI-212	
1592.47	4840.74	20	2.04	1.78	362.66	9.56	TL-208	
1620.73	4926.60	23	2.08	1.75	286.90	11.44	BI-212	
2014.90	6123.99	11	0.51	1.43	17.60	4.43		
2103.65	6393.58	27	2.65	1.39	395.07	9.88	TL-208	
2614.53	7945.93	28	2.49	1.28	2964.55	2.81	TL-208	

AN EXAMPLE OF A SHAMAN GENERATED AUTOMATED RADIONUCLIDE REPORT SAR

APPENDIX B

```
                              SHAMAN GENERATED REPORT
                              AUTOMATED RADIONUCLIDE REPORT
                              Particulate Version

SAMPLE INFORMATION ====================================================

Station ID:         ABC12               Detector ID:        ABC12-001
Station Type:                           Detector Type:

Station Location:
Detector Description:

Sample ID:                              Sample Geometry:
Sample Quantity:      19000.00 m3       Sample Type:        Particulate

Collection Start:   2001/03/01 01:11    Sampling Time:        23.14 hours
Collection Stop:    2001/03/02 00:20    Decay Time:           24.28 hours
Acquisition Start:  2001/03/03 00:37    Acquisition Time:     23.51 hours
Acquisition Stop:   2001/03/04 00:07    Avg Flow Rate:       843.12 m3/hr

Collection Station Comments:

IDC Analysis General Comments:
Analysis Wed Mar 14 10:57:11 2001


ACTIVITY SUMMARY ======================================================

NATURAL RADIOACTIVITY:

Nuclides Identified and not Quantified:

Tl-208, Pb-210, Bi-212

Nuclides Quantified:

Nuclide            Half-Life            Conc(uBq/m3)        %RelErr        Notes

Be-7               53.29 d                 7.1E+03          0.34
Pb-212             10.64 h                 1.0E+04          0.27
```

APPENDIX B

An example of a Shaman Generated Automated Radionuclide Report SAR

ACTIVATION-PRODUCT RADIOACTIVITY:

None Found

FISSION-PRODUCT RADIOACTIVITY:

None Found

MINIMUM DETECTABLE CONCENTRATION FOR KEY NUCLIDES ==========

Nuclide	Half-Life	MDC(uBq/m3)
Zr-95	64.02 d	2.34
Zr-97	16.9 h	8.32
Nb-95	34.97 d	1.28
Mo-99	2.748 d	28.22
Ru-103	39.26 d	1.13
Te-132	3.204 d	2.93
I-131	8.04 d	1.56
I-133	20.8 h	5.65
Cs-134	2.062 a	1.56
Cs-136A	13.16 d	2.26
Cs-137	30.1 a	1.37
Ba-140	12.75 d	15.38
Ce-143	1.377 d	13.50

PEAK SEARCH RESULTS ==========

```
      39 peaks found in spectrum by automated peak search.
      38 peaks associated with nuclides by automated processing.
       0 peaks judged insignificant.
       0 peaks out of energy range.
       1 peaks not associated with nuclides by automated processing.
      97 percent of peaks were associated with nuclides.

 Note: '*' indicates that a peak was a component of a multiplet.
```

An example of a Shaman Generated Automated Radionuclide Report SAR

APPENDIX B

Energy	Centroid	Width	FWHM	%Eff	Net Area	%RelErr	Nuclide	Nts	EmRate	%RelErr	Signif	ExplTotal	ExplShare
40.19	119.79	0	0.72	25.24	3285.06	2.27	Bi-212		0.1538	2.27	13.30	95.17	95.17
46.87	139.97	0	0.75	28.87	826.99	6.26	Pb-210		0.0338	6.26	3.46	100.00	100.00
67.65	202.76	0	0.82	31.50	263.98	21.81	ESCPK1		0.0099	21.81	0.91	61.10	61.10
73.14	219.33	0	0.84	31.07	2134.08	3.38	Tl-208		0.0812	3.38	7.37	129.73	112.88
73.14	219.33	0	0.84	31.07	2134.08	3.38	Bi-212		0.0812	3.38	7.37	129.73	16.85
75.10	225.27	0	0.84	30.87	29997.14	0.62	Tl-208		1.1484	0.62	84.84	113.88	13.47
75.10	225.27	0	0.84	30.87	29997.14	0.62	Pb-212		1.1484	0.62	84.84	113.88	100.41
77.37	232.12	0	0.85	30.60	46182.52	0.49	Pb-212		1.7835	0.49	107.44	109.11	108.80
77.37	232.12	0	0.85	30.60	46182.52	0.49	Bi-212		1.7835	0.49	107.44	109.11	0.31
85.05	255.32	0	0.87	29.55	740.11	7.36	Tl-208		0.0296	7.36	2.78	186.95	186.95
87.46	262.60	0	0.87	29.19	15350.00	0.87	Tl-208		0.6214	0.87	51.77	114.39	2.15
87.46	262.60	0	0.87	29.19	15350.00	0.87	Pb-212		0.6214	0.87	51.77	114.39	112.24
90.14	270.69	0	0.88	28.78	4830.74	1.77	Pb-212		0.1984	1.77	18.13	86.64	84.97
90.14	270.69	0	0.88	28.78	4830.74	1.77	Bi-212		0.1984	1.77	18.13	86.64	1.67
115.40	347.02	0	0.93	24.87	1205.70	4.75	Pb-212		0.0573	4.75	4.80	76.31	76.31
233.31	703.24	0	1.09	14.08	279.13	15.79	Tl-208		0.0234	15.79	1.26	35.98	35.98
234.77	707.65	0	1.09	14.00	378.01	11.70		U	0.0319	11.70	1.72	0.00	0.00
238.63	719.34	0	1.10	13.81	68091.49	0.40	Pb-212		5.8281	0.40	113.48	82.32	82.32
252.38	760.86	0	1.11	13.14	158.39	27.76	Tl-208		0.0142	27.76	0.67	115.54	115.54
277.31	836.19	0	1.13	12.10	2263.64	2.95	Tl-208		0.2211	2.95	9.14	90.25	90.25
288.11	868.80	0	1.14	11.69	588.10	8.59	Bi-212		0.0594	8.59	2.35	77.56	77.56
300.07	904.95	0	1.16	11.28	3028.00	2.44	Pb-212		0.3173	2.44	11.59	66.22	66.22
328.02	989.40	0	1.18	10.42	179.43	21.27	Bi-212		0.0204	21.27	0.89	88.25	88.25
374.89	1130.99	0	1.22	9.24	222.52	14.96	USRPK1		0.0285	14.96	1.30	100.00	100.00
377.07	1137.59	0	1.22	9.19	370.65	9.63	USRPK2		0.0476	9.63	2.21	100.00	100.00
415.26	1252.98	0	1.25	8.42	118.41	23.88	Pb-212		0.0166	23.88	0.80	190.67	190.67
452.79	1366.34	0	1.28	7.78	350.34	9.32	Bi-212		0.0532	9.32	2.56	93.30	93.30
477.47	1440.90	0	1.30	7.41	89264.08	0.34	Be-7		14.2437	0.34	390.09	100.00	100.00
510.62	1541.06	0	1.32	6.95	5037.43	1.49	ANNPK1		0.8561	1.49	35.60	100.00	17.35
510.62	1541.06	0	1.32	6.95	5037.43	1.49	Tl-208		0.8561	1.49	35.60	100.00	82.65
583.03	1759.85	0	1.37	6.12	15793.91	0.81	Tl-208		3.0482	0.81	113.49	100.43	100.43
657.47	1984.73	0	1.43	5.43	163.43	14.21	USRPK3		0.0355	14.21	1.51	100.00	100.00
727.02	2194.88	0	1.48	4.90	3411.60	1.81	Bi-212		0.8229	1.81	28.01	104.32	104.32
762.96	2303.44	0	1.51	4.66	191.98	11.46	Tl-208		0.0487	11.46	1.92	126.69	126.69
785.26	2370.83	0	1.53	4.51	429.52	6.36	Bi-212		0.1125	6.36	4.14	108.76	108.76
860.19	2597.21	0	1.60	4.08	1969.08	2.44	Tl-208		0.5701	2.44	18.67	97.28	97.28
893.19	2696.90	0	1.62	3.91	155.04	15.45	Bi-212		0.0469	15.45	1.65	89.31	89.31
1078.40	3256.47	0	1.80	3.12	179.76	10.06	Bi-212		0.0681	10.06	2.22	91.91	91.91
1093.27	3301.40	0	1.81	3.07	438.27	5.73	Tl-208		0.1690	5.73	5.31	84.14	84.14
1512.54	4568.09	0	2.29	1.95	152.61	10.90	Bi-212		0.0924	10.90	2.16	62.36	62.36
1592.26	4808.94	0	2.40	1.80	502.03	5.01	ESCPK2		0.3292	5.01	6.71	182.42	182.42
1620.75	4895.02	0	2.44	1.75	420.43	5.81	Bi-212		0.2835	5.81	5.76	75.12	75.12
2103.68	6354.07	0	3.18	1.35	534.87	4.74	ESCPK3		0.5646	4.74	7.44	143.14	143.14
2615.05	7899.02	0	4.14	1.02	4401.93	1.55	Tl-208		7.1422	1.55	60.53	43.59	43.59
2688.70	8121.53	0	4.29	0.99	85.16	21.04	USRPK4		0.1465	21.04	1.79	100.00	100.00

APPENDIX C RECOMMENDED STANDARD LIST OF RELEVANT RADIONUCLIDES FOR IDC EVENT SCREENING [13]

CTBT relevant fission products (42)	CTBT relevant non-fission products (43)
Sr-91	Na-24
Y-91	K-42
Y-93	Sc-46
Zr-95	Sc-47
Nb-95	Cr-51
Zr-97	Mn-54
Mo-99	Co-57
Tc-99M	Co-58
Ru-103	Fe-59
Rh-105	Co-60
Ru-106	Zn-65
Ag-111	Zn-69M
Pd-112	Ga-72
Cd-115M	As-74
Cd-115	As-76
Sn-125	Rb-84
Sb-125	Rb-86
Sb-126	Y-88
Sb-127	Zr-89
Sb-128	Rh-102
Te-129M	Ag-106M
I-130	Ag-108M
Te-131M	Ag-110M
I-131	Sb-120
Te-132	Sb-122
I-133	Sb-124
I-135	Cs-132
Cs-136	Ba-133
Cs-137	Cs-134
Ba-140	Eu-152M
La-140	Eu-152
Ce-141	Tm-168
Ce-143	W-187
Ce-144	Ir-190
Nd-147	Ir-192
Pm-149	Au-196
Pm-151	Au-196N
Sm-153	Au-198
Eu-155	Pb-203
Sm-156	Ra-224
Eu-156	U-237
Eu-157	Np-239
	Am-241