*Extended Evaluations of the
Commercial Spectrometer Systems for
Safeguards Applications*

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by

D. T. Vo

Abstract

Safeguards applications require the best of the spectrometer system with excellent resolution, stability, and throughput. Instruments must perform well in all 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 five different germanium detectors. Considering the performance of the Digital Signal Processors (DSP), digital-based spectroscopy may become the way of future 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 a simple counter to single channel analyzer (SCA) to multichannel analyzer (MCA). Even the MCA has 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 five different 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.

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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.

II. SPECTROSCOPY SYSTEMS

A. MCA Descriptions

1. NIM

The NIM system was a standard system which consisted of an Ortec 4002D NIM bin power supply, a Canberra 3106D High Voltage (HV) power supply, a Canberra 8077 Fast Analog to Digital Converter (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 μ s and a Canberra 2025 AFT Research Amplifier with the shaping times of 0.5, 1, 2, 4, 6, and 12 μ s. The Ortec 672 Spectroscopy Amplifier with triangular shaping was used for data collected at the 1-, 2-, 3-, and 6- μ s shaping times, and the Canberra 2025 AFT Research Amplifier with triangular shaping was used for data collected at the 4- μ s 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 μ s in steps of 0.8 μ s. 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 rate. However, it may not be realistic to adjust these parameters for every single measurement. Therefore, some general cusp and flattop values are needed. Reference 1 describes the method of obtaining the best cusp and flattop for a detector. In Ref. 1, the cusp value of 0.8 and the flattop value of 1.6 μ s were found to be the best general-purpose parameters for the germanium detectors. The tilt controls the flattop slope and the DSPEC optimizer automatically sets its value. 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 the DSPECs together into a single local area network (LAN). Likewise, multiple computers can also be set using a 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 Multichannel 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 convenient and is normally not used due to 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 μ s and the other with 1 and 2 μ s for a total of three shaping time constants: 1, 2, and 6 μ s. 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 large distance. In this experiment, the Dart was connected to 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 had the shaping time of 1 and 2 μ s. The Nomad Plus can be connected to the PC by either the parallel port or by the DPM 37-pin D-type connector. If the DPM is used, a DPM interface card is required. With the DPM data 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 μ s and the other with 1 and 2 μ s for a total of three shaping time constants: 1, 2, and 4 μ s. 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 16x10x5 cm, the same as that of the MCA166 itself), the operating time can be increase by 150%. The MCA166 unit used in the evaluation has the shaping time constants of 1 and 2 μ s. 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 has shaping time of 1 and 2 μ s. 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 connections 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 lists 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 had the shaping time of 0.5 and 2 μ s, which only the 2 μ s shaping 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

The 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 μ s to 28 μ s 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 μ s in the range of 0 μ s to 1.0 μ s and by steps of 0.2 μ s in the range of 1.0 μ s to 3.0 μ s. 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 μ s as equivalent to the Gaussian shaping times of 1, 2, 4, and 6 μ s. 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 amplifier. The flattop value can be manually set or automatically optimized by the BDC. 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 $[X \cdot (\text{rise time}) + (\text{flattop})]$ 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. 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 I was 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 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 inhibit 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, a 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, replacing the internal HV power supply board with the appropriate one changes the HV power supply. 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 shows the summary of the specifications of all the systems.

In addition to the electronics described above, a MatchMaker (from Ortec) was also used for interfacing between the Canberra ADC of the NIM system to the computer. MatchMaker can interface with many different ADCs from various manufacturers, and it can be connected to the computer by ethernet, DPM, parallel, or serial link. It was used for the NIM-DSPEC comparison in Section V.

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, Dart, 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 these systems from EG&G Ortec were connected to the computer by either the ethernet or the parallel 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 long time to setup the system to do simple data acquisition.

Table I. Specifications of the spectrometer systems.

	NIM	DSPEC	Dart	Nomad+	Inspector	MCA166	92X-II	M3CA	2060DSP
Shaping time (μ s)	.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 μ s succ. approx.	12 μ s succ. approx.	100-MHz Wilkinson	8 μ s succ. approx.	7 μ s succ. approx.	100-MHz Wilkinson	N/A
ADC channel (max)	16K	16K	8K	16K	8K	4K	16K	4K	
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/ control by	Ortec, Canberra / Hardware	Ortec	Ortec, Canberra / Software	Ortec, Canberra / Software	Canberra	Ortec, Canberra / Software	Ortec, Canberra / Hardware	none	N/A
Amplifier polarity switch	external	internal	software	internal	software	software	internal	software	external
Power supply	AC	AC	5.6 h NiCd	8 h Lead acid, AC	3 h NiCd	6 h Li	AC	8 h (50%) Ni-MH	N/A
Dimensions, include battery pack (cm)	48x54x22	31x35x14	14x30x9	46x33x18	27x33x6	10x16x5	31x35x14	10x22x9	7x22x20
Weight, include battery pack (kg)	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, 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 Canberra System 100 MCA board
Computer operating software & 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 [§]

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 from GBS-Elecktronik was 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 National Laboratory (LANL). It is simple to setup and acquire data. However, due to the very low-speed serial link (only 9.6 kbaud), the communication between the M3CA and the computer is

^{*} 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 one 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.

^{**} At the time of this writing, the MCA166 was able to run with a version of Maestro from Ortec.

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 have to be sent for each channel (unsigned long integer). In this case, it would take more than 13 s to transfer a 4K 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. Detector descriptions

Five detectors of various sizes were used for the evaluation. Table II lists the specifications of these detectors. The 25% coaxial detector is mildly degraded and the large coaxial detector (92%) is badly degraded. The remaining three detectors perform comparable to or slightly better than the specifications.

Table II. Specification of the detectors. The specified resolutions are the warranted values (if listed) or the measured values from the manufacture.

Germanium detector	Planar	Coaxial	Large Coaxial	Handheld Coaxial	Tabletop Coaxial
Manufacture	Canberra	Canberra	Ortec	Ortec	Ortec
Manufacture date	Nov 1989	Sep 1995	Jul 1991	Jun 1997	Sep 1998
Diameter (mm)	16.0	60.0	78.8	70.4 mm	55.7 mm
Length (mm)	13.0	42.0	83.5	29.5 mm	56.2 mm
Relative Efficiency (%)	N/A	25	92.2	26.3	28
FWHM @ 1.33MeV, 6 μ s shaping, 1kHz	N/A	1.75 keV	2.15 keV	2.20 keV	1.75 keV
FWHM @ 1.33MeV, 2 μ s shaping, 1kHz	N/A	1.94 keV	N/A	N/A	1.95 keV
FWHM @ 1.33MeV, 2 μ s shaping, 30kHz	N/A	2.00 keV	N/A	3.50 keV	2.00 keV
FWHM @ 122keV, 6 μ s shaping, 1kHz	510 eV	750 eV	838 eV	780 eV	750 eV
FWHM @ 122keV, 2 μ s shaping, 1kHz	N/A	850 eV	N/A	820 eV	870 eV
FWHM @ 122keV, 2 μ s shaping, 30kHz	N/A	880 eV	N/A	850 eV	880 eV

D. 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, the serial link can communicate at a very long 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-IIIs) can be linked together into a single LAN using BNC connectors. For such a system, a single computer can control a single or multiple detectors and multiple computers can control a single or multiple detectors.

III. TEST OF NINE MCAS USING THE PLANAR AND 25% COAXIAL DETECTORS

A. Data acquisition

The planar and the 25% coaxial germanium detectors were used in the measurements (see Table II). 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) and 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 the measurements lasted about four months. For all 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 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.

The setup of all the systems was as described in Section II. In addition, the DSP systems use the rise time in place of the shaping time of the analog systems. They use the rise time constants of 2.4, 4.0, 8.0, and 12.0 μs (which would roughly correspond to 1-, 2-, 4-, and 6- μs shaping time) for this evaluation. The 2060DSP could use the rise time of 2.0 μs , which would better represent the 1- μs shaping time, 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 DSPEC used the general-purpose parameters for germanium detectors [1], cusp value of 0.8 and flattop value of 1.6 μs , throughout these measurements. For the 2060DSP, the flattop values for these detectors 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. Also, 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.

B. Analysis

All nine 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 single software can be performed on all the data sets (so if there are any biases from the analysis algorithms, they should be the same for all 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 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 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 .

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.

Figures 2, 3, and 4 compare the energy resolution and throughput of all the systems. 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 the 2- μs shaping time.

The second worst system is the Inspector. Its energy resolution for most of the time is ranked as seventh or eighth out of nine units tested, and its throughput is always the worst one. At high count rate (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 are 100 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. 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.

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, 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

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 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 time and 30 kHz is very bad (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 III shows the overload 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 III 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 1- and 2- μs shaping times but at 6- μs shaping time, its resolution is not good and it gets worse at higher count rate. In trying to improve its resolution at 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 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 well 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.

Due to the closely packed data points on the graphs, it is difficult to view the data in detail. Tables IV and V display the FWHMs and throughput rates of all the systems for close inspection.

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.

Table III. 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

Table IV. Energy resolutions of all the systems. The unit of the FWHMs is keV.

Detector Source Peak Shaping	Input Rate (kHz)	NIM	DSPEC	Dart	Nomad+	Inspector	MCA166	92X-II	M3CA	2060DSP
Planar ⁵⁷ Co 122 keV 1 μ s	1	0.533	0.529	0.536	0.529	0.539	0.540	0.536		0.528
	3	0.535	0.529	0.536	0.529	0.537	0.539	0.534		0.529
	10	0.539	0.531	0.539	0.531	0.537	0.535	0.537		0.532
	30	0.541	0.537	0.545	0.536	0.541	0.534	0.539		0.540
	50	0.548	0.542	0.548	0.539	0.545	0.536	0.542		0.546
Planar ⁵⁷ Co 122 keV 2 μ s	1	0.510	0.514	0.515	0.511	0.518	0.517	0.515	0.529	0.513
	3	0.512	0.514	0.515	0.512	0.518	0.518	0.516	0.529	0.514
	10	0.515	0.513	0.518	0.514	0.520	0.519	0.517	0.532	0.519
	30	0.525	0.516	0.521	0.519	0.524	0.520	0.522	0.537	0.527
	50	0.530	0.518	0.528	0.523	0.529	0.526	0.526	0.543	0.536
Coaxial ⁵⁷ Co 122 keV 2 μ s	1	0.859	0.861	0.877	0.847	0.895	0.866	0.869	0.928	0.873
	3	0.861	0.861	0.880	0.851	0.896	0.863	0.865	0.928	0.871
	10	0.861	0.864	0.884	0.857	0.897	0.867	0.867	0.934	0.869
	30	0.868	0.901	0.912	0.893	0.910	0.868	0.874	0.947	0.874
	50	0.883	0.907	0.928	0.902	0.920	0.871	0.883	0.962	0.879
Coaxial ⁵⁷ Co 122 keV 4 μ s	1	0.738	0.751			0.759				0.752
	3	0.745	0.752			0.759				0.749
	10	0.752	0.758			0.778				0.750
	30	0.765	0.769			0.813				0.761
Coaxial ⁵⁷ Co 122 keV 6 μ s	1	0.726	0.721	0.822						0.717
	3	0.719	0.723	0.838						0.717
	10	0.729	0.734	0.897						0.722
	30	0.767	0.770	1.119						0.740
Coaxial ⁶⁰ Co 1332 keV 2 μ s	1	2.426	1.831	2.342	2.381	2.464	2.266	2.568	2.448	1.916
	3	2.456	1.820	2.348	2.377	2.477	2.231	2.559	2.448	1.916
	10	2.438	1.820	2.325	2.387	2.442	2.232	2.574	2.462	1.922
	30	2.448	1.846	2.341	2.417	2.460	2.276	2.584	2.538	1.934
	50	2.510	1.882	2.375	2.451	2.474	2.391	2.707	2.678	1.945
Coaxial ⁶⁰ Co 1332 keV 4 μ s	1	1.853	1.773			1.847				1.823
	3	1.860	1.757			1.823				1.838
	10	1.861	1.770			1.845				1.841
	30	1.886	1.792			1.864				1.875
Coaxial ⁶⁰ Co 1332 keV 6 μ s	1	1.801	1.755	1.835						1.822
	3	1.779	1.752	1.847						1.827
	10	1.807	1.755	1.924						1.850
	30	1.898	1.792	2.222						2.313

Table V. Throughput rates of all the systems. The unit of the throughput is kHz.

Detector Source Peak Shaping	Input Rate (kHz)	NIM	DSPEC	Dart	Nomad+	Inspector	MCA166	92X-II	M3CA	2060DSP
Planar	1	0.419	0.417	0.405	0.405	0.398	0.415	0.449		0.428
⁵⁷ Co	3	1.394	1.407	1.380	1.387	1.305	1.393	1.484		1.448
122 keV	10	4.658	4.731	4.373	4.542	3.838	4.614	4.680		4.920
1 μ s	30	11.831	11.847	10.337	11.047	7.716	11.139	11.788		13.393
	50	16.247	16.228	13.550	14.743	9.453	14.833	15.602		19.290
Planar	1	0.405	0.405	0.417	0.401	0.436	0.403	0.449	0.399	0.426
⁵⁷ Co	3	1.377	1.384	1.379	1.354	1.361	1.368	1.453	1.316	1.445
122 keV	10	4.371	4.478	4.189	4.187	3.792	4.203	4.469	3.733	4.794
2 μ s	30	9.551	10.324	8.797	8.872	6.297	8.417	9.737	6.930	11.786
	50	11.319	12.630	10.126	9.978	5.460	9.117	11.359	7.581	15.775
Coaxial	1	0.491	0.501	0.528	0.509	0.489	0.487	0.509	0.505	0.514
⁵⁷ Co	3	1.502	1.495	1.506	1.484	1.481	1.559	1.515	1.455	1.591
122 keV	10	4.898	4.997	4.292	4.808	4.299	5.035	4.962	4.398	5.567
2 μ s	30	10.984	11.632	9.819	10.549	7.540	9.932	10.659	7.708	14.095
	50	12.629	13.962	11.448	11.408	7.776	10.129	11.825	7.704	18.173
Coaxial	1	0.505	0.496			0.487				0.503
⁵⁷ Co	3	1.415	1.437			1.358				1.531
122 keV	10	4.326	4.399			3.837				5.075
4 μ s	30	7.262	7.920			5.023				10.444
Coaxial	1	0.498	0.488	0.512						0.501
⁵⁷ Co	3	1.353	1.389	1.385						1.494
122 keV	10	3.445	3.882	3.742						4.570
6 μ s	30	3.638	5.323	4.247						7.807
Coaxial	1	0.057	0.056	0.054	0.053	0.054	0.052	0.058	0.051	0.059
⁶⁰ Co	3	0.177	0.182	0.177	0.174	0.170	0.187	0.188	0.167	0.187
1332 keV	10	0.597	0.618	0.561	0.583	0.467	0.605	0.606	0.508	0.665
2 μ s	30	1.252	1.422	1.220	1.212	0.726	1.217	1.316	1.035	1.681
	50	1.423	1.683	1.313	1.313	0.622	1.270	1.451	1.107	2.221
Coaxial	1	0.054	0.055			0.052				0.058
⁶⁰ Co	3	0.174	0.176			0.158				0.182
1332 keV	10	0.529	0.546			0.414				0.607
4 μ s	30	0.874	0.961			0.502				1.265
Coaxial	1	0.055	0.055	0.053						0.058
⁶⁰ Co	3	0.166	0.170	0.169						0.177
1332 keV	10	0.426	0.484	0.438						0.552
6 μ s	30	0.411	0.671	0.474						0.959

C. Ranking the systems

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

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 1- μ s shaping time with the planar detector (Fig. 2). It is difficult to say that 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 2- μ s shaping time is comparable to that of the Inspector at 1- μ s shaping time. Thus the comparison of the resolutions should be made between those of the Dart at 2- μ s shaping time to those of the Inspector at 1- μ s shaping time. In this manner, the Dart would seem to perform much better than the Inspector.

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. Then the resolutions can be compared directly. However, all these systems have limited and discrete shaping time values and cannot 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 2- μ s 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 some constants. Also, the resolution is related quadratically to the shaping time and exponentially to the input count rate. In this low input count rate range (less than 50 kHz for 2- μ s shaping time and 30 kHz for 4- and 6- μ s shaping time), the exponential dependency of the resolution on the input count rate may be approximated by a linear function. Figure 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:

$$\text{Throughput} = a_1x_2\exp(a_2x_1^{a_3}x_2^{a_4}) \quad \text{and} \quad (1)$$

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

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

For the coaxial detector, the throughput and resolution data of the NIM system at 2-, 4-, and 6- μ s shaping times are fitted to these two-dimensional surfaces. Figure 6 shows, as an

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

example, the fitted surfaces of the throughputs and resolutions of the NIM system using 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 2- μs shaping time are then fitted to the curve

$$\text{Throughput} = a_1 x \exp(a_2 s^{a_3} x^{a_4}) \quad (3)$$

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 2- μs shaping time.

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

$$s' = (\text{NIM's 2-}\mu\text{s shaping}) * (\text{other's 2-}\mu\text{s shaping}) / (\text{NIM's equiv. shaping}) = 2*2/s = 4/s$$

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

With the equivalent shaping time s' , the resolution differences at 2- μ s shaping time and s' - μ s 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 FWHM of the other system obtained at 2- μ s shaping time. These new FWHMs would represent the resolution of the other system at s' - μ s shaping time.

The calculation of the MCA166's equivalent resolution is shown, as an example, in Fig. 6. The heavy line in the throughput plot at 2.5- μ s shaping time of the NIM system corresponds to the curve of the MCA166's throughput at 2.0- μ s shaping time. Equivalently, one may say that the throughput of the NIM at 2.0- μ s shaping time is about the same as those of the MCA166 at 1.6- μ s shaping time. From the resolution plot, the differences of the resolutions of the NIM system between the 1.6- μ s and 2.0- μ s shaping times are obtained. Assuming the differences of the resolutions of the MCA166 are also the same then the resolutions of the MCA166 at 1.6- μ s shaping time can be calculated by adding these resolution differences to the resolutions of the MCA166 at 2- μ s 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 2- μ s 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 resulting 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 2- μ s 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 μ s. 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 3- μ s shaping time and the DSP systems at 6.4- μ s 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 resulting resolutions of the systems are then linearly fitted, and the fitted parameters are shown in Table VI together with the equivalent shaping times.

Table VI. Variables of the data fitted to the curve $[\text{FWHM} = a(\text{input rate}) + b]$ and the shaping times equivalent to 2- μ s shaping time of the NIM system.

Detector Source Peak		NIM	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 (μ s)	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 (μ s)	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 (μ s)	2.000	2.348	1.826	1.823	1.120	1.771	2.079	1.530	3.963

Figure 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 2- μ s 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 1- μ s shaping time are about the same as those of the NIM system at 2- μ s shaping time. Thus the equivalent resolutions of the Inspector should be close to its measured resolutions at 1- μ s shaping time (which they appear to be). At the other extreme, from Fig. 4, the throughputs of the 2060DSP at 4- μ s shaping time are about the same as those of the NIM system at 2- μ s shaping time. Therefore the equivalent resolutions of the 2060DSP are about the same as its measured resolutions at 4- μ s shaping time. Since the simple checkings 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.

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

Table VII 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.

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

Detector / Source / Peak	NIM	DSPEC	Dart	Nomad+	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 ranking	3	1	7	4	8	5	6	9	2

IV. TEST OF THE DSP SYSTEMS WITH THE LARGE GERMANIUM DETECTOR

In the last section, we saw the DSP systems performing better than the analog systems, especially with the mildly degraded 25% coaxial detector. It is of interest to test these DSP systems with some different detectors.

A badly degraded, large, 92% germanium detector (Table II) is tested with both the DSP systems and also with the NIM. The NIM is included as a reference to the other systems' performance. The performance of this detector in this test was much worse than that in the specification sheet. Despite the worse-than-specified performance of the detector, the relative performance of the NIM, DSPEC, and 2060DSP when used with this detector should still be valid.

A. Setup and data acquisition

Only a ^{60}Co source was used for this test. The data were collected at three different shaping time constants: 2, 3, and 6 μs . These would correspond to 4-, 6-, and 12- μs rise times of the DSP systems. For the NIM system, as before, the pulse shape was set to the triangular shaping. For the DSPEC, the general-purpose parameters [1], cusp of 0.8 and flattop of 1.6 μs , could be used in the test. However, since this detector has a much larger efficiency and the pulses of this detector have much longer decay time than those of the 25% detector, it was thought best if the optimal parameters for this 92% detector were found. Therefore, a batch file was created to collect data overnight at various cusp and flattop values. From those data, the optimal cusp value of 0.6 and flattop value of 1.2 μs were obtained. Those values were used throughout the measurements. The DSPEC's optimizer automatically determined the tilt values. For the 2060DSP, the flattop for this large detector was optimally found by the Ballistic Deficit Correction function to be 1.0 μs .

The data were collected at the input rates of 3, 10, 30, 60, and 90 kHz at 2- and 3- μs shaping times and 3, 10, 30, and 60 kHz at 6- μs shaping time. The 9.5- μCi ^{60}Co source was moved close to or far away from the detector to achieve the desired count rates. The ADC conversion gain and range were set at 8K on all the systems. The amplifier gains were adjusted so that the 1332.5-keV peak was at about channel 7950. No stabilizer was used to stabilize the peaks. The DSPEC stored the spectra data in the Ortec CHN format and the NIM and 2060DSP stored the data in the Canberra MCA format. As in Section III, the NIM and 2060DSP spectral data were then converted to the Ortec CHN format to be used with the analytical functions in the Ortec Maestro software. The energy calibrations were done using the 1173.2-keV and 1332.5-keV peaks of ^{60}Co .

B. Analysis

Table VIII shows the resolution and throughput of the systems at various shaping times and input rates.

To ease the viewing of the data, the resolution and throughput results in Table VIII are fitted to the equations

$$\begin{aligned}\text{Resolution} &= b_1 + b_2 \exp(b_3 x) \\ \text{and Throughput} &= a_1 x \exp(a_2 x^{a_3})\end{aligned}$$

where a_i and b_i are unknown variables and x is the input rate. The results from the fits are presented in Fig. 8.

The throughput of the 2060DSP is the best. However, its resolution is bad, even worse than that of the NIM at large shaping time. The throughput of the DSPEC is between those of the NIM and 2060DSP, and the resolution of the DSPEC is absolutely superior comparing with those of the NIM and 2060DSP. Even at 2- μ s shaping time, the resolution of the DSPEC is better than those of the NIM and 2060DSP at 3- or 6- μ s shaping time.

From Fig. 8, the 2060DSP system cannot be used effectively with this detector due to its bad resolution. The NIM may be used with this detector but only at 6- μ s shaping time or more and at the input rate of 20 kHz or less. The DSPEC can be used with this detector at all count rates and at many different shaping times.

Figure 9 shows the comparison of the NIM system at 6- μ s shaping time and of the DSPEC at 2-, 3-, and 6- μ s shaping times. The NIM system resolution and throughput are the worst and may be used only when the input rate is less than 10 kHz. The DSPEC can be used at 6- μ s shaping time when the input rate is less than 30 kHz and at 3- μ s shaping time when the input rate is less than 40 kHz. Considering the trade-off between the resolution and throughput, the DSPEC at 2- μ s shaping time seems to be the best. At low count rate, its resolution is about the same as that of the NIM and is only about 8% worse than that of the DSPEC at 6- μ s shaping time. At very high input rate, up to 100 kHz, its resolution is still reasonable, only 3.1 keV for the 1332-keV peak, and its throughput is many times better than the rest.

Table VIII. Resolution and throughput of the systems.

Shaping (μ s)	Input (kHz)	1332 keV FWHM (keV)			1332 keV peak rate (Hz)		
		NIM	DSPEC	2060DSP	NIM	DSPEC	2060DSP
2	3	5.66	2.85	4.41	264	265	270
2	10	5.68	2.86	4.47	938	1005	1059
2	30	5.77	2.92	4.74	1962	2330	2653
2	60	5.72	2.98	5.16	2136	2809	3489
2	90	5.81	3.08	5.61	1659	2429	3279
3	3	3.86	2.70	3.65	257	257	267
3	10	3.85	2.75	3.77	876	936	1006
3	30	3.89	2.89	4.10	1544	1873	2220
3	60	4.17	3.22	4.63	1289	1820	2428
3	90	4.80	3.60	5.19	464	1212	1838
6	3	2.83	2.63	3.11	240	245	257
6	10	2.94	2.61	3.29	673	783	881
6	30	3.42	2.82	4.70	702	1103	1493
6	60	5.61	3.69	6.71	253	611	1042

Fig. 8. Comparative resolution and throughput of the three systems using the ^{60}Co source.

Fig. 9. Comparative resolution and throughput of the NIM at 6- μs shaping time and of the DSPEC at 2-, 3-, and 6- μs shaping time using the ^{60}Co source.

Table IX lists the comparison at the maximum throughput rates. At its maximum throughput rate, the resolution of the DSPEC at 2- μ s shaping time is only slightly worse than that at 6- μ s shaping time while the throughput is about 2.5 times greater. Likewise, when comparing with the NIM at 6- μ s shaping time, its resolution is slightly better and its throughput is 3.5 times better.

Table IX. Specifications of the systems at their maximum throughput rates.

System @ Shaping	Input rate (kHz)	Peak rate (kHz)	FWHM (keV)	Dead time %
NIM @ 6 μ s s	19.6	0.81	3.12	57.6
DSPEC @ 2 μ s s	57.3	2.83	2.98	54.8
DSPEC @ 3 μ s s	42.3	2.00	3.02	54.9
DSPEC @ 6 μ s s	26.0	1.13	2.78	56.1

It is recommended, for the applications requiring high or a wide range of input rate, the DSPEC with the shaping time of 2 μ s (i.e., rise time of 4 μ s) should be used.

The DSPEC has some setback such as it does not have the count rate meter so one cannot monitor the input rate. However, it has the digital dead-time display and in some circumstances, the digital dead-time display can be more useful than the count rate meter. From Table IX, the dead times of all the systems at various input rates and shaping time constants are at about 56% at maximum throughput rate. So regardless of the shaping time (or rise time), one should try to reduce the input rate when the dead time is greater than 56%. The DSPEC can be run at less than 56% dead time because even though the throughput is less than optimal, the resolution is better. However, one should not run it at larger than 56% dead time because both the resolution and throughput will be worse.

V. TEST OF THE DSPEC WITH OTHER GERMANIUM DETECTORS

The DSPEC performs better than the 2060DSP and the NIM when used with the large, badly degraded 92% coaxial detector. In the previous two sections, the tested detectors were old and degraded. In this section, the DSPEC is tested with two newer coaxial germanium detectors.

The NIM and MatchMaker combination system and the DSPEC system were used with two coaxial germanium detectors, one handheld and one tabletop (Table II). Only 2- μ s shaping time was used for this test. As in the previous section, the NIM-MatchMaker system was included as a reference.

A. Setup and data acquisition

The NIM system was a standard system (as described in Section I.A.1) except that instead of interfacing directly with the Canberra S100 MCA board, the ADC interfaces with the Ortec MatchMaker which in turn is connected to the computer by ethernet through the 3Com Etherlink III PCMCIA card. The BLR and PZ of the amplifier were set at "auto" and the PUR output from the amplifier was connected to the PUR input of the MatchMaker. A triangular shaping time of 2 μ s was used throughout the measurements.

For the DSPEC, the setup is the same as described in Section I.A.2. The general-purpose parameters [1], cusp of 0.8 and flat top of 1.6 μ s, were used in the test. The rise time was set at 4- μ s, which would roughly correspond to 2- μ s shaping time of the NIM systems.

In these measurements, the NIM-MatchMaker and DSPEC systems were connected by ethernet together into a LAN using the 3Com Etherlink III LAN PC card with the IBM ThinkPad 660 as the host computer.

As for the software, the MatchMaker was shipped with the Maestro for MatchMaker V4.11. This version of Maestro can control only the MatchMaker and no other system. The Maestro for Windows V4.10 and earlier versions can control DSPEC and some other systems from Ortec but not the MatchMaker. The Maestro for Windows V4.12 and later versions can control both the MatchMaker and DSPEC. This is convenient because one can use a single computer and a single software to operate both systems. We used Maestro for Windows V4.12 to control the data acquisition of both systems.

For the measurements, each detector was measured separately. The first output of each detector was connected to the DSPEC and the second output was connected to the amplifier of the NIM-MatchMaker system so that both systems can acquire data at the same time.

Two sources, 29 μCi of ^{57}Co and 9.5 μCi of ^{60}Co , were used. The data were collected at the input rates of 1, 3, 10, 20, 40, 60, 80, and 100 kHz for both sources. Additionally, for the ^{57}Co source, data were also acquired at 120 kHz. The sources were moved close to or far away from the detector to achieve the desired count rates. The input rates were read from the Canberra 2071AS Dual Counter Timer. The ADC conversion gain and range were set at 8K on both systems. The amplifier gains were adjusted so that the 122-keV peak of ^{57}Co was at channel 3200 and the 1332-keV peak of ^{60}Co was at channel 7800. The gain stabilizers of the two systems were used to stabilize the peaks. The zero stabilizers were not used. The energy calibrations were done using the 122- and 136-keV peaks (for the ^{57}Co source) and the 1173- and 1332.5-keV peaks (for the ^{60}Co source).

B. Analysis

Table X shows the resolution and throughput of the detector systems at various input rates. To ease the viewing of the data, the resolution and throughput results in Table X are fitted

Table X. Resolution and throughput of the detector systems.

Detector	Input (kHz)	122-keV FWHM (keV)		122-keV peak rate (kHz)		1332-keV FWHM (keV)		1332-keV peak rate (kHz)	
		DSPEC	NIM-MatchMaker	DSPEC	NIM-MatchMaker	DSPEC	NIM-MatchMaker	DSPEC	NIM-MatchMaker
Handheld	1	0.7082	0.7747	566	566	1.802	3.036	63.4	63.3
	3	0.7023	0.7891	1762	1758	1.811	3.024	201.2	198.7
	10	0.7056	0.7536	5594	5535	1.853	3.034	558.5	541.9
	20	0.7214	0.7665	7949	7822	1.905	3.136	997.6	943.0
	40	0.7409	0.7929	11514	11111	2.050	3.327	1472.1	1341.2
	60	0.7709	0.8196	12337	11730	2.152	3.529	1553.4	1401.9
	80	0.8030	0.8614	11379	10778	2.361	3.884	1457.1	1294.9
	100	0.8525	0.9072	9871	9237	2.549	4.285	1255.3	1121.5
Tabletop	120	0.8993	0.9632	7908	7473				
	1	0.8047	0.8272	499	499	1.679	1.903	66.3	66.0
	3	0.8095	0.8391	1727	1720	1.695	1.925	187.0	185.0
	10	0.7981	0.8079	4181	4171	1.720	1.970	640.6	618.5
	20	0.8062	0.8101	7459	7328	1.782	2.094	1146.8	1073.9
	40	0.8192	0.8324	11287	10783	1.915	2.376	1688.2	1510.3
	60	0.8381	0.8567	12180	11549	2.062	2.584	1788.3	1571.0
	80	0.8541	0.8885	11535	10815	2.226	2.889	1652.3	1455.2
	100	0.8723	0.9243	10077	9363	2.439	3.315	1406.7	1253.2
	120	0.8954	0.9577	8289	7742				

to the equations

$$\text{Resolution} = b_1 + b_2 \exp(b_3 x)$$

$$\text{and Throughput} = a_1 x \exp(a_2 x^{a_3}),$$

where a_i and b_i unknown variables and x is the input rate. The resulted fits are presented in Figs. 10 and 11.

Fig. 10. Comparative resolution and throughput of the two systems with the handheld detector.

From Fig. 10, the DSPEC is much better than the NIM-MatchMaker system in both the resolution and throughput. The results in Table X show that the resolution of the handheld detector is very bad at high energy and may not be usable with the analog systems at small shaping time. However, with the DSPEC, the resolution of that detector, even at small shaping time, is quite good while the throughput is still better than that of the NIM-MatchMaker system. In other words, the DSPEC can make a bad detector like this handheld detector look good.

Figure 11 shows the comparison of the NIM-MatchMaker system and the DSPEC with the tabletop detector. This detector is an average detector, somewhat better than the handheld one. For this detector, the DSPEC is still better than the NIM-MatchMaker system in both the resolution and throughput at both low and high energy and is much better at high-count rate.

Considering the trade-off between the resolution and throughput, one may like to operate the system at some count rate where the throughput is best while the resolution is still reasonable. From the resolution and throughput curves in Figs. 10 and 11, one should not operate the system at an input count rate above 60 kHz where the throughput is less than optimal and the resolution is getting much worse. It is of interest to see how the systems perform near the optimal

Fig. 11. Comparative resolution and throughput of the two systems with the tabletop detector.

throughput. Table XI lists the performance of the two systems at input rate where the throughput is at maximum and at 90% of the maximum.

At either maximum throughput or 90% of maximum throughput, the NIM-MatchMaker's resolution of the 1333-keV peak of ^{60}Co is quite large and may not be good enough for good isotopic analysis while the resolution of the DSPEC is still good. Also, note that at 90% maximum throughput, the throughput rates of the systems are only 10% less but the resolution is much better than those at maximum throughput. Regarding the trade-off between the resolution and throughput, it is recommended that, if possible, these systems should be operated at input count rate corresponding to about 90% of maximum throughput.

As mentioned in Section IV, the DSPEC does not have a count rate meter but has the digital dead-time display and sometimes, the digital dead-time display is better than the count

Table XI. Specifications of the systems at their maximum and 90% of maximum throughput rates.

Detector	Source	Peak (keV)	Max throughput	Input rate (kHz)		Peak rate (kHz)		FWHM (keV)		Dead time (%)	
				DSPEC	NIM-MM	DSPEC	NIM-MM	DSPEC	NIM-MM	DSPEC	NIM-MM
Handheld	^{57}Co	122	100%	54.9	53.3	12.2	11.7	0.763	0.811	63.4	63.3
			90%	33.5	32.2	11.0	10.5	0.734	0.781	45.1	46.8
	^{60}Co	1333	100%	57.7	55.7	1.56	1.41	2.159	3.491	57.5	60.5
			90%	36.3	34.4	1.41	1.27	2.006	3.258	39.3	42.5
Tabletop	^{57}Co	122	100%	59.9	58.1	12.2	11.5	0.836	0.856	57.0	58.7
			90%	37.8	36.3	11.0	10.4	0.818	0.830	38.6	40.5
	^{60}Co	1333	100%	56.9	55.3	1.80	1.59	2.035	2.531	55.6	60.2
			90%	36.2	34.3	1.62	1.43	1.885	2.256	37.2	42.2

rate meter. From Table XI, the dead times of all the systems at maximum throughput are at about 57%, and at 90% of maximum throughput are at about 36%. So the system should never acquire data at greater than 57% dead time because both the resolution and throughput will be worse. If possible, one should adjust the measurement so that the dead time is about 36% for optimal resolution and throughput.

One interesting point that should be mentioned regarding the combination of the Ortec 672 Spectroscopy Amplifier and the Canberra 8077 Fast ADC. In the NIM and S100 (from Canberra Inc.) system, the PUR output of the amplifier is connected to the anti-coincidence gate of the ADC. In the NIM-MatchMaker system, the PUR can be connected to either the anti-coincidence gate of the ADC or the PUR input of the MatchMaker. Comparison was made between the NIM-S100 and NIM-MatchMaker systems where the PUR is connected to the anti-coincidence gate of the ADC. There is no difference in the results (both resolution and throughput). However, when the NIM-S100 system with the PUR connected to the anti-coincidence gate of the ADC is compared with the NIM-MatchMaker with the PUR connected to the PUR input of the MatchMaker, the resolution remains the same while the throughput of the second system appears to be somewhat better. Figure 12 shows the ratios of the throughput rates of the systems measured with the ^{57}Co source and the tabletop detector. The throughput of the NIM-MatchMaker system is better than that of the NIM-S100 system, up to 10% or more for input rate larger than 100 kHz.

Fig. 12. Ratio of the NIM-MatchMaker's throughput to NIM-S100's throughput.

VI. CONCLUSIONS

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

The best MCAs of all are the DSP systems. For the mildly degraded 25% coaxial detector, it looks like both of these two systems, the 2060DSP and the DSPEC, perform at about the same level: the 2060DSP is better at low energy while the DSPEC is better at high energy. 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 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.

For the planar detector, the DSPEC is somewhat better than the 2060DSP. The 2060DSP appears to be good at low input rate. However, at higher input rate, its resolution is bad and may not be usable for an input rate much greater than 50 kHz regardless of its excellent throughput.

For the large 92% detector, the DSPEC is superior comparing it with the 2060DSP (and with the NIM or other analog systems). This detector, with its resolution so badly degraded, is not usable with a small shaping time. With a larger shaping time (e.g., 6 μ s), one may be able to use this detector but only at very small input rate, one in the order of a few kHz. Even with the BDC, the 2060DSP cannot effectively minimize the large ballistic deficit effect of this detector. This results in poor resolution for the 2060DSP. However, with the cusp and tilt parameters, which the 2060DSP does not have, or with perhaps somewhat different technology in reducing the ballistic deficit effect, the DSPEC greatly improves the resolution and makes this detector usable even at a small shaping time and over a wide range of input rate.

The one major setback of the 2060DSP is that it does not have the stabilizers and cannot be used with an external stabilizer. (A Canberra 8233 Digital Stabilizer was connected to the 2060DSP in an attempt to stabilize the peaks and it did not work.) Twenty-four 1-h spectra with the ^{60}Co source were taken sequentially in a 24-h period in a temperature-controlled room show signs of large drifting. (The 1332.5-keV peak is seen to drift from -72 eV to 159 eV on average with the standard deviation of 42 eV.) It therefore may not be used effectively with the applications where a long counting time is required. For applications that require long counting times, the model 9660 ICB Programmable Digital Signal Processor (9660DSP) from Canberra may be the better choice. It has about everything that the 2060DSP has plus the gain and zero digital stabilizers. From the descriptions of the 9660DSP, which is very much the same as that of the 2060DSP, it is expected that the 9660DSP can perform as well as the 2060DSP. The 9660DSP communicates with the computer through the Canberra model 556 Acquisition Interface Module (AIM) and not the System 100 MCA board like that of the 2060DSP.

The best compact and portable systems, in general, are the MCA166 and the Dart. Despite its very compact size, the MCA166 seems to perform comparable to the NIM and all other analog systems. However, it does have some setbacks such as the small maximum ADC channel (only 4K), 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 computer 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 μ s) 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 μ s should be purchased and used. One should not purchase a Dart with shaping time of 6 μ s until the resolution is improved. 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.

Overall, the DSPEC has been shown to out perform all other systems. The DSPEC can make a bad detector (like the 25% coaxial or the handheld detector used in this test) look good and an average detector (like the tabletop detector) look better. With its ability to make an old, unusable, badly degraded detector (like the 92% detector) usable, it can in effect extend a detector's usable lifetime. One disadvantage of the DSPEC is that even though it is compact, it is AC-powered and not a portable system. In the future, EG&G Ortec may be able to combine the technologies of both the DSPEC and the Nomad (a high-power portable system from Ortec) into one DSP-portable unit.

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:

- What system is the best for one's needs?
- How convenient is the system?
- What is the technical support and how available is it?
- What software applications does the manufacture 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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