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APPLICATIONS OF A PORTABLE MCA IN NUCLEAR SAFEGUARDS

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Introduction

In 1981 a small, battery-operated multichannel analyzer (MCA) prototype developed at Los Alamos National Laboratory was delivered to the International Atomic Energy Agency (IAEA).[1,2] The intent was to produce an instrument for inspector (nonscientist) use. Automated measurement programs were built into the MCA. An enhanced, commercially produced MCA* is now available, which was patterned after and is software compatible with the prototype. After an extensive review of the hardware and software of the available portable MCAs, the IAEA has chosen this MCA to be used by IAEA inspectors throughout the world. Inspectors from the EURATOM Directorate of Safeguards are also using these MCAs in inspections throughout Europe.

While this MCA's portability and programmability make it ideally suited for infield applications, its powerful built-in intelligence and communications protocol make it a strong candidate for distributed data acquisition and control systems.

The user-instrument interface philosophy is so easy to use that in domestic and international training schools, the operators manual is not used.

PMCA Applications Programs

The portable DSD-2056-4K multichannel analyzer (PMCA) has typical features found on classical MCA designs. A unique feature of the PMCA, shown in Fig. 1, is the USER key, which switches the unit from a general purpose MCA to a sophisticated measurement tool for one of several specific measurements that can be selected from the menu displayed on the 2-line by 16-character liquid crystal display (LCD). For complex measurements that are performed frequently or by several different people, it is desirable to have a unique program for each particular measurement. The advantages of using such application programs are as follows:

1. The programmed steps lead the user through a defined procedure reducing the possibility of errors due to improper procedural steps, and assurance is provided that measurements are performed identically even though several different people are performing them.
2. All calculations are done by the application program, eliminating the possibility of keying in the wrong value if transferring the data manually to a calculator or other computer. The internal calculation capability provides immediate results allowing conclusions to be made quickly. In addition to the main result, such as uranium enrichment, other useful information, such as error propagation, count rates, etc., is easily calculated and displayed.

Several application programs exist for the PMCA. These programs are either internal (programmed in PROMs that reside inside the PMCA) or external (written on another computer that communicates with the PMCA that acquires the data and does some internal calculations to get the results).

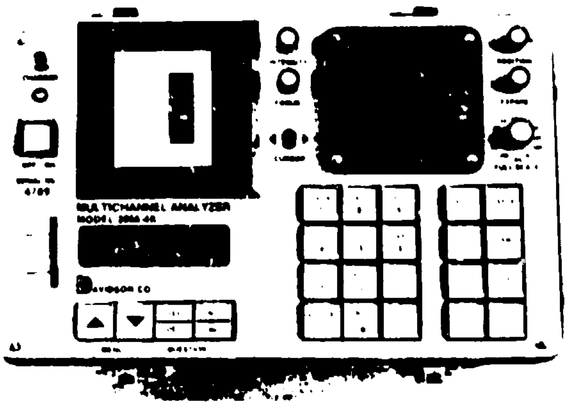

Fig. 1. Front panel of PMCA.

Internal Application Programs

A basic understanding of the PMCA operating system software is necessary to write internal application programs. The operating system can be divided into two main parts: a utilities package and a basic commands package. The system software was written in Motorola 6809 assembly language to produce compact code. The hardware constraints of the system (portability, battery operation) and the original limitation of a 64K address space on 8-bit microprocessors made compact code desirable.

The utilities package contains the individual hardware drivers for the PMCA specific devices like the analog-to-digital converter (ADC), discriminators, amplifier, etc. It also contains drivers for the interactive user interfaces with the LCD, keypad, cathode-ray-tube display, realtime clock, cassette tape, and RS-232 serial port. The utilities also contain higher level subroutines that provide interfaces useful to application programs. The hardware driver for the LCD simply outputs a character to an LCD position. The higher level LCD subroutines print a number on the LCD, which involves converting internal numbers into ASCII strings and then formatting that string to the LCD. Similarly, subroutines exist to input floating-point or integer numbers from the keypad and convert these ASCII strings into internal number representation.

The basic commands package uses the utilities package to create the command sequences that are executed on each keypush. Each keypush consists of a menu of prompts that appear in the LCD window, and actions and calculations associated with those prompts.

The utilities package and the basic commands each use about 8K bytes of memory. To give the applications programmer access to general purpose subroutines the following convention is used. Necessary external

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*Marketed by D. S. Davidson Co., North Haven, CT as Model DSD-2056-4K.

variables are declared to be located at memory locations that do not change in subsequent system software upgrades. A set of subroutine vectors pointing to general purpose subroutines in the utilities and basic commands is located at defined memory locations that also do not change with system software upgrades. Using this vector approach allows the internal system software to be changed without changing user software because the links between the two programs remain constant. The application program executes a utility subroutine by doing a subroutine call to the vector: the vector initiates a jump to the present location of the utility subroutine where the subroutine is actually executed.

Approximately 30K of memory is available for user application software. A typical user application program consists of these parts:

1. Set up the PMCA parameters according to a specified memory table of settings for high voltage, detector type, etc.
2. Input parameters and information for the measurement.
3. Carry out defined steps to acquire data. This may involve prompts to position certain standards, sources, etc.
4. Do measurement related analysis on the acquired data.
5. Display calculated results.

Some parts of an application program are just executing procedures or subroutines that already exist in the utilities or basic commands. Other parts contain code unique to the application program. In the present applications programs, the subroutines to do the PMCA setup, input specified parameters, and acquire the data are written in assembly language. These subroutines make use of several modules from the utilities and basic commands. The data analysis is different for each program and is now being written in FORTRAN. The final results are displayed from FORTRAN. Typical application programs use about 12-15K bytes of ROM memory.

The most sophisticated application, the compact densitometer, involves the measurement of elemental plutonium concentration in solution by measuring the absorption of gamma rays with energies just above and just below the plutonium K-edge (energy = 121.6 keV) by a known amount of Pu solution.[3] The ^{75}Se 121.1-keV line lies just below this edge and the ^{57}Co 122.1-keV line lies just above the edge. The amount of Pu is determined by measuring the relative intensities of these lines when they pass through a solution with Pu and through a similar solution without Pu. The 88 keV ^{109}Cd gamma ray, which is fixed relative to the detector and does not pass through the solution sample, is used to correct for any count-rate-dependent losses.

The user application program installed in the PMCA prompts the user through steps for this measurement. The regions of interest (ROIs) are automatically set for the user. The ROIs are calculated based on specified energy regions: the energy calibration is made using the 88 and 121 keV peaks. A background measurement is performed. The 121 and 122 keV peak intensities are measured without Pu solutions in place. A calibration constant is determined by measuring the intensity of the gamma rays after they have passed through a standard Pu solution or an option exists to enter a predetermined calibration constant. Then the user is prompted through intensity measurements using unknown solutions. The results and propagated errors are calculated with the intensities of ^{75}Se and ^{57}Co, corrected for decay time.

An in-plant densitometer that uses an ND660 analyzer to do measurements, analysis, and control obtains accuracies of ~0.4%.[4] The portable K-edge yields accuracies of 1-2% and precisions similar to the accuracies of the in-plant installation. Hence the PMCA is not the factor limiting the accuracy.

The NaI enrichment program, based on the enrichment meter principle,[5] is used to measure uranium enrichment. This user-friendly application program is resident in the PMCA. In normal use one selects predefined values for the instrument setup. The PMCA high voltage, amplifier polarity, etc., are the automatically set. The calibration constants can be determined by using 2 to n standards by the PMCA, or previously determined values for calibration constants can be entered. The user is prompted to supply the percent enrichment of each standard. Data are then acquired and new calibration constants calculated. Once the calibration constants are known, the user can measure unknown samples: the percent enrichment and uncertainty are calculated for each sample. The program has other enhancements that can be selected such as reanalyzing data from tape, checking if a new standard fits the calibration constants previously used, and changing the preset PMCA parameters. Table I shows results obtained by six teams of inspectors at a training school in Los Alamos using the internal NaI enrichment program.

The UF_6 cylinder enrichment measurement program uses a high-resolution gamma (HRG) detector to measure enrichment of material inside a UF_6 cylinder. The current UF_6 program in the PMCA prompts the user for the wall material linear attenuation coefficient, wall thickness, and calibration constant. Once these values are entered, a spectrum from the cylinder is acquired. The program calculates the enrichment and uncertainty and displays the results. The present version of the program was written for the prototype MCAs: it will soon be updated to do PMCA setup, allow for reanalyzing data from tape, and have an option to determine a calibration constant. The original program was used for an extensive study by a Euratom scientist in which 1.7% uncertainty for low-enriched uranium was obtained.[6]

External Application Programs

An external applications program uses the communication protocol defined for the RS 232 port.[7] A PMCA key can be pushed by sending an ASCII string representing that key to the PMCA's RS-232 port. For example, to "push" the SETUP key send the five characters, SETUP, followed by a carriage return. The PMCA constantly monitors the serial port for keypushes to execute: once it finds a keypush string it executes the same action as if that key were pushed on the keyboard. The possible strings that can be sent are listed in Table II. In addition to the strings corresponding to key labels, there are some virtual keys such as OFFKEY, which disables keypad entry, and ONKEY, which enables keypad entry.

An external application program can be written on any computer that has a RS 232 port that can be used to communicate with the PMCA. The PMCA setup and data acquisitions are accomplished by a series of "key pushes," which imitate what a user would do if performing these actions using the keypad. During this process, the PRINT key is frequently used to echo via the serial port the present contents of the LCD: this provides a handshake so the external computer knows which keypushes the PMCA has executed. Once the data are acquired the I/O key is used to dump data from the PMCA: this may involve dumping data from all the channels or using just data from the ROIs. The

TABLE I

NaI ENRICHMENT MEASUREMENT RESULTS

Team \ Sample	408	1127	1125	1126	324	12	13	17	27	38	66
A	0.711	0.730	1.96	3.06	10.22	11.94	13.09	17.4	26.8	37.58	65.8
B	0.714	0.698	1.96	3.07	10.15	11.87	13.13	17.22	27.08	37.76	66.25
B*	--	--	--	--	--	--	--	--	25.95	35.77	53.66
C	--	0.736	1.961	--	10.20	--	13.16	17.36	26.93	37.65	66.07
D	0.703	--	1.949	3.063	10.22	11.90	13.06	17.40	26.76	37.56	65.98
E	0.687	0.6816	1.95	3.004	10.20	11.94	12.97	17.23	26.59	37.11	63.48
F	--	0.726	1.961	3.040	10.16	11.99	-	17.35	26.81	37.67	65.56
Declared Value	0.717	0.723	1.961	3.063	10.20	11.9	13.11	17.53	27.09	38.00	64.41

*Results obtained if pileup rejector was not used.

TABLE II

PMCA EXTERNAL COMMUNICATION PROTOCOL
ASCII STRINGS

0	ACQUIRE	YES
1	MCS	NO
2	USER	NEXT
3	SETUP	CE
4	PRESET	ENTER
5	MEMORY	END
6	PLOT	DISPLAY
7	I/O	NORMAL
8	TAPE	EXPAND
9	CALIB	PRINT
Control E	CALC	RIGHT
Control P	ROI	LEFT
Control N	UP	DIAG
Control R	DOWN	ONKEY
Control D	INC	OFFKEY
Control U	DEC	ONHS
Control L		OFFHS

analysis is performed in the external computer and results can be displayed or printed by the external computer.

The first application of external control was a Pu-inventory verification system, which used a neutron coincidence counter, a HRG detector, a PMCA, and an HP-85 computer.[8] The neutron counter determines the amount of spontaneously fissioning Pu, a mixture of ^{238}Pu, ^{240}Pu, and ^{242}Pu. Using the isotopic fractions determined by the HRG detector and the PMCA, the total amount of plutonium is determined. The HP 85 is programmed to gather neutron data and calculate the ^{240}Pu effective mass. The program also totally sets up the PMCA gain, high voltage, ROIs, etc. It starts data acquisition, initiates data transfer, makes quality assurance checks, and calculates and reports isotopics. The operator then checks the measured isotopic results against declared values; then he can specify whether the measured or declared isotopics are to be used to calculate the total Pu. This unit is being evaluated at Savannah River Laboratory.

The external computer programs have been written in BASIC, which can easily access the PMCA via a serial port and is understood by many people. To implement measurements that are difficult to define until some experience is gained with the particular equipment, BASIC provides an ideal development environment because BASIC programs can be easily modified. The maximum data transfer rate of the PMCA is 19600 baud; most application programs have used 4800 baud due to constraints imposed by the external computer (Epson HX-20 running MICROSOFT BASIC). The execution of the external programs takes longer than those installed in PROM inside the PMCA, but the advantages are easier programming and program modification.

In order to make the development of external computer programs more efficient, a group of subroutines to do commonly used functions were written in BASIC. The subroutines were originally written in BASIC for use on the Epson HX 20 and have now been adapted to the IBM-PC. A specific application program is constructed by using applicable subroutines from the general package and then adding code to perform the specified procedure and analysis. Subroutines that do the following are available:

1. The PMCA setup is accomplished by using values from a predefined table or allowing the user to enter new values for detector type, amplifier polarity, high voltage, NaI detector stabilizer (enabled or disabled), lower and upper level discriminators, zero level, threshold, pulse pile-up rejector(enabled or disabled), memory subgroup, and preset count time.

2. The ROIs can be set up using a table of beginning and ending channels for each ROI, a table of beginning and ending energies for each ROI, or allowing the user to manually set the ROIs from the PMCA keypad.

3. The data acquisition sequence acquires data using the ACQUIRE key or allows reanalyzing data from the cassette tape.

4. Data are dumped from the PMCA using the I/O key. If individual channel data are used by the extended program, the desired data are stored in arrays in the external computer.

5. The full width at half maximum (FWHM) can be calculated for any ROI.

6. The integral or net area of any ROI can be read from the CALC function.

7. The integral or net sums of any ROI can also be calculated using channel data stored in the arrays.

Two major applications, which use external control, are now under development at Los Alamos. One development will soon be tested at the Oak Ridge Y-12 plant. This is a portable cart with a PMCA, a HX-20, and a complement of NaI detectors. It will be used to measure uranium holdup in high-enriched powder transfer lines. Figure 2 shows a technician placing one of the detectors over a simulated transfer pipe. The HX-20 controls data acquisition and analysis. Results are printed on the HX-20's internal printer. The use of this system is mainly for inventory and it may have limited use in process control.

Fig. 2. Simulated uranium-holdup measurement.

The other external programmed application is measurement of plutonium holdup of solid materials in pipes and "process modules" such as compressors. Unlike the uranium holdup, which is measured through pipes throughout the plant, all the Pu holdup measurements are made inside gloveboxes. The HX-20 plays the same role in this application.

PMCA Performance

A series of acceptance tests were made on 35 PMCAs before they were delivered to the IAEA. One of the tests was to determine the "ultimate" resolution of the ADC. Low count-rate tests were made using a PGT planar detector (Model IGP 310 with Model 873 low power preamplifier). The summary for PMCAs for both deliveries to the IAEA is shown in Table III. The range of resolutions is shown and the average is inside the parenthesis. We observed that injecting the output from an Ortec 572 amplifier into the direct input of the PMCA gave worse resolution than using the PMCA internal amplifier.

Another test was a resolution vs count rate test. A coaxial detector (PGT Model LGC78D with a Model RG-11C preamplifier) was used for this test. For the last 20 units delivered to the IAEA, the resolution at 185.7 keV for ~3.4 k/s and for ~26 k/s count rate is shown in Table IV. The ^{235}U source was fixed at

TABLE III

"ULTIMATE" RESOLUTION SUMMARY

	FWHM 122 keV	FWHM 186 keV
Units 1-15	0.57-0.60 (0.59)	0.66-0.70 (0.675)
Units 16-35	0.59-0.64 (0.61)	0.69-0.72 (0.71)

~3.4 k/s and the increased count rate was produced using a ^{57}Co source. The resolution averaged 1.0 keV at the low rate and 1.27 keV at the high rate. Using a laboratory system of a Canberra Model 2020 amplifier and Canberra Model 8077 ADC, resolutions of 0.763- and 0.790-keV were obtained with this particular detector. In Los Alamos, using our PMCA SN4789, we obtained the resolutions shown in Table V.

TABLE IV

RESOLUTION RESULTS

Serial Number	Resolution, Units of keV: Planar Detector (1.5 k/s) 122 keV	Planar Detector (1.5 k/s) 186 keV	Co-axial Detector (3.4 k/s) 186 keV		Co-axial Detector (26 k/s) 186 keV	Units of %: NaI Detector (5.4 k/s) 186 keV
5827	0.61	0.72	1.2	-	1.4	10.6
5826	0.59	0.70	1.0	-	1.3	10.8
5828	0.59	0.70	1.0	-	1.4	10.6
5829	0.59	0.69	1.0	-	1.3	10.1
5831	0.64	0.72	1.0	-	1.2	10.6
5830	0.59	0.70	1.0	-	1.1	10.1
5834	0.63	0.71	1.1	-	1.3	10.6
5833	0.60	0.69	1.0	-	1.3	10.1
5832	0.61	0.71	1.0	-	1.2	10.6
5835	0.61	0.71	1.2	-	1.4	10.2
5836	0.60	0.70	1.1	-	1.2	10.[illegible]
5837	0.59	0.69	1.0	-	1.2	10.0
5838	0.61	0.72	1.0	-	1.2	10.8
5839	0.61	0.70	1.0	-	1.3	10.1
5840	0.61	0.72	1.0		1.2	11.0
5841	0.60	0.68	1.0	-	1.3	10.1
5842	0.60	0.69	1.0	-	1.2	10.3
5843	0.63	0.72	0.98	-	1.3	10.7
5844	0.64	0.73	1.0	-	1.2	10.5
5845	0.61	0.70	0.97	-	1.4	10.8

TABLE V

TEST RESULTS ON PMCA SN4789

Rate	Pile-up Rejector	Area	Area Uncertainty	Normalized Area	% Dead Time	Resolution (keV)
3.4k	ON	181427	316	1	-	0.95
21.5k	ON	180239	443	0.993	55	1.1
21.5k	OFF	133334	580	0.735	39	1.1
33k	ON	177491	702	0.978	70	1.2

A test of the pulse pileup rejector (PPUR) was also made by checking the area of a peak from a fixed source as the count rate varied. The acceptance tests showed a slight positive bias (~1%) in the area at high rates. Because the procedure used during checkout was optimized for resolution, adjustments were made that moved the peak centroid. We repeated the measurements in Los Alamos. For this test on PMCA SN4789 we made four sets of three measurements and averaged the results of the measurements. Table V lists the measured areas. The area is the 186-keV peak of a fixed ^{235}U source. The count rate was increased by bringing a ^{57}Co source close to the detector. From these data we observe ~1% loss in going from 3.4k/s to 21.5k/s. Notice the ~27% loss if the PPUR is turned off. With the PPUR on. ~2% of the count rate is lost in going from 3.4k/s to 33k/s.

The results of NaI resolution tests are shown in Table IV. The same Harshaw Model 852 detector was used with all PMCAs for this test. The measurements were made with a gross count rate of ~5k/s. The average resolution at 185.7 keV is 10.4% with a range of 10.1-11.0%. The stated resolution overestimates the actual resolution because it is calculated on the basis of the 1/2 height on the high-energy side. A plot of a spectrum taken with a detector, which gave 10.2% resolution with a PMCA. is shown in Fig. 3.

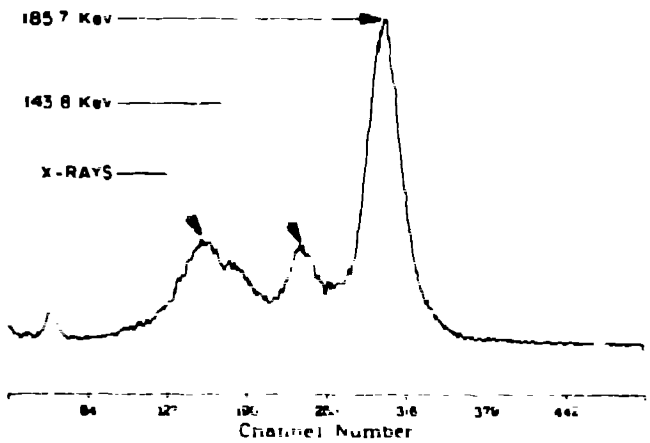

Fig. 3. Typical NaI spectrum of ^{235}U collected with the PMCA

The lock range of the NaI stabilization circuitry was tested by adjusting the stabilization setpoint so the 186-keV peak fell approximately at channel 300 within 512 channels. The high voltage setpoint was first set 100 volts higher and then 100 volts lower than the stabilization setpoint. In each PMCA the stabilization circuitry brought the peak back to channel 300 within the 1-channel uncertainty of the centroid calculation program.

Checks of the NaI stabilizer temperature compensation circuit were not made because the NaI detectors to be used with the PMCA were not available.

In the ROI setup. resolution and centroid calculations were all done using an HX 20 computer and the external communications package of the PMCA. The setup and analysis routines were written in BASIC on the Epson HX-20.

Summary and the Future

The DSD-2056-4K PMCA is a standard tool used in both international and domestic safeguards. This tool and the built-in user programs have been field proven. For applications where the manpower to program built-in programs is not available, programs in external computers can control the PMCA. A set of general purpose setup and analysis subroutines have been written in BASIC to be used directly or as a guide in the external applications.

While safeguards and the nuclear industry are just beginning to make use of the present PMCA. we are looking into ways of making it easier to write internal programs for the PMCA and into replacing its current 8-bit processor with a 16-bit processor to give it the capability to do very involved analysis such as peak fitting and detailed plutonium isotopic analysis.

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