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A MICROCOMPUTER BASED SHELF SYSTEM TO MONITOR SPECIAL NUCLEAR MATERIALS IN STORAGE

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ABSTRACT

Diversion of special nuclear material has become a matter of grave concern in recent years. Large quantities of this material are kept in long-term storage and must be inventoried periodically, resulting in a time-consuming activity that exposes personnel to additional radiation. A system that provides continuous surveillance of stored special nuclear materials has been developed. A shelf monitor has been designed using a single component microcomputer to collect data from a Geiger Muller tube that monitors gamma emissions and a scale that monitors the total weight of the special nuclear material and its container. A network of these shelf monitors reports their acquired data to a minicomputer for analysis and storage. Because a large number of these monitors is likely to be needed in most storage facilities, one objective of this program has been to develop a low cost but reliable monitor.

INTRODUCTION

As a result of increasing worldwide terrorism and publicity alledging the vulnerability of stored special nuclear materials (SNM), diversion of SNM has become a matter of grave concern in recent years. Large quantities of this material are kept in long-term storage and must be inventoried periodically, resulting in a time-consuming activity that exposes personnel to additional radiation. A system providing continuous surveillance of stored SNM has been developed that consists of a network of monitors placed beneath the stored SNM. These shelf monitors are designed to provide timely detection of tampering with stored SNM by monitoring the gamma ray emissions and the weight of the SNM, to provide a backup for access control, and to reduce or eliminate the need for physical inventories.

Additional sensors can be either added to or substituted for the present devices; for example, a continuously monitored fiber optic seal or a temperature-sensing device to monitor the heat generated by plutonium.

The objective of the present research program has been to develop a reliable, inexpensive monitor and associated data processing equipment capable of continuous real-time monitoring of stored SNM. Criteria used in designing this system have been strongly influenced by an effort to keep the cost to a minimum.

REAL-TIME MONITORING OF STORED SNM

Careful management of SNM requires that one address the problem of physical identification, inventory, and increased security of the material while in storage. Consideration of these problems has led to the design, fabrication, and operation of a controlled SNM storage system. This system provides a means of continuously monitoring the presence of this material by monitoring an attribute of the material. In addition, these devices are inexpensive and have a negligible effect on material storage and handling procedures.

Most vaults contain standard flat shelving on which cans of SNM are stored in an upright orientation. The shelf monitors that have been developed are attached on the shelf and placed beneath each can of material. Each shelf monitor continuously monitors the gamma rays emitted from the SNM as well as the gross weight of the material and its container.

Gamma-ray radiation is detected with a shielded and collimated Geiger Muller (GM) tube. Figure 1 shows that only those gamma rays emitted from SNM placed directly above the GM tube are detected. The pair of parallel plates separated by springs, also shown in Fig. 1, is used as the weight sensor to monitor the gross weight of the SNM and its container. These parallel plates form a variable capacitor that is part of an oscillator circuit whose frequency is dependent upon the weight of an object placed upon the capacitor. The scale frequency and the gamma-ray counts are stored as counts in the shelf monitor electronics, the heart of which is an Intel 8748 microcomputer. Figure 2 is a photograph of the electronics board showing the major electronic components and the lead collimator/shield for the GM tube. Figure 3 shows the electronic package mounted in a metal housing with the parallel plate weight sensor off to the side. A fully assembled shelf monitor is shown in Fig. 4. The estimated cost of each monitor, if produced in quantity, is about $100.

The shelf monitor utilizes a small (8-mm diameter x 45-mm long) and inexpensive halogen-quenched GM tube that operates at 425 volts and costs approximately $15. The small size allows the tube to be completely shielded from any extraneous radiation. The collimator/shield is designed so that it only views the material under surveillance, and is necessary in order to reduce the crosstalk from adjacent sources. Another purpose for the collimator/shield is to reduce the count rate in the tube. Most halogen-quenched tubes are advertised as having an infinite lifetime. However, it is recognized by some manufacturers that a realistic lifetime for GM tubes is approximately 5×10^{10} counts. A count rate of 1000 cps corresponds to an average lifetime of 1.6 years. Therefore, in order to obtain a reasonable lifetime, each tube should have a collimator or filter to reduce the count rate to about 200 cps.

The need for a weight sensor becomes obvious when one realizes that the GM tube can only monitor a few 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. The parallel plate weight sensor used in this application satisfies several conditions. It must be transparent to the plutonium gamma rays because the gamma detector is located beneath it. In addition, it should accommodate cans as large as 20 cm in diameter and several kilograms in weight, and should be inexpensive to produce. When the parallel plates, which comprise 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 is varied merely by touching the container, the weight sensor can also be considered as a disturbance indicator. The incremental cost of the weight sensor is $15.

An additional module similar to a shelf monitor has been designed and occupies 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 and scale function has been replaced by a time-interval subroutine.

MICROCOMPUTER NETWORK

A network of these shelf monitors reports their acquired data to a minicomputer for analysis and storage. While the number of shelf monitors that can be interfaced to a minicomputer system is practically unlimited, a system configured as shown in Fig. 5 would contain 892 shelf monitors. A Data General NOVA 3* minicomputer is used to collect the gamma-ray and weight data from each shelf monitor in the system, and these data are compared to previously acquired data for each shelf monitor with any significant deviation resulting in an alarm. During the period of storage, a gamma count rate and a weight measurement are obtained as often as every 5 seconds.

The objective of a reliable, inexpensive shelf monitor was established because of the potential number of units necessary to implement a network. The intial prototype system consisting of a 16-shelf-monitor array is shown in Fig. 6. When the number of monitors per storage vault is in the thousand category, the cost of the monitors becomes painfully large, even when the unit cost is in the $100 range. A 9600-baud serial data party line transmission system was selected to minimize the communication costs. Establishing a data format compatible with RS232 standard allows data communication

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* Reference to a company or product name here or elsewhere in this report does not imply approval or recommendation of the product by the University of California or the US Department of Energy to the exclusion of others that may be suitable.

with existing minicomputer hardware. This method allows for two-way communications between the shelf monitor and the computer, so that all shelf monitors can be controlled by the computer. An 8-bit character is transmitted to the monitors, which stops the count, and each monitor can be interrogated individually when the computer sends out a code word that only a single monitor recognizes.

A block diagram of a shelf monitor is shown 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 first and then transmit two 8-bit characters corresponding to the 16-bit scale count and two 8-bit characters corresponding to the 16-bit gamma count. The received data input of the minicomputer forms the response bus that receives the shelf monitor data.

Universal "broadcast commands" provide a mechanism for simultaneous command functions applicable to all shelf monitors. The broadcast commands produce no response from any shelf monitor. The broadcast commands include master reset, inhibit counting (pause), enable counting (continue), disable the primary bus (enable secondary), and disable the secondary bus (enable primary).

Two command/response channels are available without a cost penalty because the line driver and the line receiver are packaged as dual functions, two each in an individual integrated-circuit package. System reliability is therefore enhanced in that a failure affecting the bus can be bypassed by switching to the other bus.

MICROCOMPUTER IMPLEMENTATION

The shelf monitor function was initially implemented with hard-wired logic before single-component microcomputers were commercially available. 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 design required approximately forty integrated circuit packages and determined the 8- by 8-in. size of the printed-circuit card.

The electronics cost was reduced 50% by replacing the hard-wire logic with the Intel 8048 single-component microcomputer. The 8048 is the nonerasable equivalent of the 8748 and is available, in quantity, at $10 per copy. Use of the 8748 reduces the chip count from 40 to 7 and reduces the printed-circuit card size to a 4- by 4-in. area, as shown in Fig. 2.

The Intel 8048 is a totally self-sufficient 8-bit parallel computer fabricated on a single silicon chip using N-channel silicon gate MOS process. The microcomputer contains 1024 8-bit bytes of program memory, 64 8-bit bytes of RAM data memory (working registers), 27 I/O lines, and an 8-bit timer/counter in addition to on-chip oscillator and clock circuit. The 8048 is designed to be an efficient controller as well as arithmetic processor. The microcomputer has extensive bit handling capability as well as facilities for both binary and 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 gamma and scale inputs to the microcomputer are shown in Fig. 7. The 16-bit gamma count is software accumulated and interrupt routine driven by the microcomputer external interrupt. The interrupt routine including the double precision processing requires only 40 μs. The 16-bit scale count is initially accumulated in a 24-bit word, which is 8-bit hardware and 16-bit software. The 8-bit timer/counter internal to the microcomputer preprocesses the approximately 25-kHz signal from the scale 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 interrupt routine and therefore also only requires 40 μs to process the interrupt. The 24-bit word allows approximately 10 s of data accumulation before overflowing. The scale count is divided by sixteen before data transmission.

MICROCOMPUTER SOFTWARE DEVELOPMENT

The shelf monitor operational program was written in modular form and stored on floppy disks utilizing an Intel microcomputer development system (MDS). The MDS was configured with the Intellec MDS-800, a Texas Instrument 733 data terminal, a Teleray CRT terminal, dual single-density floppy disk drives, and a PROMPT-48 personal programming tool. The operational program was edited using the ISIS-II (Intel System Implementation Supervisor) editor. The program was assembled using Version 1.2 ISIS-II 8048 assembler. Subsequent software modifications have been assembled using Version 2.0 of the 8048/UPI-41/8021 macroassembler.

Initially, the object was manually loaded into the PROMPT-48 for program debugging and EPROM programming. Subsequent object files have been automatically downloaded with the PROMPT-SPP hardware and software. Hard copy of the list files has been provided by the TI-733 data terminal.

The software development cycle has been approximately 1 to 2 months from start to debugged code. The operational program consists of approximately 250 (1024 available) bytes of program memory and utilizes 18 bytes of data memory (64 available). The operational program was debugged utilizing the PROMPT-48 with its I/O port capability.

MINICOMPUTER SOFTWARE DEVELOPMENT

A typical shelf monitor system has been shown in Fig. 5. This system will monitor as many as 892 cans of SNM in a vault using a NOVA 3 minicomputer. The 892 shelf monitors are apportioned equally to four sets of command/response buses that are driven by four RS232C interfaces of the NOVA 3. Note that four timer monitors are also part of this system. It should also be noted 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 RS232C signals to form those used on the command and response buses.

Although the minicomputer controlling the entire shelf monitor system is a Data General NOVA 3, any minicomputer with four RS232C interfaces could have been used. The following peripheral devices are attached to the NOVA 3:

64-k word memory Versatec 1200A printer/plotter
9-track tape drive
10-Mbyte moving head disk.

This configuration is near minimal for the number of shelf monitors shown in Fig. 5. The successful operation of this system required a significant software development effort for that software residing in each shelf monitor and the controlling software, which resides in the NOVA 3. The NOVA 3 computer system shown in Fig. 5 was used to develop the NOVA 3 resident software, while the 8748 resident software was developed on an Intel microcomputer development system.

DISTRIBUTED SOFTWARE

While most of the intelligence of this system resides in the NOVA 3, considerable intelligence resides in each shelf monitor. Thus, distributed software is used to control and acquire data from this system. The executive residing in each shelf monitor was written in Intel MCS 8048 assembly language whose macroexpansion facility was used heavily. The NOVA 3 control programs were written mostly in FORTRAN IV with the exception of the RS232C interface drivers, and are subordinate to the Data General RDOS. The RS232C drivers were written in NOVA 3 macroassembly language.

SHELF MONITOR EXECUTIVE

An event-driven executive resides in each shelf monitor. The events that drive the executive are 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 that examines every command that comes down the command bus. If a received command is a broadcast command, it is executed; otherwise the command is compared 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 by appropriate broadcast commands being executed.

Whenever a gamma pulse occurs and interrupts have been enabled, an interrupt is requested on the external interrupt input to the 8748. The executive services this interrupt by incrementing a 16-bit software counter where the gamma counts are kept. Whenever a scale 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 scale and gamma interrupt occur simultaneously, the gamma interrupt is serviced fist while the scale interrupt is latched to prevent its being lost. The executive now uses 25 bytes of read/write memory and 400 bytes of read-only memory.

NOVA 3 RESIDENT SOFTWARE

The NOVA 3 minicomputer has responsibility for controlling the entire system of shelf monitors. In order to reduce the complexity of the control program, which is resident in the NOVA 3, as many control and input/output activities as possible are performed by the Data General RDOS. The functions performed by RDOS include:

1. Scheduling of all activities (tasks).

2. Gross timing of shelf monitor counting.

3. Transfer of all data to/from external devices. These functions are performed using system calls to RDOS.

The shelf monitor system control program does the following in support of the shelf monitor system:

1. Carries on a man/machine dialogue to configure the shelf monitor system.

2. Performs the routine acquisition of data from each shelf monitor in the system.

3. Processes acquired data to detect any tampering with SNM under surveillance.

4. Issues messages describing system exceptions to a human operator.

System startup first requires the bootstrapping of RDOS. The applications program that operates the shelf monitor system is then run. The applications program acquires the following information from the human operator by way of a man/machine dialogue:

1. Identity of each RS232C interface with shelf monitors.

2. Identity of each shelf monitor associated with an RS232C interface.

When a system is running, 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 the following:

1. Issue reset and count command.

2. Wait for response.

3. Wait for a nominal counting time (5 s).

4. Issue hold counts command.

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 scale and gamma-rates using time from timer.

11. Queue alarm message if calculated scale and gamma rates deviate significantly from average scale and average gamma rates.

12. Calculate approximate new average scale and gamma rates using present scale and gamma 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 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 and scale information, and byte 6, which contains a check sum that forces the low-order 8 bits of a sum of the 6 bytes to equal 254.

A variety of error conditions can occur in the system response to a dispatched command as follows:

1. I/O error detected by RDOS.

2. No response received.

3. First byte not the same as command dispatched.

4. Bytes 2 through 5 contain power-up default data counts.

5. The low-order 8 bits of the sum of all 6 bytes does not equal 254.

Every response from a dispatched command is examined for all of the above possible error conditions. If an error is detected, an error message describing the condition is queued. Additionally, an appropriate command dispatch sequence is executed until all lost data are recovered error free. If the lost data cannot be recovered after a specified number of unsuccessful retries, the defective device (RS232C interface and/or shelf monitor) is sent no more commands appropriate to it.

A past history of each shelf monitor must be saved if current scale and gamma rates are to yield possible alarm information. It is known that the scale and gamma rates may drift significantly over long periods (days and weeks). Thus, it was 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 and scale readings of 892 monitor systems, 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 described as follows:

$$A_n = (1/n)P + (n-1)/n\ A_o \quad . \qquad (1)$$

A_n is the new average, A_o 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 count rate and average scale rate. These are kept as floating point quantitites. An additional 16-bit status word is associated with each shelf monitor. This status word tells the applications program whether or not the monitor is operative or in use. The status word also contains initial timing sequence information and how many points are in the average count rates It is possible to configure the system before the cans of SNM are put on each monitor. The initial timing sequence is a time period wherein no data are 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 is variable but is usually less than 10 minutes. When a shelf monitor is first placed in service, the first scale and gamma rates read are all that is known about the monitor. While it is desirable 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 is to be given if a significant deviation from average scale or gamma count rates is detected. The scale frequency is sufficiently stable that a deviation of ± 3 counts/s is considered significant. The gamma alarms proved more difficult to establish. It was finally decided that gamma deviations greater than 3.5 to 4.0 standard deviations from the average count rate were signficant. Calculating the standard deviation for the most recent 100 gamma points is conceptually easy; however, the last 100 points would have to be saved and great computational effort would have to be expended for each deviation calculated. If the gamma points are assumed to have a Poisson distribution, the standard deviation of the gamma rate can be calculated using only knowledge of the average gamma rate and the average counting time.

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

σ is the standard deviation, G_a is the average gamma count rate, and T_c is the counting time. T_c is normally chosen to be nominal count time used by RDOS to time a counting period.

Messages are occasionally sent to the operator to advise him of abnormal conditions of various kinds occurring 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 input/output operation or a count operation to be finished. The objective here 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 can 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 period of the transaction, it can dequeue any tampering messages associated with the can of SNM. The message queue is examined every 2 s for ready messages.

NOVA 3 TASK STRUCTURE

Six tasks perform the above described functions. All tasks are written in FORTRAN IV and use its task monitor for their scheduling. Task MONCHK is active when the shelf monitor system control program first starts executing. This task performs the following functions: 1) receives information from a human operator on the operational status of every shelf monitor to be watched; 2) creates the remaining tasks and, if desired, prints periodic reports giving the status of each monitor that is active in the system. MONCHK has the highest priority of the six tasks.

Task RDACK reads and checks all shelf monitors in the system as follows:

1. Dispatches all commands to the RS232C interfaces.

2. Checks for errors in responses to commands.

3. Calculates gamma and scale rates from data read from monitors.

4. Checks for alarms.

5. Calculates the approximate average count rates.

This task executes as often as it can to acquire the count rate data it needs to check for alarms. This 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 tasks are active if their execution is desired.

Task TMTT is used to time the period required for a response to a command dispatched by RDACK. If no response is received in 4 s, task RDACK is notified that the command produced no response. This task executes every 0.5 s with a very short execution time. Task TMTU performs another timing function. This task can effect a delay in the start of calculation of the average scale and gamma rates after the time the monitor is first identified to the system. The delay is approximately 5 to 10 minutes. This task executes every 2 min with a very short execution time.

Task RMTT reads the 6-byte response to every command sent to the RS232C interface. This task executes when demanded by task RDACK. The execution of this task is timed by task TMTT. If this task 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 task RDACK. Task MSGWR examines the message queue every 2 s or as often as possible, whichever is longer for queued messages. The messages are then printed and dequeued. Messages with a time delay have their delays updated and remain queued. Normally, this task 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 contains 50 messages that have 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.

OPERATIONAL EXPERIENCE

Three separate and parallel shelf monitor arrays containing a total of 96 monitors have been operational since May 1979. One of these arrays, located in a plutonium storage vault five miles from the NOVA 3 mini-computer, contains 64 shelf monitors and is linked to the NOVA 3 by standard voice grade telephone lines. The other two arrays, located at the same site as the NOVA 3, each contain 16 monitors and are also linked to the computer by telephone lines. Transmissions between each array and the computer over these telephone lines has been virtually error free. The use of telephone lines to link these shelf monitor arrays to the computer demonstrates that a centralized computer can be used to monitor and control arrays that are located at distant locations from the computer.

Except for a problem with a batch of faulty chips, the operation of the monitors during test and evaluation has been quite stable and reliable. Figure 8 shows a plot of both gamma and weight sensor output for a period of 13 hours. A test was performed during this run that required a can of SNM to be removed from the shelf monitor for 30 seconds and then replaced on the monitor. Because the can was not placed back in exactly the same position as it was originally, the gamma count rate and the scale frequency have changed and this change results in an alarm for the thresholds that were employed during the test. The gamma detectors, the weight sensors, and the associated electronics have provided consistent and reliable data during the test and evaluation period.

SUMMARY

Special nuclear material in long-term storage in a vault is an attractive target for a diverter. A shelf monitor system has been designed that will enable constant surveillance of this material using a variety of sensors. A single-component microcomputer collects data from a GM tube that monitors gamma emissions and from a scale that monitors the total weight of the container and contents. A network of the microcomputer shelf monitors reports the acquired data to a minicomputer for analysis, storage and alarm if necessary. One objective of this research program has been achieved with the development of a reliable, inexpensive monitor network and associated data processing equipment capable of real-time monitoring.

FIGURE CAPTIONS

Fig. 1. Arrangement of shelf monitor sensors.

Fig. 2. Shelf monitor electronics board.

Fig. 3. Shelf monito- with weight sensor removed.

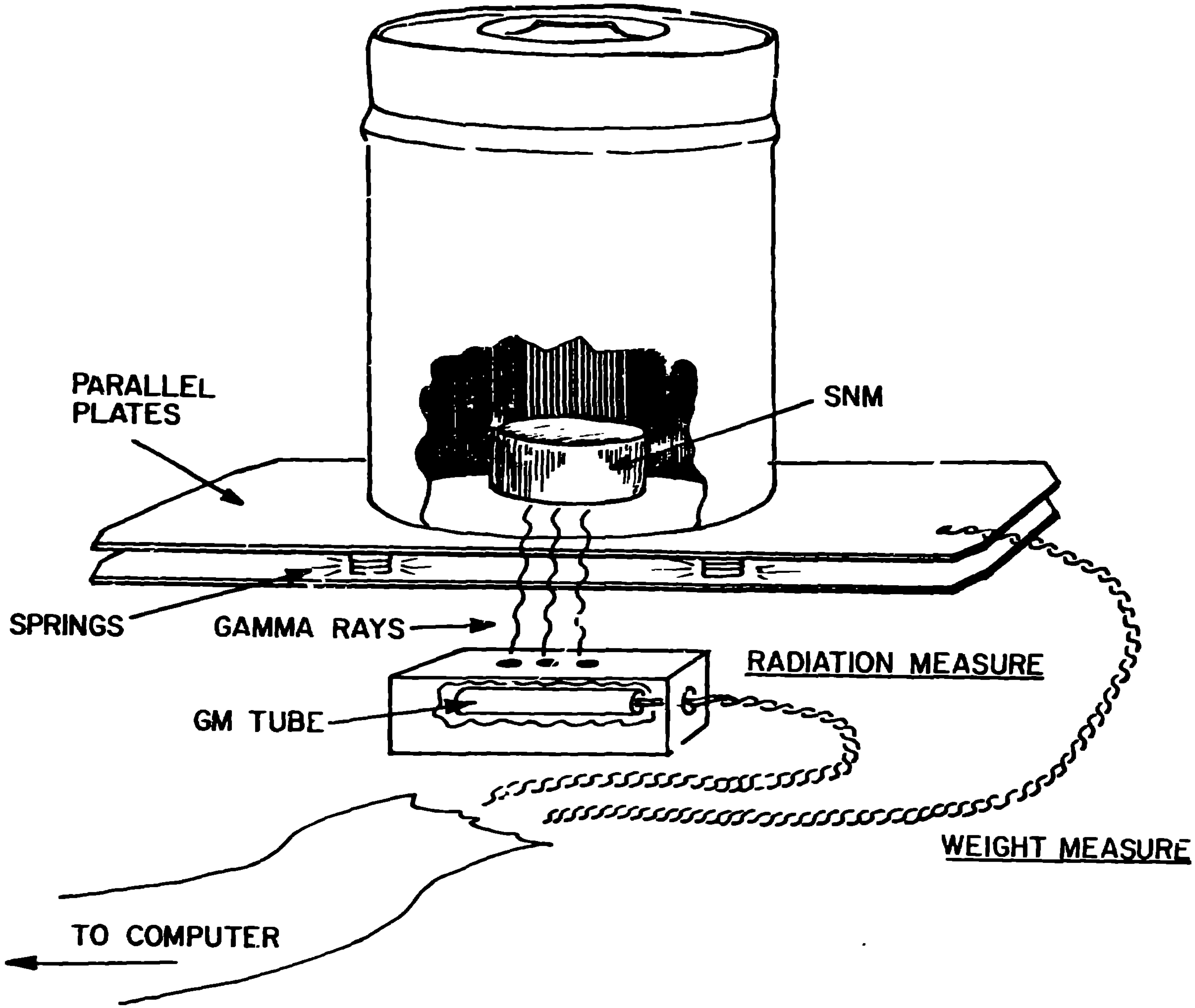
Fig. 4. Assembled shelf monitor.

Fig. 5. Block diagram of shelf monitor system.

Fig. 6. Sixteen-can prototype.

Fig. 7. Shelf monitor block diagram.

Fig. 8. Time history of a shelf monitor showing coinicdent gamma and gamma



V. Chelson
Figure 1

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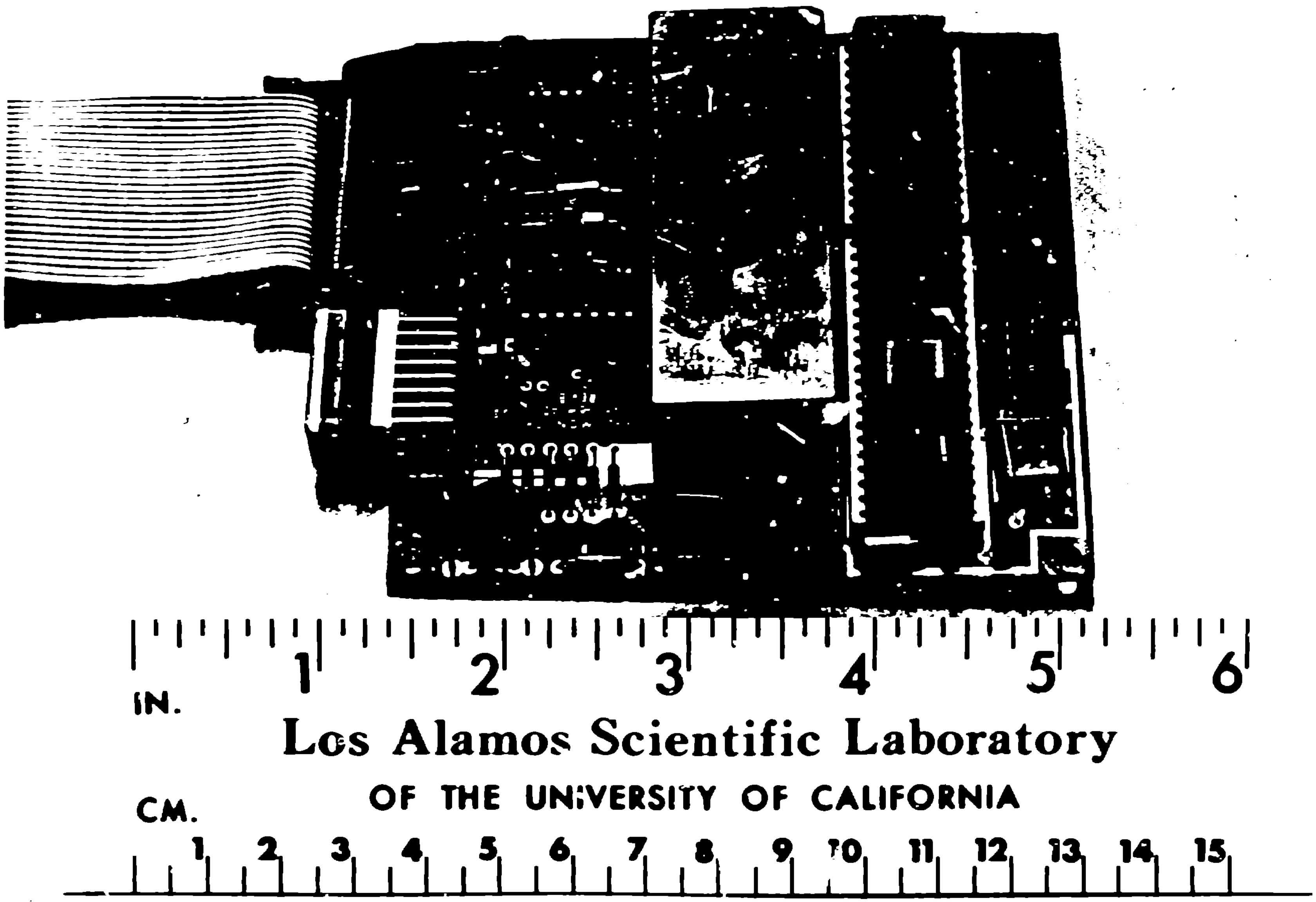
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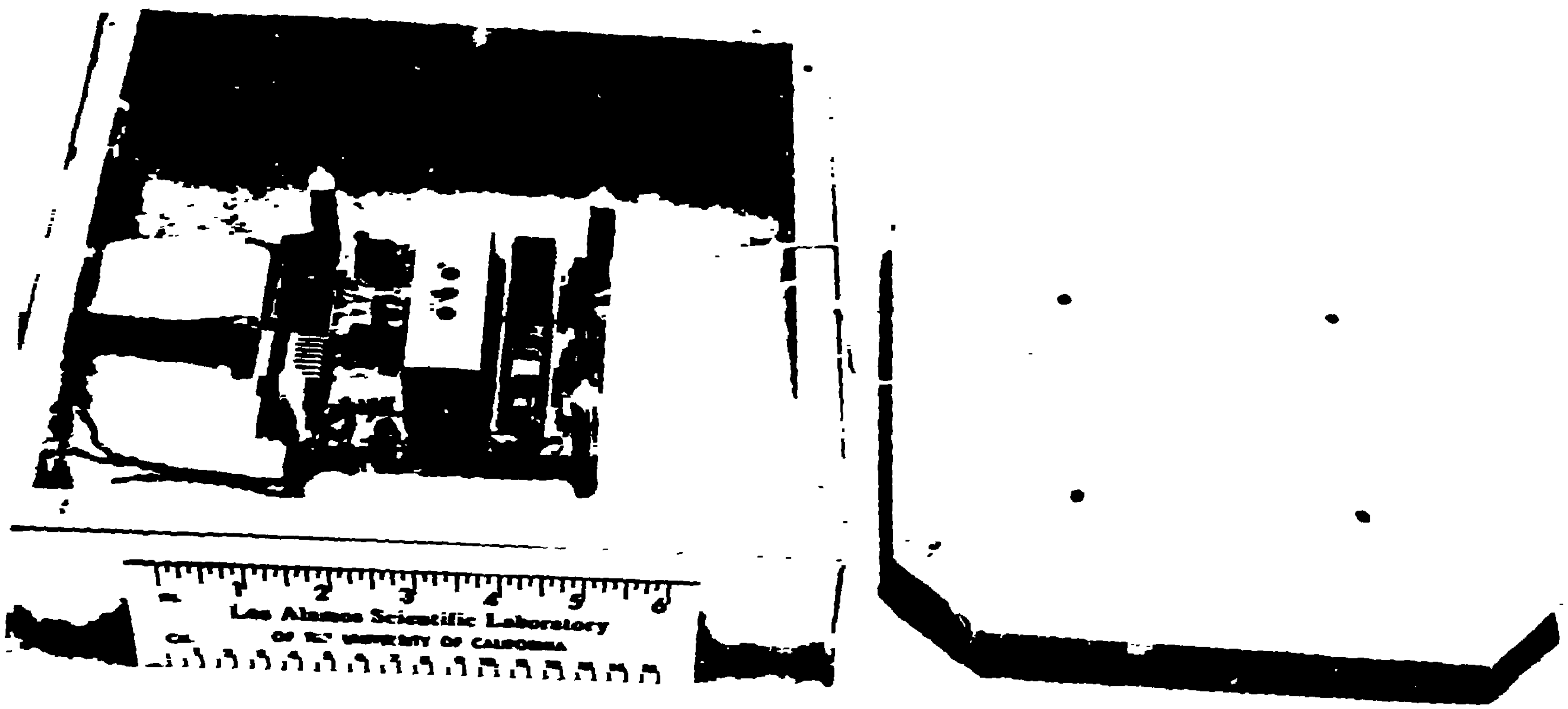

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Figure 4 62%


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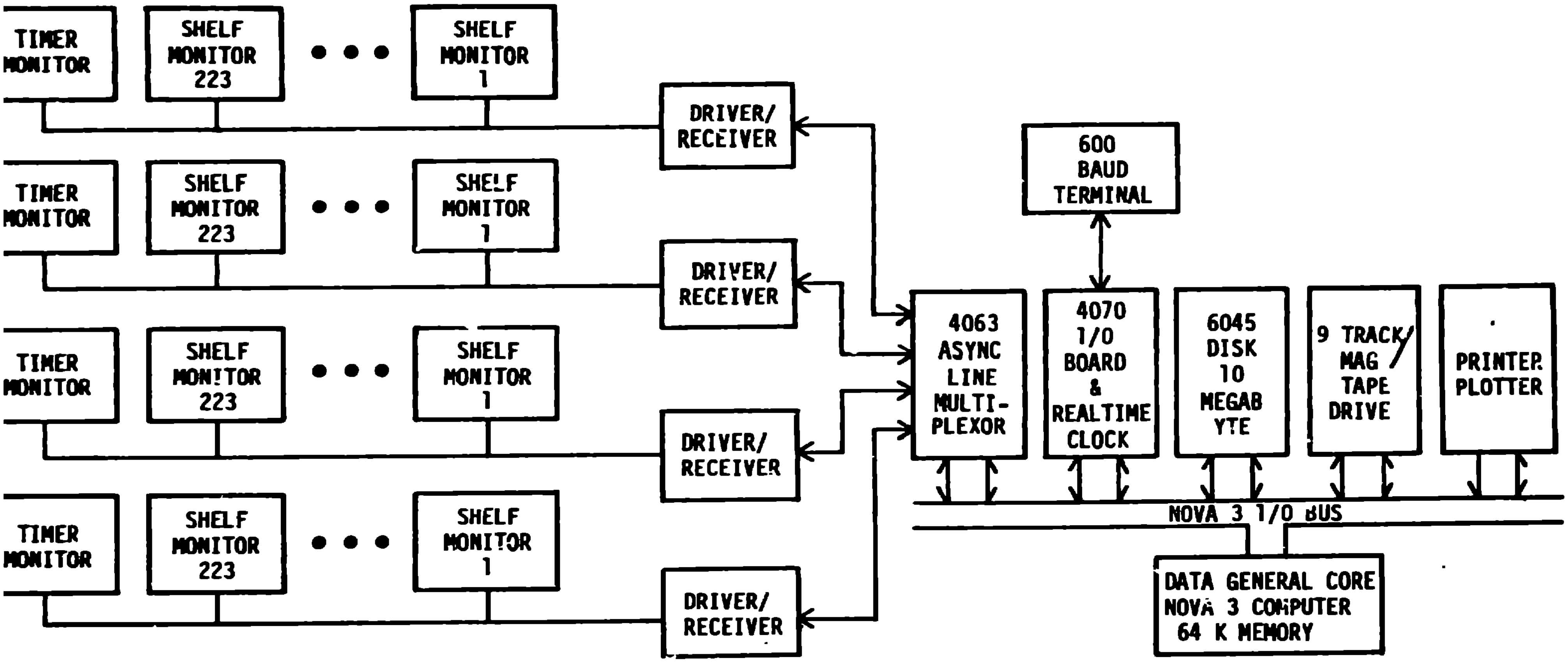

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Figure 5   572

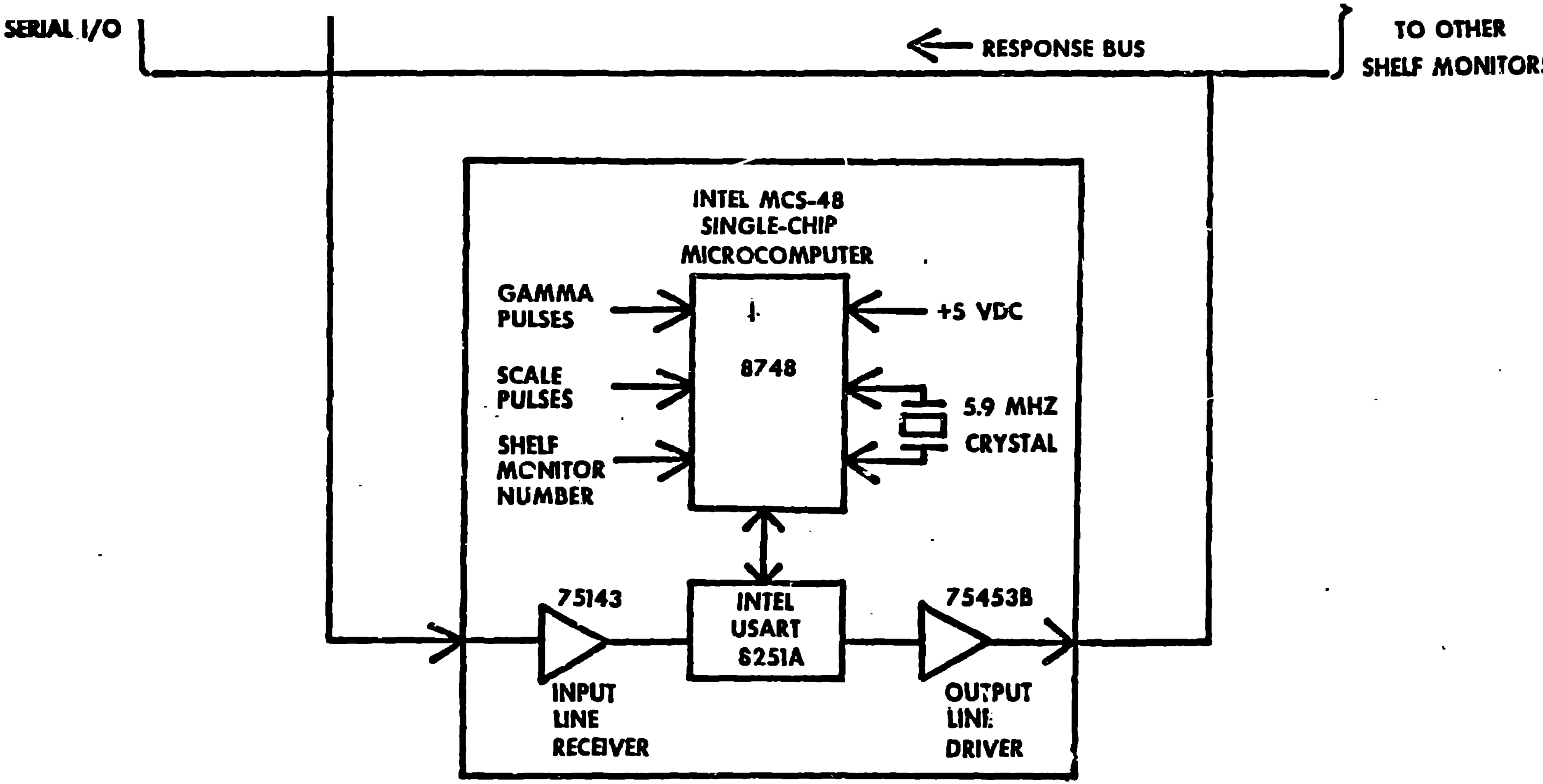

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Figure 7 57%

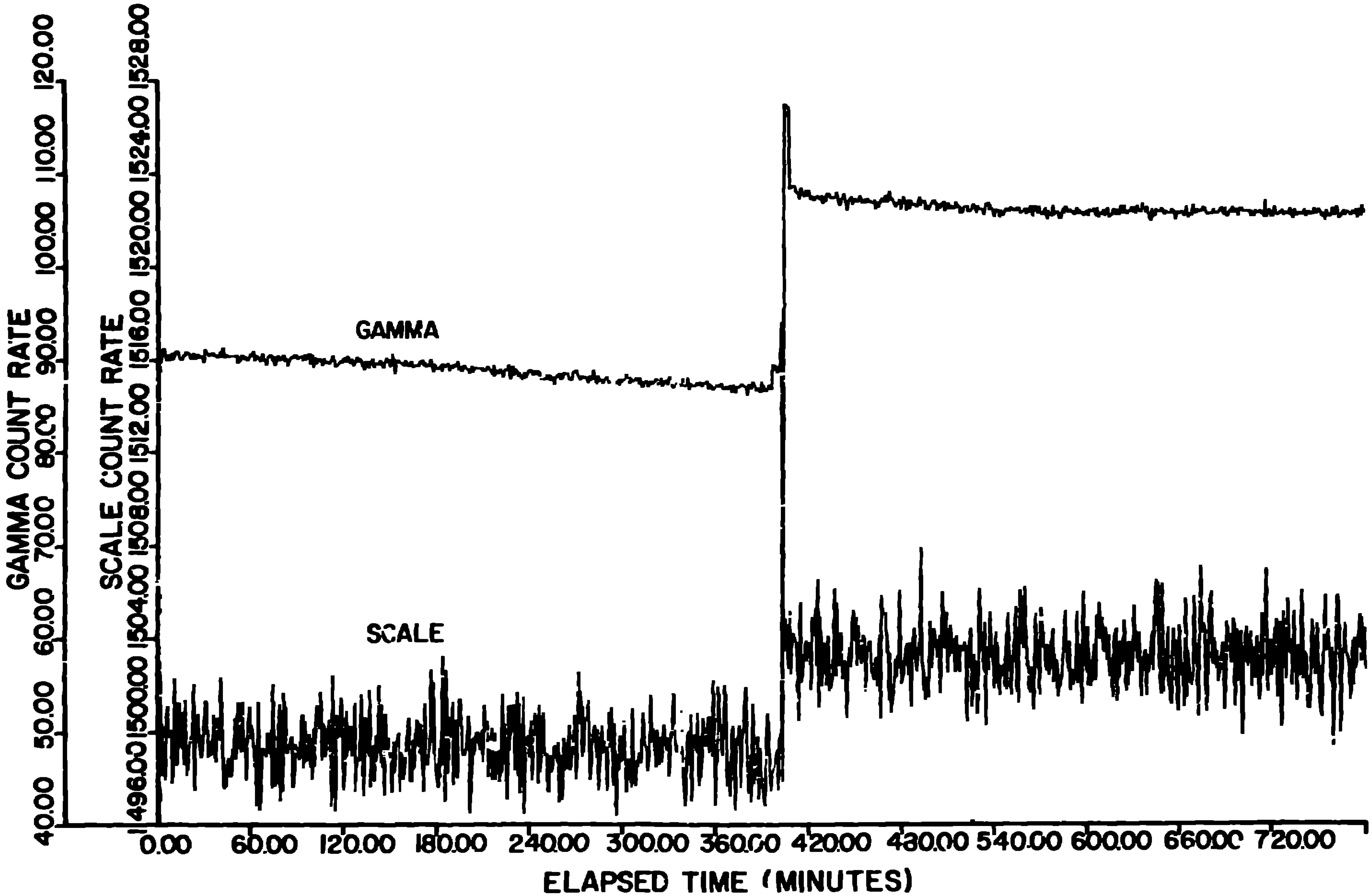

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Figure 8 57%