Evaluating the Commercial Spectrometer Systems for Safeguards Applications Using Germanium Detectors

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Abstract

Safeguards applications require the best spectrometer systems with excellent resolution, stability, and throughput. Instruments must perform well in all the situations and environments. Data communication to the computer should be convenient, fast, and reliable. The software should have all the necessary tools and be easy to use. Portable systems should be small in size, lightweight, and have a long battery life. Nine commercially available spectrometer systems are tested with both the planar and coaxial germanium detectors. Considering the performance of the Digital Signal Processors (DSP), digital-based spectroscopy may be the future of gamma-ray spectroscopy.

I. INTRODUCTION

Gamma-ray spectroscopy has been a very important aspect of the history of nuclear physics and safeguards. As the gamma-ray detector has been gradually improved from Geiger counter to scintillator to lithium-drifted solid state detector to high-purity germanium detector, the accompanying hardware also has been improved from simple counter to single channel analyzer (SCA) to multichannel analyzer (MCA). Even the MCA has also been improved throughout the years, from the conventional single-package MCA to the computer-controlled MCA. Most of the MCA systems today use the computers to control the spectroscopy hardware and to emulate the functions of the MCAs. The controller can almost be any type of computer: mainframe, mini- or microcomputer, workstation, etc., but the most common ones are personal computers (PC). For a portable MCA system, a notebook computer or even a palmtop computer can be used instead of the full-sized PC.

Nine commercially available spectrometer systems of this type (computer controlled) are tested with both the planar and coaxial germanium detectors. The nine systems are the standard Nuclear Instrumental Methods (NIM) system (mixing of the modules from both Ortec and Canberra), the Digital Gamma-Ray Spectrometer (DSPEC), Dart, 92X-II Spectrum Master, Nomad Plus from Ortec[*], inspector and model 2060 Digital Signal Processor (2060DSP) from Canberra[†], Miniature Modular MultiChannel Analyzer (M3CA) from Aquila[‡], and the Mini MultiChannel Analyzer (MCA166) from GBS-Elektronik[§], Germany. Figure 1 shows the seven stand-alone systems used in the evaluation. Performance data relevant to the safeguards applications are presented.

II. SPECTROSCOPY SYSTEMS

A. Hardware Descriptions

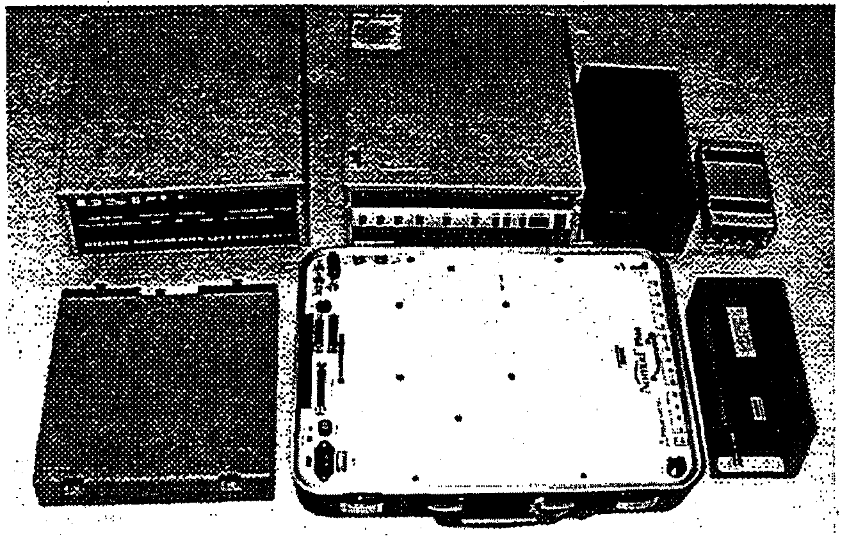


Fig. 1. Seven stand-alone systems used in the evaluation. From left to right and front to back: Inspector, Nomad Plus, M3CA, DSPEC, 92X-II, Dart, and MCA166.

1. NIM

The NIM system was a standard system which consisted of an Ortec 4002D NIM bin power supply, a Canberra 3106D HV power supply, a Canberra 8077 Fast ADC, a Canberra 8232 Digital Stabilizer, and a Canberra 2071AS Dual Counter Timer. Two amplifiers were used with the system: an Ortec 672 Spectroscopy Amplifier with the shaping times of 0.5, 1, 2, 3, 6, and 10 μs and a Canberra 2025 AFT Research Amplifier with the shaping times of 0.5, 1, 2, 4, 6, and 12 μs. The Ortec 672 Spectroscopy Amplifier with triangular shaping was used for data collected at the 1-, 2-, and 6-μs shaping times and the Canberra 2025 AFT Research Amplifier with triangular shaping was used for data collected at the 4-μs shaping time. The Baseline Restorer (BLR) was set to "auto." The Canberra 4610 System 100 MCA board was used for interfacing. The IBM docking station I was used to hold the MCA board, and the host computer was an IBM ThinkPad 760L. The System 100 software can control as many as four MCA boards (that is, if there are sufficient slots in the computer to hold four MCA boards). Each MCA board in turn can be connected to an ADC. Thus each computer can control up to four NIM systems (with Canberra ADCs) or other compatible systems.

2. DSPEC

DSPEC is an AC-powered, stand-alone unit. Unlike the traditional signal processing where the pulses from the preamplifier are processed by the analog amplifier and then digitized by the ADC, DSPEC digitally processes the pulses directly from the preamplifier using a quasi-trapezoid pulse shape. The four parameters that control the pulse shape are rise time, cusp, flattop, and tilt. DSPEC's rise time is roughly equivalent to twice the integration time set on a conventional analog spectroscopy amplifier and it can be adjusted in the software from 0.8 to 25.6 μs in steps of 0.8 μs. The rise times of 2.4, 4.0, 8.0, and 12.0 μs (which would roughly correspond to 1-, 2-, 4-, and 6-μs shaping time) were used in the evaluation. The cusp controls the curvature of the sides of the quasi-trapezoid and the flattop adjusts the width of the top of the quasi-trapezoid. The cusp and flattop values can be adjusted individually to obtain the best results for each different radiation source and at different count rates. However, it was determined that it is not realistic to adjust these parameters for every single measurement. Therefore, the cusp value of 0.8 μs and a flattop value of 1.6 μs, which were found to be the best general purpose parameters for germanium detectors [1], were used through out the measurements. The tilt controls the flattop slope and its value was automatically set by the DSPEC optimizer. The DSPEC's BLR can be set to auto, fast, slow, or manual. In this evaluation, it was set to auto. Each DSPEC processes the output of a single detector. DSPEC can be connected to the computer by means of an ethernet BNC connector, Dual-Port Memory (DPM) 37-pin D-type connector, or low-speed serial link. If there are more than one DSPEC controlled detector, with the ethernet data link connection method, multiple systems could be setup to be controlled by one computer by chaining all of the DSPECs together into a single local area network (LAN). Likewise, multiple computers can also be set using LAN to control single or multiple DSPECs. The DSPEC can also communicate with the computer using the DPM data link. It requires a DPM interface card, such as the Advance Data Collection and Management (ADCAM) interface card from Ortec that plugs into the host computer. If the DPM data link is used, it is still easy to connect up to eight DSPEC-controlled detectors or many other combinations of Ortec Mutichannel Buffers (MCB) to one computer. A dual-port fan-out module is needed to turn the single connector on the interface card into enough connectors for the multiple systems. The serial link of the DSPEC is provided for convenience and is normally not used because of the low data-transfer speed. In this experiment, DSPEC was connected to either the IBM ThinkPad 560 or the IBM ThinkPad 760XD by ethernet through the 3Com Etherlink III PCMCIA card.

3. Dart

Dart is a portable system. The operating time with a standard germanium detector using two fully charged batteries is 5.6 h without power saving at 100% duty cycle and is 7 h with power saving at 50% duty cycle. Each Dart has two shaping time constants, short and long. The pair of shaping time constants can be selected and ordered from a pool of various shaping constants. Two Dart units were used in the evaluation, one with the shaping time of 2 and 6 μs and the other with 1 and 2 μs, for a total of three shaping time constants: 1, 2, and 6 μs. The Dart is connected to the PC by either the parallel or serial port. A maximum of eight Darts can be daisy chained and controlled by one computer through the parallel link. The serial link allows the computer to control the Dart from a long distance. In this experiment, the Dart was connected the IBM ThinkPad 760XD by the parallel link.

4. Nomad Plus

Nomad Plus can be used as either an AC-powered unit or, despite its weight, a portable system. The battery operating time is 8 h. Each Nomad Plus has two shaping time constants, short and long. The unit that was used in the evaluation has the shaping time of 1 and 2 μs. The Nomad Plus can be connected to the PC by either the high-speed parallel printer port or by the DPM connector. If the DPM is used, a DPM interface card is required. With the DPM link, it is possible to connect up to eight Nomad Pluses or other Ortec MCBs to one computer using the dual-port fan-out module. For long-distance communication, an optional serial link can be used. In this experiment, the Nomad Plus was connected to the IBM ThinkPad 760XD by the parallel link.

5. *Inspector*

Inspector is a portable system. The operating time with a standard germanium detector using two fully charged batteries is 3 h without power saving at 100% duty cycle. In the Battery Save mode, the batteries can operate for at least 24 h. In this mode, the actual data acquisition is delayed until the high voltage has reached its preset value and the internal electronics are thermally stable. The Battery Standby mode can extend the batteries' life up to 80 h. In this mode, when a command is received, the Inspector automatically returns to the Battery Save mode. Each Inspector has two shaping time constants, short and long. Two Inspector units were used in the evaluation, one with the shaping time of 1 and 4 μs and the other with 1 and 2 μs for a total of three shaping time constants: 1, 2, and 4 μs. The Inspector is connected to the PC by the serial link. The PC used was the IBM ThinkPad 760D.

6. *MCA166*

MCA166 is a portable system. The operating time with a fully charged battery pack is 14 h for standard NaI detectors, and 6 h for standard germanium detectors. With a small external battery pack (size 16 x 10 x 5 cm, the same as that of the MCA166 itself), the operating time can be increased by 150%. The MCA166 unit used in the evaluation has the shaping time constants of 1 and 2 μs. The MCA166 is connected to the PC through the serial port. The PC used was the IBM ThinkPad 560.

7. *92X-II*

92X-II is an AC-powered stand-alone system. Each 92X-II has two shaping time constants, short and long. The 92X-II unit used in the evaluation had a shaping time of 1 and 2 μs. The 92X-II can be connected to the computer by means of ethernet BNC connector, DPM, or by the serial link. It can be linked to the computer the same way as the DSPEC (described in section II.A.2). That is, multiple systems can be daisy chained into a LAN using ethernet or parallel connection with other systems using DPM. In this experiment, the 92X-II was connected to the IBM ThinkPad 760XD by ethernet through the 3Com Etherlink III PCMCIA card.

8. *M3CA*

M3CA is a portable system. The manual listed the operating time of a fully charged battery as 8 h at 50% duty cycle. There is no listing of the battery lifetime running at 100% duty cycle. Therefore, in actual data acquisition, the M3CA battery lifetime may be much less than the 8 h listed. There is no setting for automatic power saving mode to automatically turn off the power of the nonessential components when not acquiring data to save battery power. To switch to the power-saving mode, the user has to manually turn off the power of the amplifier board, the ADC board, or the HV power supply board. To acquire data, the powers of the amplifier, ADC, and HV boards are then manually turned on. The user needs to allow for some time delay for the HV to reach its preset value and for the electronics to become thermally stable before starting to acquire data. Each M3CA has two shaping time constants, short and long. The unit used in the evaluation has the shaping time of 0.5 and 2 μs, which only the 2 μs shaping time was used in the evaluation of the germanium detectors. The M3CA is connected to the PC through the serial port. The PC used was the Digital HiNote Ultra CT475.

9. 2060DSP

2060DSP is not a complete system but a standard double-width NIM module. It replaces the traditional amplifier-ADC combination in a standard NIM system. Also, with the built-in counter, it can also replace the count-rate meter as well. Besides the essential functions such as amplifier gain adjustments, baseline restoration, and pole zero compensation, the 2060DSP also uses the automatic Ballistic Deficit Correction (BDC) to optimize performance with detectors of different sizes and varying charge collection times. It does not use the stabilizers. The 2060DSP's BLR can be set to auto, hard, medium, and soft. In the evaluation, the BLR was set to auto. Like the DSPEC, the 2060DSP digitally processes the pulses from the preamplifier using a trapezoid pulse shape. The 2060DSP employs only two parameters to control the pulse shape: rise time and flattop. In a sense, it is the same as the DSPEC with the cusp set at 1.0 (the side of the quasi-trapezoid is a straight line with zero curvature) and the tilt value of zero (the flattop's slope is zero). The 2060DSP has 35 rise times ranging from 0.4 μs to 28 μs with the step size dependent on rise time range: small step size for small rise time and large step size for large rise time. The flattop can be changed by steps of 0.1 μs in the range of 0 μs to 1.0 μs and by steps of 0.2 μs in the range of 1.0 μs to 3.0 μs. With these range-dependent step sizes, the 2060DSP can be optimized better than the DSPEC which has only fixed step sizes. The 2060DSP manual lists the rise times of 1.2, 2.8, 5.6, and 8.8 μs as equivalent to the Gaussian shaping times of 1, 2, 4, and 6 μs. However, in the evaluations, those associated rise times were found to be too small. Therefore, the DSPEC's equivalent shaping time is adapted, i.e., the rise time is roughly equivalent to twice the integration time set on a conventional analog. The rise times of 2.4, 4.0, 8.0, and 12.0 μs (which would correspond to 1-, 2-, 4-, and 6-μs shaping time) were used in the evaluation. A rise time of 2.0 μs, which would better represent the 1-μs shaping time, could be used in place of 2.4 μs. However, the rise time of 2.4 μs was used instead so that it would be the same as that of the DSPEC. The flattop values were automatically optimized by the BDC and they turned out to be 0.8 μs and 0.5 μs for the coaxial and planar detectors used in the evaluation, respectively. The 2060DSP also employs a Pileup Rejector (PUR) Guard function which proved to be effective in optimizing the system. The PUR interval is defined as [X*(rise time) + (flattop)] where X is the PUR Guard time selection. There are eight PUR Guard time selections ranging from 1.1 to 2.5. Increasing the PUR Guard time extends the PUR interval to protect subsequent events from being corrupted by anomalies associated with the tail of the previous event. The throughput is also reduced as the PUR Guard time is increased. The user therefore should take into account the tradeoff between the resolution and throughput when setting the PUR Guard. In the evaluation, the PUR Guard times were set at 1.1 for the coaxial detector and 1.5 for the planar detector. These values were found to be optimal for these detectors. The 2060DSP communicates with the computer through several different interfaces. In this evaluation, the Canberra 4610 System 100 MCA board was used for the interfacing. The IBM docking station Iwas used to hold the MCA board, and the host computer was an IBM ThinkPad 760L. These are the same as those used in the NIM system described above. Note that the 2060DSP is a NIM module and not a complete system. To complete the system, an Ortec 4002D NIM bin power supply and a Canberra 3106D HV power supply were used.

All of the systems described above can support both the P-type and N-type germanium detectors, and also the NaI detectors. For the NIM and the 2060DSP system, the internal jumper board of the Canberra 3106D HV power supply is moved to the desired position to change the HV polarity. The HV inhibitor of this HV power supply works only with the Canberra germanium detectors or other detectors that use the TTL-type Inhibit circuits. To use with the Ortec detectors, an Ortec HV power supply is needed. Likewise, to use with the NaI detectors, an HV power supply for NaI detectors is required. For the DSPEC, 92X-II, and the Nomad Plus, the HV power supply is changed by moving the internal jumper board to the desired position. The Dart and the Inspector use the software to change the HV power supply. For the MCA166 and the M3CA, the HV power supply is changed by replacing the internal HV power supply board with the appropriate one. Note that these two systems may not come with all the HV power supply boards. It should be taken into consideration when purchasing these systems. Table I below shows the summary of the specifications of all the systems.

Table I. Specifications of the spectrometer systems.

	Nim	DSPEC	Dart	Nomad Plus+	Inspector	MCA166	92X-II	M3CA	2060DSP
Shaping time (μs)	.5, 1, 2, 4, 6, 12	0.4 to 12.8, step 0.4	short, long	short, long	short, long	short, long	short, long	short, long	35 various shapings
Pile-Up rejector	yes	yes	yes	yes	yes	yes	yes	yes	yes
Baseline restorer	auto, PZ, high	auto, fast, slow, man	auto	auto	none	auto	auto	none	auto, hard, med, soft
Pole zero	auto, manual	auto, manual	auto, manual	auto	auto, manual	manual, auto	auto	manual	auto, manual
Stabilizer	zero, gain	zero, gain	zero, gain	zero, gain	zero, gain	gain	zero, gain	none	none
ADC gate	yes	yes	yes	yes	no	no	yes	no	yes
ADC	450-MHz Wilkinson	N/A	12 μs succ. approx.	12 μs succ. approx.	100-MHz Wilkinson	8 μs succ. approx.	7 μs succ. approx.	100-MHz Wilkinson	N/A
ADC channel (max)	16K	16K	8K	16K	8K	4K	16K	4K	16K
High Voltage	+-5KV Ge, +-2KV NaI	+-5KV Ge, +-1.5KV NaI	+-5KV Ge, +1.25KV NaI	+-5KV Ge, +-2KV NaI	+-5KV Ge, +1.3KV NaI	+-3KV Ge, +1KV NaI	+-5KV Ge, +-2KV NaI	+-4.5KV Ge, +1.2KV NaI	N/A
HV inhibit	Ortec, Canberra	Ortec	Ortec, Canberra	Ortec, Canberra	Canberra	Ortec, Canberra	Ortec, Canberra	none	N/A
Amplifier polarity	external	internal	software	internal	software	software	internal	software	external
Power supply	AC	AC	5.6 hrs NiCd	8 hrs Lead acid, AC	3 hrs NiCd	6 hrs Li	AC	8 hrs (50%) Ni-MH	N/A
Dimensions, includes battery pack (cm)	48x54x22	31x35x14	14x30x9	46x33x18	27x33x6	10x16x5	31x35x14	10x22x9	7x22x20
Weight, includes battery pack	23.2	7.7	2.5	10.3	3.2	0.7	7.7	3.2	1.8
Computer interface	34-pin ADC to Canberra System 100 MCA board	ethernet, 37-pin DPM, 19.2 kbaud serial	parallel, 38.4 kbaud serial	parallel, 37-pin DPM	19.2 - 115.2 kbaud serial	38.4 kbaud serial	ethernet, 37-pin DPM, 38.4 kbaud serial	9.6 kbaud serial	34-pin ADC to Canberra System 100 MCA board
Computer operating software and system	S100 software with Wins 3.x	Maestro with Dos, 16- & 32-bit Windows	Maestro with Dos, 16- & 32-bit Windows	Maestro with Dos, 16- & 32-bit Windows	Genie-PC with OS/2, Genie-2000 with 32-bit Windows	MCA 166 software with Dos, Windows	Maestro with Dos, 16- & 32-bit Windows	M3W software with 16-bit Windows	S100 software with Wins 3.x
Manufacture	Ortec and Canberra	EG&G Ortec	EG&G Ortec	EG&G Ortec	Canberra	GBS-Elecktronik	EG&G Ortec	Aquila	Canberra
Price ($1000)[**]	~ 15	12.5	10	9.9	7	~ 6[††]	10	10[‡‡]	6[§§]

B. Software Descriptions

The software the NIM and 2060DSP systems used for collecting data was the System 100 software from Canberra. It is an easy "setup and run" program. The communication between the ADC or the 2060DSP module, the MCA board, and the computer is fast so the user does not notice any delay in sending a command to the MCA board and seeing the results on screen.

For the DSPEC, the Dart, the 92X-II, and the Nomad Plus, the software used to acquire data was Maestro from EG&G Ortec. This software is also easy to setup and run. In this experiment, all of the systems from EG&G Ortec were connected to the computer by either the ethernet or the parallel printer port links which are fast. Therefore no delay was seen when sending commands to the systems and observing the returning results.

The software the Inspector used to acquire data was the Genie-PC from Canberra. This software runs under the OS/2 operating system. (Canberra Industry, Inc., has recently upgraded the software, named Genie-2000, to run with Windows 95 and NT). This software has many nice features, but it is a bit complicated to setup for data acquisition. In addition to the complication, the Inspector communicates with the computer through the low-speed serial link which is very slow. When the Inspector acquires data and is in the data-transferring mode, there are several seconds delay between sending the command to the Inspector and receiving the answers. Due to both of these problems, the complicated software and the slow communication, it takes a rather long time to setup the system to do simple data acquisition.

For the MCA166, the software used to acquire data was the Mini MCA166 emulation software from GBS-Elecktronik. The MCA166 emulation software is DOS based, written and optimized for the HP Palmtop hardware (with screen resolution of 640 by 200 pixels). Therefore, some features of the software are not optimum for desktop or laptop computers. (A Windows version of the software is also available but was not used in the evaluation.) It is simple to setup and acquire data. Even though the MCA166 communicates with the computer through the low-speed serial link, the delay time between sending a command and receiving an answer is negligible, less than one second.

The software the M3CA used to acquire data was the M3W from Los Alamos. It is simple to setup and acquire data. However, due to the very low-speed serial link (only 9.6-k baud), the communication between the M3CA and the computer is extremely slow. The M3CA is setup to transfer the whole updated spectrum, one after another. When the largest number of counts in a channel is greater than 65535 counts, four bytes has to be sent for each channel (unsigned long integer). In this case, it would take more than 13 s to transfer a 4-K spectrum. When the M3CA is transferring data, it would not accept any other commands so that the user has to wait until the data transferring is done to execute another command. Even though the M3W program is simple, it may take up to 15 or more minutes to setup the M3CA to acquire a simple spectrum due to the waiting time for the data transfer.

C. Communication specifications

The high-speed parallel printer port link and the dual-port memory 37-pin D-type connector link are fast but bulky and short. The maximum distance for those links is only several meters. The serial link is very slow which makes the communication between the user, the computer, and the system difficult (e.g., the user has to wait several seconds for the data transfer to complete before executing another command). However, a serial link can communicate at a very large distance, which may be greater than 100 m. The best communication of all the evaluated systems was by the ethernet which is very fast and the communicating distance can be very long, much greater than 1,000 m. With ethernet, multiple computer and detector systems (such as DSPECs and 92X-IIs) can be linked together into a single LAN using BNC connectors. For such a system, a single computer can control single or multiple detectors and multiple computers can control single or multiple detectors.

III. DATA ANALYSIS AND DISCUSSION

Two detectors were used in the measurements: One was an 8-year-old germanium planar detector manufactured by Canberra and the other was a 2-year-old germanium coaxial detector with a relative efficiency of about 25%, also manufactured by Canberra. The detectors were shielded with lead bricks and cadmium sheets (except the fronts) to reduce the background gamma rays. The sources used were 54 µCi of ^{57}Co (for the planar detector), 8.4 µCi of ^{57}Co and 9.8 µCi of ^{60}Co (for the coaxial detector) at the beginning. The total time for all of the measurements lasted about four months. For all of the measurements, each source was measured separately. The sources were moved close to or far away from the detectors in order to achieve the desired count rates which were 1, 3, 10, and 30 kHz for the 4- and 6-µs shaping times, and 1, 3, 10, 30, and 50 kHz for the 1- and 2-µs shaping times. Most of these systems (except the NIM, the M3CA, and the 2060DSP) are not equipped with a count rate meter, so the second outputs of the detectors were connected to an amplifier-counter set of a NIM system to monitor the count rate. When running with the coaxial detector, the ADC conversion gain and range were set at 8K on all of the systems except those of the MCA166 and M3CA, where they were set to the maximum channel conversion available which was 4K. For the planar detector, the ADC conversion gain and range were set at 4K on all the systems. The amplifier gains were adjusted so that for the ^{57}Co data, the 122-keV peak was at channel 3000 and for the ^{60}Co source, the 1173-keV peak was at channel 7000 (except for the MCA166 and M3CA, where the 1332-keV peak was set at about channel 3900). The gain stabilizers, if available, were set on either the 122-keV (^{57}Co) peak or the 1173-keV (^{60}Co) peak. The zero stabilizers were not used.

All of these systems store the spectral data in many different formats, and they all were converted to the Ortec CHN format to be used with the analytical functions in Ortec Maestro software. The reason for the file format conversion is that the same analytical functions from a single software can be performed on all of the data sets (so if there are any biases from the analysis algorithms, they should be the same for all of the data sets). The energy calibrations were done using either the 122.06-keV and 136.47-keV peaks of ^{57}Co or the 1173.23-keV and 1332.49-keV peaks of ^{60}Co. Because the dead-time corrections for all of the systems are not exactly the same, the recorded live times in the spectra were not used to calculate the throughput rate. The total counts in the 122-keV and 1332-keV peaks were used instead. For all of the results shown in Figs. 2, 3, and 4, the analysis was done on the 122-keV peak of the ^{57}Co and the 1332-keV peak of the ^{60}Co.

Figures 2, 3, and 4 compare the energy resolution and throughput of all the systems. It is seen that, in general, the M3CA has the worst energy resolution and the second worst throughput for all the count rates and most of the energy range. It is only slightly better than the 92X-II in resolution with the ^{60}Co source at 2-µs shaping time. The second worst system is the Inspector. Its energy resolution for most of the time, is ranked at number 7 or 8 out of 9 units tested and its throughput is always the worst one. At high count rates (30 kHz at 4-µs shaping time and 50 kHz at 2-µs shaping time), its throughput is only about a third of that of the system with the best throughput, the 2060DSP. The reason for the low throughput rates of the Inspector and the M3CA is mainly due to the ADCs which are100 MHz Wilkinson. If those are upgraded to 400 or 450 MHz (like that of the Canberra 8077 Fast ADC of the NIM system) or fast successive-approximation ADCs (like those of most other systems) then the throughput rates would probably be comparable to the others.

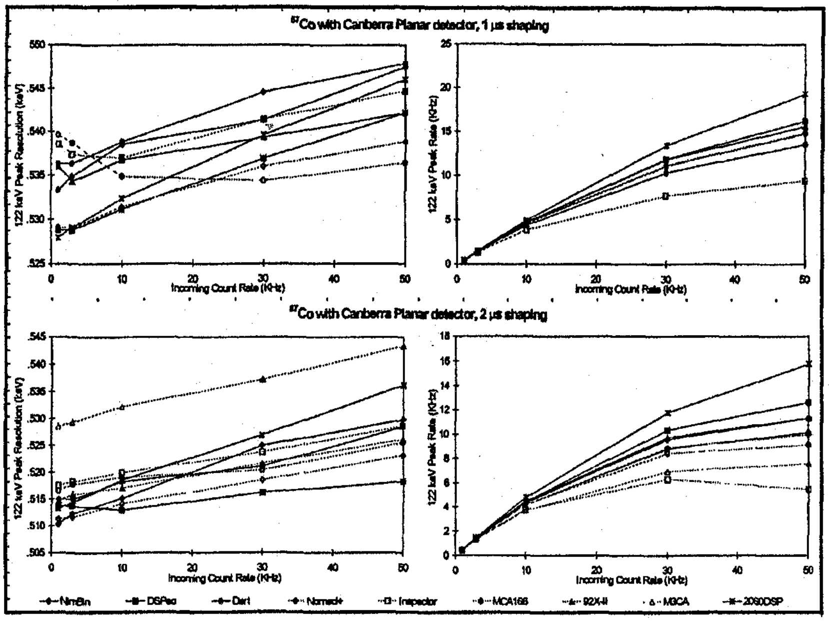
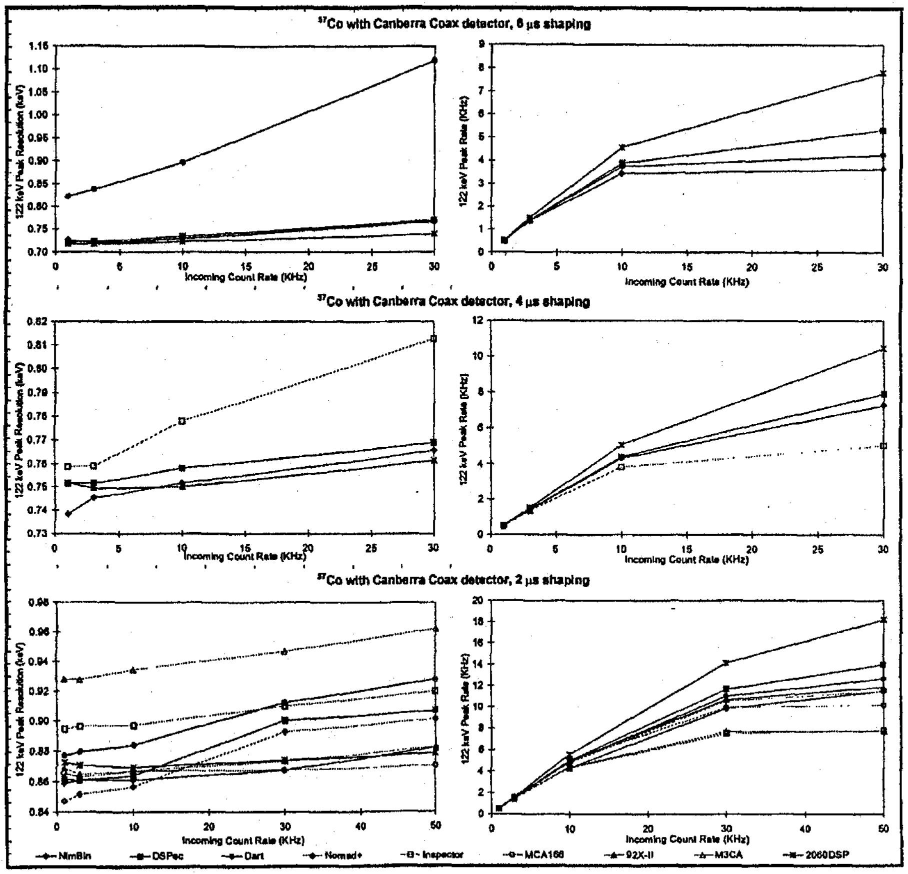


Fig. 2. Comparative resolutions and throughputs of all the systems with the planar detector using the ^{57}Co source. The rise times of the DSPEC and 2060DSP are reported as their shaping time equivalents. The actual rise times of DSPEC and 2060DSP are about twice the shaping time equivalents

Fig. 3. Comparative resolutions and throughputs of all the systems with the coaxial detector using the ^{57}Co source. The rise times of the DSPEC and 2060DSP are reported as their shaping time equivalents. The actual rise times of DSPEC and 2060DSP are about twice the shaping-time equivalents



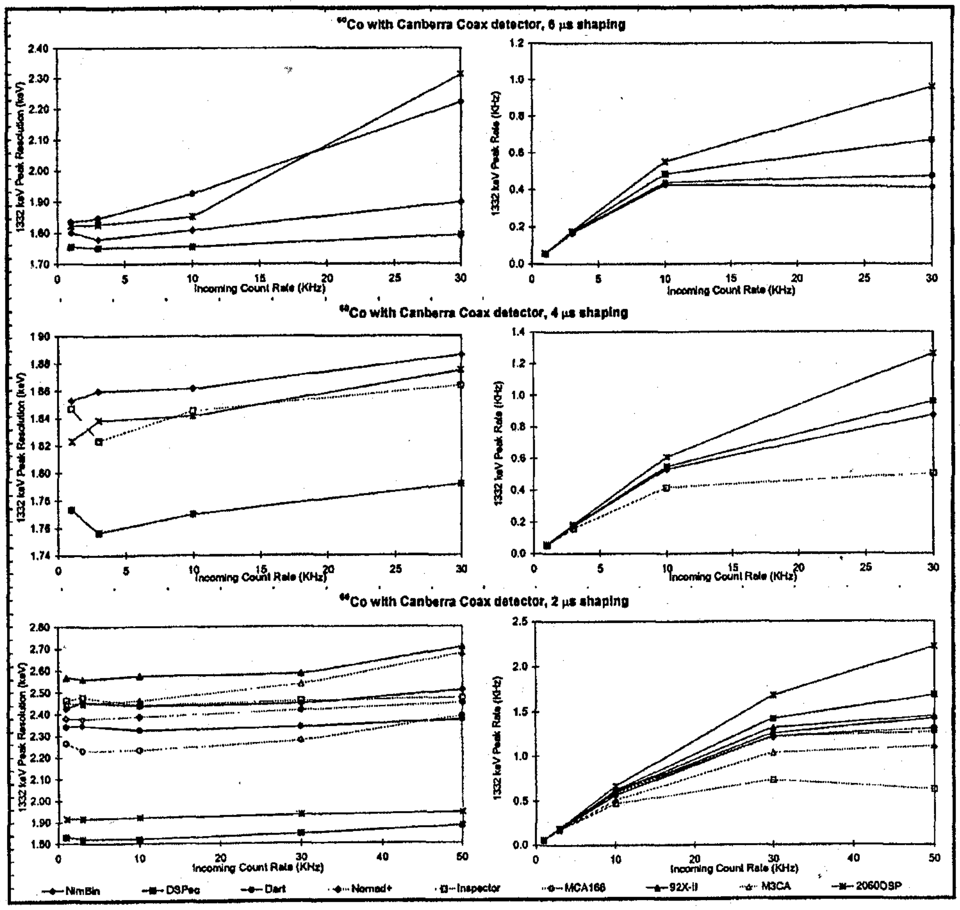


Fig. 4. Comparative resolutions and throughputs of all the systems with the coaxial detector using the ^{60}Co source. The rise times of the DSPEC and 2060DSP are reported as their shaping time equivalents. The actual rise times of DSPEC and 2060DSP are about twice the shaping time equivalents.

The best systems in general are the DSPEC and 2060DSP. For low energy (e.g., 122 keV of ^{57}Co), their energy resolutions are about the same as the analog systems. However, at high energy (e.g., 1332 keV of ^{60}Co), they perform exceptionally better than any other, especially for the 2-µs shaping time where they are about 0.6 keV better than all the other systems. As for the throughput, it is clearly seen that the results with DSPEC and 2060DSP are superior to all the analog systems at all count rates and shaping times. Note that the performances of the DSPEC and 2060DSP can even be improved more if the BLRs are distinctively set to accommodate different count rates instead of "auto" as was done in the evaluation. In addition, the parameters used for the advanced shaping of the DSPEC were the general purpose parameters [1]. If one can individually adjust the parameters for optimal performance for each different radiation source at different count rates, then the results for DSPEC would be even better.

It is interesting that the resolution of the 2060DSP with the ^{60}Co source at 6 µs shaping and 30 kHz is bad (see Fig. 4). It is probably due to the overload of the 2060DSP. After the 2060DSP reaches the overload point, its resolution deteriorates exponentially instead of linearly as the count rate increases. At a count rate of 28 kHz, the full-width half maximum (FWHM) of the 1332-keV peak is still reasonable, only 2.0 keV. However, when the count rate is increased to 30 kHz, the FWHM increases to 2.3 keV, and at 32 kHz, the FWHM is 3.8 keV. The peaks are completely washed out when the count rate is above 36 kHz. The overload is a function of energy, the rise time, and the count rate. Table II shows the overload count rates of the 2060DSP when used with the coaxial detector and with the ^{57}Co and ^{60}Co sources. The overload count rate is taken as the point when the FWHM is about 10% larger than what it should be. The overload occurs at a much lower count rate for the ^{60}Co source than with the ^{57}Co source. When both the ^{57}Co and ^{60}Co sources are measured at the same time, the overload count rates are somewhere between the values of ^{57}Co and ^{60}Co as shown in Table II depending on the ratio of the mix.

Of all the remaining systems, the Nomad Plus and the MCA166 seem to have slightly better resolution: the Nomad Plus at low count rate and the MCA166 at high count rate. All other systems have comparable energy resolution and throughput. As for the Dart, it performs reasonably well at the 1- and 2-µs shaping times, but at the 6-µs shaping time, its resolution is not good and it gets worse at higher count rates. In trying to improve its resolution at the 6-µs shaping time, the Pole-Zero (PZ) was manually adjusted instead of automatically tuned. The resolution did improve somewhat but was still bad. The reported data for the Dart at the 6-µs shaping time are from the manually tuned PZ.

For the 92X-II, it performs satisfactorily with the ^{57}Co source but not too good with the ^{60}Co source. It is probably because of the coaxial detector's ballistic deficit effect and because it could not PZ correctly. (Ballistic deficit occurs when the charge collection time of the detector is too long and the amplifier is unable to completely shape and filter the pulses from the detector. This effect is shown more clearly with large detectors and large energy.) The tails on the low-energy side of the peaks were clearly seen in all of the ^{60}Co spectra, even at low count rate, and the automatic PZ could not correct for that. If the 92X-II had the manual PZ, one could attempt to manually PZ the system and would probably get somewhat better results than the ones reported here.

Table II. Overload count rates at various rise times of the 2060DSP with the coaxial detector.

Rise time (µs)	^{60}Co Input rate (kHz)	^{57}Co Input rate (kHz)
7.2	80	
8.8	57	
10.4	38	
12	30	73
15.2	24	53
18.4	18	42
21.6	15	36

In general, the throughput for the 12-µs (or better) successive approximation ADC performs comparable to the 450-MHz Wilkinson ADC and much better than the 100-MHz Wilkinson ADC. However, the successive approximation ADCs have a setback. It is the piling up of the counts of the channels near the end of the spectrum which make those channels unusable. For the Dart, Nomad Plus, and 92xII, the last 192 channels of the 8K spectrum (or 91 channels of the 4K spectrum) are piled up and cannot be used. For the MCA166, the cutoff channel is 3967 for a 4K spectrum.

Ranking the systems

Out of nine systems, the performance of the DSPEC and 2060DSP seems to be the best; that of the M3CA and Inspector seems to be the worst; and the rest of the systems seem to be comparable. However, the judgment of how well a system performs by comparing with others done above requires juggling the resolution and throughput so that the result for either one is tentative.

It is known that for a certain system with the same shaping time, different pulse shapes would result in different resolutions and throughputs. For example, for the NIM system, the triangular pulse shape would give somewhat better resolution and worse throughput than the Gaussian pulse shape.

The nine evaluated systems employ many different pulse shapes and each different pulse shape will affect the resolution and throughput performance. In addition, for a defined shaping time, each different system has a slightly different pulse width and that will also affect its performance. Therefore, to rank a system using both the resolution and throughput is very difficult and unreliable.

As an example, the Inspector seems to have better resolution and worse throughput than the Dart at the 1-µs shaping time with the planar detector (see Fig. 2). It is difficult to say the Inspector performs, in general, better or worse than the Dart based on that observation alone. One may, however, notice that the throughput of the Dart at the 2-µs shaping time is comparable to that of the Inspector at the 1-µs shaping time. Thus the comparison of the resolutions should be made between those of the Dart at the 2-µs shaping time to those of the Inspector at the 1-µs shaping time. In this manner, the Dart would seem to perform much better than the Inspector.

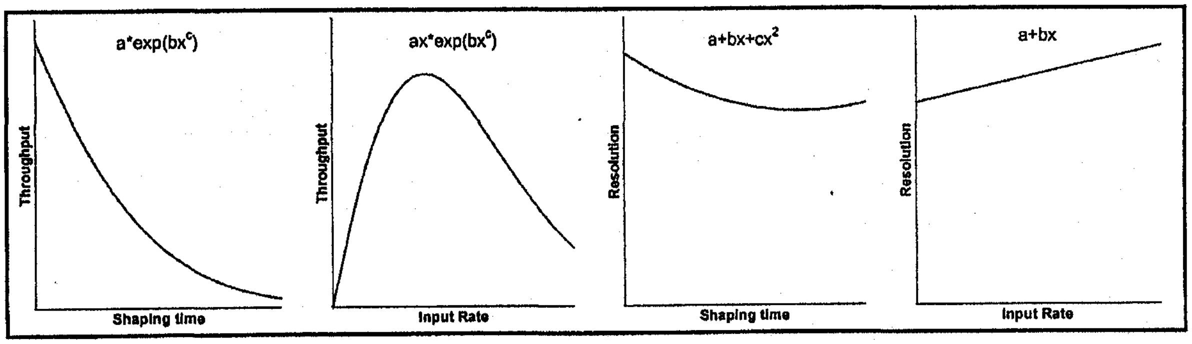


Fig. 5. The shapes of the throughput and resolution curves as functions of shaping time and input rate.

In order to compare the systems in a manner similar to that in the example above, it is ideal if one can adjust the shaping times so that the throughput rates are the same for all the systems. However, all of these systems have limited and discrete shaping time values and can not all together be adjusted to match one another. Therefore, a scheme is derived to normalize the throughputs of the systems to those of the NIM system at the 2-µs shaping time. Then, the resolutions corresponding to the normalized throughputs of the systems can be directly compared.

From Figs. 2, 3, and 4, the throughput behaves as $\exp(bx_1^c)$ and $x_2\exp(bx_2^c)$, where x_1 is the shaping time, x_2 is the input count rate, and b and c are constants. Also the resolution is related quadratically to the shaping time and linearly to the input count rate. Fig. 5 shows the general shapes of the throughput and resolution as functions of shaping time and input count rate. Combining the analytical behaviors gives the two dimensional surface formulae:

$$\text{Throughput} = a_1 x_2 * \exp(a_2 x_1^{a3} x_2^{a4}) \quad \text{and} \qquad (1)$$

$$\text{FWHM} = (b_1+b_2x_1+b_3x_1^2) + x_2(b_4+b_5x_1+b_6x_1^2)\ , \qquad (2)$$

where x_1 = shaping time (µs), x_2 = input count rate (kHz), and a_i and b_i are unknown variables.

For the coaxial detector, the throughput and resolution data of the NIM system at the 2-, 4-, and 6-µs shaping times are fitted to these two-dimensional surfaces. Figure 6 shows, as an example, the fitted surfaces of the throughputs and resolutions of the NIM system using the coaxial detector and the ^{57}Co source.

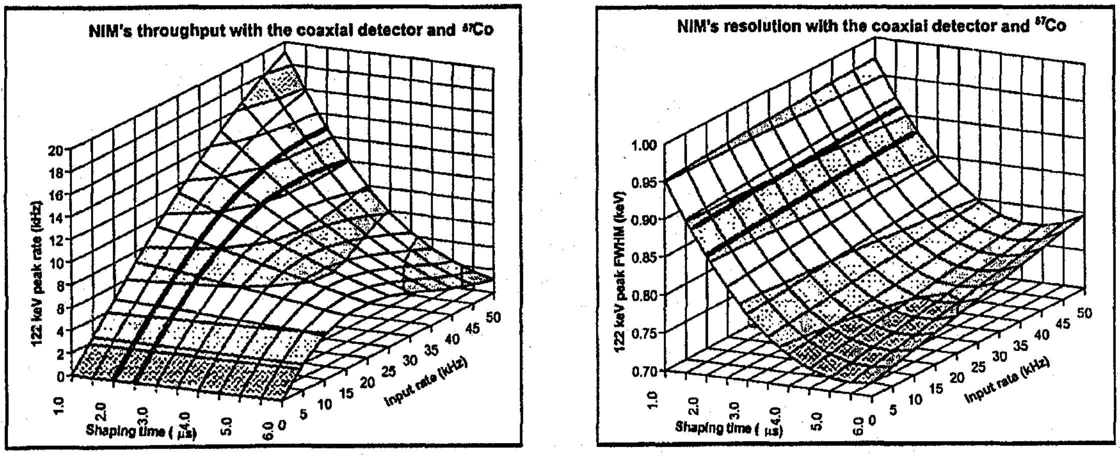


Fig. 6. Fitted surfaces of the throughput and resolution of the NIM system with the coaxial detector and the ^{57}Co source.

From the fit of the throughput data to Eq. 1, the variable a_i is found. The throughput data of the other systems at the 2-µs shaping time are then fitted to the curve

$$\text{Throughput} \quad = \quad a_1 x * \exp(a_2 s^{a3} x^{a4}) \quad , \quad (3)$$

where x is the input count rate, a_i is the constant found in fitting Eq. 1, and s is the NIM equivalent shaping time to be determined.

From the fit of Eq. 3, the shaping time s is found. This shaping time is the shaping time of the NIM system such that its throughput is about the same as that of the other system at the2-µs shaping time.

Assuming that the ratio of the shaping times is proportional to the ratio of the corresponding throughputs. Then the shaping time of s' of the other system which would produce the same throughput as that of the NIM system at the 2-µs shaping time can be found using the relationships

$$s' = (\text{shaping of NIM at 2 µs}) * (\text{shaping of other at 2 µs}) / (\text{NIM equivalent shaping})$$
$$= 2*2/s = 4/s \quad .$$

With the equivalent shaping time s', the resolution differences at the 2-µs shaping time and the s'-µs shaping time can be calculated using Eq. 2 (with the constant b_i found from the fit earlier). The resolution differences are then added to the FWHMs of the other system obtained at 2-µs shaping time. These new FWHMs would represent the resolution of the other system at s'-µs shaping time.

Calculating the MCA166's equivalent resolution is shown, as an example, in Fig. 6. The heavy line in the throughput plot at the 2.5-µs shaping time of the NIM system corresponds to the curve of the MCA166's throughput at the 2.0-µs shaping time. Equivalently, one may say that the throughputs of the MCA166 at the 1.6-µs shaping time is about the same as those of the NIM at the 2.0-µs shaping time. From the resolution plot, the differences of the resolutions of the NIM system between the 1.6-µs and 2.0-µs shaping times are obtained. Assuming the differences of the resolutions of the MCA166 are also the same, then the resolutions of the MCA166 at the 1.6-µs shaping time can be calculated by adding these resolution differences to the resolutions of the MCA166 at the 2-µs shaping time.

The equivalent shaping times and resolutions of six systems (Dart, Nomad Plus, Inspector, MCA166, 92X-II, and M3CA) were calculated using the method described above. As for the DSPEC and 2060DSP, since these two systems have data at all three shaping times like that of the NIM, their throughput and resolution data were fitted to Eqs. 1 and 2 in the same manner as that of the NIM. The throughput data of the NIM at the 2-μs shaping time are then fitted to Eq. 3 (with the constant a_i found in the surface fit of the DSPEC or 2060DSP system). The resulted shaping time s is the shaping time of DSPEC or 2060DSP such that its throughput is about the same as that of the NIM at the 2-μs shaping time. Apply this shaping time s to Eq. 2 then the equivalent resolutions can be calculated.

For the planar detector, data with the ^{57}Co source were collected at only two shaping times: 1 and 2 μs. To fit the data to Eqs. 1, 2, and 3, a third set of data is needed. Therefore, the data were also collected for the NIM system at the 3-μs shaping time and the DSP systems at the 6.4-μs rise time. The resolutions with equivalent throughput of all the systems are then found in the same way as those of the coaxial detector.

The result resolutions of the systems are then linearly fitted and the fitted parameters are shown in Table III together with the equivalent shaping times.

Table III. Variables of the data fitted to the curve [FWHM = a(input rate) + b] and the shaping times equivalent to the 2-μs shaping time of the NIM system.

Detector Source Peak		NimBin	DSPEC	Dart	Nomad+	Inspector	MCA166	92X-II	M3CA	2060DSP
Planar ^{57}Co 122 keV	a	4.01E-04	1.06E-04	2.44E-04	2.21E-04	9.51E-05	1.22E-04	2.28E-04	2.17E-04	7.11E-04
	b	0.5109	0.5087	0.5192	0.5161	0.5387	0.5249	0.5144	0.5433	0.5059
	Shaping time.	2.000	2.361	1.740	1.722	1.072	1.572	2.026	1.302	3.185
Coaxial ^{57}Co 122 keV	a	4.61E-04	9.24E-04	1.06E-03	1.17E-03	4.79E-04	9.26E-05	3.21E-04	6.52E-04	2.75E-04
	b	0.8576	0.8408	0.8960	0.8649	0.9556	0.8979	0.8770	0.9886	0.7800
	Shaping time	2.000	2.254	1.764	1.796	1.313	1.614	1.860	1.312	3.326
Coaxial ^{60}Co 1332 keV	a	1.31E-03	1.06E-03	7.66E-04	1.66E-03	1.20E-03	3.01E-03	2.57E-03	5.12E-03	1.39E-03
	b	2.4310	1.8033	2.4091	2.4500	2.8743	2.3249	2.5165	2.6366	1.8366
	Shaping time	2.000	2.348	1.826	1.823	1.120	1.771	2.079	1.530	3.963

Fig. 7 shows the linearly fitted curves of the equivalent resolutions of all the systems. These curves represent the resolutions of the systems with the throughput rates equal to that of the NIM system with the 2-μs shaping time. The validity of this method of calculating the equivalent resolution can be easily checked with the real data. From Fig. 2, the throughputs of the Inspector at the 1-μs shaping time are about the same as those of the NIM system at the 2-μs shaping time. Thus the equivalent resolutions of the Inspector should be close to its measured resolutions at the 1-μs shaping time (which they appear to be). At the other extreme, Fig. 4, the throughputs of the 2060DSP at the 4-μs shaping time are about the same as those of the NIM system at the 2-μs shaping time. Therefore, the equivalent resolutions of the 2060DSP are about the same as its measured resolutions at the 4-μs shaping time. Since the simple checking show that the method is valid for the Inspector and 2060DSP (which have the worst and best throughput rates, respectively), it can be assumed that the method is also valid for other systems.

Table IV shows the ranking of the performance of the systems. This ranking is based on the resolutions of the system taken at a moderate input rate (10 kHz). The ranking may change slightly if different input rates are used for the ranking. The DSPEC and 2060DSP systems rank highest, and the M3CA and Inspector are the lowest. The NIM system can claim the third highest rank outright. The remaining four systems share the intermediate rankings.

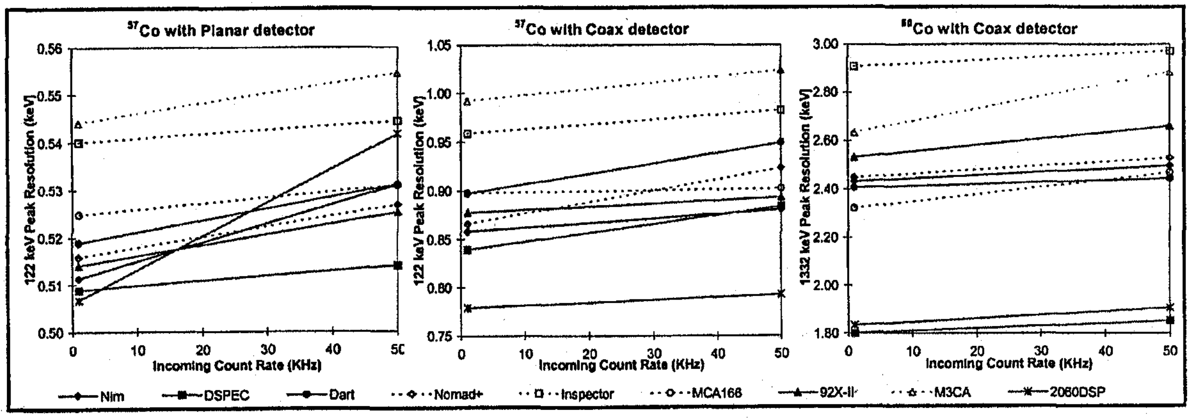


Fig. 7. Resolutions of the systems with throughput rates equal to those of the NIM system at the 2-μs shaping time.

Table IV. Ranking of performance (at 10 kHz input rate, based on Fig. 7).

Detector / Source / Peak	NimBin	DSPEC	Dart	Nomad Plus	Inspector	MCA166	92X-II	M3CA	2060DSP
Planar / ^{57}Co / 122 keV	3	1	6	5	8	7	4	9	2
Coaxial / ^{60}Co / 122 keV	3	2	7	4	8	6	5	9	1
Coaxial / ^{60}Co / 1332 keV	5	1	4	6	9	3	7	8	2
Overall	3	1	7	4	8	5	6	9	2

IV. CONCLUSIONS

Nine different gamma-ray spectroscopy systems were evaluated. It is a surprise to see some very compact and portable systems such as the Dart and MCA166 match the bulky NIM system in performance.

The best systems of all are the DSP systems, and it looks like both of these two systems, the 2060DSP and the DSPEC, perform at about the same level. For the applications that require very high throughput and reasonable resolution, the 2060DSP may be better. For the applications that require good resolution and moderately high throughput, the DSPEC may be the better choice. In general, both systems perform much better than their analog counterparts. If the detector displays the presence of the ballistic deficit, the superiority of the 2060DSP and DSPEC is even more pronounced as with the case of the coaxial detector used in this evaluation with the ^{60}Co source at the 2-μs shaping time. The digital signal processing circuits of the 2060DSP and DSPEC can minimize the ballistic deficit effectively which results in much better resolution. With many different combinations of their advanced shaping (i.e., the rise time, flattop, cusp, and tilt for the DSPEC, and rise time and flattop for the 2060DSP), they can be used optimally with many different types of detectors of both new and degraded ones. They are strongly recommended to be used with high-resolution detectors in safeguards isotopic measurements, especially with the larger detectors due to their superior resolutions at high energy. The one major setback of the 2060DSP is that it does not have the stabilizers and cannot be used with an external stabilizer It therefore may not be used effectively with applications where a long counting time is required.

The best compact and portable systems, in general, are the MCA166 and the Dart. Despite its very compact size, the MCA166 seems to perform comparably to the NIM and all other analog systems. However, it does have some setbacks such as the small maximum ADC channel (only 4K) and the low HV boards (only +-3 kV), which may not work with some germanium detectors requiring larger HV, and the software which runs with DOS systems is optimized for the low resolution of the computer's screen. The last setback (the ability to run with the low power computer) is also an advantage that it can be combined with a HP Palmtop to make a very compact portable system. The Dart performs satisfactorily at small shaping times and its software is easy to use. Its resolution at large shaping times (6 µs) is bad and should be looked into by the manufacture. It is recommended that, for safeguards isotopic measurements, only the Dart with shaping times of 2, 1, or 0.5 µs should be purchased and used. The 92X-II and the Nomad Plus perform comparable to the NIM system and can replace the NIM system where it is appropriate. The Inspector has the worst throughput and should not be used in places where high count rate is demanded. The M3CA has the lowest ranking and unless it is upgraded by the manufacture, it is recommended not to be used with the high-resolution (germanium) detectors in safeguards isotopic measurements.

The performance and the price play an important role in deciding what system to purchase. However, they are not the only factors. Before buying a system, one should consider some of the questions below:

- Which is the best system for one's needs?
- How convenient is the system?
- What is the technical support and how available is it?
- Which software applications does the manufacturer support to use with the system and how expensive are they?
- How adaptable is the system to user-developed applications software?

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[§] GBS-Elektronik GmbH, im Rossendorfer Technologiezentrum, Bautzner Landstrabe 45, 01454 Groberkmannsdorf, Germany, Ph (0351) 2695231

[**] Price includes the basic operating software and the interface board (if required).

[††] The MCA166 comes with two HV power supply boards. Price may vary with the exchange rate.

[‡‡] The M3CA price includes 1 HV boards. Add $600 for each additional HV board.

[§§] Add about $6000 for the mini-NIM bin, HV power supply, interface board, and software to complete the system.