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*A Real-Time Inventory System
for Special Nuclear Material in Storage*

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A Real-Time Inventory System for Special Nuclear Material in Storage



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CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. A CONTINUOUS-MONITORING APPROACH	2
III. SELECTION OF COMPONENTS FOR THE SHELF MONITOR	7
A. GM Tubes	8
B. Cadmium-Telluride Detectors	8
C. Parallel-Plate Weight Sensors	9
D. Other Weight Sensors	9
E. Time Monitor	10
IV. MICROCOMPUTER FOR THE SHELF MONITOR	10
V. SOFTWARE DEVELOPMENT FOR THE NETWORK MINICOMPUTER	12
A. NOVA 3 Resident Software	12
B. NOVA 3 Task Structure	15
VI. RESULTS AND DISCUSSION	16
VII. CONCLUSIONS	17
GLOSSARY	18

A REAL-TIME INVENTORY SYSTEM FOR SPECIAL NUCLEAR MATERIAL IN STORAGE

by

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ABSTRACT

Special nuclear material (SNM) in long-term storage is particularly vulnerable to diversion, hence it must be inventoried periodically. Inventory procedures are time consuming and expose personnel unnecessarily to radiation. Los Alamos scientists have developed an alternative method for taking inventory: a system that provides continuous surveillance of all SNM stored in a vault. The system features a network of shelf monitors, one monitor for each container in storage. A shelf monitor detects the gamma-ray emissions and weight of the container resting on it and transmits the data in real time to a minicomputer for analysis. Reliable and inexpensive, the shelf monitors are attractive for deployment in a storage facility where hundreds or thousands of them are required.

I. INTRODUCTION

Because diversion of SNM in long-term storage poses a serious threat, periodic inventories are conducted to ensure that none has been diverted. Manual inventories are time consuming and expose personnel to radiation; therefore, alternatives to manual inventory-taking are being explored.

Our solution to inventory-taking problems is a vault-monitoring system that provides continuous surveillance of SNM stored in containers. The system requires each container to rest on a shelf monitor, which senses its weight and gamma-ray emissions and transmits that information in real time to a dedicated minicomputer for analysis. By using a network of shelf monitors, one for every container in a vault, it is possible to detect diversion of SNM in a timely fashion and reduce or eliminate the need for physical inventories. If access controls fail and some material is removed, the shelf system produces an alarm. The system features reliable, inexpensive shelf monitors connected to a minicomputer that continuously monitors stored SNM in real time.

This report discusses the shelf monitor approach to vault monitoring, describes the selection of equipment and development of computer programs, and reports the results of our experimentation. Details of the minicomputers and software used for the monitoring network are also provided.

II. A CONTINUOUS-MONITORING APPROACH

To address the problems of physical identification, inventory, and increased security of stored SNM, we designed and tested a storage system to control SNM. The system consists of a network of shelf monitors that continuously monitor the presence of SNM by focusing on two of its attributes, in this case, gamma-ray emissions and weight.

Most vaults contain standard flat shelving on which containers of SNM are stored upright. The shelf monitors that we developed were attached to a shelf. On each monitor we placed one container of SNM. The monitor continuously measured the gamma rays emitted from its resident container as well as the container's gross weight.

To detect the gamma radiation, we placed a shielded and collimated Geiger-Müller (GM) tube below the sensing plate of each monitor. The GM tube detects only those gamma rays emitted from the container of SNM located directly above it. A pair of parallel plates separated by springs (Fig. 1) serves as the weight sensor to monitor the combined mass of the SNM

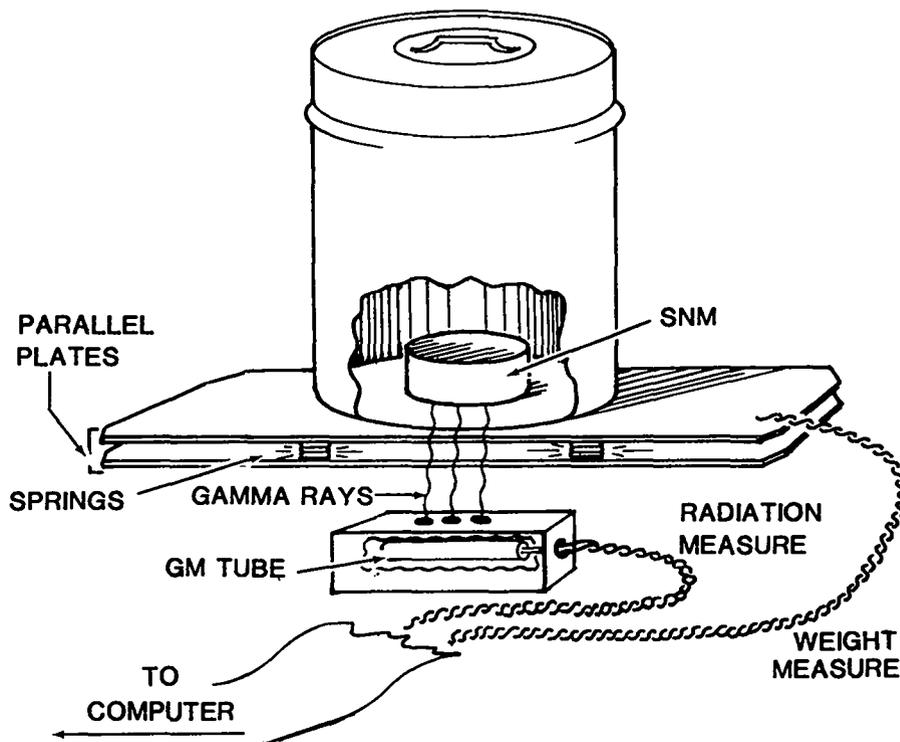


Fig. 1.
Arrangement of shelf monitor sensors.

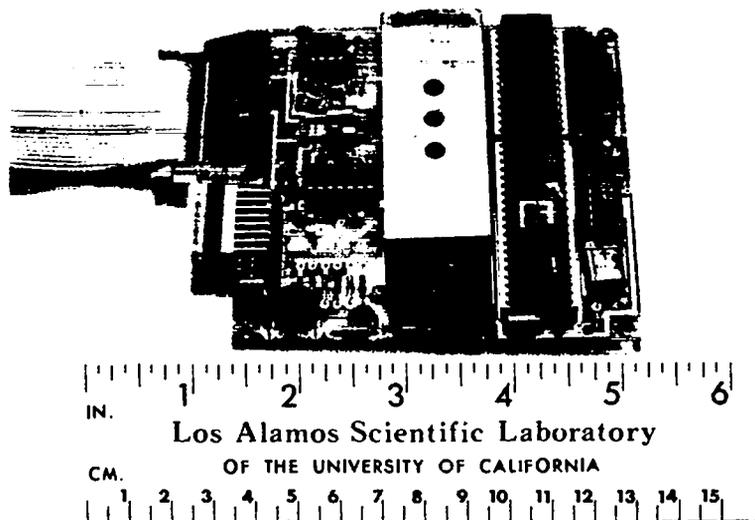


Fig. 2.
Shelf monitor electronics board.

and its container. These parallel plates form a variable capacitor that is part of an oscillator circuit whose frequency depends on the weight of an object placed upon the capacitor. The oscillator frequency and the gamma-ray counts are stored as counts in the shelf monitor electronics, the heart of which is an Intel* 8748 microcomputer. An electronics board supports the major electronic components and the lead collimator/shield for the GM tube (Fig. 2). The electronics package is mounted in a metal housing with the parallel-plate weight sensor on one side (Fig. 3). A fully assembled shelf monitor appears in Fig. 4. The estimated cost per monitor is about \$125 in quantity production.

A network of shelf monitors acquires data and transmits it to a minicomputer for analysis and storage. The number of shelf monitors that can be connected to a minicomputer system is almost unlimited. A system configuration such as the one in Fig. 5 would contain 892 shelf monitors. A Data General NOVA 3 minicomputer collects the gamma-ray and weight data from each shelf monitor in the system. Each shelf monitor compares current data to previously acquired data; any significant deviation results in an alarm. While a container remains in storage, the network obtains a gamma-ray count rate and measures the weight of the container every 5 s.

A reliable, inexpensive shelf monitor was our objective, because of the potential number of units necessary to implement a network. The prototype system consisted of an array of 16 shelf monitors (Fig. 6). When the number of monitors in a storage vault is several thousand, their cost becomes exorbitant, even when the unit cost is about \$100. Therefore, we tried to

*Intel Corp., 3065 Bowers Avenue, Santa Clara, CA 95051.

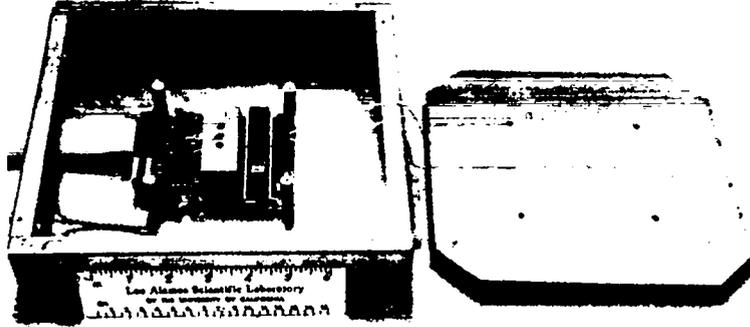


Fig. 3.
Shelf monitor with weight sensor removed.

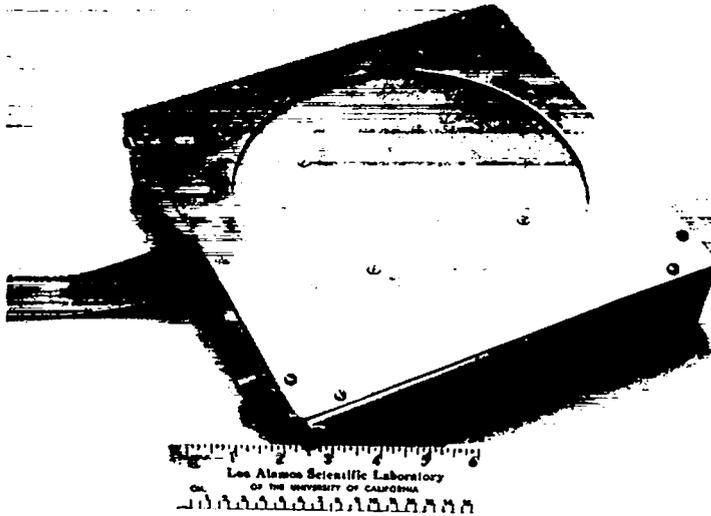


Fig. 4.
Assembled shelf monitor.

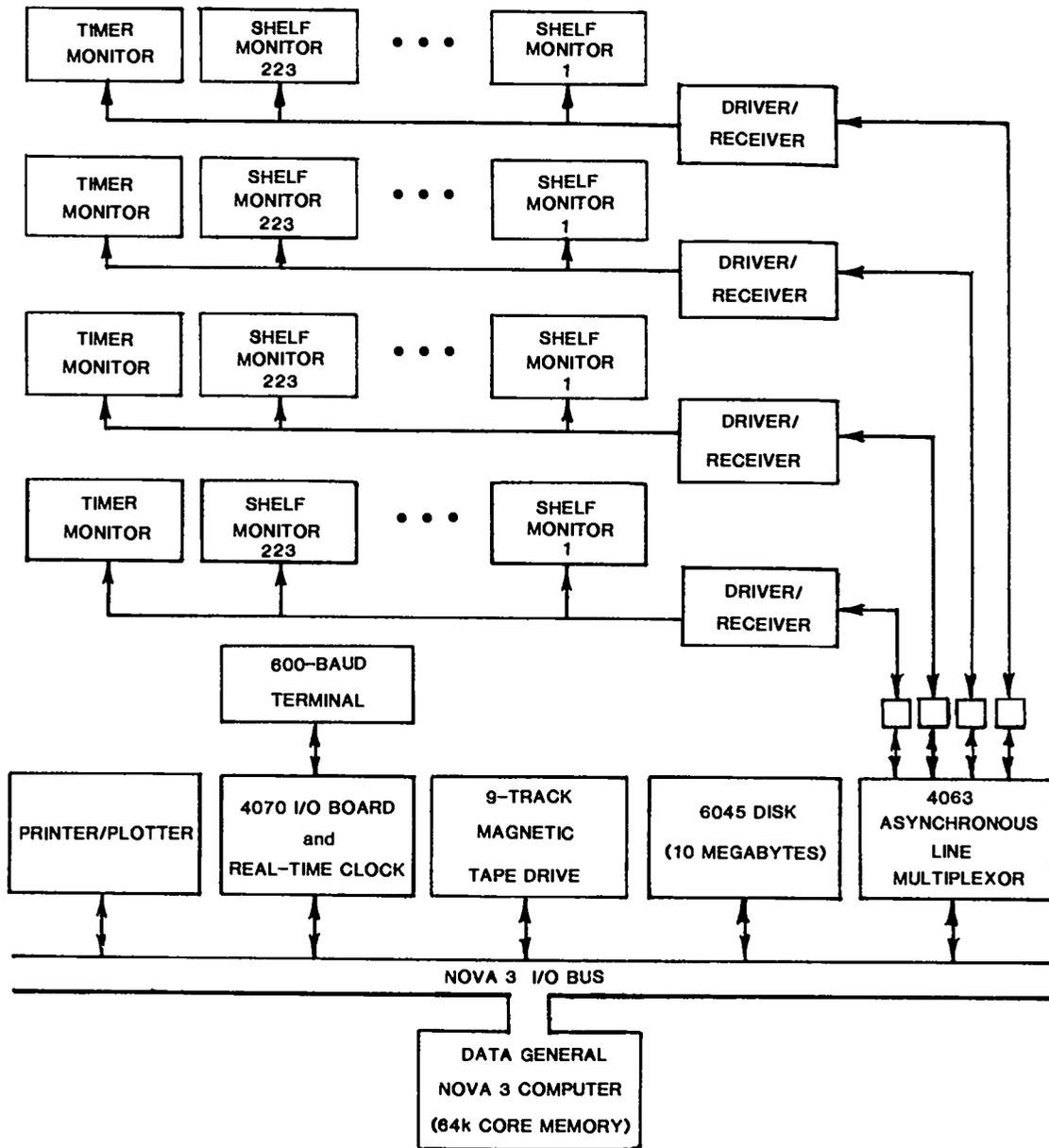


Fig. 5.
Block diagram of shelf monitor system.

minimize communication costs by selecting a party-line transmission system that handles 9600-baud serial data. By establishing a data format compatible with the RS232 standard interface, we enabled data communication with existing minicomputer hardware. This method allows two-way communication between a shelf monitor and the minicomputer so that all shelf monitors are under minicomputer control. To stop data acquisition, the minicomputer transmits an 8-bit character to the monitors. The minicomputer can interrogate each monitor individually by sending a code word that only one monitor recognizes.

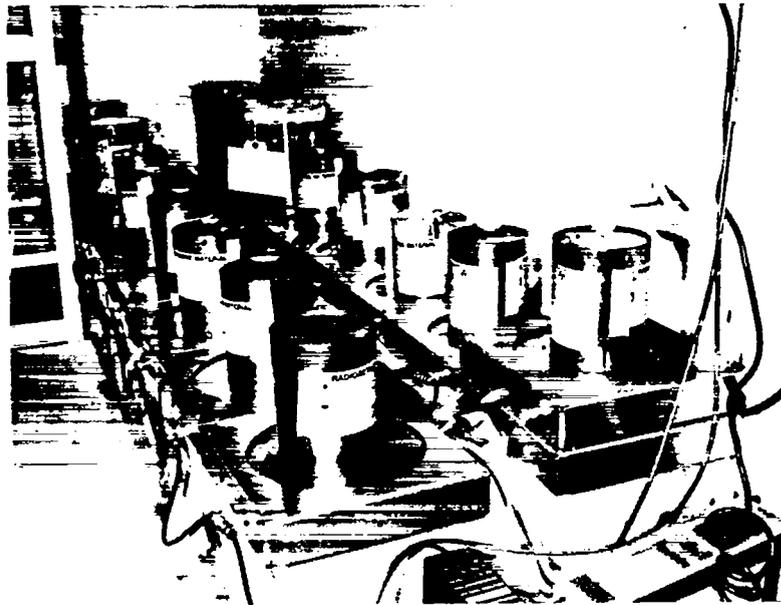


Fig. 6.
Sixteen-container prototype in Pajarito Canyon vault.

Initially, the shelf monitor function was implemented with hard-wired logic before single-component microcomputers were available commercially. The material cost for the printed-circuit packaged electronics was approximately \$70. This implementation suffered all the inflexibilities associated with a hard-wired logic design. The data required approximately 40 integrated circuit packages, which determined the 20- by 20-cm size of the printed-circuit card.

By replacing the hard-wire logic with the Intel 8048 single-component microcomputer, we halved the electronics cost. The 8048 microcomputer is the nonerasable equivalent of the Model 8748 and is available in quantity at \$10 per unit. Use of the 8748 microcomputer reduces the chip count from 40 to 7, thereby reducing the printed-circuit card size to a 10- by 10-cm area (Fig. 2).

Whereas most of the intelligence of the shelf monitor system resides in the NOVA 3 minicomputer, some intelligence resides in each shelf monitor. Thus, distributed software is used to control and acquire data from the network of monitors. The executive program that resides in each shelf monitor was written in Intel MCS 8748 assembly language whose macro-expansion facility was heavily used. The NOVA 3 control programs, which are subordinate to the Data General operating system, were written mostly in FORTRAN IV, with the exception of the RS232C interface drivers, which were written in NOVA 3 macroassembly language.

III. SELECTION OF COMPONENTS FOR THE SHELF MONITOR

Plutonium exhibits some unique and some common properties that can be monitored. It is one of the few substances that emits both neutron and gamma radiation and has a high density in its metallic form. It is also an alpha emitter, producing a measurable amount of heat. Detectors vary in their capacities to sense any of the above attributes. Neutron detectors are relatively large and are difficult to shield; cross-talk would be difficult to control. Gamma-ray detectors, however, can be rather small and can be well shielded for low-energy gamma radiation. Such detectors can be obtained at a low cost. Heat sensors are useful only in those cases where enough material is present to generate a measurable amount of heat. The weight of the material can be measured but cost and accuracy also must be considered. Because the Intel 8748 microcomputer has a dual port capability, a maximum of two sensors was considered; thus, the gamma-ray detector and weight sensor were chosen for use in the shelf monitor.

A block diagram of the shelf monitor appears in Fig. 7. The transmitted data from the minicomputer forms a command bus, which addresses each shelf monitor with an 8-bit identification (ID) code. The transmitted ID code is compared by each microcomputer to the eight switch settings corresponding to the physical or geographical shelf location where the shelf monitor is installed. A match of the 8-bit ID causes the microcomputer to echo the ID and then transmit four 8-bit characters, two that correspond to the 16-bit weight sensor count and two that correspond to the 16-bit gamma-ray count. The received data input from the minicomputer forms the response bus that receives the shelf monitor data.

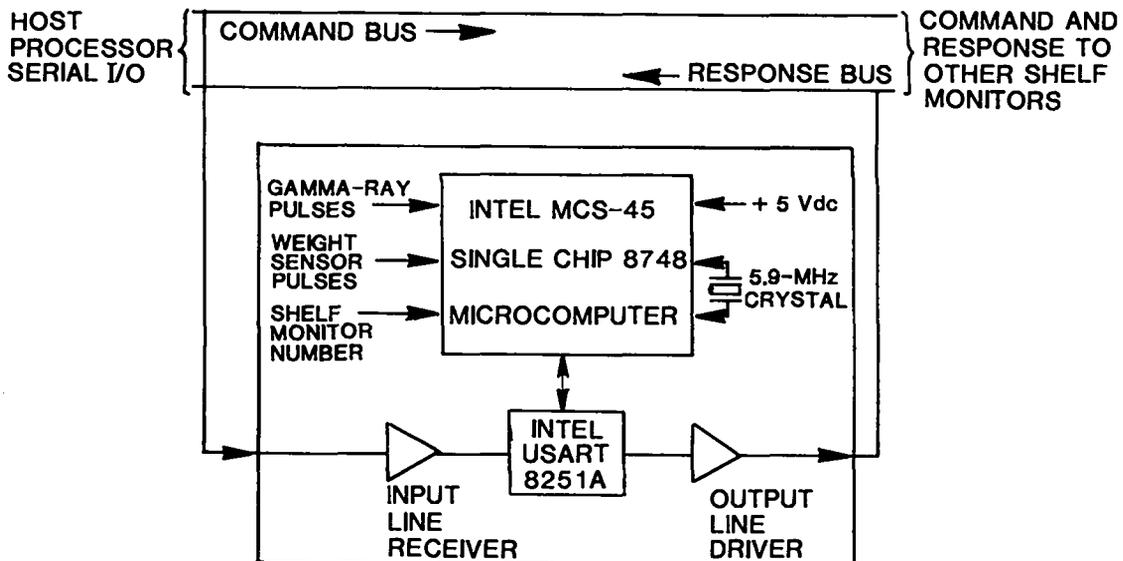


Fig. 7.
Shelf monitor block diagram.

Universal broadcast commands are a means of issuing simultaneous commands to all the shelf monitors in a network. The broadcast commands, which produce no response from the shelf monitors, include: reset the master switch (MASTER RESET), inhibit counting (PAUSE), enable counting (CONTINUE), disable the primary bus (ENABLE SECONDARY), and disable the secondary bus (ENABLE PRIMARY).

Although a weight sensor and a gamma-ray detector were selected as primary attribute measurement devices, various devices are available, each type offering its advantages and disadvantages. The gamma-ray detectors we considered were the GM tube and a newly developed cadmium-telluride solid-state detector; the weight sensors we considered included the parallel plate geometry, the strain gauge or load cell, and a piezoresistive material. Discussion of the advantages and disadvantages of each detector type follows.

A. GM Tubes

The shelf monitor uses a small (8-mm diam by 45-mm long), inexpensive, halogen-quenched GM tube that operates at 425 Vdc and costs approximately \$15. Because of its size, the tube can be completely shielded from extraneous radiation. The collimator/shield, which was designed so that the tube only views the material under surveillance, is necessary to inhibit the crosstalk from adjacent sources and to reduce the count rate in the tube. Although most halogen-quenched tubes are advertised as having an infinite lifetime, some manufacturers recognize that a realistic lifetime for GM tubes is approximately 5×10^{10} counts. A rate of 1000 counts/s corresponds to an average lifetime of 1.6 yr. Therefore, to obtain a reasonable lifetime, each tube should have a collimator or filter to reduce the rate to about 200 counts/s.

B. Cadmium-Telluride Detectors

The GM tubes and their associated circuitry performed well; however, we wanted to eliminate the 425-Vdc power source that must be bused to each detector. For this purpose, we investigated cadmium-telluride crystals, which are available in a small size (2-mm cube) and can operate with a 5-V bias. We obtained 16 cadmium-telluride detectors, complete with all the circuitry required to supply a logic pulse to our microcomputer. These crystals are less expensive than the normal high-quality cadmium-telluride detectors used for obtaining gamma-ray spectral information. The less expensive detectors are rejects from the high-quality detector production, but still can measure total gamma-ray flux; they promise to be good substitutes for GM tubes from a standpoint of gamma-ray counting efficiency, count rate, and expected lifetime.

We subjected the cadmium-telluride detectors to two different types of testing to determine their performance characteristics. A separate bench test of each detector was made, followed by a test of the detector integrated into a functioning shelf monitor. Individual detectors for observing the same source produced greatly varied count rates. Those detectors integrated into shelf monitors detected varying gamma-ray count rates by orders of magnitude; some detectors produced very high count rates.

As a result of these investigations, we reached several conclusions.

- Cadmium-telluride detectors, even considering economy of scale, are more expensive to buy and use than are GM tubes.
- Although a solid-state detector is more efficient per unit volume than is a GM tube in measuring gamma radiation, the small size of the cadmium-telluride chips resulted in few net counts.
- The count rates from the cadmium-telluride detectors exhibited a much larger variance than that of the GM tubes.
- The cadmium-telluride detectors operate with a bias of 5 V. However, the high gain required creates a serious noise problem.
- The additional adjustment required for each shelf monitor using a cadmium-telluride detector is a serious drawback.

We concluded that the cadmium-telluride detector is an unsuitable replacement for the GM tube used in the shelf monitor.

C. Parallel-Plate Weight Sensors

The need for a weight sensor became obvious when we realized that a gamma-ray detector can only monitor the first millimeters of PuO_2 . The remaining material above this layer does not appreciably contribute to the count rate in the detector due to self-absorption of the gamma radiation. Hence, we introduced a parallel-plate weight sensor that must satisfy several conditions when used in this application. The weight sensor must be transparent to the plutonium gamma rays because the gamma-ray detector is located beneath it. It should accommodate containers as large as 20 cm in diameter and weighing several kilograms. Moreover, the sensor should be inexpensive to produce.

Operation of the weight sensor is straightforward. When the parallel plates, which compose the weight sensor, move relative to each other, their capacitance changes, which in turn changes the frequency of the oscillator. This frequency change results in a change in the number of counts per time interval recorded in a counter located in the microcomputer. This count is handled in exactly the same manner as the count obtained from the GM tube. Because the capacitance of the plates varies if someone lightly touches the container, the weight sensor can also be considered a disturbance indicator.

D. Other Weight Sensors

Although the parallel-plate, spring weight sensor works satisfactorily, its recognized shortcomings, such as its large dimensions and use of four-coil springs, induced us to continue searching for an alternative. We conducted experiments to determine the feasibility of replacing the spring mechanism with another type of weight sensor. Two possibilities that resulted from the investigation were strain gauges and piezoresistive sensors.

Strain gauges accurately measure weights and pressures. Usually a strain gauge is built into a load cell, which is incorporated into a weight- or pressure-measuring apparatus. We find that a load cell capable of measuring weight costs more than \$200, which exceeds the range of reasonable cost for the shelf monitors.

A piezoresistive compound, Pressistor*, was the other alternative. A thin film of Pressistor compound changes its dynamic resistance with increasing pressure on the film. We used two experimental arrangements to study the properties of this compound: a rod and plate arrangement and overlapping plates. Various weights were placed on a brass rod that was in contact with a Pressistor film. The dynamic resistance of this junction was measured as a function of the load placed on the rod. Whenever a load was placed on the rod, a change in the resistance of the material was observed. Unfortunately, this change in resistance could not be duplicated. Because the resistance of the material is exponentially related to the applied pressure, the variation in observed resistance using the same loading was as high as a factor of 10. We tried several different film thicknesses and curing conditions to reduce these variations; all were unsuccessful. None of the expected piezoresistive properties were observed using this configuration. As a result of these experiments, we concluded that piezoresistive material was not a suitable substitute for the parallel plate and spring configuration.

E. Time Monitor

A time monitor module, similar to the shelf monitor module, was designed to occupy one address location on the serial bus. The module, when commanded, responds with the time interval over which the minicomputer allows an accumulator cycle. The hardware/software design is identical to a shelf monitor except the gamma-ray and weight sensor functions have been replaced by a time-interval subroutine.

IV. MICROCOMPUTER FOR THE SHELF MONITOR

The Intel 8048 microcomputer is a totally self-sufficient, 8-bit parallel computer fabricated on a single silicon chip using an N-channel silicon gate metal-oxide semiconductor (MOS) process. The microcomputer contains 1024 bytes of program memory, 64 bytes of random access memory (RAM) (working registers), 27 input/output (I/O) lines, an eight-bit timer/counter, and an on-chip oscillator and clock circuit. The 8048 microcomputer design makes it an efficient controller as well as arithmetic processor. The microcomputer has extensive bit-handling capability as well as facilities for both binary and binary-coded decimal (BCD) arithmetic. Efficient use of program memory results from an instruction set consisting mostly of single byte instructions and no instructions over two bytes in length. The erasable programmable read-only memory (EPROM) version of the 8048 microcomputer, the 8748 model, was used in the shelf monitor.

*Manufactured by Innovation Laboratories of College Station, Texas.

The gamma-ray and weight sensor inputs to the microcomputer are shown in Fig. 7. The 16-bit gamma-ray count is software-accumulated in an interrupt-driven routine by the microcomputer external interrupt. The interrupt routine, including the double-precision processing, requires only 40 μ s. The 16-bit weight sensor count is initially accumulated in a 24-bit word, which is 8 bits of hardware and 16 bits of software. The 8-bit timer/counter of the microcomputer preprocesses the nominal 25-kHz signal from the weight sensor's oscillator. When the 8-bit timer/counter overflows, an interrupt is generated that increments the 16-bit software accumulation. This interrupt routine is identical in instruction composition to the gamma-ray interrupt routine and, thus, it also only requires 40 μ s to process an interrupt. The 24-bit word allows approximately 10 s of data accumulation before overflowing. The weight sensor count is divided by 16 before data transmission.

The shelf monitor resident software was developed in modular form and used an Intel microcomputer development system (MDS). The MDS was configured with the Intellec MDS-800, a Texas Instruments* 733 data terminal, a Teleray** video terminal, dual single-density floppy disk drives, and an Intel PROMPT-48 personal programming tool.

An event-driven executive program resides in each shelf monitor. Three events drive the executive: power-up, event counter/timer overflow, and external interrupt. When the power is first turned on or restored, the executive initializes the counters to known, very large values and puts the counter in a hold condition. The executive then goes into a wait loop, examining every command that comes down the command bus. If the executive receives a broadcast command, it executes it; otherwise, it compares the command to the address of the shelf monitor. When both are identical, the shelf monitor responds with the 6-byte response described previously. In the case of the timer monitor, a 6-byte response is made to all global commands. The event counters and external interrupts are enabled when appropriate broadcast commands are executed.

Whenever a gamma-ray pulse occurs (and interrupts are enabled), an interrupt is requested on the external interrupt input to the 8748 microprocessor. The executive services this interrupt by incrementing a 16-bit software counter where the gamma-ray counts are kept. Whenever a weight sensor pulse occurs and the counter has been enabled, the event counter is incremented. An interrupt is requested whenever this 8-bit counter overflows. The executive services this interrupt by incrementing a 16-bit software counter. Whenever a weight sensor and gamma-ray interrupt occur simultaneously, the gamma-ray interrupt is serviced first while the weight sensor interrupt is latched to prevent its loss. At present, the executive uses 25 bytes of read/write memory and 400 bytes of read-only memory.

*Texas Instruments, Inc., Digital Systems Division, P. O. Box 1444, Houston, TX 77001.

**Research Inc., Teleray Division, P. O. Box 24054-T.R., Minneapolis, MN 55424.

V. SOFTWARE DEVELOPMENT FOR THE NETWORK MINICOMPUTER

A typical shelf monitor system based on a NOVA 3 minicomputer can monitor as many as 892 containers of SNM in a vault (Fig. 5). The 892 shelf monitors are apportioned equally to four sets of command/response buses that are driven by four EIA* RS232C interfaces of the NOVA 3. Four timer monitors are also part of this system, one for each bus. Note that each of the four strings of 223 shelf monitors could be in a different vault at remote sites with modems between the RS232C interfaces and the receiver/driver circuitry that converts interface signals to form signals used on the command and response buses.

Although the minicomputer that controls the entire shelf monitor system is a Data General NOVA 3, any minicomputer with four RS232C interfaces could have been used. Three peripheral devices are attached to the NOVA 3: a 64k word memory, a Versatec 1200A printer/plotter, a 9-track tape drive, and a 10M byte moving head disk. This configuration is near minimal for the number of shelf monitors in Fig. 5.

The successful operation of the shelf monitor required a significant software development effort. The software that resides in each shelf monitor was discussed in Sec. IV. This section discusses the controlling software that resides in the NOVA 3 (Fig. 5), which was used to develop its resident software.

A. NOVA 3 Resident Software

The NOVA 3 minicomputer controls the entire system of shelf monitors. To reduce the complexity of the control program, which is resident in the NOVA 3, as many control and I/O activities as possible are performed by the Data General Real-Time Disk-Oriented Operating System (RDOS). Among the functions performed by RDOS are: (a) scheduling of all activities (tasks), (b) gross timing of shelf monitor counting, and (c) transfer of all data to and from external devices. These functions are performed using system calls to RDOS.

The shelf monitor system control program performs the following functions in support of the shelf monitor system. The control program (a) carries on a man/machine dialogue to configure the shelf monitor system, (b) performs the routine acquisition of data from each shelf monitor in the system, (c) processes acquired data to detect any tampering with SNM under surveillance, and (d) issues messages describing system exceptions to a human operator.

System startup begins with the bootstrapping of RDOS. Then an applications program that operates the shelf monitor system is run. The applications program acquires the following information from the human operator by way of a man/machine dialogue: the identity of each RS232C interface with shelf monitors and the identity of each shelf monitor associated with an RS232C interface.

*Electronic Industries Association, 2001 Eye Street N.W., Washington, DC 20006.

When a shelf monitor system is in operation, a routine monitoring sequence is performed every 5 to 80 s, depending on the number of monitors in the system. The routine monitoring sequence consists of twelve steps:

- (1) issue reset and count command;
- (2) wait for response;
- (3) wait for a nominal counting time (5 s);
- (4) issue command to hold counts;
- (5) wait for a response;
- (6) issue command to read timer monitor;
- (7) wait for response;
- (8) issue command to read shelf monitor;
- (9) wait for response;
- (10) calculate weight sensor and gamma-ray rates using time from timer;
- (11) queue alarm message if calculated weight sensor and gamma-ray count rates deviate significantly from average weight sensor and average gamma-ray count rates; and
- (12) calculate approximate new average weight sensor and gamma-ray count rates using present weight sensor and gamma-ray count rates and old average rates.

Steps 8 through 11 are repeated until all shelf monitors on a single line have been read and their data processed. All RS232C interface lines in the system are serviced as described above.

Whenever a command is sent to a string of shelf monitors, the command dispatch sequence is executed. Because every command should provoke a 6-byte response, the command dispatch sequence is identical for all commands regardless of type, broadcast, or device specific. A 6-byte response consists of the first byte, which is merely an echo of the command dispatched, bytes 2 through 5, which contain timer or gamma-ray and weight sensor information, and byte 6, which contains a check sum that forces the low-order eight bits of a sum of the six bytes to equal 254.

Five error conditions can occur in the system response to a dispatched command.

- (a) I/O error detected by RDOS.
- (b) No response received.
- (c) First byte not the same as command dispatched.
- (d) Bytes 2 through 5 contain power-up default data counts.
- (e) The low-order eight bits of the sum of all six bytes do not equal 254.

The NOVA 3 software examines every response from a dispatched command for all of the above possible error conditions. If it detects an error, it queues an error message describing the condition and executes an appropriate command dispatch sequence until all lost data are recovered error free. If the lost data cannot be recovered after a specified number of unsuccessful retries, the executive sends no more commands to the defective device (RS232C interface and/or shelf monitor).

A past history of each shelf monitor must be saved if current weight sensor and gamma-ray rates are to yield possible alarm information. Because we knew that the weight sensor and gamma-ray rates may drift significantly

over long periods (days and weeks), we decided that an average count rate consisting of the last 100 points read would be used as the basis for the detection of tampering. At least 175 000 16-bit words of storage would be required to save the most recent 100 gamma-ray and weight sensor readings of 892 shelf monitors and considerable computation time would be required to compute the average count rates each time a new data point was acquired. Thus, all averages are calculated using an approximation to the true average,

$$A_n = (1/n)P + (n-1)/n A_0 , \quad (1)$$

where A_n is the new average, A_0 is the old average, P is the point being added to the average, and n is the number of points in the new average. By using this approximation, the only data that need to be saved for each shelf monitor are average gamma-ray count rate and average weight sensor rate. These are kept as floating-point quantities.

An additional 16-bit status word is associated with each shelf monitor. This status word tells the applications program the functional status of the associated monitor available. The status word also contains initial timing sequence information and the number of points in the average count rates. It is possible to set up the system before the containers of SNM are placed on the monitors. The initial timing sequence is a time period wherein no data is acquired from the monitor in the sequence. This permits a time delay between entry into the system of a shelf monitor and the acquisition of data from it. This time delay varies, but is usually less than 10 min. When a shelf monitor is first placed in service, the first weight sensor and gamma-ray count rates read are all that is known about the monitor.

Although it is convenient to use 100 points as the basis of the approximate average calculation, the average will require the acquisition of at least 100 points for it to converge to a value that can be used to trigger alarms. Three bits in the status word are reserved for indicating the number of points in the old average count rates. The range of values indicating the number of points is 0 through 7. Each time a point is added to the average count rates associated with the shelf monitor, the number of points is incremented and its new value is used in calculating the average count rates according to Eq. (1). Upon reaching the value 7, the number of points is assumed to be 100 for the purpose of performing the calculations in Eq. (1) and is incremented no further.

An alarm occurs if a significant deviation from average weight sensor or gamma-ray count rates is detected. The frequency produced by the weight sensor circuitry is sufficiently stable that a deviation of ± 3 counts/s is considered significant. The gamma-ray alarms proved more difficult to establish. We finally decided that gamma-ray deviations greater than 3.5 to 4.0 standard deviations from the average count rate were significant. Calculating the standard deviation for the most recent 100 gamma-ray points is conceptually easy; however, the last 100 points have to be saved and great computational effort has to be expended for each deviation calculated. If the gamma-ray points are assumed to have a Poisson distribution, the standard deviation σ of the gamma-ray count in counts/s can be calculated from the average gamma-ray count rate and the average counting time:

$$\sigma = \frac{(G_a T_c)^{1/2}}{T_c},$$

where σ is the standard deviation, G_a is the average gamma-ray count rate, and T_c is the counting time. T_c is a nominal count time used by RDOS to time a counting period.

Messages occasionally advise the operator of abnormal conditions of various kinds that occur in the system. All such messages are placed in a queue to be printed at a time during which the computer is waiting for an I/O operation or a count operation to finish. The objective is to not delay the routine counting activities when a group of messages stack up. It is possible that an authorized individual may remove a container of SNM from the vault and then notify the shelf monitor system of the transaction. Tampering messages are queued subject to a time delay before they are actually printed. Thus, if the shelf monitor system gains knowledge of the transaction within a reasonably short time of the transaction, it can dequeue any tampering messages associated with the container. The system examines the message queue every 2 s.

B. NOVA 3 Task Structure

The control program has seven tasks to perform the functions described in Sec. V-A. All tasks are written in FORTRAN IV and use the task monitor to schedule them. The monitor check (MONCHK) is active when the shelf monitor system control program first starts executing. MONCHK performs two functions: it (a) receives information from a human operator on the operational status of every shelf monitor to be watched and (b) creates the remaining tasks (and, on request, prints periodic status reports of each active monitor). Of the seven tasks, MONCHK has the highest priority.

RDACK reads and checks all shelf monitors in the system. It (a) dispatches all commands to the RS232C interfaces, (b) checks for errors in response to commands, (c) calculates gamma-ray count and weight sensor rates from data read from monitors, (d) checks for alarms, and (e) calculates the approximate average counts rates. RDACK executes as often as it can to acquire the count rate data it needs to check for alarms. The task is idle when it is waiting for a response to a command or is waiting for a counting time period to end. During these idle periods, the other six tasks may be active.

TMTT times the period required for a response to a command dispatched by RDACK. If no response is received in 4 s, RDACK is notified that the command produced no response. RDACK executes every 0.5 s with a very short execution time.

TMTU performs another timing function. It can delay the start of calculating the average scale and gamma-ray count rates after the time the monitor is first identified to the system. The delay is approximately 5 to 10 min. RDACK executes every 2 min with a very short execution time.

RMTT reads the 6-byte response to every command sent to the RS232C interface. RMTT executes when demanded by task RDACK. TMTT times the

execution of RMTT. If RMTT takes too long to execute, it is terminated abnormally.

All messages to the operator are queued so that they can be printed without delaying the data-acquisition activities of RDACK. MSGWR examines the message queue every 2 s or as often as possible, whichever is longer for queued messages. MSGWR then prints and dequeues them. Messages with a time delay have their delays updated and remain queued. Normally, MSGWR has a very short execution time because the message queue is usually empty. However, there is room for as many as 250 messages in the queue at any one time. The set of possible messages numbers 50 with similar formats, each of which is determined by the content of the message. As many as three numeric quantities can be associated with a single message.

VI. RESULTS AND DISCUSSION

Three operationally separate shelf monitor arrays containing a total of 96 monitors were in operation from May 1979 to September 1980. One of these arrays, located in a plutonium storage vault 5 miles from the NOVA 3 minicomputer, contained 64 shelf monitors and was linked to the microcomputer by standard voice-grade dedicated telephone lines. The other two arrays, located at the same site as the NOVA 3, each contained 16 monitors and were also linked to the minicomputer by telephone lines. One array was in the Pajarito Canyon vault and the other was a test frame for various measuring experiments. Transmissions between each array and the minicomputer over the telephone lines was error free. The use of telephone lines to link the shelf monitor arrays to the minicomputer demonstrates that a centralized computer can be used to monitor and control arrays located at distant locations.

Except for a problem with a batch of faulty chips, the operation of the monitors during the test and evaluation period was quite stable and reliable. The Pajarito Canyon vault array experienced the highest component failure rate of seven monitors that stopped transmitting data; the failure in each case was due to a universal synchronous/asynchronous receiver/transmitter (USART) chip. The same chip had been the cause of almost every failure during the initial burn-in period. The manufacturer acknowledged that early batches of these chips were defective and that we probably had received one of these batches. Another cause of problems was the oscillator chip that we found to be fragile when subjected to a small static charge; it is the most likely circuit element responsible for unstable weight sensor operation in several monitors. Two gamma-ray detectors (using GM tubes) failed during the test and evaluation period and one other displayed erratic behavior.

Figure 8 plots both gamma-ray and weight sensor output for a period of 13 h. A test performed during this run required that a container of SNM be removed from the shelf monitor for 30 s and then replaced on the monitor. Because the container was not replaced in exactly its original position, the gamma-ray count rate and the frequency produced by the weight sensor circuitry changed. This change resulted in an alarm for the thresholds that were employed during the test. The gamma-ray detectors, the weight sensors, and the associated electronics provided consistent and reliable data during the test and evaluation period.

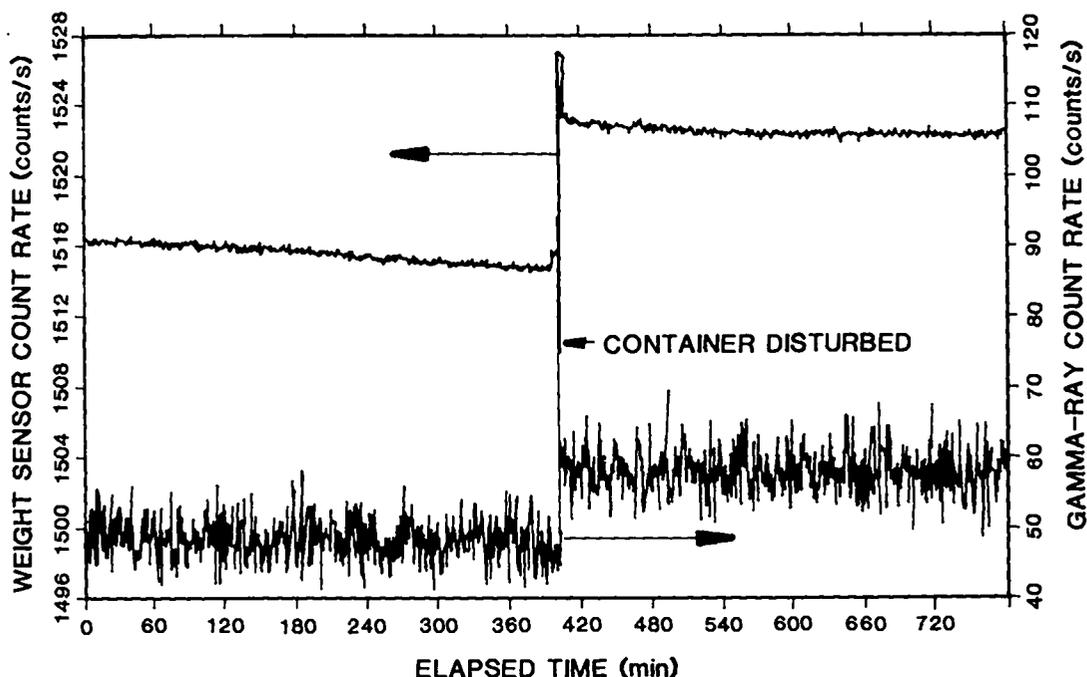


Fig. 8.
Time histories of gamma-ray and weight sensor rates for quick removal and replacement of an SNM container.

VII. CONCLUSIONS

As we have described in this report, the Los Alamos shelf monitor system uses a variety of sensors to provide constant surveillance of SNM containers in vault storage. Each shelf monitor consists of a single-component microcomputer (part of a small, low-cost electronics package), a GM tube that monitors gamma-ray emissions from the containers, and a weight sensor that monitors the total weight of a container and its radioactive contents. Each microcomputer in the shelf monitor network collects the data from the GM tubes and weight sensors and transmits it to a minicomputer for analysis and storage. When unwarranted tampering occurs, the system produces an alarm.

The result of this research and development program is a reliable, inexpensive shelf monitor network with associated data processing equipment that is capable of real-time monitoring and with the software necessary to operate a real-time monitoring system. The shelf monitor system can be retrofit into existing vault storage systems because of its flexibility. This flexibility derives from the system's capacity to accept any type of sensor whose output can be reduced to a series of logic pulses that can be counted by a microcomputer. This flexibility extends to the microcomputer software, which can be changed to fit specific applications because of its uv erasable memory. The program not only produced a shelf monitor system for SNM containers in storage, but it also produced an electronics package that is compatible with different sensors and that can be placed in networks containing thousands of monitors.

GLOSSARY

BCD	binary-coded decimal
EPROM	erasable programmable read-only memory
GM	Geiger-Muller
ID	identification
I/O	input/output
MDS	microcomputer development system
MONCHK	monitor check
MOS	metal-oxide semiconductor
RAM	random access memory
RDOS	Real-Time Disk-Oriented Operating System
SNM	special nuclear material
USART	universal synchronous/asynchronous receiver/transmitter

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