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# REACTOR SAFETY SYSTEM DESIGN USING HARDENED COMPUTERS

James A. Mahaffey

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Georgia Institute of Technology
Engineering Experiment Station
and
School of Nuclear Engineering
Atlanta, Georgia 30332

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# ABSTRACT

A technology transfer from a specific section of the military electronics industry to the nuclear power industry is proposed. Hardened, ruggedized digital computers and peripheral equipment have been successfully used for real-time data acquisition in military projects over the past decade. The superior reliability and survivability of this type of machinery under normal and abnormal conditions makes it attractive for use in certain critical areas of computerized reactor plant instrumentation and control. Hardened computers are available on the commercial market, and are used in process industries as well as in hazardous military applications. Characteristics and advantages of military equipment are examined, and a simple application is outlined.

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# FOREWORD

This document is a condensation of three reports written for EG&G Idaho, Inc., under subcontract no. K-8206:

Report 1, "Availability of Hardened Computer Systems," June 1980.

Report 2, "LOFT Functional Requirements for AOC Hardened Computer Systems," July 1980.

Report 3, "AOC Conceptualized System Design," September 1980.

These reports were the products of a one-year study of military computer systems and their possible application to critical functions in the nuclear power plant environment. The study was inspired by several successful projects at the Georgia Tech Engineering Experiment Station involving the use of mil-spec minicomputers for real-time data acquisition and display for military radar systems.

Several topics that were studied in some detail were left out of this brief summary report, such as an analysis of hardware and software failures in early nuclear plant computer installations, a study of the merits of redundant systems, and reports on the future uses of Ada, the new high-order, error-resistant computer language. Material that was considered interesting at the time but not immediately applicable, such as a report on the fault-tolerant multiprocessor concept, is also missing from this report.

Topics for which additional depth is available from the three original reports are referenced with superscripts.

## I. Introduction

Since their almost simultaneous beginnings in the early 1940's, nuclear engineering and digital computer engineering have evolved on paths that were likely to converge. As the size and complexity of nuclear power plants have multiplied, so have the speed and volume requirements of the control room data collection. The data-handling capabilities of computers have multiplied in parallel with the needs of the nuclear industry.

The level of involvement of computers in nuclear reactor operations has been partially limited by the failure probabilities inherent in digital hardware. Failure-mode problems have followed computer development since the beginning, when it was found that the Harvard Mark I relay computer would run for no more than a few hours without experiencing complete failure, due to a random fault in one of its thousands of logic elements. Computer logic design progressed through generations, vacuum tubes to solid state, always followed by a new set of component failure problems. The Iliac IV, considered to be a highly advanced example of the use of discrete transistor logic, was the largest, fastest computer in the world a few years ago. But, like its Mark I ancestor, it would run for only a few hours between failures. In both cases the individual components were not reliable enough to support continuous duty cycle operation on the scale imposed by each quantum advancement in machine complexity.

Process control computer technology is presently in a state of measured sophistication, not powerful enough to outdistance the reliability of its component parts, but powerful enough to be of important use in nuclear operations. Given environmental conditions within limits of temperature and humidity, a minicomputer system has a mean time between failures (MTBF) of about 1,000 hours. The mean time to repair (MTTR) varies over a wide range. Reduction of a system failure can involve touching a reset switch, or it can involve the long wait associated with ordering parts that are not readily available.

There are currently three identifiable problem areas in the hardware component of computerized reactor safety systems:

A. Reliability. There must be an excellent probability that a safety system computer will be functional during an incident where it would prove useful. Computer systems generally are too dependent on the operation of relatively fragile rotating memory devices, room environmental controls, and power line stability. Survivability under abnormal conditions, such as seismic shock, is not likely.

B. Maintainability. No digital computer is built claiming to have an infinite MTBF, so provision must be made to reduce a failure quickly. Diagnostic time should be minimized, as well as the effort required to replace a failed component.

C. Design Stability. A safety system computer should have a design life of a decade, such that it will not become obsolete and unsupportable during its useful tenure.

These three problems have been met and addressed in the area of military technology. Military uses of small computers are in some extremely critical applications, where hardware failure is very costly. Fighter plane control systems, missile launch systems, and radar warning systems use ruggedized minicomputers. Machines in this subclass of computers are known as mil-spec computers.

These machines are built to withstand extremely abnormal conditions, physical abuse, and electrical insults. The techniques used to harden the mil-spec computers are costly. However, the results of this extra expense are attractive to any critical application. By hardening a computer against temperature, shock, and vibration, operational reliability is enhanced under normal conditions. In addition to an increased MTBF of 5,000 to 10,000 hours, a mil-spec computer meets shock and vibration requirements, and is able to operate under high or low temperature conditions.

The military computers are specifically suited for real-time data collection and display. They are typically small, conservatively designed, 16-bit minicomputers, with no exceptional data-handling power. They are built for special imbedded-computer applications, involving rapid data acquisition and manipulation, and are generally not useful for large data-base management or large simulation codes. Speed and memory reach of mil-spec computers compares favorably with most commercial minicomputers.

Mil-spec computer systems are composed of small boxes connected together by cables. A single box can contain a processor plus memory, with other boxes containing extended memories, interfacing hardware, or mass storage. This "box-level" system construction is a remnant of the mil-spec computer's origins as a flight computer. The concept of quick maintenance by unplugging a failed box and replacing it with a spare is characteristic of fighter plane avionics technology. Each box unit is equipped with self-diagnosis capabilities, and in many cases can signal its own failure. Rapid fault reduction capability is one of the most important aspects of military technology that is transferable to the nuclear industry.

The requirement for strict adherence to the military standards and specifications tends to ensure design stability in the hardened computer family. Ruggedized general-purpose computers were first built to mil-specs over ten years ago. Not only are the first machines still in use, but equivalent machines are still being manufactured and designed into new systems. The original instruction-set architecture has undergone staged improvements, but assembly-level software written ten years ago is upwardly compatible with the latest mil-spec computers. In this way the military standards discourage obsolesence. Mil-spec computer technology is self protected against being phased out.

Military computers are purposefully built using commonly available component parts, to avoid problems with the availability of spares. Although all parts are rigorously screened for hardness characteristics, standard, off-the-shelf items can usually be substituted in emergency repairs. Circuit board-level spares and special parts, such as power supply transformers, are readily available from the manufacturers.

In addition to the ruggedized computers, mil-spec peripheral equipment, cables, and rotating memories are available, making it possible to harden a complete system. A completely militarized computer system may not be appropriate in a nuclear power plant, but a hardened core system of data collectors, concentrators, and displays can be assembled where reliability and emergency survivability are needed. The advantages of using mil-spec system components are summarized as follows:

1. For any computer-controlled information system to be a useful part of a power plant's instrumentation, it must be attuned to the psychological needs of the operators. This is a point that plant computer systems have lacked. Generally, the plant operators have avoided dependence and familiarity with well-meaning computer installations, because of a perceived or imagined sense that the computer is unreliable, and therefore cannot be relied on in an

off-normal incident or bothered with in normal operations.

Confidence in the equipment must be established, to the point where an operator has as much faith in his computer hardware as he has in the copper wires feeding the analog instrumentation. Computer systems will not take a fully active role in plant operations until this is achieved.

The mil-spec computer equipment has a real, measurable reliability advantage over commercial equipment built for process control, and it has an even more important apparent reliability, coming from its rigid, orderly construction, its stark simplicity, and its reputation in demanding military applications.

If the plant operators accept this type of computer as the most dependable equipment available at any price, then its use will have been justified.

2. By virtue of being hardened against shock, vibration, and high temperatures (table 3), a mil-spec computer is able to survive earthquakes, explosions, and cooling system failures, as well as radiation loads, without hardware modifications. Furthermore, all equipment of this type is tested for these qualities in hot rooms, thermal shock cabinets, and on shake tables in the factory as a standard feature. This eliminates a need for environmental testing by the end-users. Equipment said to be "mil-qualified" is built to a design for which specimens have passed rigorous qualification trials.
3. The percent availability of mil-spec computers is enhanced by the structure of hardware maintenance procedures for these machines, as well as the high reliability. The problems of maintainability

of complex systems in the field under time-stressed conditions has been faced by the military for at least the past decade. The system components designed to meet these needs have inherent qualities which speed up and simplify fault diagnosis, such as automatic test features and remote diagnostics. Once a fault has been isolated, it can quickly be corrected by box-level swapouts. No tools or external test equipment are needed for this procedure.

Confidence in the system is increased if hardware faults are easily detectable and repairable, even if the system uses hardware redundancy as an additional safety margin.

4. The availability of spare parts and continued hardware and software support is assured by the long-term goals of military programs in which this type of computer is used. An example of such a program is the Ground Launched Cruise Missile, an entirely new weapons system which will be maintained for at least the next decade. The ground support system for this program is the ROLM AN/UYK-19, which is a computer family introduced by ROLM in 1972. The life of the AN/UYK-19 design will be in excess of 20 years.

Judicious placement of hardened components in a plant safety system, using the design principles that have proven highly successful in military programs, will benefit the commercial nuclear power industry.

## II. Mil-Spec Computer Types and Characteristics

The need for small, extraordinarily reliable computers was seen in the late 1960's when experiments began with jet airplane flight controls. In this "fly-by-wire" system the plane is controlled by a computer, with the pilot giving direction indirectly through a computer interface to the controls. The flight computer thus became a major safety-system in the airplane, as computer failure meant loss of the plane. Design methods were developed for increasing digital computer reliability under normal and abnormal conditions.

This design philosophy is implemented in the "ruggedized" or "environmentally hardened" computers currently being manufactured.

### A. General Type Characteristics

Unique design features of environmentally hardened computers are the cabinet configuration and cooling methods.

The typical cabinet is built to the ATR criterion, which is a standard for aircraft radio chassis. The ATR is an aluminum alloy box, 7.625 inches high, 10.125 inches wide, and 19.56 inches long. All power and signal connections are made through the front. As there are no openings for cable runs or air circulation, the chassis can be made waterproof. Figure 1 shows a front and top view of a typical ATR chassis, and a "fractional" ATR chassis. Smaller versions of this design, called "half ATR" or "three-quarters ATR" are used to house hardened minicomputers or microcomputers.

Circuit boards are 9.5 inches by 6.5 inches fiberglass, with up to 14 embedded layers of printed wiring. All circuit components, integrated circuits, transistors, resistors, etc., are cooled individually by conduction. An aluminum thermal frame maintains thermal contact with each component, conducting heat to the side edges of the circuit board. Figure 2 shows a typical circuit board, with component layout and the heat-conduction paths.

To protect against flexing of the circuit board, metal stiffeners are

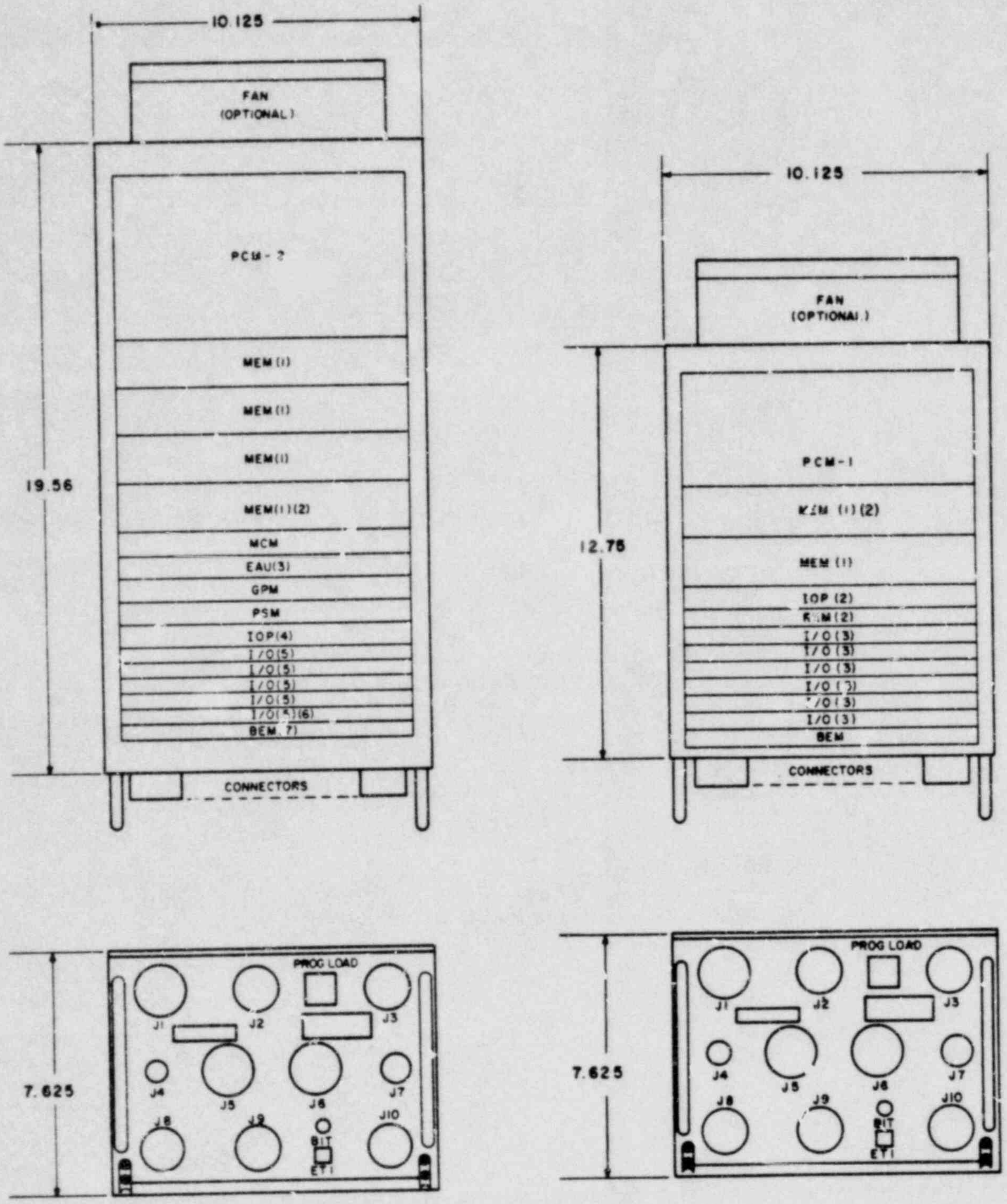


Figure 1. Front and top views of a standard ATR computer chassis, and a shortened version.

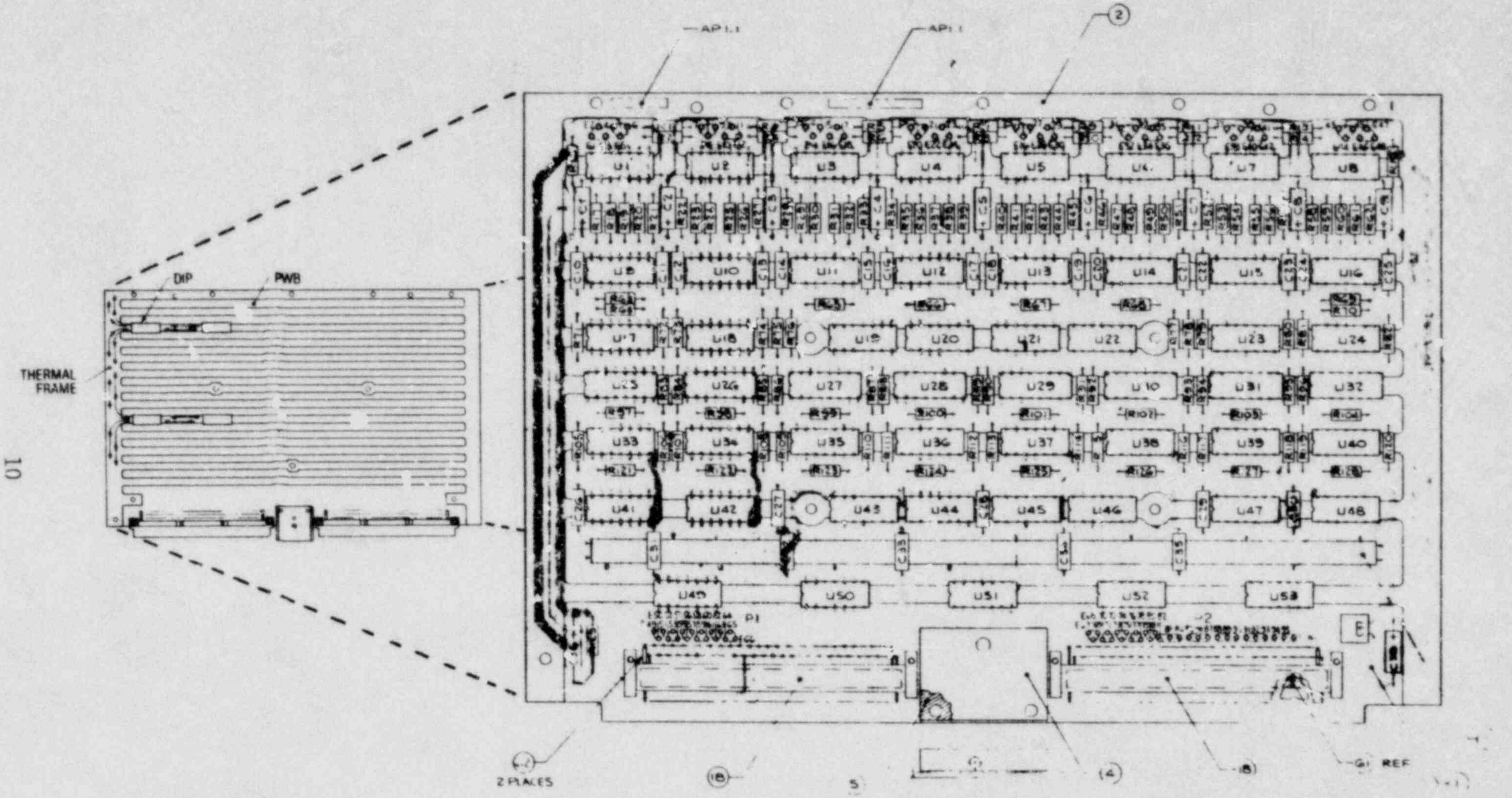


Figure 2. A ruggedized circuit board, showing the thermal frame which runs under each component.

bolted to the component side of the board. There are two varieties of stiffeners: bars running lengthwise across the board, or a stamped sheet of aluminum covering the components and bolted at the board edges.

Heat generated by the circuitry is conducted directly to the cabinet walls. The small size of the mil circuit board ensures short heat conducting paths. There are two methods used for cooling the cabinet walls: passive cooling through aluminum fins, and forced-air heat-exchangers.

Figure 3 shows the cabinet of a passively-cooled computer. Cooling fins are built into the power supply module, which is mounted in the front of the chassis. The advantage of passive cooling is that no fans are needed, and the risk of fan motor failure is eliminated. There are limits, however, to the amount of heat that can be radiated; this limits the power consumption, and therefore the speed and size, of the processor.

There are two heat-exchanger configurations: external-duct and internal-duct. In the external-duct design, air passages wrap around a standard ATR chassis. A fan exhausts air at the front of the cabinet. This heat-exchanger type can be retro-fitted to a passively-cooled chassis if unusual cooling is required. Use of an external-duct heat-exchanger violates ATR width requirements, but the extra width presents no problem if the computer is to be mounted in a standard 19-inch rack. Figure 4 shows an external-duct heat-exchanger cabinet fitted with a rack mount.

In the internal-duct design, ribbed channels are cut in the side-walls of the cabinet. Air is pulled through the channels by a squirrel-cage fan mounted on the back of the cabinet. An internal-duct cabinet is shown in figure 5.

Neither type of heat exchanger requires filters, as no air is blown

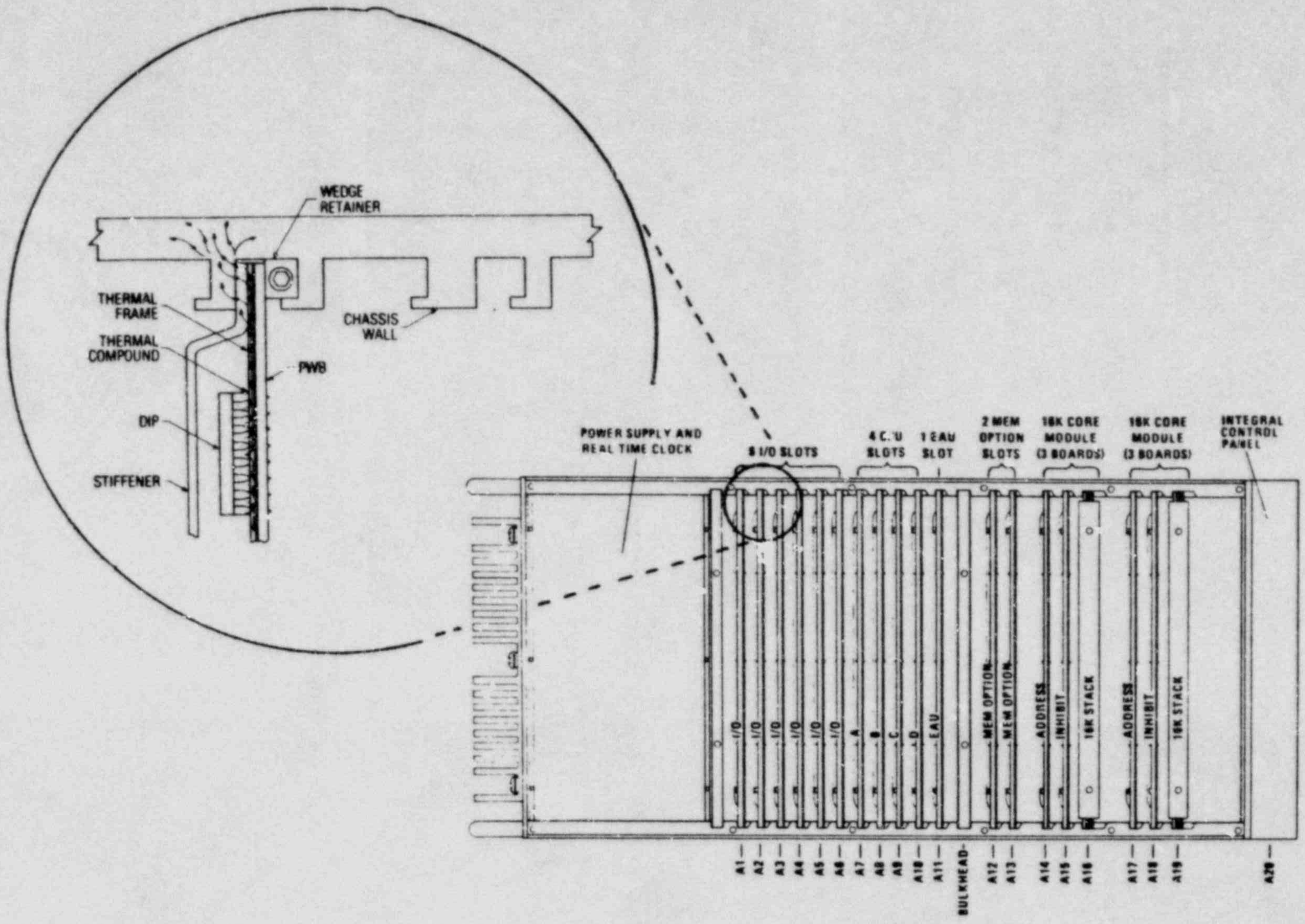


Figure 3. A passively-cooled computer chassis.

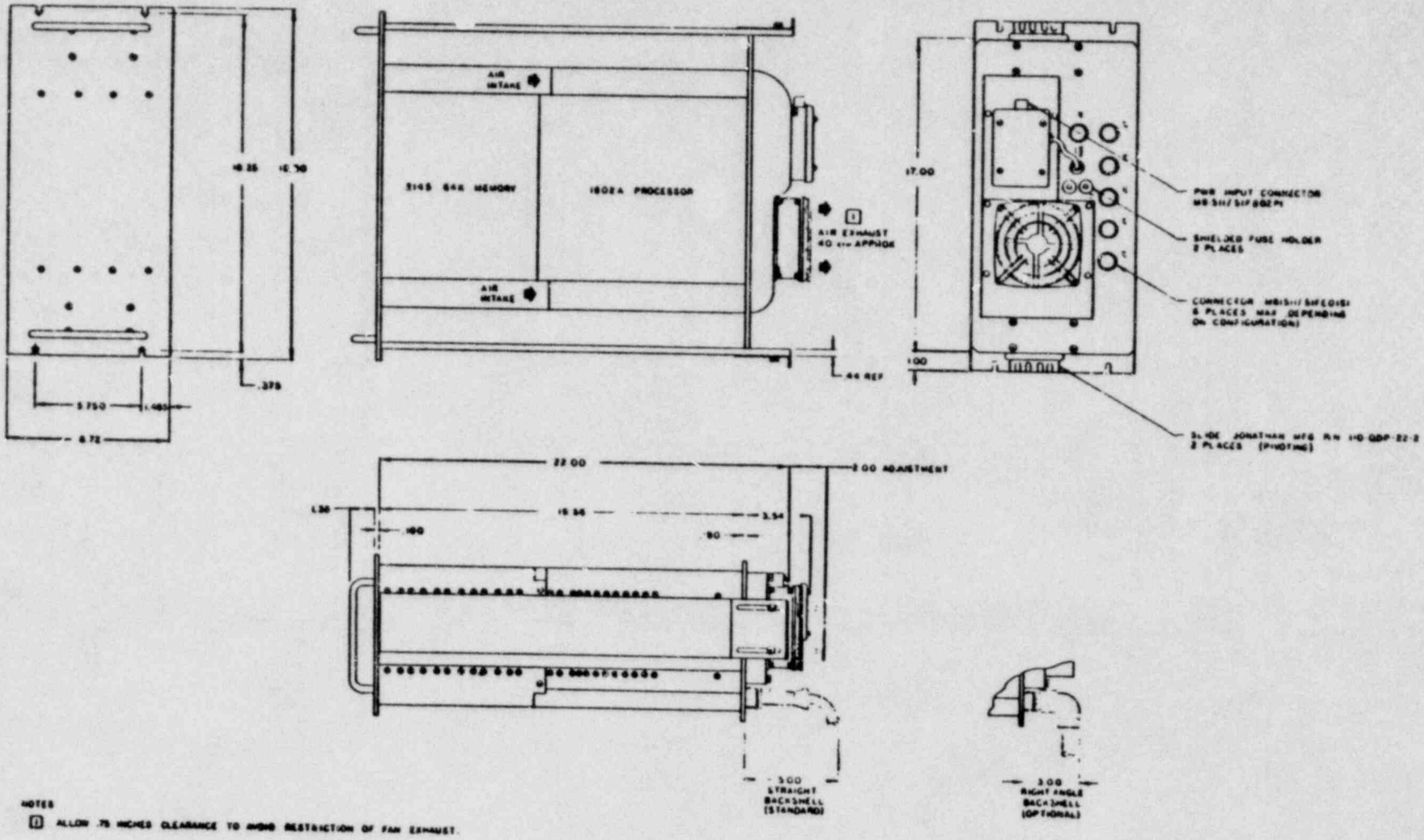
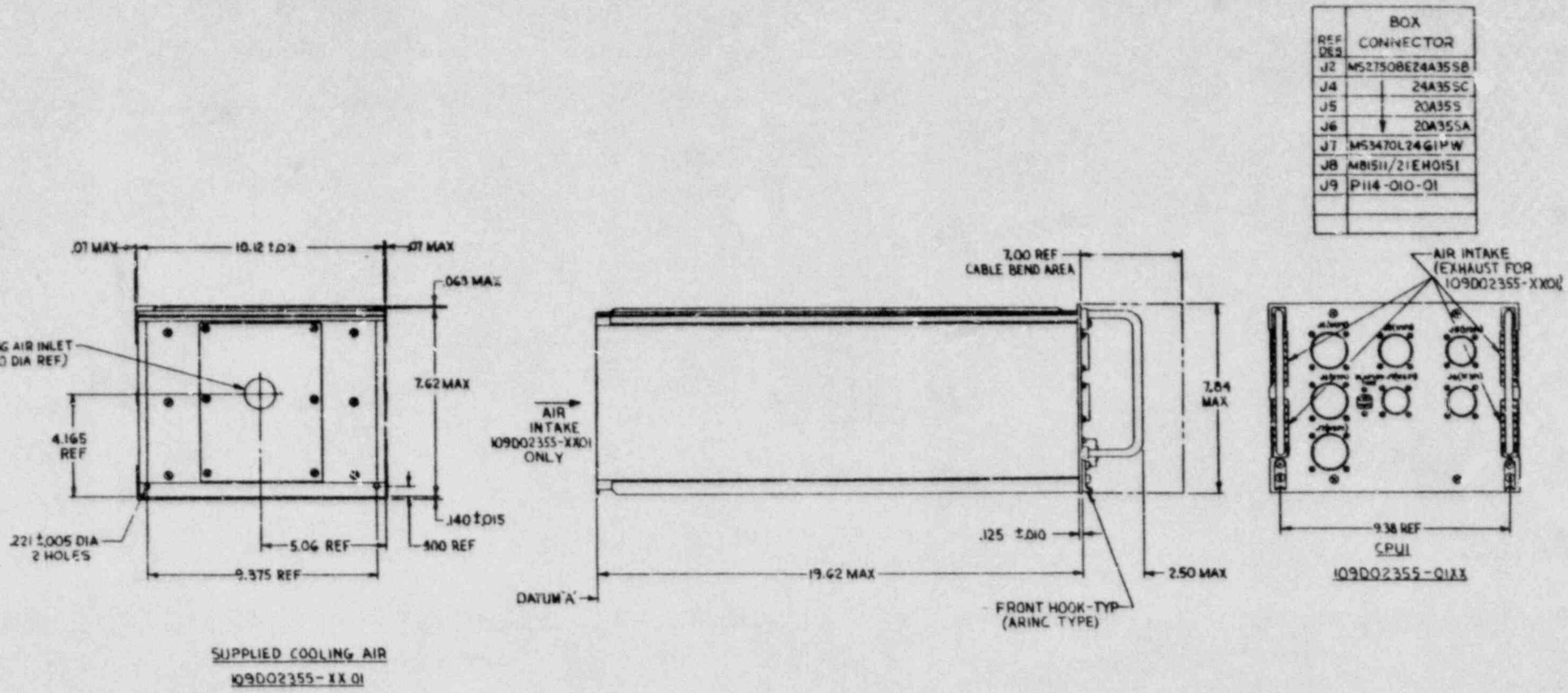


Figure 4. An ATR computer chassis fitted into a RETMA rack-mount with a forced-air heat-exchanger.



| REF DES | BOX CONNECTOR |
|---|---|
| J2 | MS27508E24A35SB |
| J4 | 24A35SC |
| J5 | 20A35S |
| J6 | 20A35SA |
| J7 | MS3470L2461PW |
| J8 | M81511/21EH0151 |
| J9 | P114-010-01 |
| | |
| | |

Figure 5. An ATR computer chassis with internal-duct heat-exchanger.

through the card cage. These conservatively-rated cooling systems are simple in design, and can maintain the computer operation under extreme air-temperature conditions. There is sufficient metallic heat capacity in the chassis to maintain operational temperature during a blower outage.

For environments of extreme shock and vibration, shock-absorber mounting trays are available. An ATR shock-mounting tray is shown in Figure 6[1].

B. General-Purpose Military Computers

General-purpose hardened computers are a sub-class of mil-spec machines, important to nuclear power considerations because they are functional copies of commercial minicomputers. There are three companies currently producing general-purpose mil-spec computers in quantity: NORDEN, ROLM and SESCO.

NORDEN Systems, famous for their gyroscopic bombsight built during World War II, is a subsidiary of United Technologies. NORDEN arranged licensing agreements with the Digital Equipment Corporation to build hardened versions of the very popular PDP-11 series minicomputers. Development of their first computer was completed in August 1977. A NORDEN design had been chosen as the ground-support computer for the MX missile program.

The ROLM Corporation has a long and distinguished record of hardened computer production. The first hardened minicomputer was released by ROLM in early 1970, based on the Data General NOVA series. A ROLM design has been chosen as the ground-support computer for the cruise-missile program. Production histories of ROLM computers are listed in table 1.

[1] Report 1, pages 2-33.

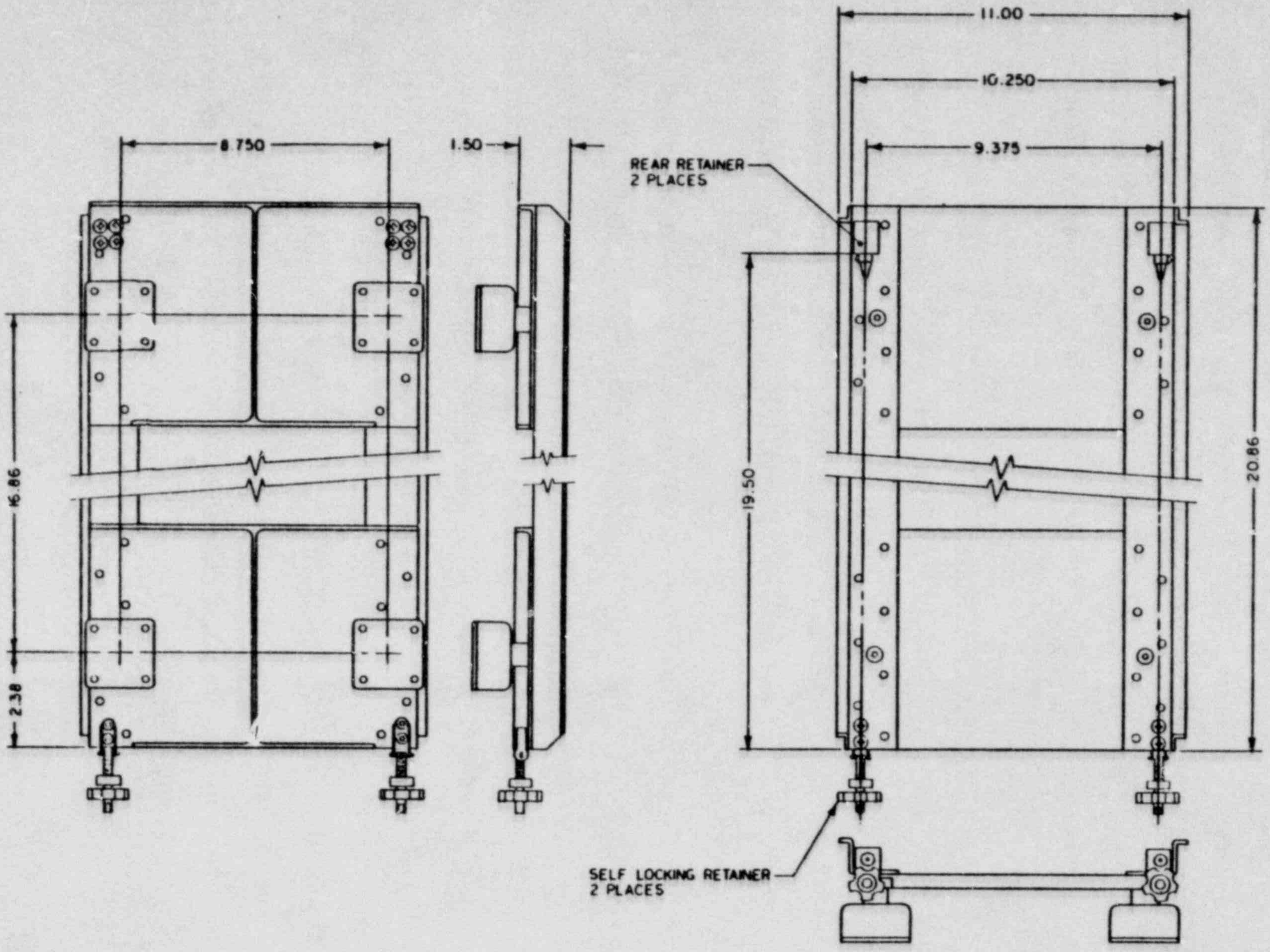


Figure 6. An ATR shock-mounting tray.

| COMPUTER | NUMBER INSTALLED TO DATE | DATE OF FIRST DELIVERY |
|---|---|---|
| ROLM 1602B | 500 | 1977 |
| ROLM 1603A | 90 | 1976 |
| ROLM 1606 | 100 | 1978 |
| ROLM 1664 | 100 | 1976 |
| ROLM 1666 | 40 | 1977 |

TABLE 1. Production histories of selected computers (Datapro Research, February, 1980).

|  | DEC PDP-11/70 | NORDEN PDP-11/70M |
|---|---|---|
| Temperature | $10^{\circ}$C to $40^{\circ}$C | $-54^{\circ}$C to $85^{\circ}$C |
| Humidity | To 90% | To 95% |
| Altitude | To 8,000 feet | To 85,000 feet |

TABLE 2. Environmental operating ranges for a commercial machine and its hardened equivalent.

| | |
|---|---|
| Operational | 10g, 5-2000 Hz, with vibration isolators; 2g, 5-2000 Hz, hard mounted. |
| Non-Operational Vibration | 5g, 5-2000 Hz, hard mounted. |
| Shock | 15 +/-2g peak, 11 +/-1 milliseconds duration, 400 lb. hammer, with isolators, or 1/2 sine pulse shape. |

TABLE 3. MIL-E-5400 specifications for shock and vibration for environmentally rugged computers.

SESCO (Severe Equipment Systems Company) is a subsidiary of Electronic Memories and Magnetics Corporation, which has been building hardened core memory systems for many years. In August 1979, SESCO began sales of the SECS 2, a hardened minicomputer which emulates the DEC PDP-11/35 instruction set. As of February 1980, SESCO claims to have delivered more hardened PDP-11s than NORDEN, with a total of 70 machines in the field.

Distinguishing design characteristics of machines currently available are as follows:

1. <u>NORDEN</u>

   a. <u>PDP-11/34M</u>

   Development of this processor was begun in October of 1976 and completed in August of 1977. This machine and the PDP-11/70M are unique among hardened computers in that they are logical replicas of their corresponding DEC commercial minicomputers. No attempt was made to condense the DEC design down into a simpler, smaller configuration. For maintenance, circuit boards from a NORDEN machine can be plugged directly into a DEC chassis, using a special extender board.

   Absolute compatibility with DEC software systems is insured by rigorous testing by DEC. The I/O bus (UNIBUS) is fully compatible with the DEC bus, making it possible to use commercial peripheral devices.

   b. <u>PDP-11/70M</u>

   The 11/70M is the most powerful hardened computer currently available. It features a memory reach of one megaword (or two megabytes) and a cache memory system. The cache is 2,048 bytes of extremely high-speed momory. Four bytes of data can be transferred from the main memory and into the cache in a single memory cycle. The processor can then access the data in the cache faster than it can in the main memory. The net increase in processing speed is approximately 80%. A cache is standard in the 11/70M, optional in the 11/34M. Failure of a cache memory does not stop the processor, but reduces speed.

Development of the 11/70M was begun in November 1977 and completed in October 1978. This computer is a logical replica of the DEC PDP-11/70. The 11/70M is generally the fastest machine under consideration. Comparisons of the environmental operating ranges of the 11/70M and its commercial counterpart are shown in table 2.

The 11/70M is also the largest hardened computer. Faithful adherence to the DEC PDP-11/70 design dictated the use of more circuitry than could fit in one ATR cabinet. A minimum configuration is three cabinets: one for the basic CPU and floating-point processor, one for memory, and one for the power supply and bus controller.

A realistic 11/70M system configuration with four cabinets is diagrammed in figure 7. This system includes an I/O chassis to provide interface to a line printer and a disk.

## 2. ROLM

### a. 1602B

The ROLM 1602B descends directly from the 1602, which

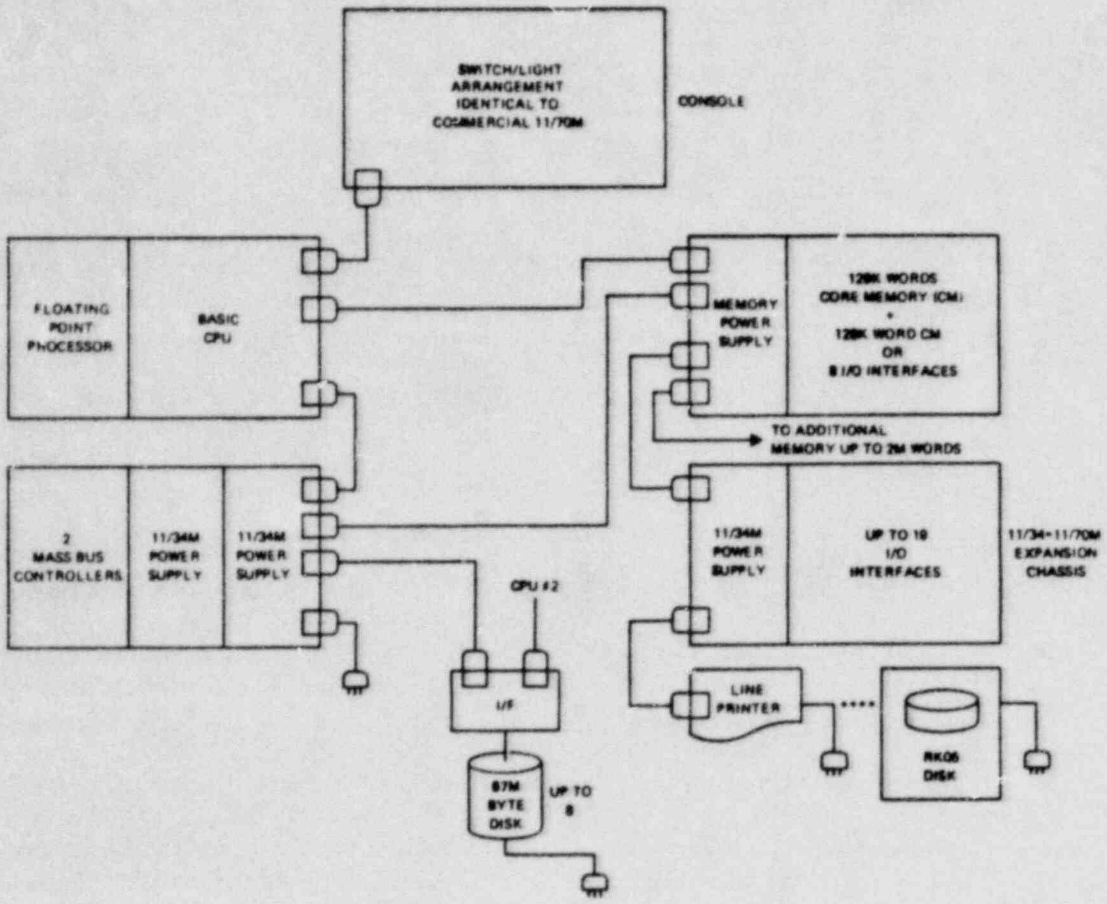


Figure 7. PDP-11/70M system diagram.

was introduced in 1972. This is a well-established design in the hardened computer world, with much field experience and formal reliability testing in its history. This machine passed its mil-qualification tests as a passively-cooled computer, but a heat-exchanger is available. Table 3 is a summary of the MIL-E-5400 specifications for shock and vibration for the 1602B.

The 1602B faithfully reproduces the instruction set of the Data General NOVA, but not its logical structure. The policy of ROLM has always been to simplify and miniaturize a commercial machine for the sake of reliability, always with a loss of speed. The NOVA has an ADD time of 0.2 usec; the 1602B ADDs in 1.0 usec. By copying only the instruction set, ROLM has established a more flexible relationship with Data General than NORDEN has with Digital Equipment. NORDEN is restricted under contract to sell computers only for military applications; ROLM has no such restriction. ROLM 1602Bs are commonly used for factory automation and other non-military applications. Comparative computer performance characteristics are shown in table 4.

The instruction-set duplication policy was violated in 1975 when ROLM implemented a unique floating-point processor in the 1664. This feature allows rapid calculations in multiply and divide operations in scientific notation. The NOVA at that time had no such floating-point hardware element, but ROLM considered this feature to be valuable enough to force a departure from the Data General standard

|  | NORDEN PDP-11/34 | NORDEN PDP-11/70 | ROLM 1602B | ROLM 1603A | ROLM 1606 | ROLM 1650 | ROLM 1664 | ROLM 1666 | ROLM MSE/30 | SESCO SECS-2 | PRIME (4) 550 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Max. Memory Size | 128K | 2M (1) | 64K | 32K | 576K | 16K | 256K | 576K(2) | 1M | 8K | 1M |
| Instruction Time |  |  |  |  |  |  |  |  |  |  |  |
| Add | 1.9 usec | 0.3 | 1.05 | 1.2 | 1.0 | 1.05 | 1.0 | 1.0 | 0.5 | 1.92 | 1.1 |
| Multiply | 9.0 usec | 3.3 | 4.9 | 7.7 | 5.4 | 4.9 | 5.4 | 5.4 | 5.1 | 9.82 | N/A |
| Divide | 12.9 usec | 8.0 | 8.9 | 7.7 | 12.6 | 8.9 | 12.6 | 12.6 | 9.3 | 12.48 | N/A |
| Memory Cycle Time | 900 nsec | 240 | 1000 | 1200 | 1000 | 1000 | 1000 | 1000 | 1000 | 960 | 750 |
| I/O Transfer Rate | 1.1M word/sec | 2.9M | 666K | 769K | 2M | 666K | 2M | 2M | 800K | 100K | 1.25M |
| Minimum Number of Cabinets | 1/2 | 3 | 1 | 1 | 1 | 1/2 | 1 | 1 | 2 | 1/2 | (3) |
| Cache Memory | Optional | Yes | No | No | No | No | No | No | Yes | No | Yes |
| Floating Point |  |  |  |  |  |  |  |  |  |  |  |
| Add | 8.9 usec | 1.7 | 4.6 | N/A | N/A | N/A | 1.4 | 1.4 | 1.1 | N/A | 3.98 |
| Multiply | 16.2 usec | 3.2 | 18.1 | N/A | N/A | N/A | 3.2 | 3.2 | 1.1 | N/A | 8.24 |
| Cooling | Forced Air | Forced Air | Passive | Passive | Forced Air | Passive | Forced Air | Forced Air | Forced Air | Passive | Forced Air |
| Commercial Equivalent | DEC PDP-11/34 | DEC PDP-11/70 | DG NOVA+ | DG NOVA | DG NOVA | DG NOVA | DG NOVA+ | DG NOVA+ | DG ECLIPSE | DEC PDP-11/35 |  |

(1) Never tested with 2M words installed.
(2) Tested with 576K words installed, capable of 1M words.
(3) Not available in ATR cabinets.
(4) A commercial system, included for comparison.

TABLE 4. Computer Performance Characteristics

instruction set. Data General eventually released a floating-point feature in the NOVA series, but the instructions were not compatible with the ROLM instructions. Versions of FORTRAN IV to be implemented on a NOVA and a ROLM machine are therefore slightly different. This difference is on the assembly-language level, and is invisible to the FORTRAN user.

b. 1603A

The ROLM 1603A was introduced in 1976 as a low-cost version of the original 1601, the first hardened NOVA. Its memory capacity is severely limited to 32K and no floating-point hardware is available. The 1603A is packaged in a passively-cooled full ATR cabinet, with an optional integral control panel.

Application for this computer could be as a backup system, executing a subset of the main computer program. It is the least-expensive hardened computer for which figures are available. Table 5 lists prices for computers built by ROLM.

c. 1606

The 1606 was introduced in 1977. This is a 1666 without the high-speed floating-point processor capability.

d. 1650

In 1976 the 1602 processor was reduced in volume by the use of large-scale integration (LSI). The processor was reduced from nine modules to one, packaged in a 1/2 ATR chassis, and designated 1650. This small computer could be

| | ROLM 1602B | ROLM 1603A | ROLM 1606 | ROLM 1650 | ROLM 1664 | ROLM 1666 | ROLM MSE/30 |
|---|---|---|---|---|---|---|---|
| Price of CPU, Power Supply, Front Panel, and Minimum Memory | 25,250 | 13,400 | 43,900 | 26,250 | 39,450 | 48,900 | 135,000 |
| Price of Memory Increment (16 K Words) | 7,000 | 6,000 | 7,000 | 7,000 | 7,000 | 7,000 | 7,000 |
| Comments | Mil Qualified | Mil Qualified | Mil Qualified | | | Mil Qualified | Includes 128 K Words of Memory |

TABLE 5. Prices of ROLM processors.

used as a remote data-gathering "node" of a network. Its instruction compatibility with the 1602B is a positive feature. The chassis is very small, 7.62 inches by 4.8755 inches by 12.56 inches, and is passively-cooled.

Built-in test equipment (BITE) for the 1650, identical to that in the 1602B, is available as an option.

e. 1664

In 1975, ROLM introduced an enhanced version of the 1602, having a ROLM-designed high-speed floating-point processor. This is a good example of a moderately powerful, single-cabinet hardened computer.

f. 1666

The 1666 was introduced in 1977 as an enhanced 1664. This computer has a memory mapping feature, which allows up to 1024K (1M) words to be addressed.

A suggested 1666 system is diagrammed in figure 8. The 1666 is external heat-exchanger cooled, with a remote control panel.

Only 64K words of primary memory can be housed in the processor chassis. Memory increments are 128K words of core memory, housed in a heat-exchanger cooled, full ATR cabinet with an independent power supply. In the interest of reduced size, ROLM does not supply core memory modules with parity checking capability. A full memory chassis (128K) uses 135 watts of power.

g. MSE/30

The MSE (mil-spec Eclipse) is a hardened version of the

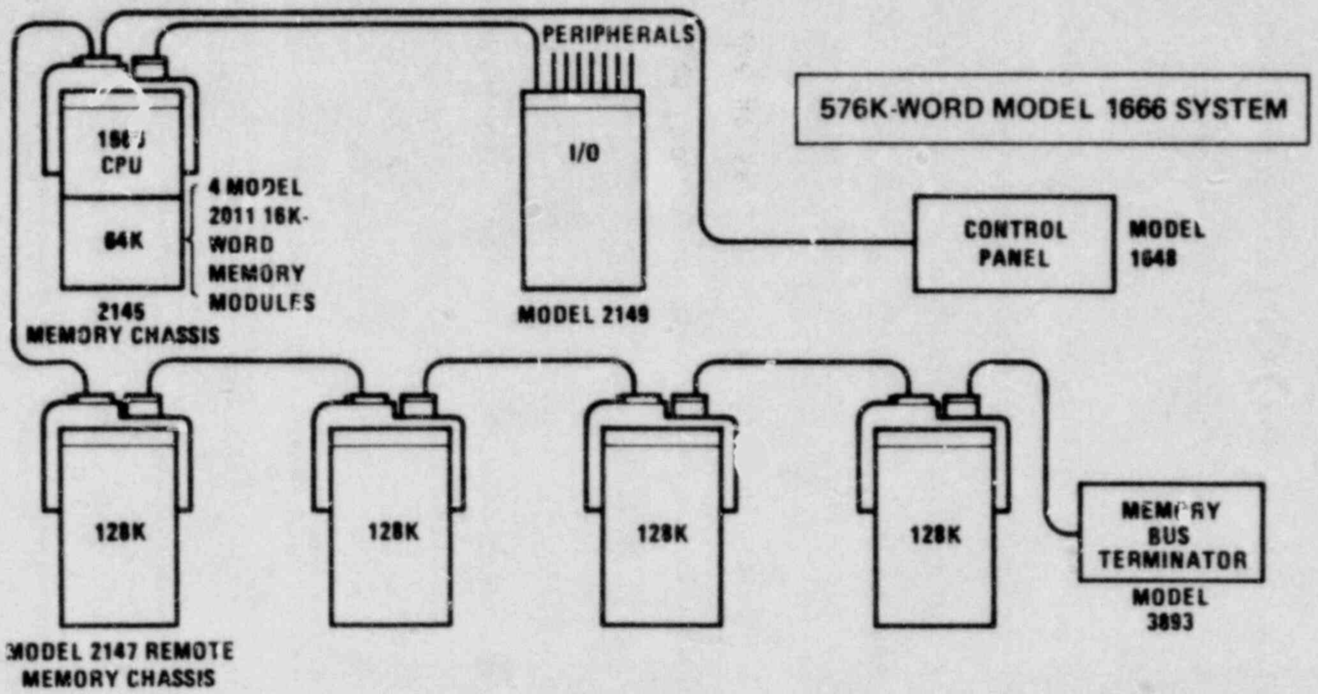


Figure 8. 576K word ROLM 1666 system.

Data General Eclipse. This new processor has a cache memory, high-speed floating-point processor, and primary memory expandable up to 1024K words.

A minimum MSE system requires two cabinets: one for the processor and minimum memory and one dedicated to I/O. Unlike all other ROLM machines, the MSE has no room in the main chassis for minimum I/O controllers. Memory is expanded in 128K increments using the same module (the 2147 remote memory) as the 1666. The three basic units of MSE expansion are diagrammed in figure 9.

The MSE/30 is an instruction set replica of the Data General Eclipse M/600. The circuitry is completely different, with the ROLM computer built specifically for reliability and hardness. The ROLM processor is 83% as fast as the equivalent commercial Eclipse. The Eclipse costs about $86,000, which is 59% of the cost of the ROLM MSE.

### 3. SESCO SECS-2

In early 1980, SESCO announced the SECS-2, a hardened processor equivalent to the DEC PDP-11/35. This computer is very similar in size, speed and instruction set to the NORDEN PDP-11/34M.

## C. Hardened Peripheral Equipment

It has been observed that there is no economy in the practice of buying an expensive, hardened computer and then buying commercial-quality peripheral equipment. In such cases the adage, "no computer system is more reliable than its least reliable component," is proven.

A few manufacturers build small quantities of system support devices,

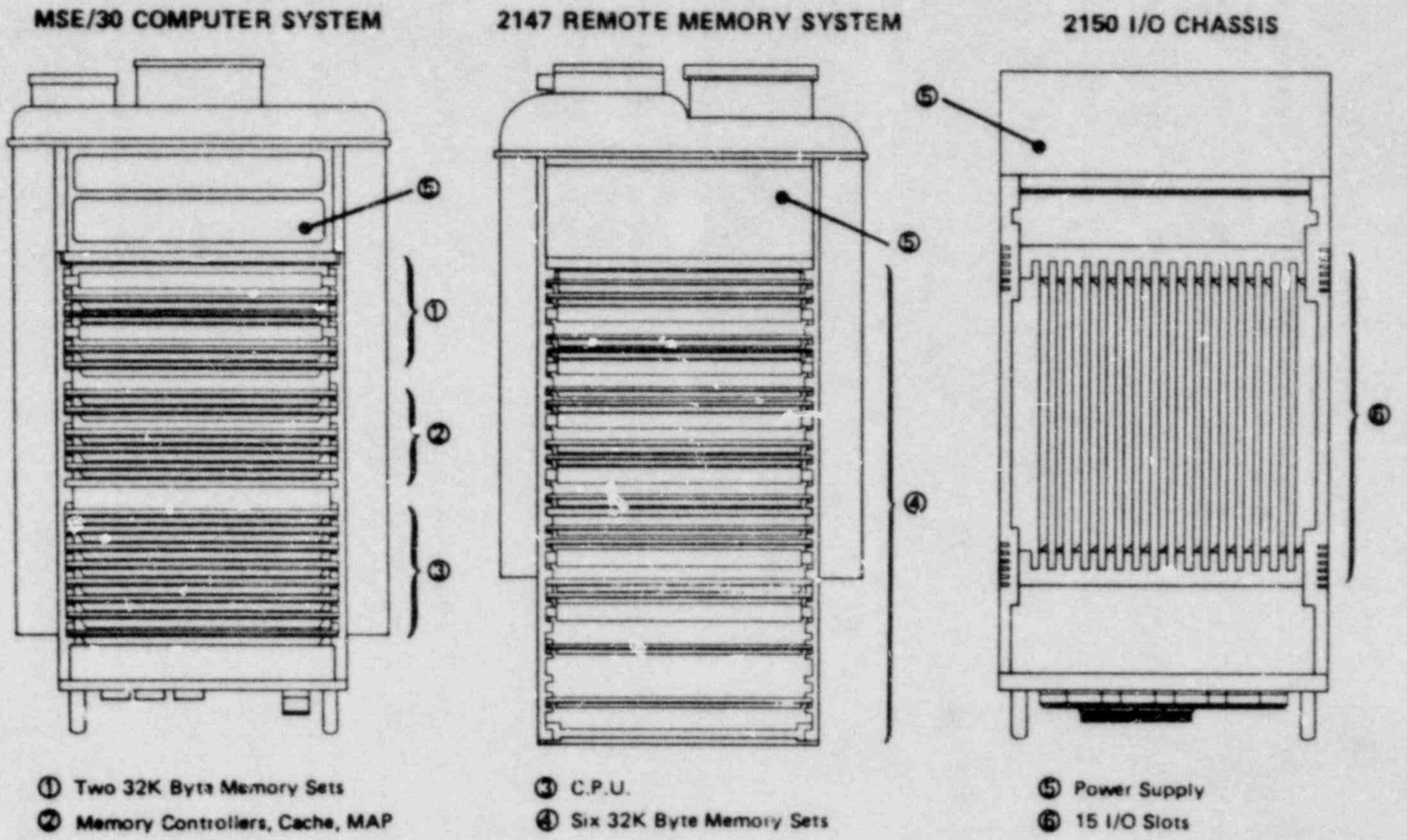


Figure 9. MSE/30 computer modules.

such as disks and tape-drives, for the general-purpose computers built by NORDEN and ROLM. These units have excellent reliability characteristics, often surpassing those of the hardened computers. Prices are understandably high, usually two or three times that of a comparable commercial unit. Reliability predictions for hardened peripherals are listed in table 6.

Several companies build hardened disk storage units for special military applications. Fixed-head disk units built by Digital Development Corporation (DDC) are particularly notable, because they interface directly to the ROLM and NORDEN machines. These disks are designed to meet the same standards for vibration, shock, and temperature as the computers. A DDC disk is designed to fit in a standard 19-inch rack, sealed inside a cylindrical aluminum cover. There is no scheduled periodic maintenance. A schematic diagram of a DDC disk chassis, with dimensions, is shown in figure 10. The MTBF of this unit is 10,000 hours. Such reliability is achieved by the use of fixed read/write heads. There is only one moving part -- the disk platter. Each of 256 tracks has a dedicated head. Specifications for the DDC series M6000 disks are detailed in table 7.

Rugged magnetic tape units (MTUs) are available, but the cost difference between the hardened and commercial models is considerable -- $29,000 for the hardened reel-to-reel MTU, $8,000 for the commercial version. Mil-spec tape drives may not be appropriate for nuclear applications, given their limited role in computer operations.

Hardened line printers with plotting capability are available. A conventional high-speed line printer is built in a hardened version by Miltope for the NORDEN and ROLM computers. This unit (Model 212A) prints 80 columns at 400 lines-per-minute. The printer costs $21,700, and the

| VENDOR | DEVICE | MTBF (Hours) |
|---|---|---|
| DDC | Fixed-head disk | 10,000 |
| Miltope | Thermal line printer | 5,000 |
| Miltope | Tape transport | 4,000 |
| Interstate | Plasmascope | 10,000 |
| Miltope | Flexible disk drive | 7,000 |
| Miltope | High-speed line printer | 9,600 |
| Miltope | Cartridge recorder | 10,000 |

TABLE 6. Calculated reliability predictions for hardened computer peripherals.

| | |
|---|---|
| Word Capacity Per Unit | 512K - 2M |
| Size | 16.80 in. x 17.55 in. x 20.00 in. |
| Weight | 120 pounds |
| Disks Per Unit (Maximum) | 2 |
| Tracks Per Surface | 64 |
| Surfaces Per Disk | 2 |
| Data Rate | 4.4 MHz |
| Disk Speed | 3,600/1,800 RPM |
| Start Time | 6 minutes ($0^oC$ - $50^oC$) |
| AC Power | |
| Voltage | 115v +/-10% |
| Phase | 1 |
| Frequency | 60/50/400 Hz |
| Start Current | 3.0A |
| Run Current | 1.5A |
| Cost | $40,300 disk, $7,000 controller |

TABLE 7. DDC Series M6000 disk specifications.

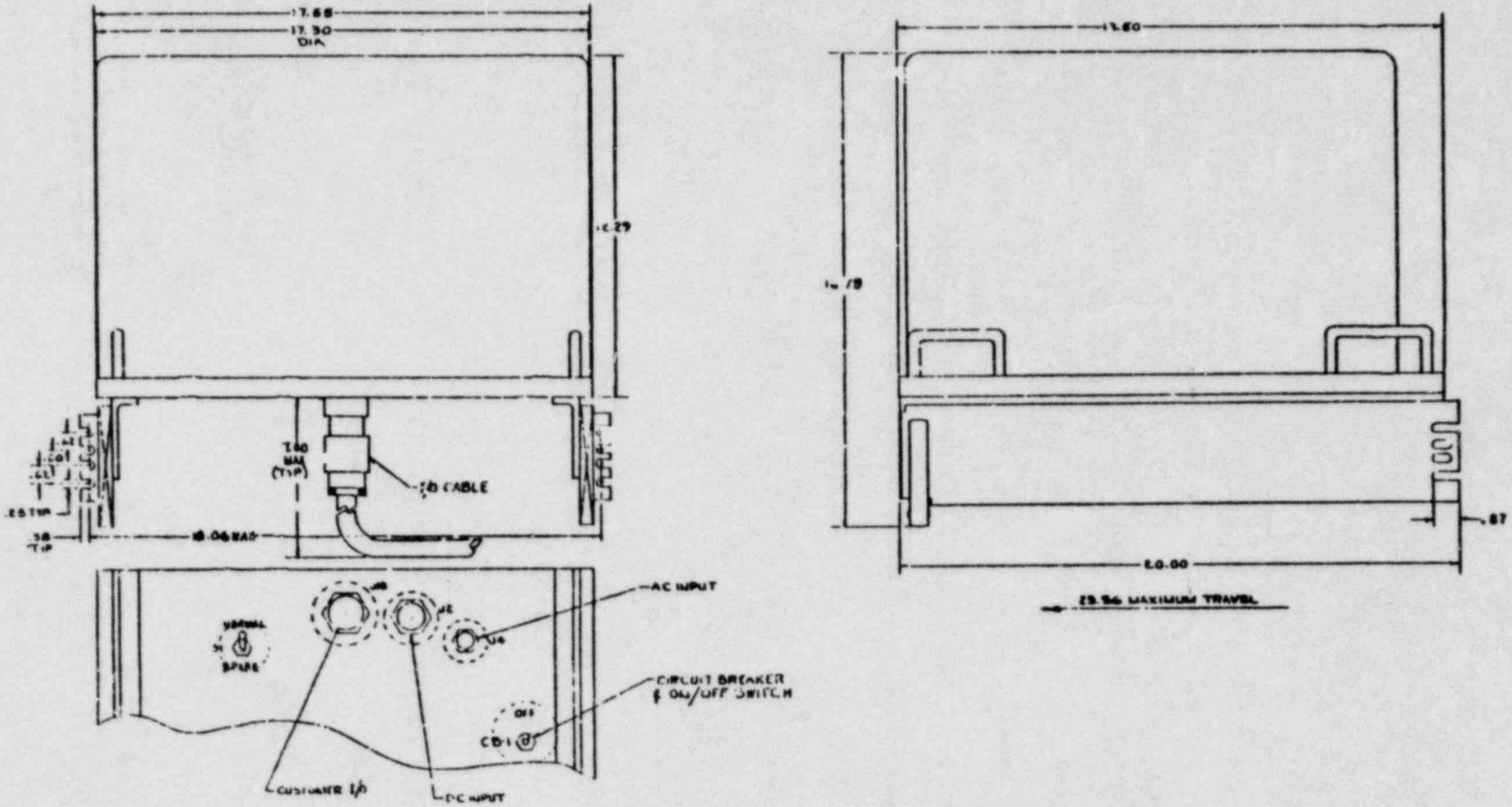


Figure 10. DDC series M6000 fixed-head disk.

controller $1,500 for a ROLM computer.

A hardened electrostatic printer/plotter is built by Versatec for the NORDEN and ROLM computers. Characters are drawn in a 16 by 16 matrix using a Xerox-like process. Graphic resolution is 200 dots per inch on an 8-1/2 by 11-inch output format. This is an inherently reliable and quiet design, as it contains no mechanical arms, hammers or pens. These printers are used in military applications for generating battlefield maps from stored data bases.

A hardened cathode ray tube (CRT) terminal is built by Sperry Univac Defense systems, the AN/USQ-69. This is basically a conventional black and white CRT housed in a rugged cabinet. Color CRT systems are quite difficult to harden, because of shock and vibration problems with the metal shadow mask inside the tube envelope. Mechanical tolerances of this component are very critical.

The more popular type of display for use in critical applications is the plasmascope. The plasmascope is a dot-matrix, 512 by 512, display device with many inherently reliable features. Two 1/4-inch plates of glass are mounted in a rigid metal frame. A neon-argon gas mixture filling the space between the parallel glass plates will glow, giving orange dots, at the addressed intersections of X and Y axis electrodes etched into the glass. The plasmascope is electronically simple, and it requires no high voltages. Contrast, stability, resolution, and clarity are excellent. Susceptibility to X-rays, radioactive materials, mercury vapor, and stray magnetic fields, as well as implosion hazards, are eliminated by the plasma design.

Hardened plasmascopes are designed for operation in non-air-conditioned environments, with exposure to high electrical and magnetic fields, atmospheric contamination, proximity to vibrating equipment, severe rain, salt, fog, fungus and dust conditions. They will withstand rough handling. Hardened plasmascopes are built by SAI Technology and Interstate Electronics.

A plasmascope has two modes of operation: refresh and storage. In refresh mode the plasmascope display can be erased completely and restored as rapidly as needed; 30 frames per second is the standard rate. In storage mode the image will remain intact without computer intervention. Points can be erased or added individually without disturbing the rest of the image.

"Touch panel" input devices are optional on all plasmascopes. This device is a 16 by 16 matrix of infrared light-emitting diodes and infrared sensors. Touching the plasmascope face at a point will interrupt a beam and signal the computer through a parallel interface.

An added feature of some plasmascopes is the ability to project images optically onto the rear of the translucent display screen. The Interstate Electronics PD2000-M hardened plasmascope is equipped with an integral microfiche projector. Any one of 256 images can be selected by computer control and projected. Any plasmascope image overlays the projected image. This is a powerful feature for a system where high-resolution color images are needed and data storage is limited. Digital storage of diagrams and pictures is highly inefficient, requiring enormous storage capability. In an efficient system, built for reliability and speed, such storage volume is not available. Photographic film is a very efficient image storage medium. A complex, color diagram can be stored in the system, with the only computer memory overhead being a 16 by 16 address of the image on the microfiche. Elements of the image which are subject to change, such as numeric readouts or fluid level indications, are supplied by the plasmascope overlay.

A disadvantage to this system is parallax. The transparency projection must be viewed through 1/2 inch of glass, the thickness of the plasmascope. To obtain adequate projection/overlay registration, the viewer must sit directly in front of the screen. Projection brightness must be adjusted for room light conditions, so as not to wash out the overlay.

Wall-sized displays have been used in several military applications. The Librascope division of Singer manufactures several models of a four-color unit. A laser beam is used to write on 35mm sprocketed film, which is then optically projected.[2] Color CRT projectors have been rejected as military large-screen systems, because of the low brightness, low contrast, and fragility of these devices.

The most current technology in this area is under test at the Center for Tactical Computer Systems (CENTACS), a unit of the Communications Research and Development Command (CORADCOM) at Fort Monmouth, New Jersey. Two technologies, the LED array by Litton Data Systems of Van Nuys, California, and the laser scanner by Electro Spezial of Bremen, West Germany, are in competition for a contract as the NATO standard. The intent of this program is to produce a bright, legible screen display of no less than one square meter area, viewable by a number of people under battlefield conditions. This will be a brigade-level field commander's situation display, to be updated in real-time by a tactical-level military computer.

Specifications are as follows:

[2] Report 2, pages 83-86.

1. 1024 x 1024 pixels resolution.
2. Size of screen to 4 x 4 meters.
3. Colors red, green, blue, and yellow.
4. Positional error less than 0.1%.
5. Contrast ratio greater than 10:1.
6. Brightness of 50 lux on a 3 x 3 meter screen.
7. Picture repetition frequency no less than 30 Hz.
8. High stability under temperature and line voltage variations.
9. Standard interfaces for existing mil-spec computer hardware.

Litton is currently employing a brute-force approach, by mounting two million LEDs on a flat panel. The large screen is made up of 1.44- by 2.88-inch modules, each containing 4096 LEDs in 2048 co-located pairs of red and green. Each module gives 2048 points, arranged in a 32 by 64 matrix. Colors available are black (all off), green, red, and yellow (all on). For a display area of one square meter, about 400 modules are used. The modules are currently being produced by Teledyne and Hughes under subcontract.

A major problem with this design is cost. A single module costs $1,000; a 4- by 4-meter display would then cost $6,400,000. The success of this design therefore depends on the success of efforts to reduce module production costs.

This system has potentially excellent hardness characteristics and compactness, both of which are necessary for its application.

The German design effort is notable for its sheer sophistication. The display is generated by a raster scanning laser technique, projecting an image onto the back of a translucent screen. Two lasers are used to produce four colors: green and blue from an argon laser, red and yellow from a krypton laser. The beams are deflected in the X and Y planes using nitro-benzine KERR cells to change the beam polarization. A control voltage across the KERR cell causes a binary change in the polarization, and deflects the beams in one of two exact angles through a birefringent prism. Ten deflection stages are cascaded together for each axis, giving $2^{10}$ or 1024 discrete beam positions in X and Y. A deflection stage is diagrammed in figure 11.

Functionally, the laser display acts like any standard CRT terminal. The operator interacts with this display through a keyboard and trackball. Refresh rate is 30 Hz, with interlace used to reduce flicker.

A prototype of this system is being used by the West German Navy. There are many problems in adapting it to the U.S. Army's needs. A specification is that it must be able to travel in a tracked vehicle. This means that it must be about 28 inches deep. The technological problems of folding the extremely long optical path into this space are formidable, as well as a sensitivity to vibration and temperature changes.

## III. Safety Parameter Display System Design Outline

The purpose of this safety system is to provide a dependable link to vital plant information, especially under emergency conditions. Reliability of the system is optimized by the extreme simplicity of its design, the use of hardened components at all critical points, and plans for maintenance and backup strategies. Further increases in reliabililty are possible through hardware redundancy. Suppose, for example, that parallel redundancy is used in the SPDS, or that two complete and independent system are in effect. Failure rates of all components in a system are summed to give the failure rate of a stand-alone system, $\lambda$. The

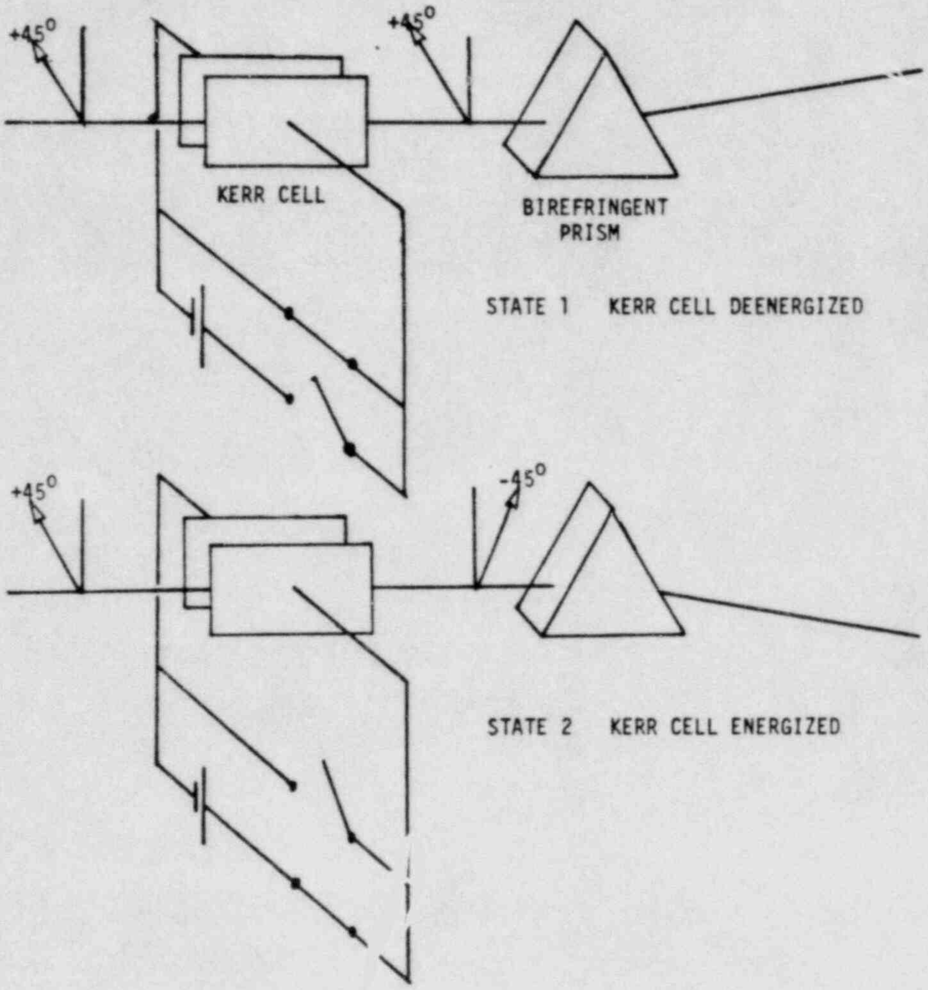


Figure 11. Electro Spezial's Laser Deflection Stage.

reliability of the redundant system over a time span t is then modeled by the equation

$$R(t) = 2e^{-\lambda t} - e^{-2\lambda t}. \tag{1}$$

If a system has an MTBF of 5,000 hours, then its failure rate is 2 x $10^{-4}$ failures/hour. The reliability of two systems in parallel over a period of one month (720 hours) is found by substituting in values,

$$\begin{aligned} R(720) &= 2e^{-0.144} - e^{-0.288} \\ &= 98\%. \end{aligned} \tag{2}$$

The reliabililty of a single, non-redundant system over the same time period would be

$$\begin{aligned} R(t) &= e^{-\lambda t} \\ &= e^{-0.144} \\ &= 87\%. \end{aligned} \tag{3}$$

The availability of a simple system is modeled with the equation

$$A = \frac{\text{MTBF}}{\text{MTBF + MTTR}} \tag{4}$$

An example is a system with a mean time before failures (MTBF) of 5,000 hours and a mean time to repair (MTTR) of one hour. The availability of this system would be

$$A = \frac{5,000}{5,000 + 1} \tag{5}$$

$$= 98.98\%.$$

For the two-unit redundant system the availability is calculated with the model

$$A = \frac{(\mu^2 + 2\mu\lambda)}{(\mu^2 + 2\mu\lambda) + \lambda^2} \quad , \tag{6}$$

where λ is the failure rate of each unit (1/MTBF), and μ is the repair rate of each unit (1/MTTR). For a redundant system with two units having the same MTBF and MTTR as in the example above, the availability is

$$A = \frac{(1 + 2 \times 0.0002)}{(1 + 2 \times 0.0002) + (0.0002)^2} \tag{7}$$

$$= 100\% \ .$$

Complex redundant systems, in which each component module has a unique failure rate and an appropriate individual level of redundancy, are more difficult to model, but the basic benefits should be clear from these examples.

An important effect of machine pairing is the tradeoff between individual computer reliability and the level of redundancy. A system consisting of two commercial-quality computers in parallel redundancy has a calculated reliability of 74% over 720 hours, if each machine has an MTBF of 1,000 hours, whereas a single hardened computer has a reliability of 87%

over the same time period. If the MTTR of the commercial system is 24 hours, then its availability is 99.95%, as opposed to 99.98% for the single-unit hardened system.

A restriction on the SPDS design is that it must be able to retrofit into existing plants. For this purpose, all data originating in the containment building are concentrated into a single cable, making it possible to add dozens of new sensors without having to make more than one new containment building penetration. The data concentrator module acts as an intelligent front-end for the safety parameter display, for other safety equipment, or for existing process computers.

New sensor equipment installed for the safety display is chosen to operate under extreme ranges, not necessarily having the accuracy and resolution of the operational sensors.

The basic Safety Parameter Display System (SPDS) consists of two data-processing nodes, connected by a high-speed link. One, to be located in or near the containment builing, acts as the data collection and concentration point. Another processor formats and controls the safety state display, located in the control room area. This system is shown as a block diagram in figure 12.

A unique set of safety parameter sensors are connected with minimum-length cables to signal-conditioning amplifiers in the data concentrator module. The data concentrator is housed in a lead shield, and all connections must be made through sealed penetrations. The data are multiplexed into one channel, and are transmitted to the display processor over an optical fiber. The fiber passes through a minimum penetration in the containment wall.

Signals are demultiplexed at the display processor module and

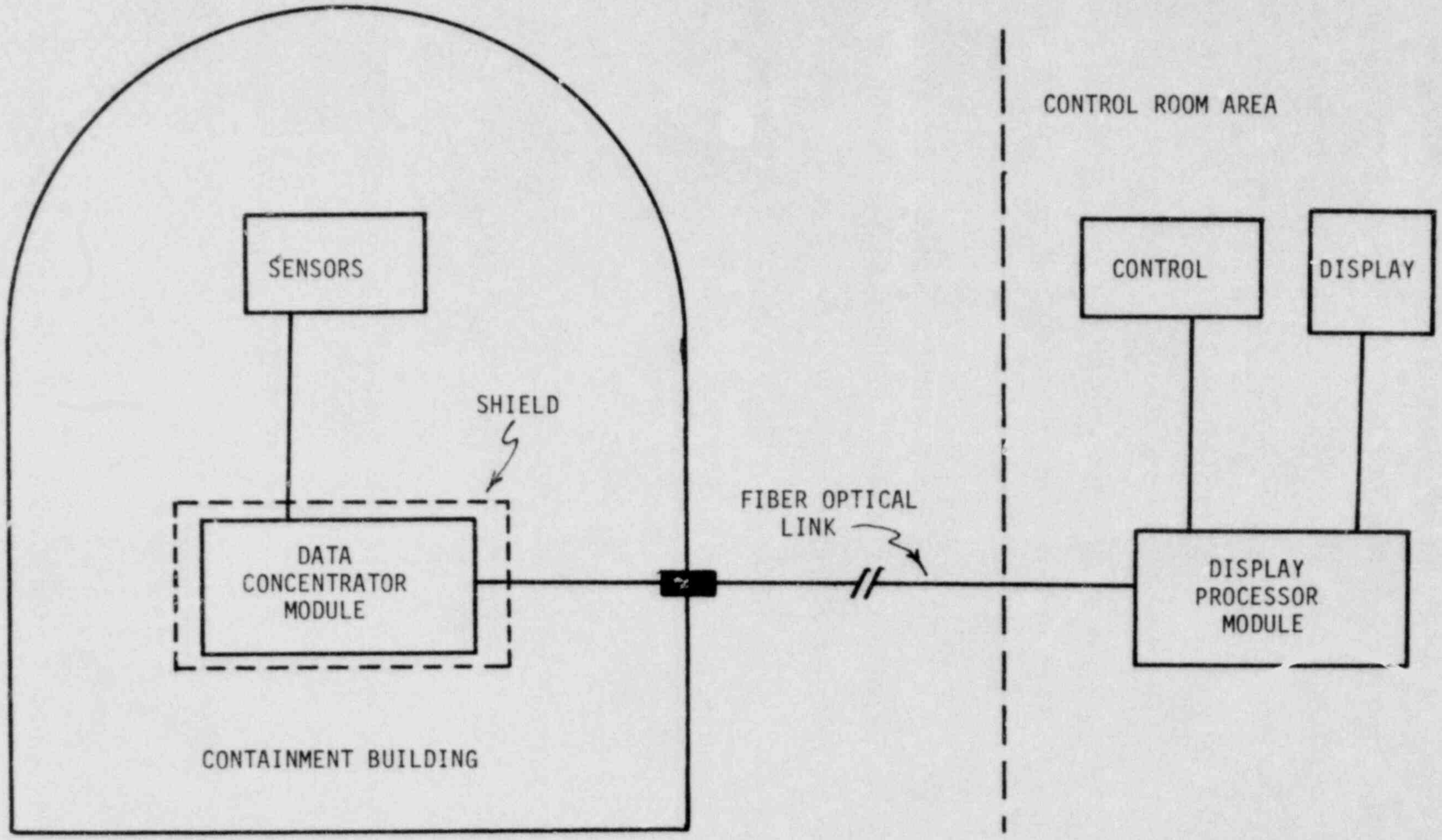


Figure 12. Basic SPDS System Block Diagram

converted to a displayed safety state.

The system is free of extraneous equipment, and it depends upon the simultaneous operation of as few components as possible. Nothing is shared with other equipment; there are no "Y" connections to other experimental or operational devices. No isolation amplifiers are necessary; all isolation is provided through the non-conductive optical fiber. No electromagnetic interference (EMI) is generated or received by the equipment. Either the containment building module or the control room area module occupies less than 12 cubic feet, including shielding and uninterruptible power supplies.

Mean time to repair (MTTR) is minimized by the use of plug-in boxes, each weighing less than 80 pounds. The system uses about 1,000 watts electrical. In theory, the containment module can be configured to withstand shield temperatures up to 275$^{\circ}$C, gamma radiation doses up to $10^8$ Rads(Si), and total immersions in water.

All equipment exceeds anticipated seismic qualifications. Cost of computer equipment, built to the most extreme mil-specs, including two processors, maximum memory configurations, control panels, and I/O modules, is approximately $150,000. The cost of sufficient spares to support the computer 100% is less than $90,000.

Software can be developed using the display processor with interfaces to commercial-quality peripherals, which are not used by the safety parameter display in operation. Additional software development, or all software development, can be carried out using on-site or off-site computers.

Both computers in the system are equipped with built-in test equipment (BITE) for automatic fault detection, and both have program loading routines stored in read-only memory (ROM).

Redundancy, if needed, can be introduced by simple duplication of modules posing risk of failures. The size of the system, in the number of signals sampled or in the processing power, is easily changed by the addition or substitution of box-level modules. Identical processors are purposefully-used for data concentrator and display nodes, to reduce the number of necessary spares.

## IV. The Data Processor in a Hazardous Environment

### A. The Hardened Processor

A processor type suggested for use in the SPDS is the ROLM 1602B. Features of this processor which make it applicable to this program are as follows:

1. Inherent radiation hardness. The 1602B is built using bipolar technology. The processor unit is based on 4-bit bipolar bit-slice devices. Intrinsically hard magnetic core memory is used. All processor support and interface circuitry is transistor-transistor logic (TTL). With slight modification, an unshielded 1602B should be able to operate with an integral radiation dose up to $10^6$ rads(Si).[3]

2. Thermal design for passive cooling. Heat sinking qualities of the 1602B chassis are superior to other machines of this type, because it was designed for use without a forced-air heat exchanger. Heat dissipation (250 watts typical) is low compared with other bipolar machines, mainly because of low speed and performance characteristics. The chassis of the 1602B processor and its

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[3] Report 3, pages 17-31

associated I/O box will adapt well to a closed shield environment with cold-plate cooling. The chassis is basically composed of six machined aluminum plates, bolted together.

3. Low cost. Cost and performance have been weighed carefully in the evaluation of mil-spec equipment for the SPDS. A high-performance hardened computer could cost as much as ten times more than the 1602B, so overshooting the performance requirements could attach unattractive costs to the system. The 1602B is a comparatively popular tactical computer in military applications, is built in quantity, and probably has the best performance-to-cost ratio of any machine of this type.

4. Design flexibility. Options for the 1602B include temperature tolerance range, built-in test equipment (BITE), DC power supply, custom read-only memory (ROM) programming, and special connector wiring. The ability to order custom interface wiring is a particular attraction of this machine. Special communications hardware, such as the fiber optical cable, can be fit in an assembly line process easily.

The 1602B and its associated software systems are appropriate for real-time data collection operations with comparatively light data processing loads. Processors in this class perform poorly in such tasks as matrix inversion or fast Fourier transform generation when compared with faster machines equipped with cache memory, writable control storage, and parallel matrix processors.

For this application, such power is not needed. Data will consist of 30 to 100 collection points, with probably a five to one mix of analog and digital signal types. Machines in this class, including the ROLM 1602A, have been used for real-time data collection and concentration on this scale in several DoD-funded radar applications, including the Waterborne Intrusion Detection System (WIDS), Long Range Area Radar for Intrusion-Detection and Tracking (LARIAT), and the Battlefield Identification Friend or Foe (BIFF) at the Georgia Tech Engineering Experiment Station.

For the needs of SPDS, 64K words should be adequate for system and data storage with margins for expansion, and without resorting to virtual disk memory. The 64K words are contained in the processor cabinet, with no need for outboard boxes. Software can be developed with the Realtime Disk Operating System (RDOS), with the resulting operational software contained completely in core, using the Real Time Operating System (RTOS).

A schematic top view of a 1602B processor with the top cover removed is shown in figure 13. The maximum addressable memory is in 16K word increments with three cards, address, inhibit, and core, comprising each memory module. Dedicated slots are reserved for the CPU circuit board, a ROM board with a non-erasable bootstrap program, and a remote control panel interface. Seven slots are available for custom applications, and interfaces located in these positions are wired to general-purpose connectors on the cabinet face as needed. The I/O bus can also be interfaced through one of these connectors, giving I/O expansion capability into an outboard cabinet.

A ROLM Model 2150 I/O chassis plugs directly into the 1602B I/O bus with a single 55-conductor cable, giving an extension for 15 circuit boards in a hardened cabinet. The 2150 is passively-cooled, and it has the same power supply as the 1602B processor. Connector access through the cabinet face is wired for a specific application.

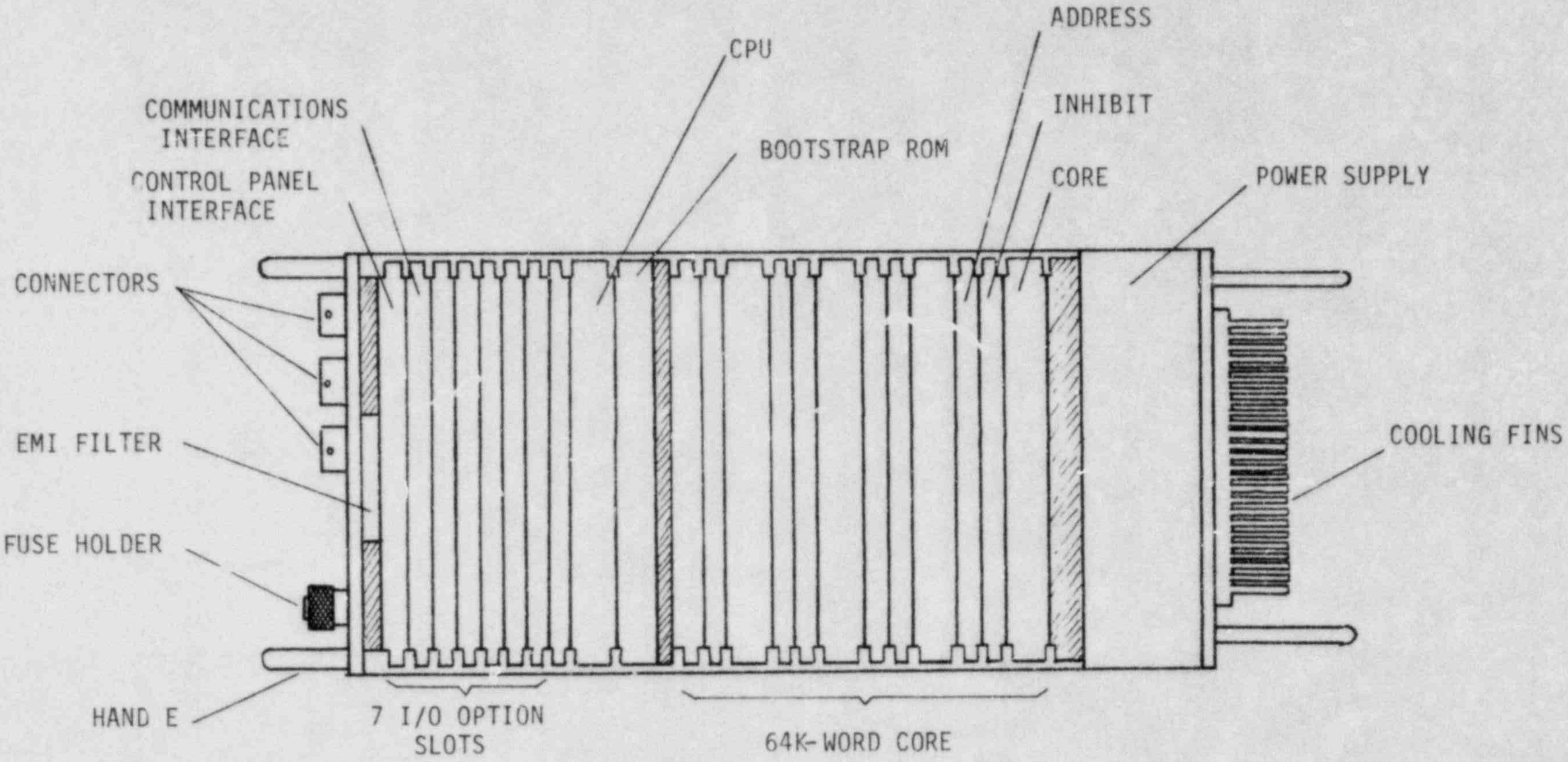


Figure 13. ROLM 1602B Processor

All electronic assemblies associated with the SPDS should be housed in such a box. If 48 or fewer analog signals are received, then the data concentrator can be reduced to two boxes -- the processor and the I/O box. This assumes that no fewer than four conditioning amplifiers can be located on a single circuit board. Proposed I/O box configurations are shown in figure 14. Up to 96 signals can be received and processed in a three-box system, but space, power and cooling requirements are all increased.

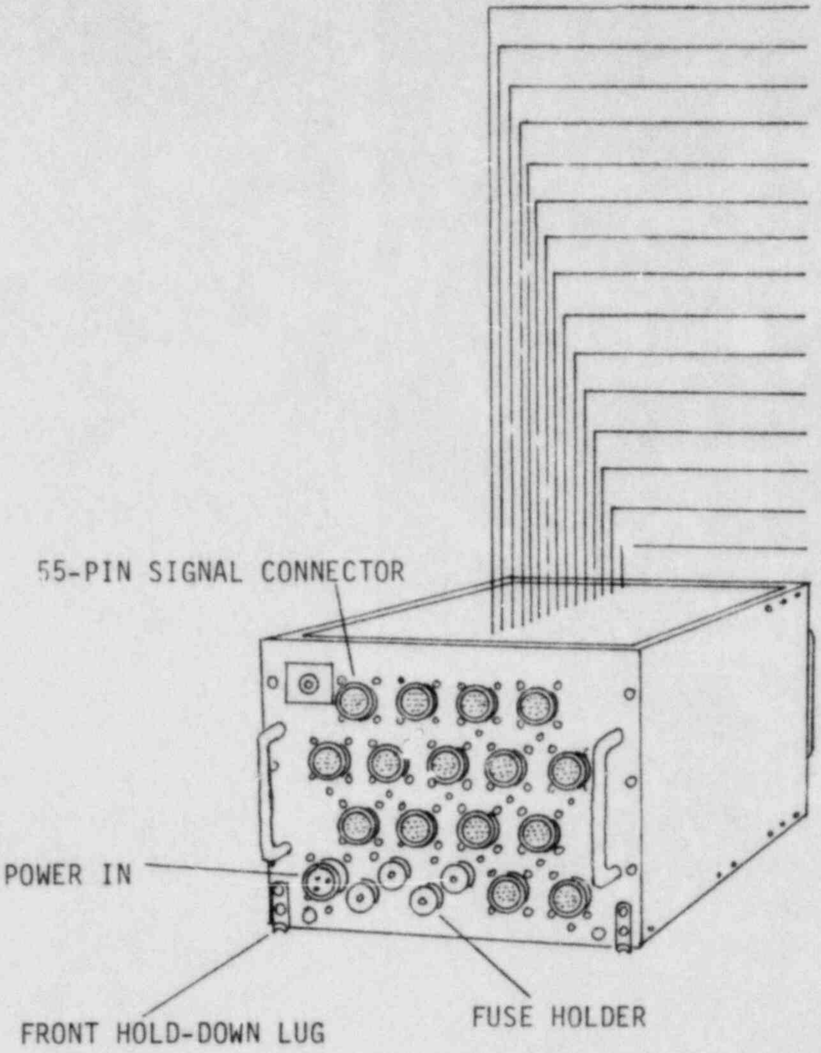
B. Shielding

The 1602B can be shielded by conventional methods to withstand the integral gamma ray burden in a power plant containment building, for the plant lifetime.

Data concentration equipment to be located in or near the containment builing occupies a volume 32 inches by 24 inches by 8 inches. Such a small volume can be easily covered with a cast metal shield. Lead is suggested as a shield material, over more exotic metals such as tantalum and tungsten, because it is cheap, easily worked, and it gives the added advantage of excellent vibration dampening qualities. The shield is three inches thick, giving an estimated gamma attenuation factor of $10^2$. The weight is about two and one-half tons.

Figure 15 is a top view of the floor-mounted shield, cut away to show the protected equipment. The data collection hardware is grouped in three modules:

1. Processor Module, containing:
    a. 1602B processor
    b. 64K core memory
    c. ROM bootstrap loader
    d. High-speed communications interface



| SLOT | | |
|---|---|---|
| 1 | 3563 | BUS REPEATER/TERMINATOR |
| 2 | 3656 | 16 CHANNEL ADC |
| 3 | 3662 | 16 CHANNEL MUX SLAVE |
| 4 | 3662 | 16 CHANNEL MUX SLAVE |
| 5 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 6 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 7 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 8 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 9 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 10 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 11 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 12 | 3800 | 6 CHANNEL CUSTOM AMPLIFIER |
| 13 | 3540 | PARALLEL I/O BUFFER (16-BIT) |
| 14 | 3800 | CUSTOM POWER SUPPLY |
| 15 | 5623 | I/O TESTER |

Figure 14. I/O Box Configuration

1 PROCESSOR
2 I/O BOX
3 UPS MODULE
4 HEAT PUMP MODULE

cables are not shown

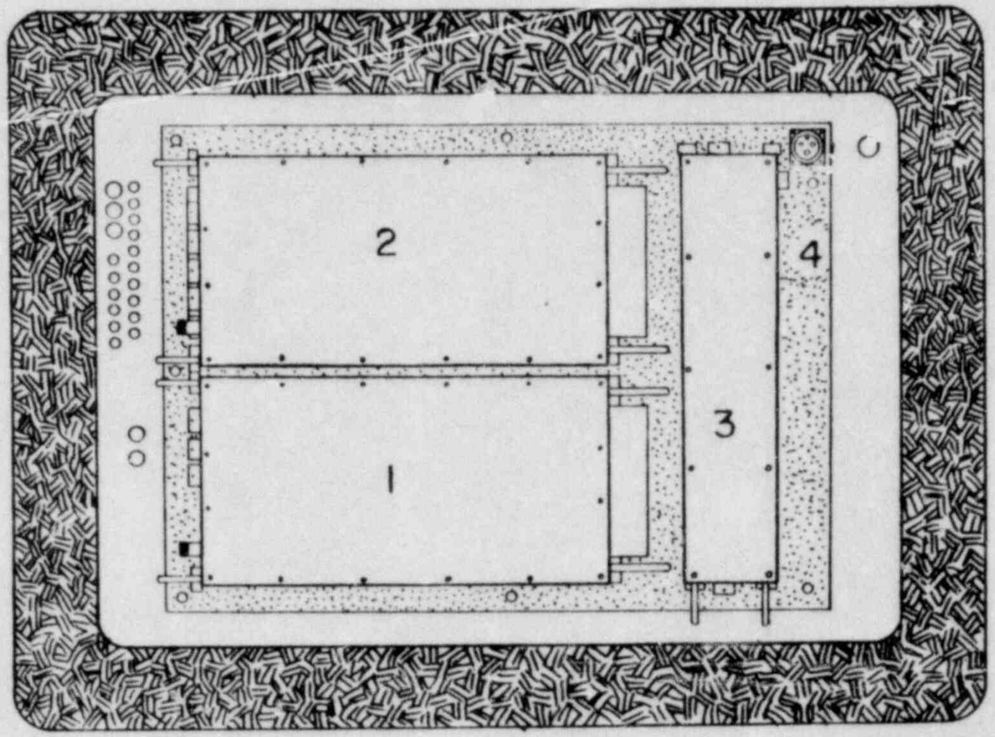


Figure 15. Top View, Floor-Mounted Lead Shield

    e. Maintenance equipment

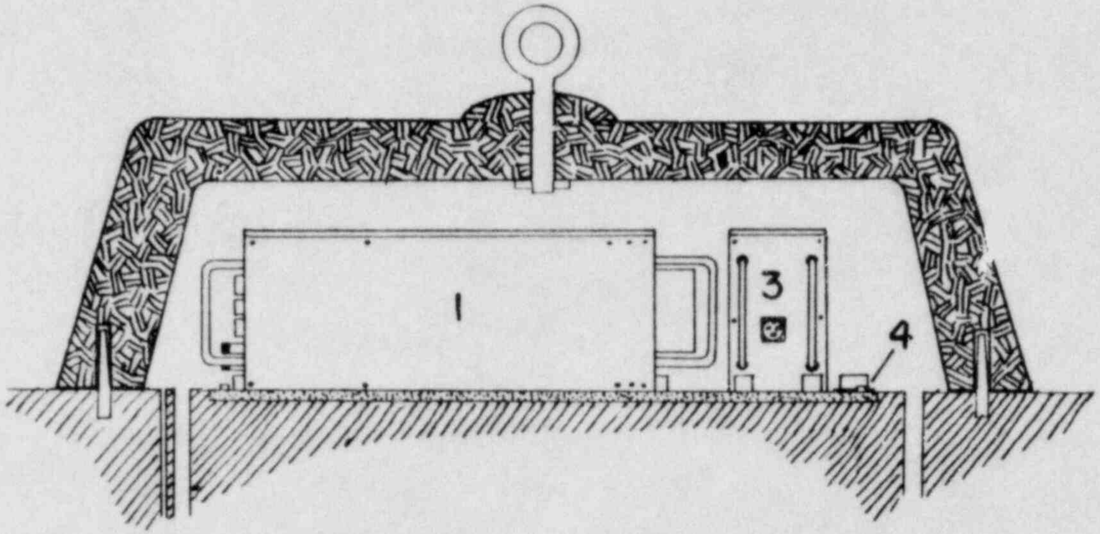
2. I/O Module, containing:
    a. ADC
    b. ADC multiplexer interfaces
    c. 16-bit digital I/O interfaces
    d. Instrument amplifiers
    e. Instrument power supplies
3. Uninterruptible Power Supply (UPS) Modules (primary batteries)

Figure 16 is a cross-sectional view of the data concentrator, showing the bottom shield and cold-plate. Heat from the computer is conducted to this plate, where it is radiated or conducted to the building floor or wall, depending upon mounting method. Power and signal cables penetrate this plate through environmental shielding junctions. The shield can be water-proofed with an appropriate gasket.

An alternate shield is shown in figure 17. This wall-mounted shield takes advantage of the excellent cold-plate properties of the containment wall. The heat path from the computer cabinets to the outside is minimized with the configuration. This design also eliminates the need for a shielded communications cable, as it penetrates the containment wall behind the computer shield.

Shield design and the placement of cable penetration is entirely dependent on what is possible in a given containment building. The purpose of this exercise is to show that all electronics needed for data collection and transmission can be protected in severe conditions under a single shield. The shielded device is small enough to be retrofitted into a fairly crowded building.

### C. Cooling System



1 PROCESSOR

3 UPS MODULE

4 HEAT PUMP MODULE

Cables (not shown) feed through holes in the floorplate.

Figure 16. Cross Section, Floor-Mounted Lead Shield

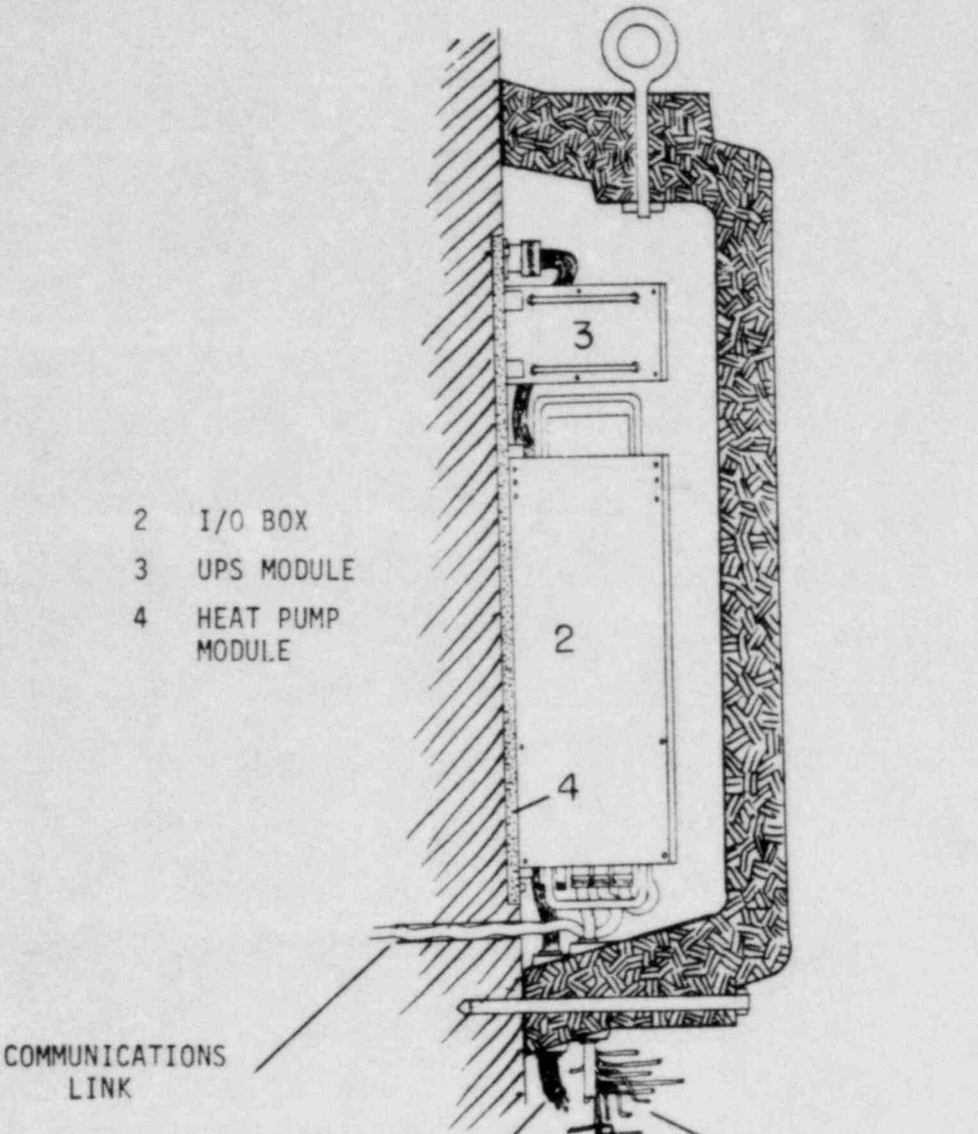


Figure 17. Cross Section, Wall-Mounted Lead Shield

Standard operating temperature range of the 1602B is 0°C to 65°C at the case. The storage temperature range (cabinet) is -55°C to 105°C. The processor and I/O box may be ordered with an optional extreme temperature range of -55°C to 95°C at the case.

The 1602B can be cooled by sinking the heat it generates through its floor plate. This eliminates any need for circulating air in the shield, and it permits the shield to be sealed. The floor plate in the 1602B cabinet is machined from a one-inch slab of aluminum, and it is an excellent heat path.

The electronic equipment in the shield can be cooled under worst-case circumstances (171°C, following a LOCA) using conventional methods, such as forced air over radiating fins or chilled water pumped through channels in the cold plate. However, these methods are highly mechanical, and depend upon continuous functioning of fan motors or pumps and sealed fluid system. The reliability and availability of the cooling system can be improved by using thermoelectric heat pump modules instead of mechanical systems.

The thermoelectric heat pump is a solid state, semiconductor device. When DC power is applied to the device, heat is absorbed on one side and rejected on the other. Figure 18 is a cross-sectional view of a typical thermoelectric cooling element.

Thermoelectric cooling modules have long been used for specialized military electronic cooling applications, where reliability and bulk are primary considerations. These devices are also used for special cooling problems in satellites and deep space probes.

The heat pump module thus consists of a 3/8-inch aluminum slab with depressions milled in the top surface to hold thermoelectric modules. Slots are milled for the electrical wires, which are bussed together at a

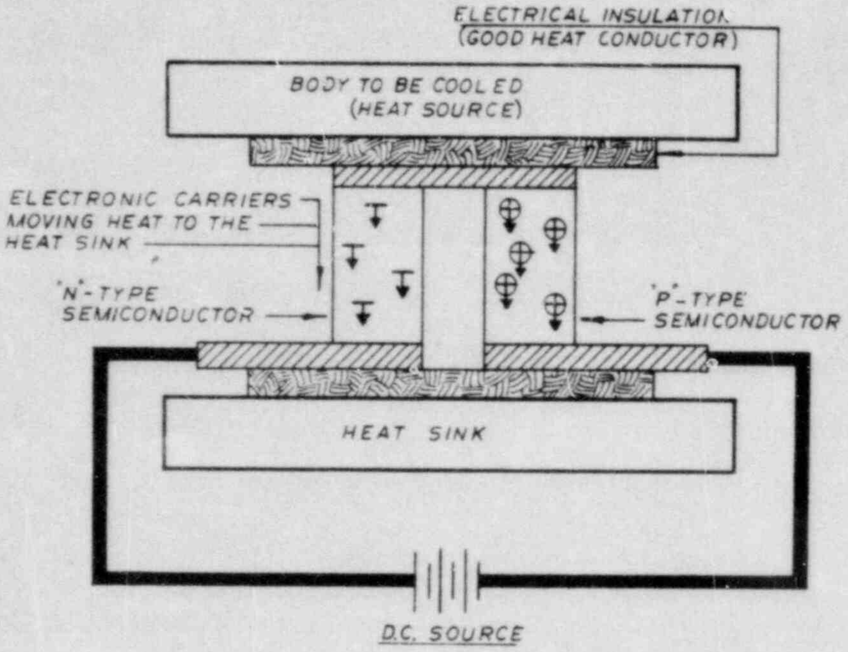


Figure 18. Cross Section, Thermoelectric Cooling Element

quick-release mil-connector for power input. Handles are provided for easy manipulation. The heat pump fits into a shallow depression in the cold plate, and is bolted down for optimum contact. The computer boxes are in direct contact with the cold junctions on the top surface of the heat pump, and snap locks press the cabinets against the cooling modules Thermal conducting grease is used in the cabinet-heat pump and heat pump-heat sink interfaces.

High performance heat pump modules needed for this application are built by Borg-Warner Thermoelectrics, Chicago, Illinois. Although semiconductor devices usually perform best at room temperature, Borg-Warner has modified the materials and the assembly solders to produce a series of high temperature modules. Heat pump modules are made to operate at hot-leg temperatures up to 275°C. The cooling load capacity and induced temperature drop across the device are actually better at higher temperatures than they are at room temperatures. The cooling capacity at 200°C is twice the value at 27°C (hot-leg temperature).

Thermoelectrics are the most reliable of all semiconductor devices. With ten years of operating experience, MTBFs between 91,400 and 300,000 hours are reported from the field. Failure is most often defined as a loss of a few degrees in cooling over a long time period. Catastrophic failures are rare. The predominant failure mode is an open circuit caused by a solder bond error on the hot-leg side (Kirkendall Effect).

Thermoelectric devices have shown no measurable radiation sensitivity.[4]

### D. Uninterruptible Power Supply

[4] Report 3, pages 42-54.

Power outage is a failure mode for the SPDS that can be reduced effectively with a simple battery backup. Standard power-fail detection circuitry in the 1602B is used in the UPS design.

From this study and other experiences it is concluded that, for a system as small as the SPDS data concentrator, battery backup is the most efficient uninterruptible power supply.

The 1602B power supply generates signals POWER FAIL, MEM OK, and +5 OK. Any primary power failure sets the POWER FAIL flag, causing an interrupt to be requested, on the highest priority. In servicing this interrupt, the real-time system will load a bit into the 16-bit output register in the I/O cabinet. This signal, which is accessible through an I/O cable connector in the cabinet face, is used to close a relay in the UPS module, which switches the primary power from line to batteries. There is sufficient capacity in the computer power supply to maintain complete operation during this transfer.

The processor and I/O boxes are supplied with the optional 28-volt DC power supplies. This eliminates the need for power inversion for battery operation; the equipment operates directly from the battery pack during a power outage. Normal power is supplied by an outboard transformer/rectifier pack, giving 28 volts at about 18 amps. A similar outboard power supply, equipped with voltage and current limits, services the heat pump module.

The battery backup circuitry is greatly simplified if long shelf-life primary cells are used, instead of rechargable batteries. Generally, rechargable batteries cannot withstand the emergency temperatures anticipated for the shielded equipment, due to electrolyte evaporation, and the switchover device requirement is more complex. For the sake of simplicity and efficiency, lithium primary cells are considered for the SPDS battery backup.

There are six types of lithium cells currently made. The type considered here is the lithium sulphur dioxide process, manufactured by Power Conversion, Inc., Mt. Vernon, New York. General specifications of the Eternacell 660-5AS are listed in table 8. Temperature tolerance limits of these batteries exceed those of the 1602B equipment. At 117°C a safety vent opens, relieving 500 psi on the electrolyte.

Ten cells, occupying 117.4 cubic inches, supply 26 ampere hours at a 10-hour rate. The UPS module is approximately 23 inches by 8 inches by 5 inches, large enough to contain 50 lithium cells, plus the transfer relay. This gives 130 ampere hours, or over seven hours at a drain of 18 amperes. There are 2.8 volts per cell, and there are five parallel banks of ten series cells each. The 50 cells weigh about 31 pounds.[5]

E. Optical Fiber Data Linking

Glass fibers can be used as optical waveguides for inter-computer communications at higher data rates and longer distances than are available with conventional coaxial cables. One channel of a full-duplex optical data link is shown schematically in figure 19. Data to be transmitted is sorted, formatted, and converted to serial form by the processor. This signal drives a pulsed light emitter through a current driver amplifier. Power transmitted is on the order of microwatts. A strand or a bundle of glass fibers is optically coupled to the light source. Length of the fiber can be up to a mile. In the receiver the fiber is coupled to a photo-diode light detector. A two-stage amplifier conditions this signal for

[5] Report [illegible], pages 55-62.

| | |
|---|---|
| Model Number | Eternacell 660-5AS |
| Capacity A.H. | 30.0 |
| Rated Load uA | 1,250 |
| Weight, Ounces | 9.87 |
| Diameter, Inches | 1.64 |
| Height, Inches | 5.56 |
| Volume, Cubic Inches | 11.74 |
| Safety Vent Temperature | 240°F |
| Maximum Internal Pressure | 450 psi |
| Electrochemical Reactions | Anode: $2Li \longrightarrow 2Li^+ + 2e^-$<br>Cathode: $2SO_2 + 2e^- : S_2O_4^{=}$<br>Cell: $2Li + 2SO_2 \longrightarrow Li_2S_2O_4$ |

Table 8. Lithium Battery Characteristics.

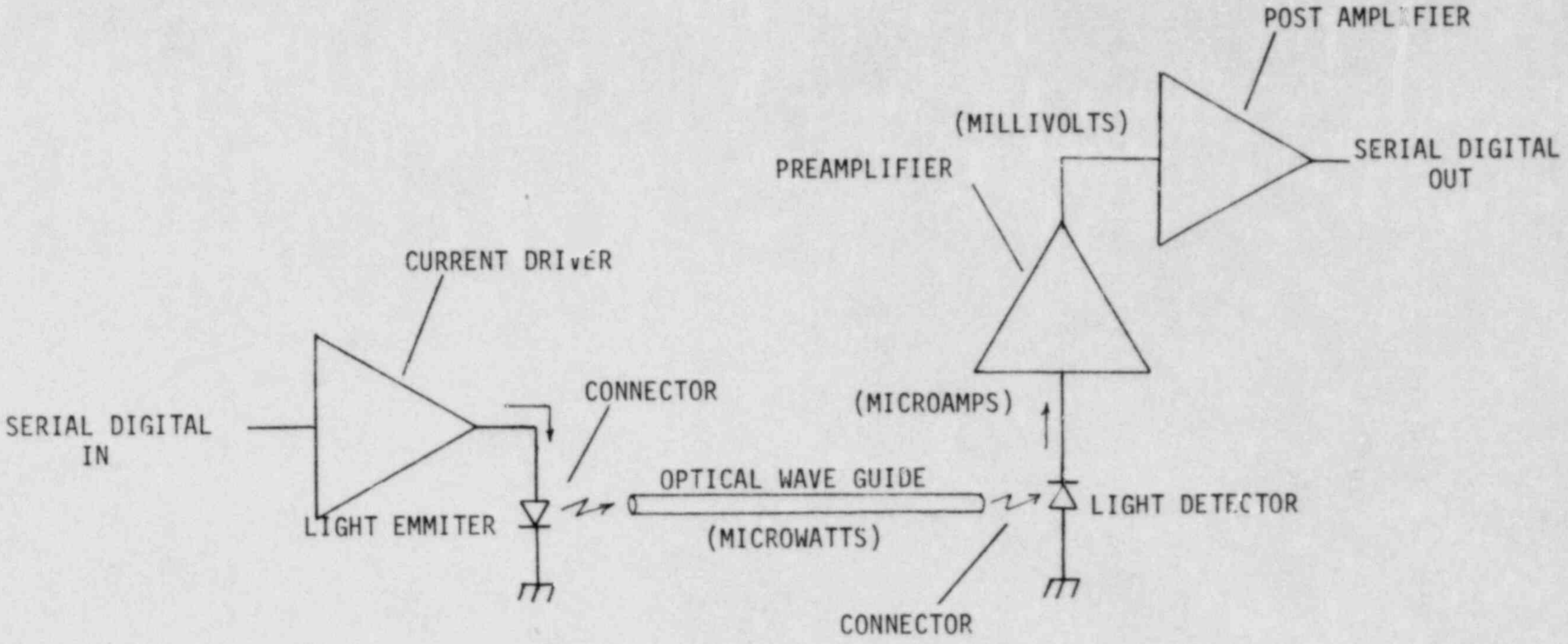


Figure 19. Optical Fiber Communications System

conversion back to parallel data in the receiving computer.

The fiber optics industry is currently devoid of standards, so specifications are difficult to quote. Transmitter switching power is typically 200 uw, with rise and fall times under 5 nsec. Light wavelength is in the 760 - 910 nm range. Light fiber diameter varies widely, but 8 mils is typical. Achievable data transmission error rates are under $10^{-8}$ errors per bit using available components. Error correcting codes can reduce the error rate to $10^{-15}$ errors per bit.

Sperry Univac is developing a fiber-optic based Common Weapon Control System (CWCS) for use with the Ground Launch Cruise Missile (GLCM) under contract to McDonnell Douglas. A standardized fiber link will be used for serial computer I/O channels, digitized voice, and multiplexed digital discrete signals. This is the first fully militarized and radiation-hardened fiber optics system. The computers used in this system are the ROLM AN/UYK-19(1666).

The Sperry Univac full-duplex transceiver module is about 3.5 inches by 1.0 inches by 0.5 inches. The unit is small enough to fit in the I/O module section of the 1602B processor cabinet, therefore eliminating the need for a separate ATR chassis. Only one channel is necessary for data comunications, with a second channel for remote processor control and data channel backup. Two transceiver assemblies will easily fit on a ROLM custom circuit board, which is 6.60 inches by 9.60 inches, with a variable thickness, depending on the position of adjacent circuit boards.

Optical fibers are not inherently radiation tolerant. Glass materials have been known to darken under radiation exposure since 1899. In fiber communications systems such darkening causes severe attenuation, with an increased error rate and eventual loss of signals. A great deal of work has been sponsored by the DoD for the purpose of rad-hardening optical fiber system components, with the goal of consistent manufacturing methods to meet the ground-launched cruise missile radiation tolerance specifications.

It is concluded that fiber optical systems are usable in reactor containment environments only when they are given shield protection similar to that needed by computer components. Fiber optics may never be used for reactor instrument cables, because of the need for heavy lead cable shielding, and the near-impossible task of shielding the digitizer/transmitter in close proximity to the reactor vessel.

A wall-mounted data concentrator module shield provides complete shielding for the optical cable, but this means that the module must be located directly over the penetration. A short, lead-shielded cable run may be necessary.[6]

F. The Display Processor

The display processor is a set of minimal computer equipment used for man-machine communications and control of the SPDS. It consists of a ROLM 1602B processor with the maximum memory complement, a communications link to the data concentrator, at least one alphanumeric/graphics display device, and a communications link to other computer equipment in the plant. The operating system is completely core resident, and depends on no rotating memories or external storage devices. This equipment has the same hardness characteristics as the in-shield equipment.

The data processor and display equipment require no periodic maintenance, and will survive any seismic shock or high ambient temperature

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[6] Report 3, pages 63-81.

conditions.

A minimum set of equipment is shown in figure 20. The set consists of the 1602B, two militarized plasmascopes, and a keyboard. The processor is equipped with a full control panel, which acts as a dedicated data analyzer, and is very useful for trouble shooting. Three views of the 1602B control panel are shown in figure 21. DATA and MEMORY ADDRESS are displayed as octal numbers using seven-segment LED readout devices.

## V. Maintenance Procedures

High-speed maintenance techniques have been developed in industries which use mil-spec computers for process control. Instead of relying on one-to-one redundancy in the computer operations, complete box-level spares are most often kept in reserve. A processor failure can be reduced in a matter of minutes simply by disconnecting the front-mounted cables, loosening the two tie-downs at the front of the box, and replacing the failed module with a spare.

The use of built-in diagnostic software is common to most environmentally hardened computers. In the ROLM 1602B the tests are stored in a microcode ROM. The ROM consists of 300 microlocations, of 52 bits per location. Applying power to the processor automatically initiates the tests. If the tests detect no errors, then a green LED is lit on the cabinet face, and program execution is started. If an error is detected, then the number of the failing subtest is placed in accumulator AC3. This number can be associated with a specific area on a specific printed circuit board, and fault isolation can be automated using this feature. Confidence level is 90%. Tests can run even if all primary memory has failed.

Remote tests can be automatically initiated on inaccessible processors

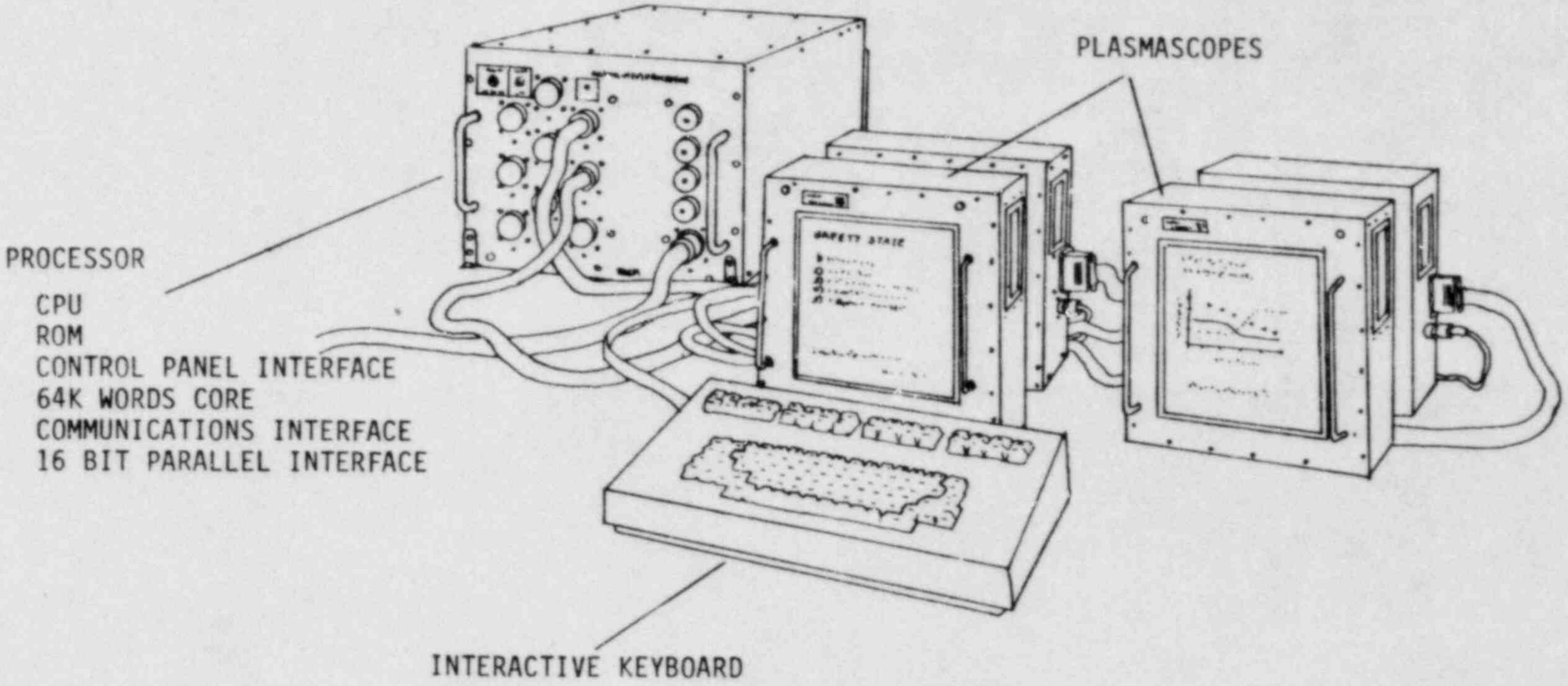


Figure 20. Display Processor Configuration

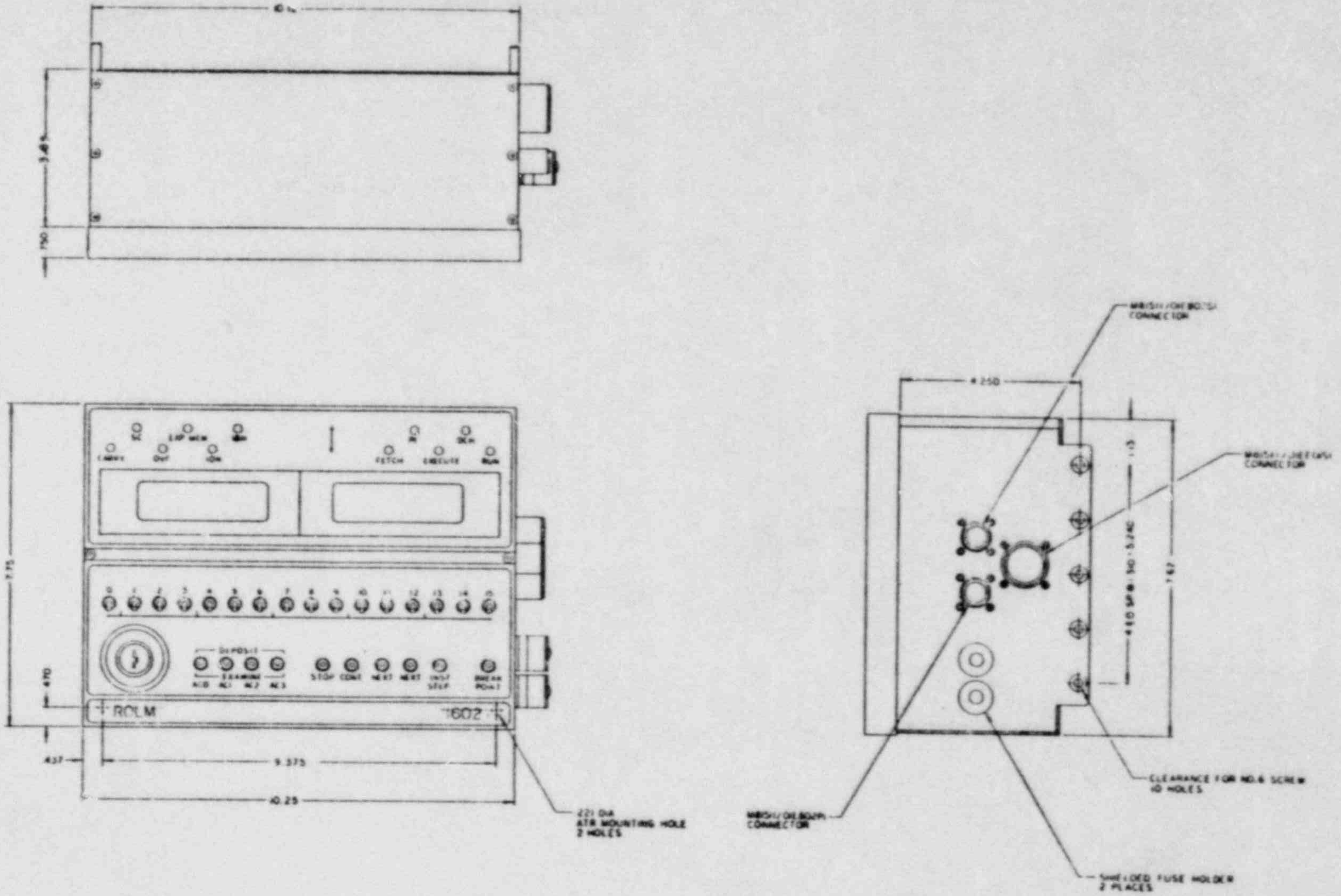


Figure 21. Control Panel

using the programmed initiation feature of the built-in test equipment (BITE). An additional remote diagnostic tool for the ROLM equipment is the Model 5623 I/O Tester Module. This is a circuit board that fits in any slot in the I/O cabinet. It is addressable as an I/O device, and it generates simulated signals on command for testing the I/O bus.

Under program control, this device can test the motherboard for breaks or shorts, and it can test all I/O devices for failed bus transmitters or receivers.

The majority of faults occurring in either processor in the SPDS can therefore be automatically detected and traced using inherent features of the 1602B.

Failed computer components can be replaced with spares on three levels: the box, the circuit board, and the integrated circuits.

1. Box Level.

A failure in the data concentrator is detected at the display processor and is isolated at least to the box level. The faulty system component can be swapped out quickly in the following steps:

a. Lift off the shield with the containment building crane.

b. Remove all connectors from the cabinet face. One-quarter anti-clockwise turn will unlock each connector.

c. Disconnect the two latches holding the cabinet to the cold plate, and remove the cabinet.

d. Slide the replacement cabinet into place against two guide pins at the back of the cabinet, and tighten the hold-down latches.

e. Replace all connectors. Manual force is required;

one-quarter clockwise turns lock each connector. Connectors can be color-coded to their sockets.

f. Lower the shield and disconnect the crane. These procedures are diagrammed in figure 22.

2. Circuit Board Level.

Once removed from the system, a processor fault can be traced on the circuit board level. Circuit board removal requires the following steps:

a. Unlock 14 captive fasteners on the top cover, and remove it. Phillips screw driver is required.

b. Loosen two bolts in the side walls of the cabinet at the left and right edges of the circuit board. This relieves the vise pressure holding the circuit thermal frame against the cabinet walls. An allen wrench is required.

c. Connect the board removal tool into two holes on the top of the circuit board, and squeeze the handle. The circuit board breaks free of the two floor connectors and slides out the top of the cabinet.

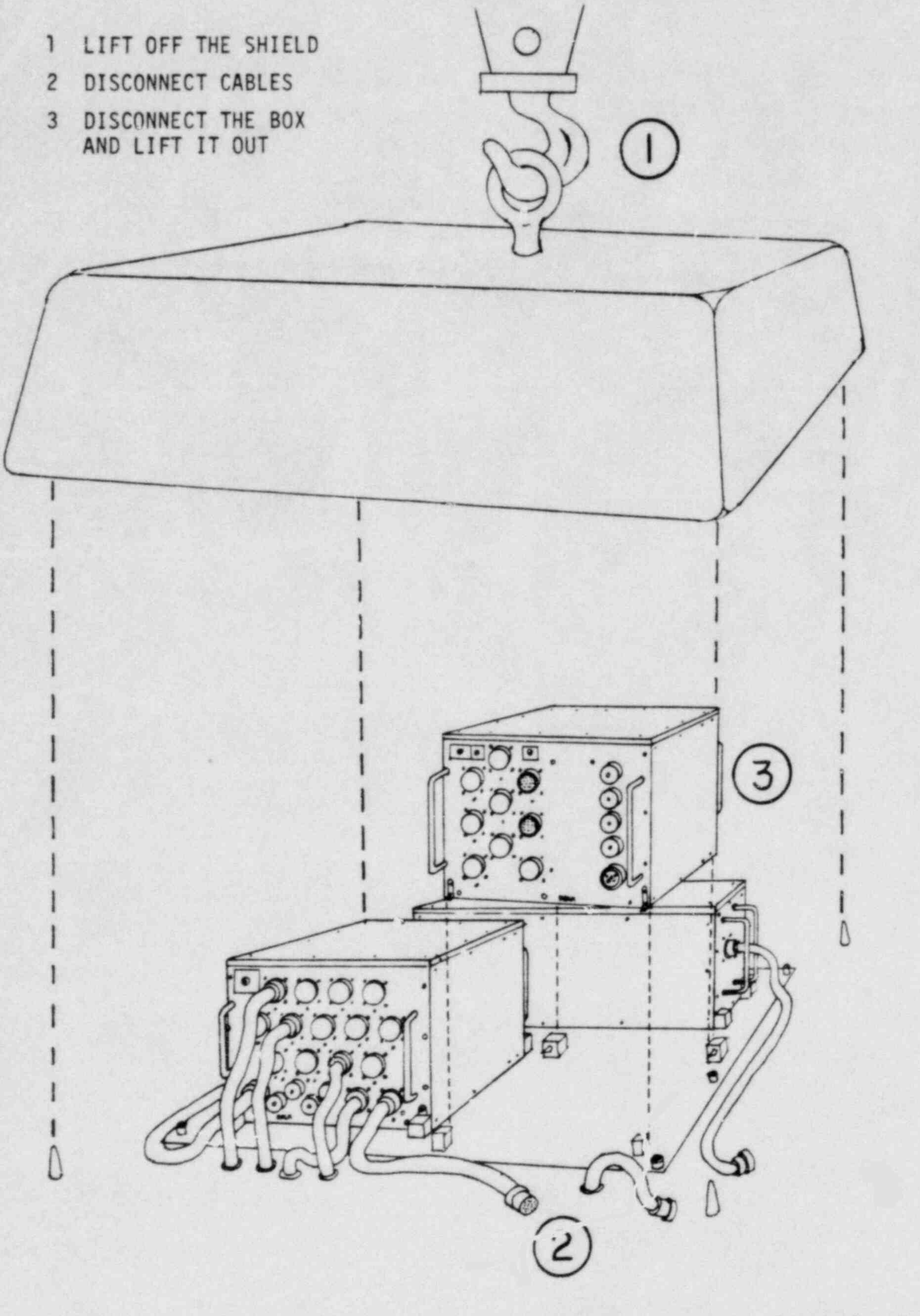
This procedure is diagrammed in figure 23.

3. Integrated Circuit Level.

Mil-spec circuit boards are unusually difficult to work on because of the 12- to 14-layer board construction and the conformal plastic coating. An integrated circuit is removed with the following steps:

a. Remove ten small screws holding the "cookie sheet" stiffeners. Each screw has two washers and a nut.

b. Remove the conformal coating with solvent or with

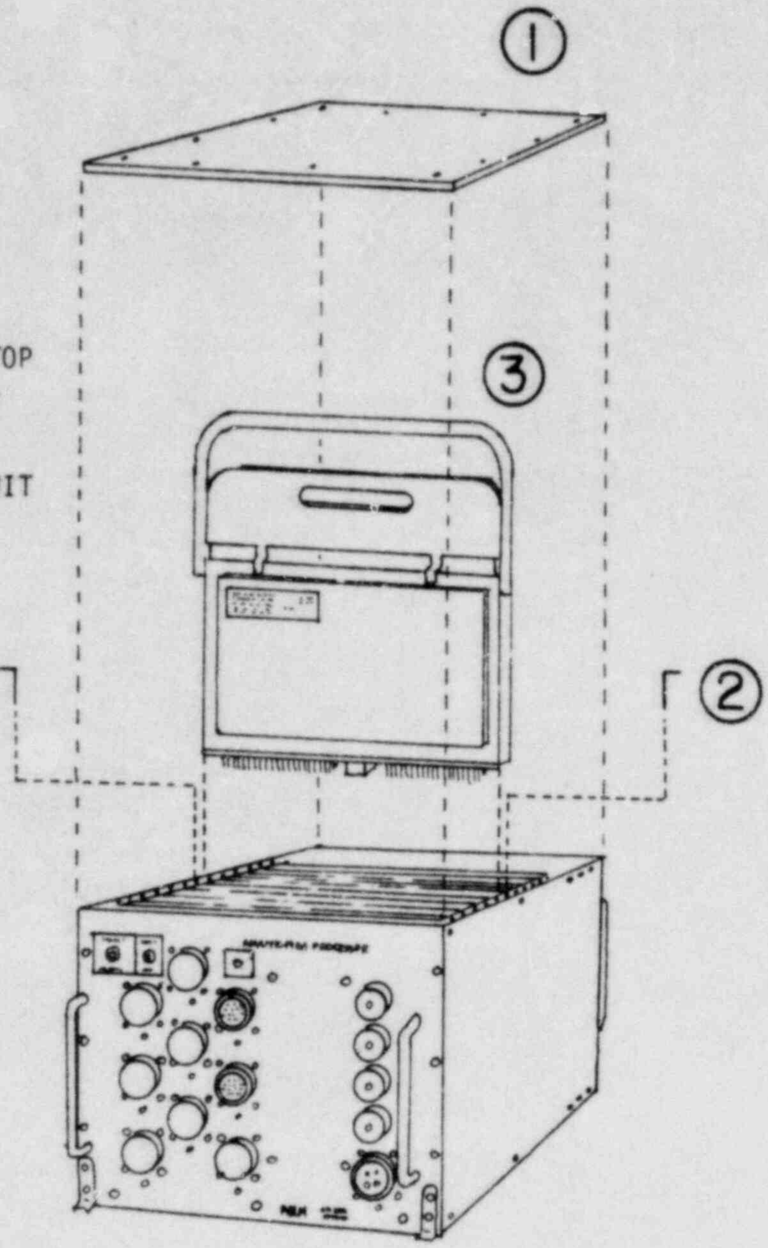


1 LIFT OFF THE SHIELD

2 DISCONNECT CABLES

3 DISCONNECT THE BOX
AND LIFT IT OUT

Figure 22. Containment Building Module Swapout Procedure.



1 REMOVE CABINET TOP
2 RUN-OUT THE VISE CLAMP SCREWS
3 REMOVE THE CIRCUIT BOARD WITH THE SPECIAL TOOL

Figure 23. Circuit Board Swapout Procedure.

localized scraping.

c. Unsolder the integrated circuit, using a combination vacuum soldering iron and solder wick.

## VI. Equipment Costs

All computer hardware, except custom-built pieces, can be priced using the current ROLM Domestic Hardware Price List. Components that are specific to this application are priced in table 9. Hardware bought by government agencies on the GSA schedule is subject to a 10.5% discount. Small quantity orders, such as 12 memory modules, are discounted 5%. Figures quoted are list price.

A three-processor system (two installed plus a spare) costs approximately $240,000. This includes 64K word memories, extreme temperature range options, I/O cabinets, special connector wiring, DC power supplies, and BITE.

## VII. Conclusions

An operational SPDS can be assembled in less than a year, to test the feasibility of using environmentally hardened equipment for optimum reliability in hazardous and non-hazardous environments, and to form a nucleus of hardware and software systems for a larger, unified safety system. Similar design methods can be used to gradually assemble a Technical Support Center, a Nuclear Network, and a new generation control room.

Delivery time for ROLM computers with custom wiring is conservatively 120 days. The logical structure and human engineering factors of the SPDS can be tested without special shielding and cooling. The advanced fiber

| Model | Option | Description | List Price |
|---|---|---|---|
| 1602B | | Processor | $17,250 |
| | 03 | Extreme Temperature Range | 2,000 |
| | 08 | Custom Loader PROM | 1,000 |
| | 11 | Special Connector Wiring | 300 |
| | 15 | BITE/Floating Point Arithmetic | 2,500 |
| | 16 | Single Cable I/O Bus Wiring Out | 400 |
| | 21 | DC Input Power | 100 |
| 1635 | | Control Panel | 0 |
| | 10 | Remote Connection | 4,175 |
| | 30 | RETMA Rack Mount-Remote | 250 |
| 1642 | | Control Panel Interface | 2,000 |
| | 07 | Reader/Terminal Connector Wiring | 300 |
| 2011 | | Core Memory - 16K Words | 7,000 |
| | 03 | Extreme Temperature Range | 2,000 |
| 2150 | | I/O Chassis | 10,000 |
| | 03 | Extreme Temperature Range | 1,000 |
| | 11 | Special Connector Wiring | 300 |
| | 21 | DC Input Power | 100 |
| 3540 | | Parallel I/O Buffer (16-Bit) | 1,050 |
| 3562 | | I/O Bus Terminator | 400 |
| 3564 | | Data Channel Controller | 1,250 |
| 3656 | | Analog-to-Digital Converter | 3,600 |
| | 06 | Differential 16-Channel Analog Mux | 700 |
| | 09 | Sample and Hold Amplifier | 600 |
| 3662 | | Differential Analog Mux Slave Module | 1,000 |
| 3800 | | Designer's Matrix Board | 350 |
| 5623 | | I/O Tester Module | 1,000 |
| PD3500 | | Plasmascope Terminal | 18,220* |
| PDA300 | | Plasmascope Display Head | 11,330* |

*Interstate Electronics Alpha/Graphic Display Products Domestic Price List

Table 9. Prices of Available Equipment.

optical communications link can be added after the system is proven using standard coaxial cables.

The requirements for this nuclear plant safety system are not unlike the reliability, data rate, and sensor load specifications for military radar projects that have successfully employed the ROLM 1602B. By using this well-developed, proven technology, many questions as to whether the safety equipment can survive nuclear plant accidents are dispelled.

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