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ABSTRACT

Radioactive materials make up a significant part of the hazardous-material inventory of the Department of Energy. Much of the radioactive material will be inspected or handled by robotic systems that contain electronic circuits that may be damaged by gamma radiation and other particles emitted from radioactive material. This report examines several scenarios, the damage that may be inflicted, and methods that may be used to protect or radiation-hardened robot control systems. Commercial sources of components and microcomputers that can withstand high radiation exposure are identified.

This report is Volume 2[1] of the two-volume Phase 2 Topical Report, *An Intelligent Inspection and Survey Robot.*

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[1] Volume 1, ARIES: Autonomous Robotic Inspection Experimental System.

DISCLAIMER

The descriptions, accounts and conclusions presented herein are those of Clemson University and the South Carolina Universities Research and Education Foundation (SCUREF) and do not necessarily represent those of the U.S. Department of Energy or any other Federal Agency.

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1.0 EXECUTIVE SUMMARY

Radioactive materials make up a significant part of the hazardous-material inventory of the Department of Energy. Much of the radioactive material will be inspected or handled by robotic systems that contain electronic circuits that may be damaged by gamma radiation and other particles emitted from radioactive material. Except for the immediate vicinity of nuclear reactors, gamma radiation is the predominant terrestrial nuclear product that can affect materials and electronic circuits. Alpha and Beta radiation are largely shielded by relatively thin containers; however, a significant amount of lead would be required to provide adequate shielding from gamma radiation from Cobalt-60. It can be concluded that shielding is not practical in most circumstances. Electronics that must be placed in the vicinity of moderate to high-level gamma emitters must be naturally radiation tolerant or should be radiation hardened to ensure operation for a prolonged period of time.

To use a mobile robot in the vicinity of high-level gamma radiation requires a special design. Since materials and electronic circuits can withstand *some* radiation without failure, the simplest approach would be simply to use an unmodified commercial mobile robot in the radioactive environment but remove it before failure occurs. Un-powered backup is another method of extending system lifetime in an ionizing radiation environment. When the primary system fails or degrades sufficiently, the backup system can be switched in to maintain system operation. Some semiconductor technologies such as bipolar devices and gallium arsenide devices are inherently resistant to damage by ionizing radiation. Bipolar circuits require appreciable power and, therefore, are undesirable for battery-operated mobile system. Gallium arsenide components are not available in sufficient variety to meet the needs of radiation-hardening mobile robots. Some commercial off-the-shelf (COTS) metal-oxide semiconductor (MOS) circuits have some inherent radiation tolerance. The thin oxide layers used in a number of modern manufacturing technologies may be able to tolerate a total dose of at least 50k rad(Si).* By careful design and lot testing, systems can be designed to meet moderate doses of radiation; however, randomly-selected off-the-shelf commercial parts cannot be guaranteed to meet a specified total-dose tolerance.

Finally, one can design circuits using circuits specifically processed to withstand high doses of radiation. Total-dose hardening to ionizing radiation is accomplished by using special manufacturing techniques that produce radiation-resistant oxide layers. Radiation-hardened MOS components and microprocessors are being manufactured for space and military applications that remain functional after exposure to a total radiation dose of over 1E6 rads(Si). At a somewhat lower price it is possible to obtain radiation-resistant components with a lower guaranteed performance such as 100k rad(Si), for example.

Successful operation of a mobile robot system in a high-radiation environment has one final essential requirement -- total-dose monitoring. Since a mobile system will usually move in an out of high radiation fields and will generally be operated in changing radiation fields, it is necessary to monitor the absorbed dose to be able to predict the useful life of the system. The RADFET, developed in England, is a semiconductor transducer that may be

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* rad(Si) = radiation absorbed dose in silicon = 100 ergs/gram silicon. 100 rad = 1 Gy.

mounted within the system electronics to indicate the total absorbed radiation dose and permit safe removal of the robot or by switching in backup electronics to extend the useful performance time.

Usually it is not possible to take a commercial design and simply substitute radiation-hardened components. In most cases a specific radiation-hardened design is necessary although it may be possible to work the other way and substitute commercial components for all or most of the radiation-hardened design to produce a less expensive equivalent system. Several radiation-hardened microprocessors are available. Radiation-hardened logic families are available that may be used to re-design the electronic circuitry in K3A robot. Radiation-hardened DC-to-DC converters to power the electronic circuitry may be obtained commercially or the radiation-hardened modules may be designed specifically for the K3A. The motor-drive power amplifiers must be completely re-designed using radiation-hardened components. The current motor-drive electronics is a closed-loop control system that receives feedback from encoders mounted on the drive motor and the steering motor. Encoders include semiconductor circuits that use light-emitting diodes (LEDs) and photo transistors that are sensitive to radiation, therefore the encoders must be replaced with components that are either inherently insensitive to radiation or are specifically radiation-hardened.

A Dumb Tethered Transport could be created by replacing all electronics with relay logic that would allow manual control of the drive and steering motors. Since a relay control system would involve no semiconductor devices, the system could survive a total dose of perhaps 1E7 rad. Such a system would have no navigational capability or safety reflexes, but it could be invoked as backup when all electronics fail and deploying a video camera or retrieving the robot mechanism are the only objectives.

We can define the Basic Radiation-Hardened System to be a teleoperated K3A transport capable of deploying a radiation-hardened video camera for initial entry and inspection applications. The electronics in the K3A mobile base has three essential modules:

- DC-1 Drive Control Computer
- MA-2 Motor Amplifier Circuit
- DC-DC Converter for powering the electronics.

The system can be operated on a tether under visual control with only the above modules in the base. For untethered remote operation a radio transceiver must be added. Additional navigation electronics is contained in the turret, including an ultrasonic sonar collision avoidance system.

Most of the mechanical structure of the K3A is aluminum or other metals, along with some plastic or elastic components. The metal structure is unaffected by exposure to radiation greatly in excess of the dose that would cause all electronic components to fail. The mechanical properties of most polymers and elastomers are not significantly affected by a radiation dose below 1M rad(Si). Teflon is a unique exception and parts that include Teflon insulation must be replaced by parts using less affected insulation. PVC plastic may release corrosive gas when exposed to radiation and should be replaced.

Conclusions: Hardening a mobile robot requires a special design – it cannot be accomplished by simply replacing radiation-soft parts with hardened parts. All Teflon and PVC must be replaced with radiation-resistant plastic. All electronics must be re-designed using radiation-hardened semiconductor components. A robot with a total-dose hardness of about 100k rad(Si) could be designed now; however, a Megarad design would pose more significant problems since parts with the higher dose assurance are becoming scarce due to the end of the cold war and discontinuation of several radiation-hardened foundries. A tethered robot with some safety mechanisms and onboard video cameras for inspection would be the simplest design and would require the re-design or replacement of only three or four electronic modules. Present K3A control firmware can be executed on a simulated Z-80 using a radiation-hardened Harris RHC-3000 processor module. A dual configuration using a special control module would produce greater reliability by providing an un-powered backup for the control computer and communication hardware. Finally, a backup mechanism involving only relays operated through a tether would make it possible to retrieve a mobile robot when all electronics fail. Providing a radiation-hardened radio communication link would require additional design effort.

2.0 INTRODUCTION

2.1 RADIATION EFFECTS ON SEMICONDUCTORS

The fact that nuclear radiation can shut down electronic systems became very obvious in 1962 when the Telstar I satellite failed as a result of radiation in the Van Allen Belts.[2] Since then the development of devices resistant to radiation has been driven by satellite, space, or weapons requirements. Teleoperated devices or robots for use on the earth's surface around radioactive materials are also subject to damage from ionizing radiation; however, the radiation environment is not an exact match to either the weapons or the space/satellite environments and the potential solutions to the semiconductor selection problem for earth-bound robots may be different.

Metal oxide semiconductor (MOS) technology has been the foundation of the very rapid growth in the development of integrated circuits based on very large scale integration (VLSI). Of particular importance are Complementary MOS (CMOS) digital circuits which require very low operating power. Most modern microcomputers are manufactured using CMOS technology. For these reasons the effect of radiation on CMOS devices is extremely important for robotics. The silicon-on-sapphire (SOS) and silicon-on-insulator (SOI) technologies are variations on the basic CMOS technology.

Without devoting any significant effort to understanding basic semiconductor physics, it can be pointed out that silicon-dioxide layers are used for insulation in the manufacture of MOS integrated circuits. In particular, the "gate" is insulated from the "channel" in MOS field-effect transistors (MOSFETs) used in VLSI digital logic. A buried oxide layer is also used between active elements and the silicon substrate of SOI devices. While some radiation effects occur in the region of silicon junction (and cause the gain effects found in TTL logic), most radiation damage in MOS devices is due initially to the formation of ion pairs when radiation deposits energy in the oxide layers.

2.1.1 Gamma Radiation

Electron-hole pairs are formed whenever gamma photons or other types of ionizing radiation deposit enough energy in the oxide layers to break atomic bonds. If a voltage is imposed across the oxide layer (such as a gate bias) the more mobile electrons are rapidly swept away under the influence of the electric field leaving behind positively charged holes with much lower mobility.

If the holes become trapped within the oxide layer they form what is called *oxide-trapped charge.* If the holes migrate to the oxide-silicon interface and become attached to disconnected chemical bonds that are due to lattice mismatch at the interface, they are known as *interface traps.* Some older publications refer to these latter trapped holes as *interface states* or *surface states.*

Most of the total-dose effect of gamma radiation on MOS devices can be described in terms of the behavior of the oxide-trapped charge or the interface traps. Some additional effects

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[2] D. S. Peck et al., "Surface effects of radiation on transistors," *Bell Syst. Tech. J.*, vol 42, p95, Jan. 1963.

of radiation known as *transient radiation effects* are caused by bursts of ionizing radiation or single energetic ions. These result in *transient upset* or *single-event upset,* respectively.

From a practical standpoint, transient effects are not likely to be significant for MOS circuits used in terrestrial robots. Weapons systems and space systems, on the other hand, require an immunity to transient effects created by nuclear weapons bursts or cosmic particles. Since most of the radiation hardening development is driven by space and weapons requirements, techniques to control transient effects have received a lot of attention.

The dominant damage to earth-bound robots will be due to total-dose accumulation of oxide-trapped charge or interface traps. These two types of total-dose effect form at different rates that are dose rate, time, temperature, and bias dependent.

The term *radiation hardened* is used to identify electronic circuits that have been designed to "pass a given set of specifications under all conditions of dose rate, bias, temperature, etc., for all doses larger than 10^5 rads(Si). *Radiation soft* circuits are typically considered those that fail a given set of specifications at 10^4 rads(Si) or less."[3]

The effects of time, temperature and dose rate are particularly important when considering whether to use radiation hardened or much less expensive radiation soft components that seem to meet some level of total-dose tolerance.

As a total dose of ionizing radiation is absorbed by the oxide layers of an MOS device, the oxide-trapped charges and interface traps both increase in proportion to the total dose. The holes trapped within the oxide lead to a shift in the threshold voltage of the device and a net positive charge tends to turn on or increase the leakage current of an n-channel FET. Holes migrate to the silicon/silicon-dioxide interface where they capture electrons and result in a reduction in transistor gain as well as a shift in the threshold voltage opposing the effect of the oxide-trapped charges. Current hardening technology is designed to improve radiation hardness by minimizing the formation of both oxide-trapped charge and interface traps.

The time, temperature, and dose rate effects on oxide-trapped charge and interface traps become particularly important when one considers using radiation soft or moderately radiation tolerant devices in robot control systems exposed to moderate doses of ionizing radiation.

By definition, radiation soft commercial devices have received no special attention during manufacture to control the formation of oxide-trapped charge or interface traps if the components are exposed to gamma radiation. Oxide hardening is mostly a result of special manufacturing processes during production of the parts. As far as *commercial* manufacture is concerned, modification of processing steps is aimed at improving production yield with no consideration to the effect on hardness. (There are some manufacturing processes that could involve x-ray lithography the must be concerned with the ionizing effects of x-rays; however, commercial production is not generally concerned with radiation exposure after manufacture.)

In general, however, manufacturers have no economic motivation to maintain exact processing procedures that will insure radiation hardness; therefore, lot-to-lot variability

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[3] T. P. Ma, and P. V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits,* Wiley, New York, 1989.

can be considerable. Experiments have demonstrated a 20-fold difference in failure threshold when different lots of commercial devices are tested.[4] According to Gover[5] the variations in gamma-dose hardness were "due primarily to what were believed to be minor changes, or even no change, in processing steps." One would expect even greater differences between samples from different commercial manufacturers producing the same part.

The great variability of radiation tolerance of rad-soft production methods suggests that lot testing and selection is required to obtain a predictable radiation tolerance. Unfortunately, lot testing does not solve the problem either using only the high dose-rate test methods specified in the early versions of MIL-SPEC 883C Test Method 1019. Much of the early data on total-dose hardness of commercial parts is based on high-dose rate testing only. The work on Post Irradiation Effects (PIE) invalidates any hardness data that does not include such data as the results of a 168 hour post-irradiation anneal as specified in Test Method 1019.4. PIE data allows one to predict how the radiation tolerance of rad-soft devices will vary if dose rates encountered during application are different than test dose rates.

Many of the applications for radiation-tolerant components is in radiation fields where the dose rates differ significantly from published testing dose rates. To keep test duration reasonable, relatively high dose rates of the order of 180,000 - 1,080,000 rads(Si) per hour are used. In real robotics applications much, much smaller dose rates will usually be experienced. It is practically impossible to test component lots at the actual dose rate expected during applications. The total-dose failure threshold during use may be much higher or much lower than the hardness determined by experiment.

The great variability in total-dose hardness as a function of dose rate is due to time-dependent effects discussed earlier. To permit high-dose-rate testing, recent modifications to MIL-SPEC-883C Method 1019.4 are directed at revealing post irradiation effects that are useful for predicting low-dose rate total-dose rate hardness. Test Method 1019.4 provides a conservative estimate of low-dose rate total dose hardness and still different test methods have been proposed to arrive at a closer estimate of low-dose behavior. The main driving force for good low-dose information is the application of rad-soft components instead or much more expensive hardened components in satellites and space vehicles.

The sequence of tests specified for Method 1019.4 are as follows:[6]

Method 1019.4

(a) Co-60 irradiate devices under worst-case bias conditions to the specified dose at a dose rate of 50 - 300 rad(Si)/s.

(b) Remove bias. Maintain zero bias between irradiation and test.

(c) Complete functional and parametric tests within 2 hours after irradiation.

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[4] A. H. Johnson, 1980 IEEE Sponsored Short Course, "Radiation Effects on Components and Component Hardening," Cornel University, Ithaca, New York, 1980.

[5] J. E. Gover, 1984 IEEE Tutorial Short Course on Radiation Effects, "Basic Radiation Effect in Electronics Technology," Colorado Springs, CO, July 1984.

[6] Fleetwood, D. M., P.S. Winokur, and T. L. Meisenheimer, "Hardness Assurance for Low-Dose Space Applications," *IEEE Trans. Nuc. Sci.*, NS-38, 1552, (1991).

(d) If the devices pass all tests in (c), irradiate the devices again under the conditions of (a) to an *additional* dose equivalent to 0.5-times the specification.

(e) Bake the devices at worst-case static bias for 168 hours at 100^{O} C, or under conditions that have been demonstrated in characterization tests to cause equal or greater degradation in the parameter(s) of interest (e.g., speed, timing, and/or output drive).

(f) Repeat the tests of (c).

Test Method 1019.4 is designed to remove oxide-trapped charge that would anneal at low dose rates and reveal any failures due to interface trap effects that would dominate at low dose rates.

The bottom line is that commercial components chosen for applications for moderate dose rates of ionizing radiation must be evaluated with high dose-rate tests that are expressly designed to reveal low-dose rate behavior by examining post-irradiation effects following the accelerated tests.

2.1.2 Heavy Particles and Cosmic Rays Found in Space

Gamma radiation will be the form of radioactivity most often encountered by electronic circuits used in DOE robotics applications. As mentioned earlier, alpha and beta radiation are effectively shielded by the containers that enclose electronic circuitry as long as air cooling is not used. Occasional cosmic rays may penetrate terrestrial electronic systems and cause a random computer upset. This is in great contrast to space where cosmic rays and an number of other heavy particles are likely to temporarily or permanently damage electronic circuits. For this reason MOS and other types of electronic components selected or manufactured for space applications must be hardened against single event upset (SEU) as well as long low-dose exposures to ionizing radiation such as x-rays produced by impact of high-energy electrons and protons.

The electrons and protons found in space are modified in intensity as they pass through the enclosures surrounding electronic circuits. However, more significantly, they interact with the packaging materials to produce secondary radiation that can also affect electronic circuits.[7] The secondary radiation may have greater penetration and may have a greater dose effect than the original radiation. The most significant secondary radiation is bremsstrahlung x-rays that are produced as the electrons decelerate while penetrating spacecraft structural materials such as aluminum. The bremsstrahlung x-rays have a continuous spectrum with great penetration and are therefore difficult to shield.

2.1.3 Terrestrial vs. Space Hardening requirements

Electronic circuits for use in space differ from requirements for terrestrial applications. While the ionization effects due to bremsstrahlung x-rays have comparable effects to

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[7] E. G. Stassinopoulos, "Radiation Environment of Space," IEEE Short Course on Microelectronics for the Natural Radiationj Environments of Space, Reno, NV, July 1990.

terrestrial gamma radiation, electronics for space applications must also be protected against penetration of heavy ions or cosmic rays that can cause logic elements to change state. This is called single-event upset (SEU) and requires testing much different from the total-dose tests defined by Method 1019.4. Space and low-level terrestrial applications may be similar from a dose-rate standpoint, however, space applications have the additional problem of SEU and hardened microprocessors for space applications must have extensive special circuitry to protect stored data or programs in memory. Redundancy must be designed into processor registers to prevent unanticipated effects during program execution or data manipulation.

Consequently, microprocessors designed for space applications have extra expensive circuitry included that is not required for terrestrial applications with a similar total dose exposure. Two different RISC processors, both known as the RH-32, are being developed for space applications. These are much more expensive than necessary for terrestrial applications due to the extensive error prevention and correction circuitry designed into the system to protect against SEU. The extra circuitry does no harm but the SEU hardness will not be challenged on the earth's surface except by an occasional cosmic ray that penetrates the atmosphere. One is faced with the problem of paying for expensive circuits with unneeded sophistication or paying for the testing required to determine whether commercial circuits have the modest total-dose hardness needed for terrestrial robotic applications. The latter could be more expensive.

2.1.4 Potential for Radiation Shielding

Sometimes lead shielding is suggested as a means of improving the radiation tolerance of electronic systems. The feasibility of such shielding is determined by examining the potential radiation threats. Alpha, Beta, and Gamma radiation sources may be present in radioactive hazardous waste which is one of the scenarios where DOE would propose using robots. Alpha particles are not a threat to electronic parts since even a sheet of paper will provide a sufficient shield. All semiconductors are encapsulated at least in plastic. Charged Beta particles have a range of about 20 feet in air and could damage electronic parts if the source were sufficiently close. Most electronic modules are within some sort of enclosure and 1/16 inch of aluminum sheet is sufficient to shield against beta particles. However, if used around dust contaminated with beta sources, an electronic enclosure must be sealed. Air cooled semiconductor electronics would not be practical if robots were to be used in an area badly contaminated with beta emitters.

Gamma rays are by far the most important terrestrial radiation source as far as electronic devices are concerned. They are photons or quanta of energy much like x-rays and as such will penetrate lead or concrete to a depth dependent on their energy. A source such as Cobalt-60 emits gamma rays with an energy spectrum that will penetrate lead over two inches thick. In fact, the gamma energies from Cobalt-60 are attenuated by a factor of 10 using a shield just under two inches thick. A shield surrounding an electronic module would have to place two inches of lead between the source and the module to allow a part with a failure threshold of 100,000 rads to operate in a radiation field where 1 Mrad total dose would be accumulated. Two inches of lead around a reasonable sized circuit enclosure would be very heavy.

The effect of shielding is readily determined using the following equation[8]:

$$I = I_0 e^{-mx}$$

where I is the intensity outside the shield and

I_0 is the unshielded radiation intensity,

m is the linear attenuation coefficient of the shielding material, and

x is the thickness of the shield.

The linear attenuation coefficient, m, is proportional to the mass attenuation and the density of the shielding material. The mass attenuation coefficient is, in turn, a function of the photon energy and the shielding material.

For a lead shield and gamma photons, the thickness required to attenuate radiation by any ratio is obtained by solving the following equation for x:

$$x = \ln (I / I_0) / m$$

To demonstrate the varying amount of shielding required by different gamma sources, it is interesting to note that 0.54 cm of lead is required to attenuate gamma emitted from Cs-137 by a decade, while a lead shield 3.43 cm thick is required to attenuate gamma emitted from Co-60 by a decade. The difference is due to the different energy spectrum of the two isotopes and the resulting mass attenuation coefficients.

Significant neutron fluxes may be found near an active reactor; however, robots are not likely to be operated regularly in such an environment. Neutrons are not considered a terrestrial radiation problem as far as CMOS circuits are concerned although neutrons can cause some displacement damage in bipolar circuits.

2.1.5 Contamination and Decontamination

If electronic circuits are shielded from alpha and beta radiation damage by sealed containers, cooling and decontamination are likely to be the main problems if hardened MOS components are used in robotic control system. If electronic circuits are enclosed in a sealed container to protect from contamination by airborne beta sources as well as ordinary dust and moisture, heat dissipation becomes a major concern. All electronic circuits produce heat. Current flowing through any resistance is the source of heat. Fortunately, CMOS circuits have very low power requirements and consequently generate very little heat. However, even a CMOS circuit generates *some* heat and circuit boards will start to rise in temperature if it is thermally insulated from the atmosphere. Generally, sealed circuits are conduction cooled by providing a thermal pathway for heat to be conducted to the case where it is radiated to the environment or cooled by external convection.

Fortunately, sealed cases are a benefit should it be necessary to decontaminate a robot. Contaminated dust circulated by an air-cooled system would be very difficult, if not impossible, to decontaminate should robot electronic repairs be required. A sealed case merely requires steam cleaning to remove surface contamination and all the circuit boards

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[8] Radiation Control and Radiological Services, *"Basic Radiation Safety Study Guide,"* University of Florida, Gainesville, 1992.

will have been completely protected from contamination. It should be noted that the radiation-hardened VMEbus processor module is a conduction cooled design that may be used in either a sealed conduction-cooled case in a robot or in a standard air-cooled rack for development work.

2.1.6 Device Hardening Technology

A reasonable variety of technologies are available with which to design digital and analog circuits. Standard Transistor-Transistor Logic (TTL), which has been around for a long time, is known to be reasonably radiation hard from the standpoint of total-dose exposure. Circuits may remain functional after exposure to megarad doses of ionizing radiation. The same is true for Emitter Coupled Logic (ECL), Integrated Schottky Logic (ISL), and Current Injection Logic (I^2L) that may be used for discrete circuit design[9]. "Generally, bipolar transistors are hard to total doses near 1 Mrad; however, this hardness capability does not translate to bipolar integrated circuits, especially those that are employing sidewall (oxide) isolation techniques to achieve high integration density."[5] However, MOS technology is the foundation of Very Large Scale Integration (VLSI) that has made the advanced microprocessor possible. Low-power CMOS processors and components are particularly important where power sources are limited.

Much money and effort has been devoted to developing radiation-hardened MOS and CMOS components. Several companies have developed extensive radiation-hardened product lines; however, according to one trade publication: "With its acquisition of the RCA/GE radiation-hardened lines, Harris became the world's largest supplier of radiation-hardened semiconductor products, posting revenue of about $100 million in 1992."[10] Other companies with radiation-hardened silicon foundries include Honeywell, IBM (now Lorel), LSI Logic, and United Technologies (UTMC). LSI Logic and United Technologies have recently announced that they are discontinuing their radiation-hardened foundry although UTMC will continue to offer a radiation-hardened product line manufactured by another contract foundry.

2.1.7 Bipolar Devices

As pointed out above, individual bipolar transistors and some discrete bipolar logic may be expected to be radiation hard to 1 Mrad. However, bipolar integrated circuits employing recessed field oxides must be specifically radiation hardened. Due to its other desirable features, most efforts to harden very-large scale integration circuits has concentrated on MOS and particularly CMOS technologies.

Gover[5] also points out that bipolar devices operating in the linear region can be very sensitive to a total-dose of ionizing radiation. This becomes important if the use of operational amplifiers, or circuits containing operational amplifiers, is contemplated.

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[9] M. A. Rose, "Radiation Effects and Hardening Techniques," 1984 IEEE Tutorial Short Course on Radiation Effects, Colorado Springs, CO, July 1984.

[10] *Military and Aerospace Electronics,* March 1994, p20.

2.1.8 Power Control Devices

Modern control systems may be radiation hardened by using radiation-hardened microcomputers, interface devices, and amplifiers. Operation of motors or other end-effectors that use significant power requires radiation-hardened components that can control reasonably large dc currents. Radiation-hardened Power Metal Oxide Semiconductor Field Effect Transistors (Power MOSFETS) fill this need. A variety of Power MOSFETS are available from the Harris Semiconductor with a total-dose hardness up to 1E6 rads(Si) and the capability of switching currents up to 50 amperes.

2.2 RADIATION EFFECTS ON PASSIVE ELECTRONIC COMPONENTS

Most passive electronic components have been shown to be tolerant of ionizing radiation in excess of 1M rad. Figure 2.1 shows a representative list of components that have been tested for radiation tolerance. It is unlikely that passive components will present a design limitation as long as particularly susceptible organic compounds are not used for insulation or for encapsulating the parts.

Table 2.1 Radiation Dose Limits of Component Parts[11]

Component	Dose limit (Rads)	
Resistor, carbon composition slug	1E7	
Resistor, carbon composition film	1E8	
Resistor, metal film	1E11	
Resistor, carbon film	1E9	
Resistor, oxide film	1E6	
Resistor, wirewound on ceramic		1E12
Resistor, wirewound on epoxy		1E9
Resistor, film potentiometer	1E7	
Resistor, wirewound variable		1E9
Resistor, film variable		1E7
Capacitor, paper	1E7	
Capacitor, ceramic	1E10	
Capacitor, glass		1E10
Capacitor, mica		1E9
Capacitor, Plastic	1E7	
Capacitor, Tantalum slug, wet		1E7
Capacitor, Tantalum slug, dry		1E9
Capacitor, Tantalum foil	1E7	
Transformers, relays	1E9*	
Quartz crystals		1E7
Foil-clad laminates (printed circuit boards)		1E7
Connectors, Duroc ceramic	3E8	
Connectors, Melamine plastic		3E8
Silicon varnish insulation	1.4E9	
Varistors, silicon	1E9	
Varistors, selenium and copper		1E5

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[11] L. W. Ricketts, *Fundamentals of Nuclear Hardening of Electronic Equipment*, Wiley-Interscience, New York, 1972.

[*] Depends on insulating materials used.

2.3 RADIATION EFFECTS ON MATERIALS

Investigation of the effect of radiation on materials has a long history. Handbooks contain extensive tables describing the response of materials to various types of radiation. Fortunately most metals are not affected significantly by gamma radiation; however, some plastics such as Teflon are damaged by rather modest total-dose exposure to ionizing radiation.

Tables 2.2 and 2.3 are derived from the *Fundamentals of Nuclear Hardening of Electronic Equipment*[12] and the *Nuclear Engineering Handbook*[13]. These tables show a number of plastic materials that may be used for structural or insulation purposes. By avoiding Teflon, nylon, Polyvinalchloride (PVC), and some forms of rubber, systems can easily be designed to withstand a total-dose exposure of over 1 Mrad.

Table 2.2. Radiation Dose Limits for common insulating materials and elastomers[11]

Material	Exposure in Rads
Silicon-treated mica	1E7
Silicon-varnished glass fiber	1E7
Polyethylene	1E7
Mylar	1E7
Teflon	1E4
Polyurethane glass fiber	1E8
Polyvinalchloride (PVC)	1E5
Polystyrene	1E8
Bakelite	1E8
Epoxy resin	1E4
Glass-bonded mica	1E8
Diallyl phthalate	1E8
Nylon	1E5
Natural rubber	1E6
Butyl rubber	1E6
Neoprene	1E6
Viton A	1E7
Silicon Rubber	1E6
Buna-*N*	1E5

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[12] L. W. Ricketts, op. cit.

[13] H. Etherington, *Nuclear Engineering Handbook,* McGraw -Hill, New York, 1958.

Table 2.3. Radiation damage to parts of motor, selsyns, relays, and switches[12]

Component part	Dose (rads) to produce 25 % change	
Brush holder, Linen-filled phenolformald		3E6
Brush holder, Paper-filled phenolformald		8E6
Grease seal, Neoprene		6E6
Grease seal, Buna-*N*	4E6	
Grease seal, Felt	5E6	
Insulating tape, Rubberized Cloth	5E6	
Insulating tape, Polyvinyl chloride (PVC)	1.2E8	
Insulating tape, Natural rubber		2.6E7
Insulating tape, Teflon-coated fiber glass		3E4
Insulating tape, Fiber glass and silicone resin		5E8
Insulating tape, Acetate cloth		1.6E7
Insulating tape, Buna-N-treated fiber glass		4E6
End punchings, Teflon-coated fiber glass		3E4
Slot insulation, Teflon-coated fiber glass		3E4
Shaft insulation, Fiber glass melamine		6.4E7
Shaft insulation, Mylar		1.2E8
Shaft insulation, Teflon		3E4
Shaft insulation, Mica with shellac	4E7	
Shaft insulation, Mica with Mylar	1.2E8	
Shaft insulation, Paper-filled phenolformald		8E6
Shaft insulation, Asbestos-filled phenolformald		5.3E8
Shaft insulation, Kel-F		1.7E7
Shaft insulation, Fish Paper		5E7
Shaft insulation, Varnished cambric		5E6
Shaft insulation, Polyvinylchloride	1.2E8	
Shaft insulation, Cellulose acetate	1.6E7	
Wire insulation, Teflon		3E4
Wire insulation, Formvar	9.7E7	
Wire insulation, Fiber glass and silicone resin		5E8
Wire insulation, Nylon		4E6
Wire insulation, Neoprene	6E6	
Wire insulation, Paper		5E6
Relay, switch base, Asbestos-filled phenolformald		1E9
Relay, switch base, Unfilled phenolformald		1E7
Gaskets, Buna-*N* rubber		4E6
Gaskets, Hycar-PA	3E6	
Connectors, Polystyrene		6E9
Connectors, Polyethylene	9E7	

3.0 RADIATION HARDENING MOBILE ROBOTS

3.1 HARDENING DEFINED

What is radiation hardening? In the simplest viewpoint hardening amounts to changing all components of a system that are affected by radiation to components that can withstand a significant radiation dose without failure. Structural materials, lubricants, elastomers, plastics, and, of course, electronics are all to be considered. However, in this chapter it is useful to broaden the definition to include even complete changes in design, rather than a simple component change, as an alternative approach to hardening.

The present ARIES inspection robot is a highly automated robot capable of autonomous behavior. Performance of this sort requires multiple computers and an array of rather sophisticated electronic vision hardware and software. The ARIES system has the specific task of inspecting drums of stored low-level hazardous waste. Radiation at the surface of the drums is limited to less than 100 rem/hr which will not affect electronic circuits significantly. An identical task in high radiation fields is unlikely and it probably makes no sense to radiation harden all the circuits in the present version of ARIES. Rather, it is necessary to examine the tasks that might require an inspection and survey robot to enter high radiation fields that would destroy the on-board electronics. Application scenarios will determine the necessary sophistication of on-board electronics and, therefore, the nature and extent of the radiation-hardening task. The hardening problem will be different for different scenarios.

Table 3.1 shows a number of potential applications for radiation-hardened robots as defined by Andrew Holmes-Seidle for the European Space Agency. Mobile robots could be employed in a number of applications where remote inspection is necessary. There is also the potential for remote manipulation. For example, an emergency situation where a fuel rod is jammed and cannot be moved by conventional means. Remote inspection and possibly manipulation is an obvious requirement.

	Common Dose Rates rad h^{-1}	Operational Life time hrs	Radiation Tolerance Requirement rad(Si)
Fuel Fabrication	10^{-1}	10^4	10^3
Cell Decontamination	10^3	10^4	10^7
Reactor Decommissioning	30	10^4	3×10^5
Fuel Processing	10^3	10^4	10^7
Fuel Handling	10^4	10^4	10^8
Underground Storage	10^3	10^4	10^7

Reactor Incident Inspection (TMI recommendation)			3×10^8

Figure 3.1. Equipment Radiation Tolerance Requirements for several scenerios.

We will, therefore, define a Basic Inspection Task where a mobile vehicle is required to enter a high-radiation area, deploy a video inspection camera, and relay images back to an operator. Additional tasks could involve deploying a variety of other sensors. The elaborate computer vision and image analysis hardware onboard the ARIES drum inspection robot is not required for the basic inspection task as defined here. The Basic Inspection Task will be defined as (1) navigation to an inspection site, (2) control of a pan-tilt mechanism to direct a camera toward a selected area, and (3) transmission of video signals to an operator. Any approach that will permit a Cybermotion K3A mobile robot to accomplish the above task will be considered "radiation hardening."

The Cybermotion K3A is called a *robot* rather than a *teleoperated vehicle* since it has on-board computer intelligence that permits certain navigation decisions, such as collision avoidance, to be made by on-board computers rather than by a human operator. Navigation is improved by the on-board controls that allow the robot to follow walls or enter doorways without colliding with obstacles not seen by the operator. In an unstructured environment a robot must be under operator control, however, computer-assisted navigation is much more satisfactory than simple teleoperation.

The following sub-tasks can, therefore, be defined to fulfill the Basic Inspection Task:

Navigate to a site under operator control while avoiding obstacles.
Direct a video camera at a particular location.
Control illumination.
Transmit video signals to an operator.
Return to the starting location (Recover the robot).

To accomplish the above tasks using the unmodified K3A the following electronic modules must remain intact:

1. Drive Control Computer, DC-1.
2. Motor Amplifier Module, MA-2.
3. DC-to-DC converters supplying power.
4. Collision Avoidance Computer, CA-1.
5. Ultrasonic Sonar Head Card, USB/8.
6. Turret Interface Panel, TIP-02
7. Ultrasonic Sensors.
8. Video camera(s).

To simply recover the robot, under manual control without the aid of the collision-avoidance computer, would require only modules 1, 2, 3, and 8. A special control board, called SPIKE, has been designed to be added to the system to bypass failed modules and retain operator control of the robot. Obviously, this board must continue to function. The hardening task is directed at insuring survival of the essential modules while the robot is operating in a high-level radiation field.

In general, it is not possible to simply procure radiation-hardened parts to replace all components in the existing electronic modules. Radiation-hardened parts are not available on a one-to-one basis to replace an arbitrary selection of parts in an existing design. Rather, it is necessary to either protect or completely re-design all electronics using specifically radiation-hardened parts that were developed for the space and strategic defense initiatives. Such a re-design is not trivial, although once the various modules have been re-designed to use the available radiation-hardened components, a much less expensive non-hardened version could be manufactured using commercial off-the-shelf parts that are equivalent to the radiation-hardened parts. In addition, an alternative microcomputer must be selected since there is no radiation-hardened equivalent to the Z-80 control computers used in the Cybermotion robot. Selection of alternative radiation-hardened microprocessors is examined in detail in papers included in the Appendix.

3.2 APPROACHES TO HARDENING THE CYBERMOTION ROBOT

Since materials and electronic circuits can withstand some radiation without failure, the simplest approach to operation in a high radiation field would be simply to use an unmodified commercial mobile robot in the radioactive environment but remove it before failure occurs. This was tried at Chernobyl and a number of mobile robots failed prematurely since it was not possible to know precisely how long an unprotected robot could operate before failure.

Shielding is sometimes suggested; however, a significant amount of lead would be required to provide adequate shielding from gamma radiation. Depending on the energy spectrum of the emitted gamma radiation, Cobalt-60, for example, requires a lead shield almost two inches thick to attenuate the exposure by one decade. Cesium-137, another common waste product, requires a one-inch lead shield to attenuate exposure by same amount. It can be concluded that shielding is not practical in most circumstances.

Some semiconductor technologies have an inherent tolerance to ionizing radiation. Bipolar semiconductor devices may tolerate relatively high levels of radiation without failure; however, the gain is generally degraded considerably. Special circuit designs would be required to insure acceptable functionality when exposed to high levels of radiation. In addition, bipolar devices require considerable power for operation and are not generally suitable for computers or logic designed for operation in mobile battery-operated applications. Gallium arsenide devices are also inherently resistant to damage by ionizing radiation. Some gallium arsenide semiconductor components have been designed for military or space applications; however, they are expensive and a broad family of parts to meet design requirements are not available.

Complimentary Metal Oxide Semiconductors (CMOS) are used for most modern designs requiring digital logic or microprocessors. The term COTS, which stands for "Commercial Off-The-Shelf" is prominent in recent military electronics publications. Some COTS CMOS circuits have some inherent radiation tolerance. The thin oxide layers used in a number of modern manufacturing technologies may be able to tolerate a total dose of at least 10 krad(Si). The National Semiconductor FACT (Fairchild Advanced CMOS Technology) logic family is resistant to ionizing radiation due to its thin gate oxide, P-well design, and low-temperature fabrication processing. Many FACT logic components function satisfactorily to several hundred krads(Si). By careful design, systems can be constructed using COTS components to meet moderate doses of radiation; however, randomly-selected off-the-shelf commercial parts cannot be guaranteed to meet a specified total-dose tolerance.

Unpowered backup is another method of extending system lifetime of electronic modules in an ionizing radiation environment. Unpowered CMOS circuits are able to tolerate much higher doses of radiation than circuits in actual operation. The survival dose of a total system can be doubled by keeping an unpowered backup system in reserve. When the primary system fails or degrades sufficiently, the backup system can be switched in to maintain system operation for an additional period of time.

One can design circuits using circuits specifically processed to withstand high doses of radiation. Total-dose hardening to ionizing radiation is accomplished by using special manufacturing techniques that produce radiation-resistant circuits. (It should be noted that there are other effects of radiation due to nuclear particles and heavy ions that require other design modifications. Here we are limiting our discussion to damage due to gamma radiation.) Radiation-hardened CMOS components and microprocessors are being manufactured for space and military applications that remain functional after exposure to a total radiation dose of over 1E6 rads(Si). Systems can be designed using such components but the individual components are much more expensive than non-hardened commercial components and the resulting system will be very expensive. At a somewhat lower price and with a broader selection of parts, it is possible to obtain radiation-tolerant components with a lower guaranteed performance: 100 krad(SI), for example.

Finally, taking a somewhat radical approach, one could design a back-up system that would replace all the drive and control electronics with relay logic. Using relay logic, drive and steering motors could be operated under manual control to recover a mobile robot with a failed electronic control system. Relays and motors will continue to operate after a total dose of ionizing radiation in excess of 10 Megarad. Vidicon-based black-and-white video cameras are available with a similar radiation tolerance that will provide the necessary visual guidance for robot navigation.

3.3 HARDENING THE ELECTRONICS

3.3.1 Control Computers

After an extensive analyze that is documented by several papers included in the Appendix, the Harris RHC-3000 was selected as an excellent processor on which to base a future radiation-hardened design. A number of lines of reasoning went into this recommendation and a few are list here:

1. The RHC-3000 is based on the MIPS 3000 Reduced Instruction Set Computer (RISC) and is one of the most advanced and powerful microprocessors available as a radiation-hardened product.
2. The Harris Corporation is one of the world's largest manufacturer of radiation-hardened electronic components and is unlikely to discontinue the product.
3. Functionally equivalent non-hardened processors are available and are widely supported.

4. Processor Modules for the VMEbus that use the R-3000 microprocessor are available in the civilian market for immediate prototype development.

5. The Harris Corporation proposed a radiation-hardened VMEbus processor module and quoted a price of about $300,000 to develop and deliver a prototype.

Since making this decision, the ARIES on-board mission control computer has been developed using the Heurikon HKMIPS/V3500 VMEbus processor module that is functionally equivalent to the Harris radiation-hardened processor module. Recently we have demonstrated that a 20 MHz R-3000 processor may be used to simulate the 4 MHz Z-80 microprocessor currently used to control the drive and steering motors in the K3A robot base. The simulation program operating on the R-3000 executes Z-80 machine instruction code at approximately the same speed as the 4 MHz Z-80. The Z-80 simulation experiments are documented in the Appendix.

Since deciding to use the R-3000 MIPS processor for prototype development, inexpensive microcontrollers based on the R-3000 have been marketed specifically for embedded control applications. These could well be the basis for a future very powerful commercial drive-control computer that is software compatible with the radiation-hardened processor. The Harris RHC-3000 seems to be a good choice for future development of a hardened processor. In addition, NASA has sponsored development of another radiation-hardened processor called the Mongoose which is functionally very similar to the RHC-3000 and provides another alternative development approach.

3.3.2 Motor Control Amplifiers

Analog versus Digital Control: Robots are controlled by servo systems that are subject to the same types of radiation damage that affect microcomputers. A servo-control loop includes sensors, amplifiers, and motor-drive circuits in addition to the electro-mechanical components discussed in the next session of this report.

Modern servo systems also generally include microcomputers and the analog-to-digital (A/D) and digital-to-analog (D/A) converters required to provide interfaces between the digital and analog modules. (Although not strictly correct, the term "analog" is commonly used to describe all circuits that use continuously varying electrical currents or voltages to represent control signals.) Some modern servo systems are completely digital and thus employ no operational amplifiers, A/D converters, D/A converters, or linear power amplifiers.

Figure 3.1 shows a simplified servo motor-control system. The system design can vary between a completely analog system, a hybrid analog-digital system, and a completely digital system. The analog system is designed with analog sensors, operational amplifiers, and linear power amplifiers. The hybrid system may be similar to the analog system except that some of the modules could include a microcomputer and appropriate A/D and D/A converters. If digital encoders are employed as position sensors, the feedback loop may be all digital. The power amplifier stage in a hybrid system could be either an analog power amplifier or a Pulse-Width-Modulated (PWM) switching-mode power amplifier. An all-digital system employs only digital sensors, a microcomputer and PWM power circuits.

A/D and D/A converters are unnecessary. A design engineer is faced with different problems when radiation hardening each of the above types of servo system.

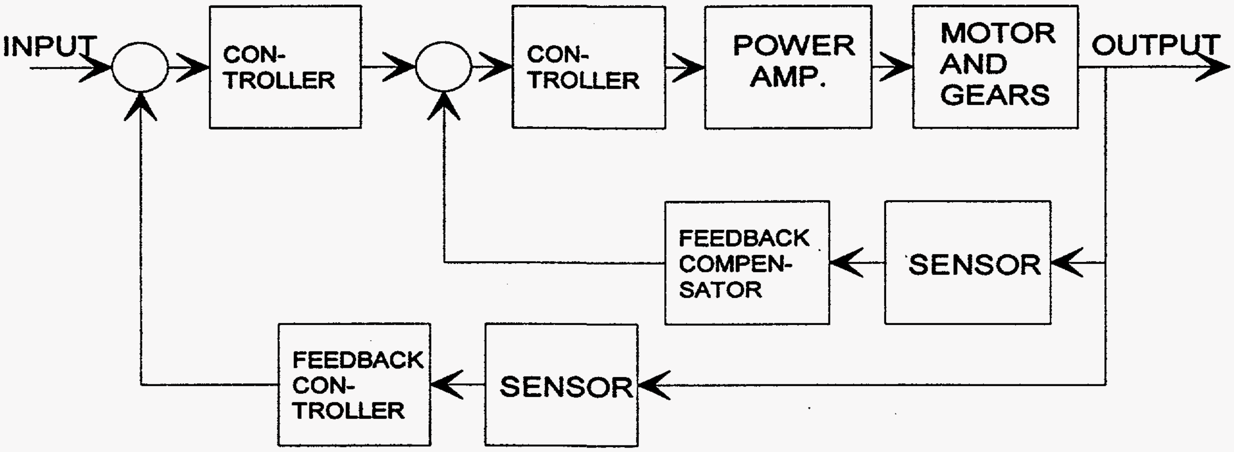

Figure 3.1. Block diagram of servo control system.

Hardening Position Control System Modules: It is probably simpler to radiation harden a completely analog servo system than either a hybrid or a completely digital system. An analog position control system will include a position sensor that is generally a potentiometer. Wire-wound potentiometers are unaffected by radiation unless susceptible insulation such as Teflon is used in manufacturing it. Single-turn and multi-turn wirewound potentiometers are available in a large variety of resistances and configurations. Position information may be either linear or rotational.

Operational amplifiers are available in radiation-hardened versions for sensor signal conditioning, signal summation, and for computing controller transfer functions. Harris Semiconductor offers operational amplifiers that are radiation hard to a total dose of 1E5 or 1E6 rad(Si). Analog Devices publishes a list of test results that indicate the radiation tolerance of their commercial operational amplifier product line. Passive devices, such as resistors and capacitors, are radiation tolerant or radiation immune if care is exercised in selection.

The motor control output of a position-control system will require power amplifiers. If bipolar power transistors are used, a degree of radiation hardness is inherent. Bipolar power transistors as a class will tolerate a total dose of up to between 1E5 and 1E6 rads(Si). Unfortunately operation of bipolar power transistors in a linear mode dissipates (i.e., wastes) considerable energy. A typical linear amplifier system for a medium sized robot manipulator requires about 1.5 kilowatts to operate. Operation of power stages in the PWM switching mode improves matters considerably. Radiation-hardened power mosfets suitable for PWM power amplifiers may be obtained from Harris Semiconductor with total dose specification of 1E6 rads(Si). (Harris recently dropped the 1E6 specification from their catalog although the devices product if being marketed.)

An analog position control system requires an analog voltage position input signal. If such a command signal is provided by a digital computer the overall system is considered hybrid and some sort of digital-to-analog (D/A) converter is required. If analog sensor information is processed by the digital computer, an analog-to-digital (A/D) converter is required. Both are available from Harris Semiconductor with total-dose tolerances between 50 Krad(Si) and 300 Krad(Si). Analog Devices also publishes the radiation tolerance of their line of A/D and D/A converters.

Sensors operating near the end effector of a robot manipulator operating in a radiation field must, of course, be radiation hardened. It is common to have digital sensors as well as analog sensors on robot manipulators. However, radiation-sensitive opto-electric devices such as light emitting diodes (LEDs) and photo transistors are included in digital positions sensors (generally called encoders). To avoid radiation damage to opto-electric position sensors one may revert to an old position technology using "resolvers". Resolvers are motor-like position sensors that were used extensively in World War II era servo systems. They are still used in spacecraft for reading attitude coordinates from instrumentation platforms, for example.

Since the resolvers are constructed like a motor, very high radiation tolerance levels are possible if radiation-sensitive insulation materials and lubricants are avoided. A resolver is a form of analog device, therefore, resolver-to-digital conversion is necessary to input position information to a hybrid or digital servo system. Natel Engineering Company, Inc. produces the HSRD1056RH resolver-to-digital converter that is radiation hardened to 1E5 rad(Si).

Most modern servo control systems are hybrid in that a significant part of the control loop is within a digital computer. Sensors and end effectors may be either analog or digital with appropriate conversion between the two modes. PWM power amplifiers may have both analog and digital inputs. Figure 4.2 is the block diagram of a typical PWM power amplifier.

It is convenient from a radiation-hardening standpoint to design an all-digital servo control system -- no analog signals are processed by the system. The main requirement is to have a very fast digital computer that can process all necessary control information during a sampling interval. All radiation-hard digital sensors are used and motor-control output is a PWM power amplifier where the pulse width is computed in the digital computer as well as all other required transfer functions. Under these conditions only the sensors and the H-bridge power control circuit must be designed from radiation-hardened semiconductor parts. Radiation-hardened P-Channel and N-Channel Power MOSFET transistors capable of controlling continuous currents up to 40 amperes are available from Harris Semiconductor. These devices have a total-dose hardness of at least 1 Mrad(Si).

3.3.3 Hardening PWM Power Amplifiers

The PWM Power Amplifier shown in Figure 3.2 is constructed with several types of components that may be obtained in radiation-hardened versions. Most of the circuit consists of operational amplifiers and passive elements such as resistors and capacitors. The block labeled PWM converter produces a square wave with a duty-cycle (pulse width divided by period) proportional to an input voltage. Such voltage-to-pulse-width converters may be constructed from a sawtooth oscillator and a summing circuit using radiation-hardened operational amplifiers. Commercial integrated circuits to perform the same conversion are available and some have been tested for total-dose hardness.

The block labeled "Control Logic" merely takes the signal from the PWM converter and drives the Power FET H-bridge in the module labeled "MOSFET Drive". To allow the motor to be driven in both directions, direction information must be computed in the PWM and used to control a "Direction" input signal to the Control Logic module. Again, this may be done with a radiation-hardened operational amplifier connected as a voltage level detector often called a "Schmidt Trigger Circuit".

While it may not be possible to find exact equivalent radiation-hardened parts for components in a commercial design, the components required to design a radiation-hardened PWM servo amplifier are available and the finished design could have specification very close to commercial modules.

Based on an earlier report[14] the University of Florida Department of Nuclear Engineering Sciences has developed a prototype radiation-hardened PWM Motor-Drive Amplifier. At the present time the commercial availability of this radiation-hardened amplifier is not clear.

3.3.4 DC-to-DC Converters

DC-to-DC power converters are required to change and 24 volt battery power of the K3A to the regulated 5 volt supply required by the computers and digital control logic in the robot. Since the circuits required for the DC-to-DC converter are very similar to the PWM circuits used in Motor-Drive Amplifier design, a prototype power converter has also been developed at the University of Florida.

In addition to the prototype developed at the University of Florida, a commercial radiation-hardened DC-to-DC converter is available from Advanced Analog, a Division of Intech. The unit price of a ART2815T DC/DC converter is $18,500. Specification state that the MIL-STD module is radiation hardened to greater than 100K rad(Si). A paper by David K. Myers reported a demonstrated performance within specifications to 1.5M rad(Si)[15].

3.3.5 Ultrasonic Ranging Circuits

The Collision Avoidance subsystem in the ARIES inspection robot is an ultrasonic ranging system using 8 ultrasonic transducers, an 8-channel ultrasonic sonar board, and a collision-avoidance computer. The ultrasonic transducers are piezoelectric barium titanate crystals that are reported to have a failure threshold of 9.5E6 rad[16]. The 8-channel ultrasonic sonar board contains a number of semiconductor parts that would be affected by gamma radiation. These include several linear bipolar devices, an A-D converter, a small amount of CMOS digital logic, and some discrete NPN and PNP bipolar transistors. The collision-avoidance system could be used unmodified until failure (as discussed elsewhere

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[14] Sias, Fred R., Jr., "Radiation Hardening Power MOSFET PWM Motor-Drive Amplifiers," Report prepared for the Department of Nuclear Engineering, University of Florida, Gainesville, April 22, 1994

[15] Myers, David K., and Richard T. Miller, "Space Radiation Characterization of the ART2800 DC/DC Converter Family and 7846 Post Regulator."

[16] Andrew Holmes-Siedle and Len Adams, *Handbook of Radiation Effects*, Oxford University Press, 1993.

in this report) or it could be completely re-designed using all radiation-hardened parts. The re-design would not be trivial but would not be as expensive as other modules since fewer semiconductor components are involved than in a processor module. Most of the semiconductor components are common so the re-design should be relatively straightforward, especially if radiation hardening were limited to meeting a 1E5 rad(Si) hardness specification.

3.3.6 Radio Transceivers

We know of no radiation-hardened spread-spectrum data transceivers; however, the technology should exist since radiation-hardened transponders have been used in satellites for some time and communication links with various explorer missions were probably designed to meet some radiation-hardness specification.

3.4 HARDENING THE OTHER ROBOT PARTS

Most of the mechanical parts of the Cybermotion robot are aluminum or other metals, along with some plastic or elastic components. The metal structure is unaffected by exposure to radiation greatly in excess of the dose that would cause all electronic components to fail. Most polymers and elastomers are not significantly affected by radiation doses below 1 Mrad(Si). Teflon is a unique exception and parts that include Teflon insulation must be replaced by parts using less affected insulation.

The only Teflon know to be in the K3A are the lead wires attached to the slip-ring assembly. The manufacturer, the Poly-Scientific Division of Litton Systems, Inc., states that the lead wire can be replaced with cross-linked polyolefin insulation that is resistant to radiation doses of 100 Mrad. The slip-ring housing is formed from a black filled polyamide plastic (Nylon) that is tolerant to a radiation dose well above 1 Mrad(Si).

Most of the hookup wire used in the Cybermotion robots is insulated with Polyvinyl Chloride (PVC) which is somewhat affected by radiation below 1M rad. Although the effect on the mechanical properties may not be significant, PVC, like Teflon, may release a corrosive halogen acid vapor when irradiated. For radiation hardness the PVC insulated hookup wire should be replaced with the cross-linked polyolefin insulated wire recommended for the slip-ring assembly.

Nylon (Polyamide) is used throughout the K3A for various plugs, washers, and standoff insulators. While unfilled Nylon is somewhat affected by radiation doses below 1M rad, the effect of the radiation on their mechanical integrity is unlikely to be significant. Fortunately, all of the plastic shim material used throughout the K3A is a Polyester (Mylar) which is very resistant to radiation damage. The elastomers used for bearing seals and the rubber treads on the wheels of the K3A are formed from a Nitrile-based rubber that reportedly can be used up to 1E8 rad[17]. Glass-epoxy laminates are used for printed-circuit boards throughout the K3A. These show good performance to 1E9 rad.

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[17] Andrew Holmes-Siedle and Len Adams, *op. cit.*

3.5 LUBRICANTS

Organic lubricants, like plastics are affected by radiation; however, gear oil and grease is available that will withstand doses of radiation above the levels that will destroy the radiation-hardened electronics. The additives that improve the high-temperature performance of lubricants also improve their radiation tolerance.

4.0 COST ESTIMATE FOR HARDENING ARIES

4.1 DESIGN FOR SURVIVAL

4.1.1 Application Scenerios:

Low-level radioactive waste is probably not a threat to electronic circuits. In fact, most low-level waste is currently handled by persons who may be protected from contamination but are not shielded from the effects of radiation. Contact Handled (CH) low-level waste drums usually have a surface dose rate of less than 100 millirem (mrem) per hour according to specifications in the Resource Conservation and Recovery Act (RCRA).

On the other hand, gamma radiation is a threat to electronic circuits that must be placed in the vicinity of high-level radioactive waste, in canyons used for nuclear weapons processing, within hot cells, near reactor fuel elements, or near operating or recently shut down reactors. A nuclear reactor accident is a scenario that is always in the back of the mind as a possible application for mobile robots with on-board computers and control electronics. Depending on the scenario, a mobile robot may be exposed to a total dose of ionizing radiation in excess of 1E6 rad(Si).

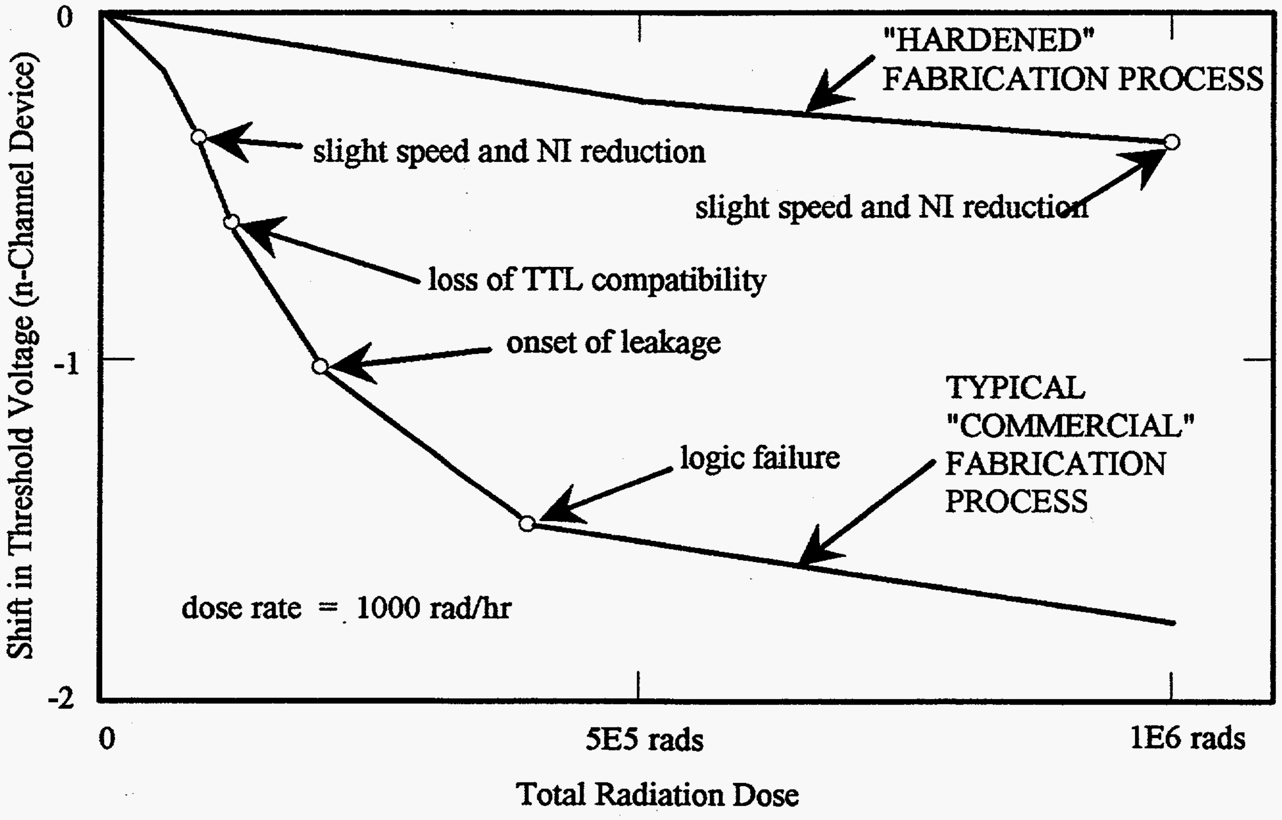

Figure 4.1. Comparison of "Commercial" and "Hardened" CMOS Devices.

(Modified from Holmes-Siedle, 1994.)

4.1.2 Alternative Designs for Robot Survival:

There are few scenerios where radiation will cause immediate failure of electronic systems. (Only military applications come to mind.) Usually failure occurs only after exposure to radiation for an extended period of time. It can be seen from Figure 3.1 that the Radiation Tolerance Requirement is a function of time. In space a requirement for high radiation tolerance is a result of very long missions where electronics is exposed to relatively low levels of radiation dose rates, but it is very difficult or impossible to repair the equipment. Robots in a terrestrial application may be exposed to higher levels of radiation; however, the radiation-hardness total-dose design requirement is really a function of the expected life of the system. The total radiation requirement shown in Figure 3.1 is based on a 10,000 hr operational lifetime which is only a little over one year of continuous use in a radiation environment.

A mobile robot is not likely to be continuously exposed to high levels of radiation. In addition, a mobile robot may be completely out of the radiation field for periods of time during which electronic modules could be replaced. The only essential requirement is that the total absorbed dose must be monitored so that failure does not occur when the robot is in use or when it cannot be retrieved for an electronics upgrade. The cost of the operational lifetime is the final bottom line irregardless of the number of electronics modules that must be replaced periodically.

Consider a mobile application in an underground storage facility. A dose rate of 1000 rads/hr would exceed 10,000 rad total dose in less than a day of continuous exposure. If the robot were operated on only a single shift, a little over a day would be required to be exposed to the same total dose if one assumes that the robot is removed from the radiation field when not in operation. It is likely that the dose rate would vary considerably during operation so several days would be required to reach a total dose of 10,000 rad.

Most modern COTS (commercial off-the-shelf) CMOS semiconductors will survive a total dose of 10,000 rad(Si). Thus one might be able to operate a mobile robot almost indefinitely by replacing soft or non-hardened electronics every week. All of the basic control electronics of the Cybermotion K3A could be replaced for about $10,000. If one assumes that the electronics modules are replaced weekly, then the system could be operated for approximately six months for a cost of $260,000 without any radiation hardening. This is much less than the cost of radiation hardening the complete robot and might be adequate for a one-time application. It is also possible that the used modules could be annealed to extend their useful lifetime.

There are several problems with using off-the-shelf components. First, COTS components have no manufacturing controls for radiation tolerance and while most will meet the expected radiation tolerance without radiation screening, there is always going to be the odd-ball part that fails at 10 per cent of its expected tolerance. Second, COTS components lose TTL compatibility long before logic failure. This is illustrated in Figure 4.1.

Finally, COTS components generally show a significant increase in leakage current well before component failure. This will result in system failure by overloading power supplies. Unexpected system failure is therefore a particular problem when using commercial off-the-shelf components in a system exposed to significant doses of radiation.

4.1.3 How hard to make it:

Since the end of the "cold war" radiation-hardened semiconductor foundries have been shut down and manufacturers are discontinuing previously advertised hardness assurance levels. The Harris Corporation, one of the largest manufacturers of radiation-hardened semiconductors, no longer offers catalog semiconductor parts with a hardness specification of 1E6 rad(Si) although the production processes have not been changed -- only the hardness assurance level. Products from discontinued foundry lines may continue to be available from over-seas foundries.

When one considers economics, it may be *much* less expensive to develop electronics for a robotic system that will survive a dose of 100 krads(Si) rather than 1 Mrad(Si). Due to the requirements of space operation commercially-manufactured modules are becoming available that have a hardness assurance rating of 100 krad(Si). This level of hardness appears to be suitable for a majority of space and satellite applications. On the other hand, the Megaradiation hardened appears to be limited to military applications that are receiving less and less support. For a first cut at a cost estimate a 100 krad(Si) design will be considered.

4.1.4 Radiation Monitoring:

As described earlier, a mobile robot will usually operate in a radiation field that varies in intensity. Total dose effects are cumulative, consequently some means of monitoring total-dose exposure is necessary in any practical environment. The RADFET developed by Andrew Holmes-Siedle in England, is a suitable sensor. Satellites International Limited developed the ESA Modular Dosimeter System for monitoring satellite absorbed dose. A modular system capable of monitoring up to 8 radiation-sensitive locations was originally delivered in 1988.

4.2 COST ESTIMATE

The cost of manufacturing a radiation-hardened version of the K3A inspection robot can be estimated by considering the following basic modules:

1. The mechanical structure
2. DC-1 Drive Control Computer
3. MA-2 Motor Amplifier
4. DC/DC Converters
5. Video cameras.
6. SPIKE board

Most of the mechanical system is aluminum or other metals, along with some plastic or elastic components. The metal structure is unaffected by exposure to radiation greatly in excess of the dose that would cause all electronic components to fail. Most polymers and elastomers are not significantly affected by radiation doses below 1 Mrad(Si). Teflon is a unique exception and parts that include Teflon insulation must be replaced by parts using less affected insulation. Hookup wire with cross-linked polyolefin insulation is tolerant to a radiation dose of 100 Mrad(Si).

The parts list for the K3A base is included in the Appendix along with the estimated radiation tolerance of each part. Radiation hardening the electro-mechanical system amounts to initiating engineering changes to eliminate Teflon or PVC insulation or components and possibly replacing radiation-sensitive optoelectronic encoders used for navigation and steering. Position feedback for servo control of drive and steering may be obtained by using resolvers and a radiation hardened resolver-to-digital converter. The hardened slip-ring assembly, dc motors, and resolvers may be obtained from the Poly-Scientific Division of Litton Systems, Inc. in Blacksburg, VA. Natel Engineering Company, Inc. produces the HSRD1056RH resolver-to-digital converter that is radiation hardened to 1E5 rad(Si). Estimated cost of re-engineering the K3A base: $100,000.

The DC-1 Drive Control Computer can be hardened by two approaches. The module can be re-designed using radiation-hardened parts or the Harris Standard Spacecraft Processor Module can be procured. Based on a similar design and the cost of radiation-hardened parts an in-house re-design could cost $180,000. The Harris processor module hardened to 100 krad can be procured for about $300,000.

The cost of re-designing and constructing a radiation-hardened version of the MA-2 Dual Motor Amplifier is estimated at $150,000. A DC/DC Converter can be procured from Advanced Analog for $18,500 and a radiation-hardened black-and-white video camera with non-browning, radiation tolerant lenses can be procured from Rees Instruments, Inc. for under $10,000. The SPIKE* board is a radiation-hardened re-design of a module that controls switching of backup modules when a radiation-induced failure occurs. A rough estimate of the incremental cost of re-designing a radiation-hardened K3A is shown in Table 4.1.

An alternative approach that could be less expensive would be to leave the electronics unmodified and design an all-relay backup system that would automatically take control when the electronics fail and allow a tethered robot to be driven out of a hazardous area using manual controls. A radiation-hardened video camera would permit a remote operator to navigate under visual control. We have little reference data with which to estimate an all-relay logic design cost; however, we feel that it would be similar in complexity to a processor re-design without the MIL-SPEC radiation-hardened parts. On this basis, Table 4.2 is a rough estimate of the incremental cost of developing an all-relay backup system that would allow an operator to recover a Cybermotion mobile robot after radiation had caused complete failure of the electronic control system.

Table 4.1

Incremental Cost to Radiation Harden Cybermotion K3A and Turret.

Engineering changes to Mechanical Structure

Resolvers, Slip Ring Assembly, Plastic Parts
$100,000

Minimum Electronics for Tethered Operation

Harris Std. Space Processor Module (Purchase)
$300,000

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* SPIKE is a reliability enhancement card for Navmaster operation in gamma radiation environments. It was specially designed for an earlier Cybermotion robot at the Savannah River Laboratory.

Dual Drive Amplifier		$150,000
DC-to-DC Converters	(Purchase)	$ 18,500
Radiation-hardened B&W Video Camera	(Purchase)	$ 10,000
RADFET Dose Monitor	(Purchase)	$ 10,000
Z-80 Simulation Software		$ 25,000
SPIKE Board Upgrade		$ 20,000
Cost Estimate		$633,500

Table 4.2

Incremental Cost to Retrofit an All-relay Backup Control System.

Engineering changes to Mechanical Structure		
Slip Ring Assembly, Plastic Parts		$ 50,000
Minimum Relay Controls for Tethered Operation		
Relay Logic Backup System		$100,000
Radiation-hardened B&W Video Camera	(Purchase)	$ 10,000
RADFET Dose Monitor	(Purchase)	$ 10,000
SPIKE Board Upgrade		$ 20,000
Cost Estimate		$190,000

5.0 CONCLUSIONS

The Mobile Inspection and Survey Robot called ARIES is designed with commercial off-the-shelf electronic components that are satisfactory for operation where total doses of gamma radiation are relatively low. Standard commercial semiconductors are likely to survive a total-dose exposure in excess of 10,000 rad(Si). Low-level hazardous waste is stored in drums that may emit a surface radiation dose rate of only 100 mrem/hr or less. However, an inspection or survey task near high-level Cobalt-60 emitters would require radiation hardening to avoid damage to the on-board control electronics. Gamma radiation degrades and ultimately causes semiconductor circuits to fail.

Relatively high energy gamma radiation from Cobalt-60 is likely to be part of the radiation spectrum emitted from potential inspection and survey tasks around high-level waste or spent reactor fuel. Since almost two inches of lead are required to provide a decade attenuation of gamma radiation with the Cobalt-60 energy spectrum, shielding is not considered a feasible means of protecting all of the electronics on-board a mobile robot.

Radiation hardening a mobile robot requires a complete re-design of the electronic control system using specifically hardened semiconductor components. A robot with a total-dose hardness of about 100k rad(Si) could be designed now; however, a Megarad design would pose more significant problems since parts with the higher dose assurance are becoming scarce or may be unavailable in the future due to the end of the cold war and discontinuation of several radiation-hardened semiconductor foundries.

A tethered robot with some safety mechanisms and onboard video cameras for inspection would be the simplest design and would require the redesign or replacement of only three or four electronic modules. Present K3A control firmware can be executed on a simulated Z-80 using a radiation-hardened Harris RHC-3000 processor module. A dual configuration using a special control module would produce greater reliability by providing an un-powered backup for the control computer and communication hardware. A special control module known as SPIKE, which was designed by Cybermotion for the Savannah River Laboratories several years ago, would be used to switch to backup modules should failures occur in highly radioactive areas.

The mechanical system of the robot would require some re-design. All Teflon and PVC plastic parts would have to be replaced as these plastics may release a corrosive gas when exposed to radiation and Teflon starts to deteriorate at around 10,000 rad. The optoelectronic parts in the encoders on the steering and drive motors would be degraded somewhat but probably would remain functional to 100,000 rad. To survive a much higher total dose the encoders should be replaced with resolvers to provide feedback information for the drive and steering servo controls.

To permit the Cybermotion robot to survive a total radiation dose of 100,000 rad(Si), it is estimated that a complete redesign of the electronics with radiation-hardened parts would require an incremental cost of over $500,000. This is due to the extremely high cost of radiation-hardened parts and modules.

An alternative much less expensive approach would be to make no attempt to radiation harden the electronics aboard the robot. Instead, a backup mechanism involving only electromechanical relays could be designed to take over when the electronics fail. If a wire communication link were trailed behind during the entry to a high-radiation area, the robot steering and drive motors could be operated through this tether which would make it possible to retrieve a mobile robot when all the electronic controls fail. Providing a radiation-hardened radio communication link would require additional design effort.

Finally, actual application of a mobile robot in a high-radiation area is likely to encounter a changing radiation intensity. In some cases the robot might be driven in and out of the radiation field and the total exposure dose would be difficult to calculate. It is recommended that one or more semiconductor total-dose radiation monitors, such as the RADFET developed in England, should be on-board the robot to collect total-dose exposure data to warn of potential electronics failure.

A radiation-hardened version of ARIES could be developed, however, the cost would be high. If the sophisticated navigation and obstacle-avoidance capability of the Cybermotion mobile robot were required, it would be necessary to re-design several electronic modules including the control computers. A less demanding task could be accomplished by providing a backup relay-logic control system that would permit tethered remote manual control if the electronics fail.

APPENDICIES

APPENDIX A: Simulation of the Z-80 Microprocessor on a Faster RISC Processor

APPENDIX B: Radiation Hardness Assessment of the Cybermotion K3A Mobile Robot

APPENDIX C: PAPERS -

Sias, Fred R., Jr., "Special Requirements for Electronics to be Used in Robots in Space", *Proceedings, 42nd Conference on Robotics and Remote Systems,* American Nuclear Society, 1994, Vol. 1.
Removed for separate processing

Sias, Fred R., Jr., and James S. Tulenko, "Update on Radiation-Hardened Microcomputers for Robotics and Teleoperated Systems", *Proceedings, 41st Conference on Robotics and Remote Systems,* American Nuclear Society, November, 1993. Removed for separate processing

Sias, F.R., J.S. Byrd, D.M. Dawson, R.O. Pettus, and R.J. Schalkoff, "Design Considerations for an Intelligent Mobile Robot for Mixed Waste Inspection", *Proceedings of the Second International Mixed Waste Symposium,* Baltimore, MD, August 17-20, 1993. Removed for separate processing

Sias, Fred R., Jr., Selecting Microprocessors Suitable for Robotic Applications in Radioactive Sites, *Proceedings of the Fifth Topical Meeting on Robotics and Remote Systems,* American Nuclear Society, Knoxville, TN, April 1993. Removed for separate processing

Sias, Fred R., and Robert M. Fox, Selecting Radiation-Resistant Semiconductors for Robots and Teleoperated Systems, *Remote System Technology Division Proceedings,* American Nuclear Society, Chicago, Nov. 1992.

Sias, Fred R., Jr., and David A. Williams, Design of a Radiation-Hardened Embedded Microcomputer, *Remote System Technology Division Proceedings,* American Nuclear Society, Chicago, Nov. 1992.

APPENDIX A

Simulation of the Z-80 Microprocessor on a Faster RISC Processor

The Cybermotion K3A mobile robot is controlled by a 4 MHz Z-80 microprocessor known as the CP-1. This processor resides in the K3A base and executes all of the basic control commands that steer and drive the robot. Another Z-80 processor, called the CA-1, in the Turret controls an array of ultrasonic transducers that provide information about the environment around the robot. The two processors work together to execute high-level navigation instructions while watching out for obstacles in the chosen path. All of this low-level code is written in assembly language and resides in EPROMS. This firmware amounts to many tens of thousands of lines of assembly-language routines.

Unfortunately, the Z-80 is an old, but powerful, control microprocessor that has never been radiation hardened. To replace the Z-80 with a modern radiation-hardened processor would normally require a complete rewrite of an enormous amount of code. In addition, the computer code is proprietary since the fundamental capabilities of the robot reside in this firmware. Alternate approaches to developing a radiation-hardened control computer have been considered.

During the summer of 1995 the feasibility of simulating the Z-80 on a faster RISC processor was studied. Clemson graduate student Robert Heil obtained a Z-80 software simulator originally developed in Germany by Udo Munk in 1989. The simulator was modified to include new instructions executed by the Zylog Z-180 processor which is a more modern and powerful version of the Z-80.

One of the available radiation-hardened microprocessors is the RHC-3000 developed by the Harris Corporation to execute the MIPS R-3000 instruction set. The RHC-3000 is a powerful RISC architecture that operates at 20 MHz or four times the speed of the CP-1 control processor in the K3A base. It was felt that there was a good chance that the simulator, written in C, would execute Z-80 code on the faster processor at a speed equivalent to the 4 MHz Z-80.

The simulator was run on several available RISC processors including a Dec Alpha, a Sun, and an HP9000. Since the HP9000 had the closest clock speeds to the anticipated radiation-hardened processor, the results shown below are for this processor:

Method of calculation:

> A set of 100 test instructions are executed in a continuous loop for X seconds.
> The number of opcode fetches is found. (R)
> The # of clock cycles for a jump 0 command (the end of the loop) is 10.
> T is the # of clock cycles for the listed inst.
> Freq = (R/X) * ((T * 100 + 10) / 101) /1e6 (Mhz) appx. = (R/X) * T / 1e6

Below is a tabulation of an assortment of instructions and their execution speeds on the simulator. The OP column show the op code followed by the assembly-language instruction.

Cycles represent the number of machine cycles required to execute on the Z-80 and Bytes represents the amount of memory occupied by the instruction on the original Z-80. The column headed f(MHz) indicates the effective Z-80 operating speed of the simulation and the percentage following is the simulation speed as a percentage of the Z-80 execution speed.

OP	Instruction	Cycles	Bytes	f(MHz)
00	nop	4	1	5.72 (143%)
01	ld BC, data16	10	3	5.06 (126%)
02	ld (BC), A	7	1	6.58 (165%)
03	inc BC	6	1	6.03 (150%)
04	inc B	4	1	2.10 (53%)
05	dec B	4	1	2.26 (57%)
06	ld B, data 8	7	2	5.29 (132%)
07	RLCA	4	1	2.65 (66%)
08	ex AF, AF'	4	1	2.02 (50%)
09	add HL, BC	11	1	6.58 (165%)
0a	ld A, (BC)	7	1	6.59 (165%)
0b	dec BC	6	1	6.03 (150%)
0c	inc C	4	1	2.11 (53%)
0d	dec C	4	1	2.27 (57%)
0e	ld C, data 8	7	2	5.29 (132%)
0f	RRCA	4	1	2.88 (72%)

Interrupt Capabilities:

Simulation of the Z-80 instruction set on the RHC-3000 meets most of the requirements of a radiation-hardened control module; however, special attention must be paid to real-time interrupts that are currently processed by the Z-80 system and must be appropriately handled by the replacement system. The DC-1 currently services five different interrupt sources:

1. Non-maskable Dead Reckoning Interrupts - max rate 3500 Hz
2. Slave Serial Interface Interrupts - max rate 1200 Hz
3. Host Serial Interface Interrupts - max rate 1200 Hz
4. PID Servo Interrupts - max rate 80 Hz
5. Main Background Interrupt - max rate 10 Hz

Estimates of the size of the corresponding Z-80 service routines are as follows:

1. 250 bytes
2. 1000 bytes
3. 1000 bytes
4. 180 bytes
5. Extremely large

Based on the size and nature of the interrupt service routines, 1 through 4 can easily be rewritten in the native code of the simulator processor and the large background interrupt will be executed by the simulator using the existing Z-80 code. All interrupts will utilize the interrupt structure incorporated in the RHC-3000 in the Harris Standard Spacecraft Processor Module.

It is concluded that the native Z-80 machine-language Firmware can be executed on the RHC-3000 at a speed sufficient to meet the control requirements of the K3A. Servicing the Z-80 interrupts on the radiation-hardened RHC-3000 appears to be straight forward.

APPENDIX B

RADIATION-HARDNESS ASSESSMENT OF K3A ROBOT BASE

December 13, 1995 at 12:27 p.m.

L	SUB	PARTNO	AMOUNT	UN	C	DISCRIPTION	MATERIAL	HARDNESS
1	10	A1010	1.00	EA	2	K3A BASE, COMPLETE	MIXED	1E4
2	10	A1003	1.00	EA	3	ASSEMBLY, CARRIAGE	MIXED	1E4
3	10	3006	1.00	EA	4	SHAFT, STEERING, MAIN	STEEL	>1E10
3	20	1507	1.00	EA	5	KEY, SQUARE, 1/4 X 1/4, 3/4 LG	STEEL	>1E10
3	30	4012	1.00	EA	4	GEAR, MITER, 25 TEETH, 10 PITCH, SIMILAR TO 4000	STEEL	>1E10
3	40	1021	1.00	EA	4	WASHER, 1/2, FLAT, PLT, USS	STEEL	>1E10
3	50	1099	1.00	EA	4	SCREW, 1/2-13, 5/8 LG, HEX HEAD	STEEL	>1E10
3	60	2005	1.00	EA	4	BEARING, BALL, MRC, DOUBLE ROW, ANGULAR CONTACT	STEEL	>1E10
3	70	1012	1.00	EA	4	NUT	STEEL	>1E10
3	80	A1013	1.00	EA	4	MACHINED, WHITET HIGGENS BHI-05 LOCK NUT MACHINED	STEELNYLON	1E5
4	10	1013	1.00	EA	5	NUT, 1 1/4-16, SS, BEARING LOCK	STEELNYLON	1E5
3	90	1507	1.00	EA	5	KEY, SQUARE, 1/4 X 1/4, 3/4 LG	STEEL	>1E10
3	100	4008	1.00	EA	4	GEAR, SPIROID, 106 TEETH	STEEL	>1E10
3	110	1014	1.00	EA	4	NUT, 1 1/8-16, SS, BEARING LOCK	STEELNYLON	1E5
3	120	5019	1.00	EA	4	CAST, COLUMN, MAIN	ALUMINUM	>1E9
3	140	1509	1.00	EA	4	RETAINING RING, INTERNAL 3.149 DIA. .082 THICK	STEEL	>1E10
3	150	2008	1.00	EA	4	BEARING, NEEDLE, SEALED .500 ID,.750 OD, .562 WIDE	STEEL	>1E10
3	160	2004	1.00	EA	4	BEARING, BALL, FAF, DOUBLE ROW, ANGULAR CONTACT	STEEL	>1E10
3	170	4009	1.00	EA	4	PINION, SPIROID, 1 TOOTH	STEEL	>1E10
3	180	1021	1.00	EA	4	WASHER, 1/2, FLAT, PLT, USS	STEEL	>1E10
3	190	1023	1.00	EA	4	NUT, 1/2-20, HEX, PLT	STEEL	>1E10
3	230	5009	1.00	EA	4	MACHINED, PLATE, RETAINING STEERING BEARING	ALUMINUM	>1E9
3	240	1138	4.00	EA	4	SOCKET HEAD CAP SCREW M6-1 X 20	STEEL	>1E10
3	250	3500	1.00	EA	4	SEAL, SHAFT, 1.000 DIA.	RUBBER NI.	1E7
3	260	5016	1.00	EA	4	MACHINED, MOUNTING, TACH/SEAL	ALUMINUM	>1E9
3	280	7003	1.00	EA	4	ENCODER, STEERING, 256PPR, QUADRATURE, 1IN. ID	OPTOELECT.	1E5
3	300	7002	1.00	EA	4	SLIPRING, 8 COM RINGS, 4 POWER RINGS	MIXED	1E4
3	330	2012	1.00	EA	4	BEARING, ROLLER, HD, 1 3/4 DIA BORE, 2.3125 OD	STEEL	>1E10
4	630	5018	1.00	EA	4	CAST, COLUMN, EXTENSION,	ALUMINUM	>1E9
3	350	1154	3.00	EA	4	SCREW, METRIC, SOCKET, CAP M12-1.75 X 30	STEEL	>1E10
3	360	2509	1.00	EA	4	BEARING, THRUST, NEEDLE, TORR	STEEL	>1E10
3	370	1515	1.00	EA	4	KEY, SQUARE, 1/4 X 1/4, 1 LG	STEEL	>1E10
3	380	2013	1.00	EA	4	RACE, INNER, 1.5000 DIA BORE 1.7490 OD., 1.010 LG	STEEL	>1E10
3	390	5021	1.00	EA	4	MACHINED, PIN, ALIGHNMENT BASE COUPLING	ALUMINUM	>1E9
3	400	5015	1.00	EA	4	MACHINED, COUPLING, BASE	ALUMINUM	>1E9
3	410	4010	1.00	EA	4	COUPLING, TURRET, TRANTORQUE 1 INCH ID, STANDARD	STEEL	>1E10
3	420	5023	1.00	EA	4	ADAPTER, SHAFT CONNECTOR	STEEL	>1E10
3	430	8000	1.00	EA	4	CONNECTOR, ELECTRICAL, MACHINED	PLASTIC	1E6
4	10	8210-206043-1	1.00	EA	5	RECEPTACLE, FEMALE, 14 PIN	PLASTIC	1E6
3	440	1039	4.00	EA	5	SCREW, 2-56, 3/8 LG ROUND HEAD, SLOTTED, PLT	STEEL	>1E10
3	450	4011	1.00	EA	4	COUPLING, FLEXIBLE, 1/2 DIA SHAFT, 44 IN-LB TORQUE	ALUMINUM	>1E9
3	460	5010	1.00	EA	4	MOUNT, STEERING MOTOR, CAST	ALUMINUM	>1E9
3	470	1136	2.00	EA	4	SOCKET HEAD CAP SCREW M10-1.5 X 10	STEEL	>1E10
3	480	7001	1.00	EA	4	MOTOR, STEERING, 24VDC, PM	MOTOR	1E8
3	490	1010	4.00	EA	5	SCREW, 8-32, 1/2 LG, SOCKET HEAD	STEEL	>1E10
3	510	1155	24.00	EA	4	LOCK WASHER, METRIC, HI COLLAR 4W CAD YELLOW, M10	STEEL	>1E10
3	520	1143	24.00	EA	4	SCREW, SOCKET HEAD, CAP M10-1.5 X 16	STEEL	>1E10
3	550	1032	12.00	EA	5	SCREW, 1/4-20, 3/4 LG, FLAT HEAD, SOCKET	STEEL	>1E10
3	590	A1000	1.00	EA	4	CHASSIS PLATE ASSEMBLY	ALUMINUM	>1E9
4	10	5005	1.00	EA	5	PLATE, CHASSIS, CAST	ALUMINUM	>1E9
4	20	1038	1.00	EA	5	PLUG, 3/4-16, 3/8 LG, FILL W/ WASHER	STEELNYLON	1E5
4	30	2009	1.00	EA	5	BEARING, NEEDLE, .8125 ID 1.0625 OD, .875 WIDE	STEEL	>1E10
4	40	3004	1.00	EA	5	SHAFT, IDLER, GEARBOX	STEEL	>1E10
4	60	1009	1.00	EA	5	NUT, 3/8-16, HEX, PLT, ELASTIC STOP	STEELNYLON	1E5
4	70	1507	1.00	EA	5	KEY, SQUARE, 1/4 X 1/4, 3/4 LG	STEEL	>1E10
4	80	3005	1.00	EA	5	SHAFT, OUTPUT, GEARBOX	STEEL	>1E10
4	90	4004	1.00	EA	5	GEAR, SPUR, DRIVE, 80 TEETH, 16 PITCH, MODIFIED	STEEL	>1E10
5	10	4004A	1.00	EA	6	GEAR, SPUR, 16 PITCH, 80 TEETH 14 1/2 PA,	STEEL	>1E10
4	100	2512	1.00	EA	5	RACE, THRUST, INA, .125 THK	STEEL	>1E10
4	110	2507	2.00	EA	5	RACE, THRUST, TORR., .062 THK	STEEL	>1E10
4	120	2500	1.00	EA	5	BEARING, THRUST, NEEDLE, INA	STEEL	>1E10
4	130	1506	1.00	EA	5	KEY, SQUARE, 1/8 X 1/8, 3/4 LG	STEEL	>1E10
4	140	4017	1.00	EA	5	GEAR, MITER, DRIVE, MAIN, 10 PITCH, 18 TEETH	STEEL	>1E10
4	160	A1004	1.00	EA	5	ASSEMBLY, IDLER GEAR	STEEL	>1E10
5	10	4005	1.00	EA	6	GEAR SET, DRIVE, 80 TEETH 20 TEETH, 16 PITCH	STEEL	>1E10
5	20	2010	2.00	EA	6	BEARING, NEEDLE, .5626 ID .750 OD, .500 WIDE	STEEL	>1E10
L	SUB	PARTNO	AMOUNT	UN	C	DISCRIPTION	MATERIAL	HARDNESS

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4 170 2508             1.00 EA 5 RACE, THRUST, TORR.                                STEEL      >1E10
4 180 1502             1.00 EA 5 RETAINING RING, EXTERNAL 9/16 DIA., .035 THICK     STEEL      >1E10
4 220 1516             1.00 EA 5 KEY, SQUARE 3/16 X 3/16, 3/4 LONG                  STEEL      >1E10
4 230 4006             1.00 EA 5 GEAR, SPUR, DRIVE, 20 TEETH 16 DP, 0.625 IN. BORE  STEEL      >1E10
4 250 1039             2.00 EA 5 SCREW, 2-56, 3/8 LG ROUND HEAD, SLOTTED, PLT       STEEL      >1E10
4 260 1503             1.00 EA 5 PIN, DOWEL, 1/4 DIA. 3/4 LG                        STEEL      >1E10
4 280 1504             2.00 EA 5 RETAINING RING, EXTERNAL, 1/2 DIA., .050 THICK     STEEL      >1E10
4 400 7015             1.00 EA 5 Motor MH2025,4 1/4"flange,12v enc.dual ch.1024 PPR LED        1E5
4 500 1505             1.00 EA 5 Buckeye Square ring AS-229S                        RUBBER     1E6
4 600 1171             4.00 EA 5 Screw, soc. Hd. Cap, M8-1.25 x 25                  STEEL      >1E10
4 700 1166             4.00 EA 5 washer,lock, M8, hi collar, zinc plated            STEEL      >1E10
4 710 2527             1.00 EA 5 RACE, THRUST, TRA-815                              STEEL      >1E10
3 620 1005             4.00 EA 5 SCREW, 3/8-16, 3/4 LG  FLAT HEAD, SOCKET           STEEL      >1E10
3 630 2011             1.00 EA 4 BEARING, NEEDLE, .500 ID .6875 OD, .312 WIDE       STEEL      >1E10
3 640 1073             1.00 EA 4 PLUG, 1/2-20, DRAIN, MAGNETIC                      STEEL      >1E10
3 660 5006             1.00 EA 4 CAST, COVER, GEARBOX,                              ALUMINUM   >1E9
3 710 9004             1.50 EA 5 GREASE, GEAR                                       MOLYGREASE ?
3 730 1044             1.00 EA 4 SCREW, 1/4-20, 1 LG,  SOCKET HEAD                  STEEL      >1E10
3 740 1140             4.00 EA 4 SOCKET BUTTON HEAD M3-.5 X 5                       STEEL      >1E10
3 760 1141             1.00 EA 4 GREASE FITTING METRIC 10-1 THREADS                 STEEL      >1E10
3 770 1086             8.00 EA 6 SCREW, 6-32, 1/4 LG, BINDER HEAD, SLOTTED, ZINC PL STEEL      >1E10
3 780 8210-66601-2    12.00 EA 5 SOCKET, GOLD, 18-14 AWG                            PLASTIC    1E6
3 790 8210-66596-1    16.00 EA 5 SOCKET, TIN, 28-24 AWG                             PLASTIC    1E6
3 800 8210-65495-017   1.00 EA 4 CONNECTOR, 10 POS. RIBBON CABLE CRIMP & SOLDER     PLASTIC    1E6
3 810 8600-3365/20     6.00 IN 5 RIBBON CABLE, 20 COND, 28 AWG                      PVC        1E7
3 820 8210-4610-6300   1.00 EA 4 HEADER, MALE, FLAT CABLE, 10 POS, W/MTG FLANGES    PLASTIC    1E6
3 830 8210-206044-1    1.00 EA 5 PLUG, MALE, 14 PIN                                 PLASTIC    1E6
3 840 8210-66595-1     2.00 EA 5 PIN, TIN, 28-24 AWG
3 850 8210-206070-1    1.00 EA 5 CABLE, CLAMP                                       IRON       >1E10
3 860 5020             1.00 EA 4 ADAPTER, SLIP RING CONNECTOR                       STEEL      >1E10
3 870 6308             1.00 EA 4 CONDUCTOR SHIELD, COLUMN EXT.                      PLASTIC    1E6
3 880 6309             1.00 EA 4 ANTI-ROTATION KEY                                  STEEL      >1E10
3 890 8210-206043-1    1.00 EA 5 RECEPTACLE, FEMALE, 14 PIN                         PLASTIC    1E6
3 900 1129             2.00 EA 4 SCREW, SOCKET HEAD, M3.-5X10                       STEEL      >1E10
3 910 1038            10.00 EA 5 PLUG, 3/4-16, 3/8 LG,  FILL W/ WASHER              STEELNYLON 1E5
3 920 1167            12.00 EA 4 washer, M6, hi-collar, 4w cad yellow               STEEL      >1E10
3 930 1120             2.00 EA 4 screw, M6-1 X 16 socket cap                        STEEL      >1E10
3 940 9016             1.00 EA 4 ID PLATE, K2A+                                     METAL      >1E9
2  20 9006             1.00 EA 3 OIL, GEAR, SAE 80W-90                              OIL        ?
2  40 6011             3.00 EA 3 SHEET METAL CLAMP, PAINTED                         IRON       >1E10
2  50 1016             6.00 EA 3 SCREW, 3/8-16, 1 5/8 LG, HEX HEAD, PLATED          STEEL      >1E10
2  60 1009             6.00 EA 5 NUT, 3/8-16, HEX, PLT, ELASTIC STOP                STEELNYLON 1E5
2  80 6000             3.00 EA 3 MACHINED, WHEEL, 8 IN DIA.                         ALUMINUM   >1E9
3  10 6000A            3.00 EA 4 WHEEL, 8 IN DIA., VULCANITE PURCHASED              RUBBER NI. 1E7
2 130 A8001-CP01       1.00 EA 3 CONTROL PANEL ASSEMBLY, K3A                        MIXED      1E4
3  10 6005             1.00 EA 4 SHEET METAL, PANEL, ELECTRONICS                    ALUMINUM   >1E9
3  20 A8170-DC1        1.00 EA 4 PC BOARD, ASSEMBLY, DRIVE COMPUTER CARD            MIXED      1E4
4  10 8170-DC1         1.00 EA 5 PRINTED CIRCUIT BOARD, DRIVE COMPUTER              EPOXY      1E8
4  20 8470-471-1/4CF   1.00 EA 5 RESISTOR, 470 OHM, 1/4 WATT, CARBON FILM           CARB FILM  1E9
4  30 8470-680-1/8CF   1.00 EA 5 RESISTOR, 68 OHM, 1/8 WATT,  CARBON FILM           CARB FILM  1E9
4  40 8470-203-1/8CF   5.00 EA 5 RESISTOR, 20K, 1/8 WATT, CARBON FILM, 5%           CARB FILM  1E9
4  50 8470-222-1/8CF   4.00 EA 6 RESISTOR, 2.2K, 1.8 WATT CARBON FILM               CARB FILM  1E9
4  60 8470-102-1/8CF   2.00 EA 6 RESISTOR, 1K, 1/8 WATT, CARBON FILM                CARB FILM  1E9
4  70 8470-103-1/8CF   9.00 EA 6 RESISTOR, 10K, 1/8 WATT, CARBON FILM, 5%           CARB FILM  1E9
4  80 8470-472-1/8CF   2.00 EA 6 RESISTOR, 4.7K, 1/8 WATT, CARBON FILM              CARB FILM  1E9
4  90 8470-223-1/8CF   4.00 EA 6 RESISTOR, 22K, 1/8 WATT, CARBON FILM               CARB FILM  1E9
4 100 8470-222-1/4CF   1.00 EA 5 RESISTOR, 2.2K, 1/4 WATT, CARBON FILM              CARB FILM  1E9
4 110 8470-472-1/4CF   3.00 EA 5 RESISTOR, 4.7K, 1/4W, CARBON FILM                  CARB FILM  1E9
4 120 8470-391-1/4CF   5.00 EA 5 RESISTOR, 390 OHM, 1/4 WATT, CARBON FILM           CARB FILM  1E9
4 130 8470-101-1/4CF   1.00 EA 5 RESISTOR, 100 OHM 1/4 WATT, CARBON FILM            CARB FILM  1E9
4 140 8470-106-1/4CF   2.00 EA 5 RESISTOR, 10MEG, 1/4 WATT, CARBON FILM             CARB FILM  1E9
4 150 8470-223X5       1.00 EA 5 RESISTOR NETWORK, 22KX5                            CARB FILM? 1E9
4 160 8480-1N4148      8.00 EA 6 DIODE, SIGNAL                                      DIODE      1E7
4 170 8150-104K50MC   43.00 EA 6 CAPACITOR, MONOLITHIC CERAMIC, .1UF, 50V           CERAMIC    1E10
4 180 8150-121K200MC   6.00 EA 5 CAPACITOR, MONOLITHIC CERAMIC, 120PF               CERAMIC    1E10
4 190 8150-680K200MC   2.00 EA 5 CAPACITOR, MONOLITHIC CERAMIC, 68PF @ 200 VOLTS    CERAMIC    1E10
4 200 8150-225K50T     1.00 EA 5 CAPACITOR, TANTALUM,   2.2UF @ 50 VOLTS            TANTALUM   1E7
4 210 8150-271K200MC   2.00 EA 5 CAPACITOR, MONOLITHIC CERAMIC, 270PF               CERAMIC    1E10
4 220 8150-270K200MC   2.00 EA 5 CAPACITOR, MONOLITHIC CERAMIC, 27PF                CERAMIC    1E10
4 230 8150-105K35E     6.00 EA 5 CAPACITOR, TANTALUM,   1.0 UF, @ 35V               TANTALUM   1E7
4 240 8150-108K10E     1.00 EA 5 CAPACITOR, ELECTROLYTIC, RADIAL, 1,000MFD @ 10 V.  ELECTROLY  1E7
4 250 8150-225K50E     1.00 EA 6 CAPACITOR, ELECTROLYTIC, 2.2UF @ 50 VOLTS          ELECTROLY  1E7
4 260 8150-686K6E      3.00 EA 5 CAPACITOR, TANTALUM, 68UF @6 VOLTS                 TANTALUM   1E7
L SUB PARTNO         AMOUNT UN C DISCRIPTION                                      MATERIAL   HARDNESS
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4 270 8313-78L05        1.00 EA 6 IC, LINEAR, BIPOLAR, VOLTAGE REGULATOR          BIPOLAR    1E5
4 280 8480-2N2222A      2.00 EA 6 TRANSISTOR, NPN, SMALL SIGNAL                   BIPOLAR    1E5
4 290 8230-4915XTAL     1.00 EA 5 CRYSTAL, 4.9152 MHZ                             QUARTZ     1E7
4 300 8230-8.0XTAL      1.00 EA 5 CRYSTAL, 8.0 MHZ                                QUARTZ     1E7
4 310 8210-14PIN       19.00 EA 6 SOCKET, IC, 14 PIN, ST, TIN                     PLASTIC    1E6
4 320 8210-16PIN       12.00 EA 5 SOCKET, IC, 16 PIN, ST, TIN                     PLASTIC    1E6
4 330 8210-18PIN        1.00 EA 5 SOCKET, IC, 18 PIN, ST, TIN                     PLASTIC    1E6
4 340 8210-20PIN        3.00 EA 5 SOCKET, IC, 20 PIN, ST, TIN                     PLASTIC    1E6
4 350 8210-28PIN        7.00 EA 5 SOCKET, IC, 28 PIN, ST, TIN                     PLASTIC    1E6
4 360 8210-40PIN        2.00 EA 5 SOCKET, IC, 40 PIN, ST, TIN                     PLASTIC    1E6
4 370 8313-74HC259      1.00 EA 5 IC, DIGITAL, CMOS, ADDRESSABLE LATCH            CMOS       1E4
4 380 8313-74HC02       2.00 EA 5 IC, DIGITAL, CMOS, QUAD INPUT NOR               CMOS       1E4
4 390 8313-LM324        1.00 EA 5 IC, LINEAR, BIPOLAR, QUAD OP AMP                BIPOLAR    1E5
4 400 8313-74HC74       6.00 EA 5 IC, DIGITAL, CMOS, DUAL D FF                    CMOS       1E4
4 410 8313-14516        7.00 EA 5 IC, DIGITAL, CMOS, DUAL D FF                    CMOS       1E4
4 420 8313-74HC138      1.00 EA 5 IC, DIGITAL, CMOS, PRIORITY ENCODER             CMOS       1E4
4 430 8313-74HC573      3.00 EA 5 IC, DIGITAL, CMOS, OCTAL LATCH                  CMOS       1E4
4 440 8313-74HC04       1.00 EA 5 IC, DIGITAL, CMOS, HEX INVERTER                 CMOS       1E4
4 450 8313-84C00        1.00 EA 5 IC, DIGITAL, CMOS, HEX INVERTER                 CMOS       1E4
4 460 8313-2064         2.00 EA 5 IC, DIGITAL, CMOS, 8K X 8 RAM                   CMOS       1E4
4 470 8313-27C64        3.00 EA 5 IC, DIGITAL, CMOS, 8K X 8, EPROM, 150 NS        CMOS       1E4
4 480 8313-84C30        1.00 EA 5 IC, DIGITAL, CMOS, 8K X 8     EPROM, 150 NS     CMOS       1E4
4 490 8313-84C40        1.00 EA 5 IC, DIGITAL, CMOS, Z80 SIO                      CMOS       1E4
4 500 8313-74HC157      1.00 EA 5 IC, DIGITAL, CMOS, MULTIPLEXER                  CMOS       1E4
4 510 8313-1489         2.00 EA 5 IC, INTERFACE, BIPOLAR, LINE RECIEVER           BIPOLAR    1E5
4 520 8313-1488         1.00 EA 5 IC, INTERFACE, BIPOLAR, LINE DRIVER             BIPOLAR    1E5
4 530 8313-ADC0808      1.00 EA 5 IC, INTERFACE, CMOS, A/D CONVERTER              CMOS       1E4
4 540 8313-74HC7266     2.00 EA 5 IC, DIGITAL, CMOS, QUAD INPUT NOR, OPEN DRAIN   CMOS       1E4
4 550 8313-74HC14       1.00 EA 5 IC, DIGITAL, CMOS, HEX SCHMITT-TRIGGER INVERTER CMOS       1E4
4 560 8313-74HC20       1.00 EA 5 IC, DIGITAL, CMOS, TRIPLE 4 INPUT NAND          CMOS       1E4
4 570 8313-74HC139      1.00 EA 5 IC, DIGITAL, 3 TO 8 DECODER                     CMOS       1E4
4 580 8313-74HC08       1.00 EA 5 IC, DIGITAL, CMOS, QUAD INPUT AND               CMOS       1E4
4 590 8313-74HC03       1.00 EA 5 IC, DIGITAL, CMOS, QUAD INPUT NAND              CMOS       1E4
4 600 8313-74HC4060     1.00 EA 5 IC, DIGITAL, CMOS, RIPPLE COUNTER               CMOS       1E4
4 610 8475-CEG14        3.00 EA 5 POTENTIOMETER, TOP ADJUST 1K, 3/8"SQ. MULTITURN FILM       1E7
4 620 8210-MLSS156-10   1.00 EA 5 CONNECTOR, MALE, .156 CNTRS, 10 POSITION        PLASTIC    1E6
4 630 8210-CE156F2210   1.00 EA 5 CONNECTOR, FEMALE, .156 CNTRS, 10 POSITION      PLASTIC    1E6
4 640 8210-3473-6010    2.00 EA 5 CONNECTOR, FEMALE, RIBBON CABLE, 10 POSITION    PLASTIC    1E6
4 650 8210-MLSS100-15   1.00 EA 5 CONNECTOR, MALE, .10 CNTRS 15 POSITION          PLASTIC    1E6
4 660 8210-CE100F2615   1.00 EA 5 CONNECTOR, FEMALE, .10 CNTRS, 26 AWG, 15 POSITIONS PLASTIC 1E6
4 670 8210-MLSS100-16   1.00 EA 5 CONNECTOR, MALE, .10 CNTRS 16 POSITION          PLASTIC    1E6
4 680 8210-CE100F2616   1.00 EA 5 CONNECTOR, FEMALE, .10 CNTRS, 26 AWG, 16 POSITIONS PLASTIC 1E6
4 690 8210-3408-6302    1.00 EA 5 CONNECTOR, STRAIGHT HEADER, LONG LATCH, 16 PINS PLASTIC    1E6
4 700 8470-753-1/8MF    1.00 EA 5 RESISTOR, 75K, 1/8 WATT,       METAL FILM       METAL FILM 1E11
4 710 8150-224K50MF     1.00 EA 5 CAPACITOR, FILM, .22UF @ 50 VOLTS               FILM ?     1E6
4 720 8210-1X28         1.00 SE 5 HEADER STRIP, 28 POS. SINGLE ROW                NYLON      1E6
4 730 8210-66506-082    2.00 EA 5 HEADER, MALE, RIBBON CABLE, 10 POSITION         PLASTIC    1E6
4 740 8150-107K16EA     1.00 EA 5 CAPACITOR, ELECTROLYTIC, AXIAL, 100UF @ 16V     ELECTROLY  1E7
4 750 8313-2803         1.00 EA 5 IC, DRIVER, BIPOLAR, 8 NPN                      BIPOLAR    1E5
4 760 8313-LM335        1.00 EA 5 IC, TEMPERATURE SENSOR                          SILICON    TEST
4 780 8280-SHUNT        2.00 EA 5 SHORTING JUMPER                                 PLASTIC    1E6
4 790 8470-12.4-1/8MF   1.00 EA 5 RESISTOR, 12.4K OHMS, 1/8 WATT METAL FILM, 1%   CARB FILM  1E9
3  30 A8170-2343        1.00 EA 4 PC BOARD ASSEMBLY, DUAL MOTOR  AMPLIFIER, 4 QUAD MIXED     1E4
4  10 8280-SS350-1D-7   8.00 EA 5 STANDOFF, SWAGE MOUNT, 6/32 THREAD, NICKLE PLATED ALUMINUM >1E9
4  20 8280-SS350-1A-7   8.00 EA 5 STANDOFF, SWAGE MOUNT, 6-32 THREAD, NICKLE PLATED ALUMINUM >1E9
4  30 8280-P529         1.00 EA 5 STANDOFF, HEX,6-32 THREAD,NICKLE PLATED, 1/4 X 1/2 ALUMINUM >1E9
4  40 8280-1-50871-9    8.00 EA 5 SPRING SOCKET, .060 PIN                         PLASTIC    1E6
4  50 8470-103-1/4CF   14.00 EA 5 RESISTOR, 10K, 1/4 WATT, CARBON FILM            CARB FILM  1E9
4  60 8470-272-1/4CF   10.00 EA 5 RESISTOR, 2.7K, 1/4 WATT, CARBON FILM           CARB FILM  1E9
4  70 8470-102-1/4CF    8.00 EA 6 RESISTOR, 1K, 1/4 WATT, CARBON FILM             CARB FILM  1E9
4  80 8470-472-1/4CF   15.00 EA 5 RESISTOR, 4.7K, 1/4W, CARBON FILM               CARB FILM  1E9
4  90 8470-152-1/4CF    5.00 EA 5 RESISTOR, 1.5K, 1/4 WATT, CARBON FILM           CARB FILM  1E9
4 100 8470-473-1/4CF    3.00 EA 5 RESISTOR, 47K, 1/4 WATT, CARBON FILM            CARB FILM  1E9
4 110 8470-203-1/4CF    1.00 EA 5 RESISTOR, 20K, 1/4 WATT,       CARBON FILM, 5%  CARB FILM  1E9
4 120 8470-224-1/4CF    8.00 EA 5 FERRITE BEAD, .031 ID                           FERRITE    >1E6
4 150 8470-471-1/4CF    8.00 EA 5 RESISTOR, 470 OHM, 1/4 WATT, CARBON FILM        CARB FILM  1E9
4 160 8180-FB73-110     8.00 EA 5 FERRITE BEAD .055 ID                            FERRITE    >1E6
4 170 8470-471-1/2CF    4.00 EA 5 RESISTOR, 470 OHM, 1/2 WATT, CARBON FILM        CARB FILM  1E9
4 180 8470-101-1/2CF    2.00 EA 5 RESISTOR, 100 OHM 1.2 WATT, CARBON FILM         CARB FILM  1E9
4 190 8480-1N4148      27.00 EA 6 DIODE, SIGNAL                                   DIODE      1E7
4 200 8210-14PIN        4.00 EA 6 SOCKET, IC, 14 PIN, ST, TIN                     PLASTIC    1E6
4 210 8210-8PIN         2.00 EA 6 SOCKET, IC, 8 PIN, ST, TIN                      PLASTIC    1E6
4 220 8480-MPSA05       4.00 EA 5 TRANSISTOR, SMALL SIGNAL, NPN, 60V              BIPOLAR    1E5
L SUB PARTNO          AMOUNT UN C DISCRIPTION                                  MATERIAL   HARDNESS
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4 230 8480-MPSA55       4.00 EA 5 TRANSISTOR, SMALL SIGNAL, PNP 60V               BIPOLAR    1E5
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3 270 8510-ASW2K20    1.00 EA 4 SWITCH, DPST, K2A CONTROL PANEL                    MIXED       1E7
3 280 8430-20A-TYPESC 1.00 EA 4 FUSE, 20 AMP, TYPE SC                              FUSE        TEST
3 290 8430-15ASB-SC   1.00 EA 4 FUSE, 15 AMP FOR CP01                              FUSE        TEST
3 300 8430-15AMP-311  1.00 EA 4 FUSE, 15 AMP, FOR CP0                              FUSE        TEST
3 310 8430-20AMP-307  1.00 EA 4 FUSE, 20 AMP, FAST ACTING, STANDARD,               FUSE        TEST
3 330 A8170-TETHER    1.00 EA 4 PC BOARD ASSEMBLY, TETHER                          MIXED       1E4
4  10 8170-TETHER     1.00 EA 5 PRINTED CIRCUIT BOARD, TETHER INTERFACE            EPOXY       1E8
4  20 8470-472-1/8CF  1.00 EA 6 RESISTOR, 4.7K, 1/8 WATT, CARBON FILM              CARB FILM  1E9
4  30 8470-104-1/8CF  1.00 EA 6 RESISTOR, 100K, 1/8 WATT, CARBON FILM, 5%          CARB FILM  1E9
4  40 8480-1N4148     1.00 EA 6 DIODE, SIGNAL                                      DIODE       1E7
4  50 8150-104K50MC   3.00 EA 6 CAPACITOR, MONOLITHIC CERAMIC, .1UF, 50V           CERAMIC     1E10
4  60 8313-1489       1.00 EA 5 IC, INTERFACE, BIPOLAR, LINE RECIEVER              BIPOLAR     1E5
4  70 8313-1488       1.00 EA 5 IC, INTERFACE, RS232C, DRIVER                      BIPOLAR     1E5
4  80 8210-MLSS100-8  1.00 EA 5 CONNECTOR, MALE, .100 CNTRS, 8 POSITION            PLASTIC     1E6
4 110 8600-26WHT/GRN  4.00 IN 5 HOOK-UP WIRE 26 GAUGE WHT/GRN                      PVC         1E7
4 120 8600-26GRY      4.00 IN 5 HOOK-UP WIRE 26 GAUGE GREY                         PVC         1E7
4 130 8600-26WHT/BLK  4.00 IN 5 HOOK-UP WIRE #26 W/BLACK                           PVC         1E7
4 140 8600-26BLU      4.00 IN 5 HOOK-UP WIRE 26 GAUGE BLUE                         PVC         1E7
4 150 8600-26WHT/ORNG 4.00 IN 5 HOOK-UP WIRE 26 GAUGE WHITE/ORANGE                 PVC         1E7
4 160 8210-8PIN       1.00 EA 6 SOCKET, IC, 8 PIN, ST, TIN                         PLASTIC     1E6
4 170 8210-14PIN      1.00 EA 6 SOCKET, IC, 14 PIN, ST, TIN                        PLASTIC     1E6
3 340 A8003-CP01-S/A  1.00 EA 4 WIRE HARNESS, FROM CP01 J2 TO J4 , ON COLUMN,& RIB PVC         1E7
4  10 8210-206037-1   1.00 EA 5 PLUG, FEMALE, 16 PIN                               PLASTIC     1E6
4  20 8210-206044-1   1.00 EA 5 PLUG, MALE, 14 PIN                                 PLASTIC     1E6
4  30 8210-206070-1   2.00 EA 5 CABLE, CLAMP                                       IRON       >1E10
4  40 8210-66099-4    7.00 EA 5 PIN, GOLD, 18-14 AWG
4  50 8210-66601-2    6.00 EA 5 SOCKET, GOLD, 18-14 AWG                            PLASTIC     1E6
4  60 8210-66595-1   10.00 EA 5 PIN, TIN, 28-24 AWG
4  70 8210-66596-1   10.00 EA 5 SOCKET, TIN, 28-24 AWG                             PLASTIC     1E6
4  80 8210-03-09-1032 1.00 EA 5 PLUG, FEMALE, 3 PIN                                PLASTIC     1E6
4 110 8210-02-09-1103 2.00 EA 5 PIN, FEMALE, 14-20AWG, E-STOP
4 140 8600-22ORG     22.00 IN 5 PVC HOOK UP WIRE, 22 AWG, ORG. 7 STRANDS, 1,000V   PVC         1E7
4 150 8600-22WHT/GRY 16.00 IN 5 PVC HOOK UP WIRE, 22 AWG, W/GRY, 7 STRANDS, 1,000V PVC         1E7
4 160 8600-22WHT/BLK 44.00 IN 5 PVC HOOK UP WIRE, 22 AWG, W/BLK, 7 STRANDS, 1,000V PVC         1E7
4 170 8600-22BRN     22.00 IN 5 PVC HOOK UP WIRE, 22AWG, BRN. 7 STRANDS, 1,000V    PVC         1E7
4 180 8600-22BLU     22.00 IN 5 PVC HOOK UP WIRE, 22 AWG, BLU 7 STRANDS, 1,000V    PVC         1E7
4 190 8600-22BLK     22.00 IN 5 PVC HOOK UP WIRE, 22 AWG, BLK. 7 STRANDS, 1,000V   PVC         1E7
4 200 8600-22GRN     16.00 IN 5 PVC HOOK UP WIRE, 22 AWG, GREEN, 7 STRANDS, 1,000V PVC         1E7
4 210 8600-22WHT/ORG 22.00 IN 5 PVC HOOK UP WIRE, 22 AWG, W/ORG, 7 STRANDS, 1,000V PVC         1E7
4 220 8600-22WHT/BRN 22.00 IN 5 PVC HOOK UP WIRE, 22 AWG, W/BRN, 7 STRANDS, 1,000V PVC         1E7
4 230 8600-18WHT/RED 54.00 IN 5 HOOK UP WIRE, 18 AWG W/RED STRANDED, 1,000V        PVC         1E7
4 240 8600-18WHT     32.00 IN 5 HOOK UP WIRE, 18 AWG WHITE STRANDED, 1,000V        PVC         1E7
4 250 8600-14WHT     16.00 IN 6 HOOK-UP WIRE #14 WHITE                             PVC         1E7
4 260 8600-14BLK     23.00 IN 5 HOOK-UP WIRE #14 BLK                               PVC         1E7
4 270 8210-CE100F2207 1.00 EA 5 CONNECTOR, FEMALE, 22 AWG, 7 POSITION              PLASTIC     1E6
4 280 8600-22GRY     16.00 IN 5 PVC HOOK UP WIRE, 22 AWG, GRY  7 STRANDS, 1,000V   PVC         1E7
4 290 8600-22YEL     16.00 IN 5 PVC HOOK UP WIRE, 22 AWG, YEL 7 STRANDS, 1,000V    PVC         1E7
4 300 8600-22WHT/YEL 16.00 IN 5 PVC HOOK UP WIRE, 22 AWG, W/YEL, 7 STRANDS, 1,000V PVC         1E7
4 310 8210-CE100F2207 1.00 EA 5 CONNECTOR, FEMALE, 22 AWG, 7 POSITION              PLASTIC     1E6
3 350 8280-F503       8.00 EA 5 SCREW, 6-32 X 1/4, NICKLE PLATED, BINDER HEAD      STEEL      >1E10
3 360 1045            2.00 EA 5 SCREW, 6-32, 1/2 LG, BINDER HEAD, SLOTTED, ZINC PL STEEL      >1E10
3 370 1057            6.00 EA 6 NUT, 6-32, KEPS, ZINC PLATED                       ALUMINUM ? >1E9
3 390 8280-F504       6.00 EA 4 SCREW, 6-32 X 3/8, NICKLE PLATED, BINDER HEAD      STEEL      >1E10
3 400 1055           16.00 EA 5 SCREW, 6-32, 5/8 LG, BINDER HEAD, ZINC PLATED      STEEL      >1E10
3 430 8280-4631       4.00 EA 4 FERRULE, RED                                       PLASTIC     1E6
3 440 A8003-DC1-MA2   1.00 EA 4 RIBBON CABLE FROM DC1 J4 TO  MA2 J1                PVC         1E7
4  10 8210-3452-6616  2.00 EA 5 CONNECTOR, RIBBON, W/CENTER-BUMP, 16 POS           PLASTIC     1E6
4  20 8600-3365/20    8.00 IN 5 RIBBON CABLE, 20 COND, 28 AWG                      PVC         1E7
3 450 A8003-S-ENCODER 1.00 EA 4 RIBBON CABLE FROM STEER ENCODER TO DC1 J5          PVC         1E7
4  10 8210-3473-6010  1.00 EA 5 CONNECTOR, FEMALE, RIBBON CABLE, 10 POSITION       PLASTIC     1E6
4  20 8210-66902-310  1.00 EA 5 CONNECTOR, FEMALE, RIBBON, 10 POSITION             PLASTIC     1E6
4  30 8600-3365/20   20.00 IN 5 RIBBON CABLE, 20 COND, 28 AWG                      PVC         1E7
3 510 1529            4.00 EA 4 RIVIT, POP, 3/32 X 1/4 LG ALUMINUM                 ALUMINUM   >1E9
3 550 8280-23N3977    4.00 EA 4 CIRCUIT BOARD SUPPORT, SCREW FASTENED, WHITE PLAST NYLON       2E5
3 560 1081            4.00 EA 5 SCREW, 6-32, 3/8 LG, PAN HEAD  SLOTTED, ZINC PLT   STEEL      >1E10
3 590 A8003-K2A-WIR   1.00 EA 4 WIRING FOR K2A BASE                                PVC         1E7
4  10 8600-10RED     29.00 IN 5 10 AWG RED. HOOK-UP WIRE                           PVC         1E7
4  20 8600-12WHT      5.50 IN 5 12 AWG. WHITE, HOOK UP WIRE                        PVC         1E7
4  30 8600-10BLK     29.00 IN 5 10AWG BLK, HOOK UP WIRE                            PVC         1E7
4  40 8280-#12-10TO12 4.00 EA 5 STUD #12 FOR 10 TO 12 AWG WIRE, NONINSULATED       COPPER     >1E9
4  50 8280-#12-18TO22 1.00 EA 5 STUD #12 FOR 18 TO 22 AWG WIRE, UNINSULATED        COPPER     >1E9
L SUB PARTNO        AMOUNT UN C DISCRIPTION                                      MATERIAL   HARDNESS
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4  60 8280-#6-10TO12  4.00 EA 6 STUD #6 FOR 10 TO 12 AWG  WIRE, UNINSULATED        COPPER     >1E9
4  70 8280-FD/10-250  2.00 EA 5 FASTON, FULLY INSULATED, FEMALE, 10 TO 12 AWG, .25 PLASTIC     1E6
4  80 8280-#6-14TO16  7.00 EA 5 STUD, #6 FOR 14 TO 16 AWG WIRE, UNINSULATED        COPPER     >1E9
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4	110	8150-474K100MF	2.00	EA	5	CAPACITOR, FILM, .47UR @ 100 VOLTS	FILM ?	1E6
4	120	8280-#6-18TO22	4.00	EA	6	STUD, #6 FOR 18 TO 22 AWGWIRE, UNINSULATED	COPPER	>1E9
4	130	8600-18RED	3.00	EA	4	FUSE HOLDER, 3AG	PLASTIC	1E6
4	140	8600-14BLK	20.00	IN	5	HOOK-UP WIRE #14 BLK	PVC	1E7
4	150	8280-#6-18TO22	2.00	EA	6	STUD, #6 FOR 18 TO 22 AWG WIRE, UNINSULATED	COPPER	>1E9
3	600	A8003-CP01-WIR	1.00	EA	4	WIRING FOR CONTROL PANEL	PVC	1E7
4	10	8600-14WHT	92.50	IN	6	HOOK-UP WIRE #14 WHITE	PVC	1E7
4	20	8600-12WHT	34.00	IN	5	12 AWG. WHITE, HOOK UP WIRE	PVC	1E7
4	30	8600-22WHT/GRY	19.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRY, 7 STRANDS, 1,000V	PVC	1E7
4	40	8280-#6-10TO12	2.00	EA	6	STUD #6 FOR 10 TO 12 AWG WIRE, UNINSULATED	COPPER	>1E9
4	50	8280-#6-14TO16	4.00	EA	5	STUD, #6 FOR 14 TO 16 AWG WIRE, UNINSULATED	COPPER	>1E9
4	60	8280-#6-18TO22	1.00	EA	6	STUD, #6 FOR 18 TO 22 AWG WIRE, UNINSULATED	COPPER	>1E9
4	70	8600-22WHT/YEL	29.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/YEL, 7 STRANDS, 1,000V	PVC	1E7
4	80	8210-73210	1.00	EA	5	TERMINAL BLK, 10 POSITION		
4	90	8210-40F6130	7.00	EA	5	TEFLON INSULATED JACK, 40 ML.	TEFLON	1E4
4	100	8210-206036-1	1.00	EA	5	RECEPTACLE, STANDARD SEX, MALE, 16 PIN	PLASTIC	1E6
4	110	1081	4.00	EA	5	SCREW, 6-32, 3/8 LG, PAN HEAD SLOTTED, ZINC PLT	STEEL	>1E10
4	120	1057	4.00	EA	6	NUT, 6-32, KEPS, ZINC PLATED	ALUMINUM ?	>1E9
4	130	8280-514-10027	1.00	EA	5	TIE ANCHOR BASE, #8		
4	140	8210-66595-1	11.00	EA	5	PIN, TIN, 28-24 AWG		
4	150	8210-66099-4	5.00	EA	5	PIN, GOLD, 18-14 AWG		
4	160	1045	2.00	EA	5	SCREW, 6-32, 1/2 LG, BINDER HEAD, SLOTTED, ZINC PL	STEEL	>1E10
4	170	1057	2.00	EA	6	NUT, 6-32, KEPS, ZINC PLATED	ALUMINUM ?	>1E9
4	180	8600-26BLU	29.00	IN	5	HOOK-UP WIRE 26 GAUGE BLUE	PVC	1E7
4	190	8600-26WHT/GRN	29.00	IN	5	HOOK-UP WIRE 26 GAUGE WHT/GRN	PVC	1E7
4	200	8600-26WHT/GRY	4.00	IN	5	HOOK-UP WIRE 26 GAUGE WHT/GREY	PVC	1E7
4	210	8600-26GRN	32.00	IN	5	HOOK-UP WIRE 26 GAUGE GREEN	PVC	1E7
4	220	8600-26WHT/VIO	4.00	IN	5	HOOK-UP WIRE 26 GAUGE WHT/VIO	PVC	1E7
4	230	8600-26WHT/BRN	32.00	IN	5	HOOK-UP WIRE #26 WHITE/BROWN	PVC	1E7
4	240	8600-22GRN	4.00	IN	5	PVC HOOK UP WIRE, 22 AWG, GREEN, 7 STRANDS, 1,000V	PVC	1E7
4	250	8600-26WHT/BLK	4.00	IN	5	HOOK-UP WIRE #26 W/BLACK	PVC	1E7
4	260	8600-26GRN	24.00	IN	5	HOOK-UP WIRE 26 GAUGE GREEN	PVC	1E7
4	270	8600-26ORN	24.00	IN	5	HOOK-UP WIRE 26 GAUGE ORANGE	PVC	1E7
4	280	8600-26WHT/ORNG	32.00	IN	5	HOOK-UP WIRE 26 GAUGE WHITE/ORANGE	PVC	1E7
4	290	8600-18WHT	32.00	IN	5	HOOK UP WIRE, 18 AWG WHITE STRANDED, 1,000V	PVC	1E7
4	300	8600-18WHT/RED	34.00	IN	5	HOOK UP WIRE, 18 AWG W/RED STRANDED, 1,000V	PVC	1E7
4	310	8600-22WHT/YEL	21.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/YEL, 7 STRANDS, 1,000V	PVC	1E7
4	320	8600-22WHT/ORG	21.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/ORG, 7 STRANDS, 1,000V	PVC	1E7
4	330	8600-22WHT/GRN	21.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRN, 7 STRANDS, 1,000V	PVC	1E7
4	340	8600-22WHT/GRY	21.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRY, 7 STRANDS, 1,000V	PVC	1E7
4	350	8600-22GRN	21.00	IN	5	PVC HOOK UP WIRE, 22 AWG, GREEN, 7 STRANDS, 1,000V	PVC	1E7
4	360	8600-26WHT	2.00	IN	5	HOOK-UP WIRE 26 GAUGE WHITE	PVC	1E7
3	610	8310-534-4616	8.00	EA	4	INSULATOR, POWER TRANSISTOR	MICA	>1E9
3	620	8600-16WHT	8.00	IN	4	HOOK-UP WIRE #16 WHITE	PVC	1E7
3	630	8600-14WHT	25.00	IN	6	HOOK-UP WIRE #14 WHITE	PVC	1E7
3	640	8600-12WHT	2.50	IN	5	12 AWG. WHITE, HOOK UP WIRE	PVC	1E7
3	650	8280-#6-10TO12	1.00	EA	6	STUD #6 FOR 10 TO 12 AWG WIRE, UNINSULATED	COPPER	>1E9
3	660	8280-#6-14TO16	1.00	EA	5	STUD, #6 FOR 14 TO 16 AWG WIRE, UNINSULATED	COPPER	>1E9
3	670	8600-22WHT/YEL	32.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/YEL, 7 STRANDS, 1,000V	PVC	1E7
3	680	8600-22WHT/GRY	16.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRY, 7 STRANDS, 1,000V	PVC	1E7
3	690	8600-22GRN	16.00	IN	5	PVC HOOK UP WIRE, 22 AWG, GREEN, 7 STRANDS, 1,000V	PVC	1E7
3	700	8600-22WHT/GRY	16.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRY, 7 STRANDS, 1,000V	PVC	1E7
3	710	8600-22WHT/GRN	16.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/GRN, 7 STRANDS, 1,000V	PVC	1E7
3	720	8600-22WHT/ORG	16.00	IN	5	PVC HOOK UP WIRE, 22 AWG, W/ORG, 7 STRANDS, 1,000V	PVC	1E7
3	730	8600-26VIO	27.00	IN	4	HOOK-UP WIRE #26 VIOLET	PVC	1E7
3	740	8600-26WHT/VIO	27.00	IN	5	HOOK-UP WIRE 26 GAUGE WHT/VIO	PVC	1E7
3	750	8600-26BLU	22.50	IN	5	HOOK-UP WIRE 26 GAUGE BLUE	PVC	1E7
3	760	8600-26WHT/BLU	16.50	IN	4	HOOK-UP WIRE 26 GAUGE WHT/BLU	PVC	1E7
3	770	8600-26ORN	16.50	IN	5	HOOK-UP WIRE 26 GAUGE ORANGE	PVC	1E7
3	780	8600-26WHT/ORNG	22.50	IN	5	HOOK-UP WIRE 26 GAUGE WHITE/ORANGE	PVC	1E7
3	790	8600-26GRY	22.50	IN	5	HOOK-UP WIRE 26 GAUGE GREY	PVC	1E7
3	800	8600-26WHT/GRY	16.50	IN	5	HOOK-UP WIRE 26 GAUGE WHT/GREY	PVC	1E7
3	810	8600-26GRN	16.50	IN	5	HOOK-UP WIRE 26 GAUGE GREEN	PVC	1E7
3	820	8600-26WHT/GRN	22.50	IN	5	HOOK-UP WIRE 26 GAUGE WHT/GRN	PVC	1E7
3	830	8600-26YEL	16.50	IN	4	HOOK-UP WIRE #26 YELLOW	PVC	1E7
3	840	8600-26WHT/YEL	22.50	IN	4	HOOK-UP WIRE #26 W/YELLOW	PVC	1E7
3	850	8600-26RED	16.50	IN	4	HOOK-UP WIRE #26 RED	PVC	1E7
3	860	8600-26WHT/RED	16.50	IN	4	HOOK-UP WIRE #26 WHITE/RED	PVC	1E7
3	870	8600-26BLK	16.50	IN	4	HOOK-UP WIRE #36 BLACK	PVC	1E7
3	880	8600-26WHT/BLK	22.50	IN	5	HOOK-UP WIRE #26 W/BLACK	PVC	1E7

L	SUB	PARTNO	AMOUNT	UN	C	DISCRIPTION	MATERIAL	HARDNESS
3	890	8600-26WHT	18.50	IN	5	HOOK-UP WIRE 26 GAUGE WHITE	PVC	1E7
3	900	8280-10F7970	5.00	EA	4	MOUNTING GROMMETS FOR SQUARE LEDS	PLASTIC	1E6
2	140	1022	2.00	EA	5	SCREW, 10-32, 1/2 LG BUTTON HEAD, SOCKET	STEEL	>1E10
2	150	8012	2.00	EA	3	BATTERY, 12 VOLT 85AH, SEALED GEL	PVC ?	1E7

L	SUB	PARTNO	AMOUNT	UN	C	DISCRIPTION	MATERIAL	HARDNESS
2	180	6016	1.00	EA	3	TURRET WRENCH	STEEL	>1E10
2	190	1099	3.00	EA	4	SCREW, 1/2-13, 5/8 LG, HEX HEAD	STEEL	>1E10
2	200	5003	3.00	EA	3	MACHINED, WHEEL HUB, MACHINED	ALUMINUM	>1E9
3	500	A1015	3.00	EA	4	ASSEMBLY, LEG, K3A	ALUMINUM	>1E9
4	10	1536-05	2.00	EA	4	KEY, STEER SHAFT, LEG, K3A	STEEL	>1E10
4	20	1535-10-001	2.00	EA	4	SHIM, PLASTIC, 2.50x1.77x.001	POLYESTER	1E7
4	30	135-10-002	2.00	EA	4	SHIM, PLASTIC, 2.5x1.77x.002	POLYESTER	1E7
4	40	1535-10-005	2.00	EA	4	SHIM, PLASTIC, 2.5x1.77x.005	POLYESTER	1E7
4	50	1535-04-001	2.00	EA	4	SHIM, PLASTIC, 1.56x1.00x.001	POLYESTER	1E7
4	60	1535-04-002	2.00	EA	4	SHIM, PLASTIC, 1.56x1.00x.002	POLYESTER	1E7
4	70	1535-04-005	2.00	EA	4	SHIM, PLASTIC, 1.56x1.00x.005	POLYESTER	1E7
4	80	1535-14-001	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LEG-TO-COLUMN, K3A	POLYESTER	1E7
4	90	1535-14-002	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LEG-TO-COLUMN, K3A	POLYESTER	1E7
4	100	1535-14-005	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LEG-TO-COLUMN, K3A	POLYESTER	1E7
4	110	5013	1.00	EA	4	HOUSING, LEG, K3A	ALUMINUM	>1E9
4	120	4021	2.00	EA	4	GEAR, STEER, 30-TOOTH, MITER, K3A	STEEL	>1E10
4	130	4002	2.00	EA	5	GEAR, MITER, DRIVE, 18 TEETH, 18 PITCH	STEEL	>1E10
4	140	3018	2.00	EA	4	SHAFT, STEER, LEG, K3A	STEEL	>1E10
4	150	3017	1.00	EA	4	SHAFT, DRIVE, LEG, K3A	STEEL	>1E10
4	160	2526	2.00	EA	4	WASHER, THRUST, TRB2840	STEEL	>1E10
4	170	2525	2.00	EA	4	WASHER, THRUST, TRB2840	STEEL	>1E10
4	180	2524	2.00	EA	4	BEARING, THRUST, NTA2840	STEEL	>1E10
4	190	2523	4.00	EA	4	WASHER, THRUST, TRA1625	STEEL	>1E10
4	200	2500	2.00	EA	5	BEARING, THRUST, NEEDLE, INA	STEEL	>1E10
4	210	2023	4.00	EA	4	BEARING, NEEDLE, 86P	STEEL	>1E10
4	220	2007	2.00	EA	5	RACE, INNER, MCGILL, NO SUB	STEEL	>1E10
4	230	2006	2.00	EA	5	BEARING, NEEDLE, MCGILL SEALED, NO SUBSTITUTE	STEEL	>1E10
4	240	1506	2.00	EA	5	KEY, SQUARE, 1/8x1/8, 3/4 LONG	STEEL	>1E10
4	250	1146	4.00	EA	4	DOWEL, 1/4 DIA. x 1/2 IN. LONG	METAL	>1E9
4	260	1145	4.00	EA	4	SCREW, CAP, SCK.HD., M6-1 X 40 MM	STEEL	>1E10
4	270	1144	2.00	EA	4	SCREW, SET, SOCKET	STEEL	>1E10
4	280	1134	2.00	EA	4	SCREW, SET, SOCKET HEAD	STEEL	>1E10
4	290	1535-13-001	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LEG-TO-KNEE, K3A	POLYESTER	1E7
4	300	1525-13-002	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LET-TO-KNEE, K3A	POLYESTER	1E7
4	310	1535-13-005	2.00	EA	4	SHIM, SPECIAL, PLASTIC, LEG-TO-KNEE, K3A	POLYESTER	1E7
3	100	A1018	1.00	EA	0	ASSEMBLY, K3A BASE COVER	ALUMINUM	>1E9
4	10	6028	2.00	EA	3	FRAME, DOOR, CUPCAKE, TOP, K3A	ALUMINUM	>1E9
4	20	6017	1.00	EA	3	COUNTERWEIGHT, K3A, DC1	METAL	>1E9
4	30	6020	1.00	EA	3	DC1 MOUNT, K3A	ALUMINUM	>1E9
4	40	5039	3.00	EA	3	ADAPTER, CUPCAKE, K3A	ALUMINUM	>1E9
4	50	5038	1.00	EA	3	CUPCAKE, BOTTOM, K3A	ALUMINUM	>1E9
4	60	5040	2.00	EA	3	DOOR, CUPCAKE, BATTERIES, K3A	ALUMINUM	>1E9
4	70	5022	2.00	EA	3	CUPCAKE, TOP, K3A, DC1 RETROFIT	METAL	>1E9
4	80	1153	2.00	EA	3	LATCH, SOUTHCO, 2-56-0371-07	METAL	>1E9
4	90	1152	2.00	EA	3	KEEPER, SOUTHCO, 2-56-0371-07	METAL	>1E9
4	100	1151	24.00	EA	3	NUT, HEX, LOCKING, M4-.7MM	STEEL	>1E10
4	110	1149	39.00	EA	3	SCREW, SOC. BUTTON HD	STEEL	>1E10
4	120	1147	16.00	EA	3	SCREW, SOC. BUTTON HD	STEEL	>1E10
4	130	1138	16.00	EA	4	SOCKET HEAD CAP SCREW	STEEL	>1E10
4	140	1034	4.00	EA	4	SCREW, M4-.7 FLAT HEAD X 10	STEEL	>1E10
4	150	5036	2.00	EA	3	KEEPER, BATTERY, K3A		
4	160	6311-01	2.00	EA	3	SPACER, BATTERY, K3A MFG FROM 6311	PVC FOAM	1E7
4	170	6311-02	2.00	EA	3	SPACER, BATTERY, K3A	PVC FOAM	1E7
3	540	A1014	3.00	EA	0	ASSEMBLY, FOOT, DUAL WHEEL, K3A	RUBBER NI	1E7
4	10	5011	1.00	EA	4	FOOT HOUSING, K3A	ALUNIMUM	>1E9
4	20	5012	1.00	EA	4	CASTING, KNEE, MACHINED, K3A	ALUMINUM	>1E9
4	30	3014	2.00	EA	4	WHEEL BEARING CARTRIDGE, K3A	ALUMINUM	>1E9
4	40	1124	2.00	EA	4	RETAINING RING, 5002-315	STEEL	>1E10
4	50	3015	1.00	EA	4	SHAFT, PINION, LEFT, K3A	STEEL	>1E10
4	60	3016	1.00	EA	4	SHAFT, PINION, RIGHT, K3A	STEEL	>1E10
4	70	6012-01	1.00	EA	4	PLATE, COVER, K3A	ALUMINUM	>1E9
4	80	B6215	2.00	EA	4	CASTING, WHEEL, DRIVE, K3A	ALUMINUM	>1E9
4	90	4019	1.00	EA	4	GEAR, DRIVE, RIGHT-HAND, TOP, MITER, K3A	STEEL	>1E10
4	100	4020	1.00	EA	4	GEAR, DRIVE, LEFT-HAND, TOP, MITER, K3A	STEEL	>1E10
4	110	4021	1.00	EA	4	GEAR, STEER, 30-TOOTH, MITER, K3A	STEEL	>1E10
4	120	4023	1.00	EA	4	GEAR, LEFT-HAND, BEVEL, K3A REV3	STEEL	>1E10
4	130	4024	1.00	EA	4	GEAR, RIGHT-HAND, BEVEL, K3A	STEEL	>1E10
4	140	4025	1.00	EA	4	PINION, LEFT-HAND, BEVEL, K3A	STEEL	>1E10
4	150	4026	1.00	EA	4	PINION, RIGHT-HAND, BEVEL, K3A	STEEL	>1E10
4	160	3502	1.00	EA	4	OIL SEAL, HARWELL, 64 X 85 X 10	RUBBER NI.	1E7
4	170	1536-01	2.00	EA	4	KEY, MACHINE, 5X5X20MM, K3A P/N .5n2qss	STEEL	>1E10
4	180	1536-03	2.00	EA	4	KEY, MACHINE, 7x8x12.7MM, K3A	STEEL	>1E10
4	200	2515	3.00	EA	4	BEARING, THRUST, axk2542	STEEL	>1E10
4	210	2516	2.00	EA	4	WASHER, THRUST, as2542	STEEL	>1E10

4	220	2019	2.00	EA	4	BEARING, BALL 60072RS1	STEEL	>1E10
4	230	2020	2.00	EA	4	BEARING, NEEDLE, HK1210	STEEL	>1E10
4	240	2517	1.00	EA	4	BEARING, THRUST, axk4565	STEEL	>1E10
4	190	1536-04	2.00	EA	4	KEY, MACHINE, 7x8x12MM, K3A	STEEL	>1E10
4	250	2520	1.00	EA	4	BEARING, TAPERED ROLLER, 32209	STEEL	>1E10
4	260	2021	2.00	EA	4	BEARING, BALL, 63072RS1	STEEL	>1E10
4	270	2022	2.00	EA	4	BEARING, BALL, 618262rz	STEEL	>1E10
4	280	2519	4.00	EA	4	WASHER, THRUST, AS3047	STEEL	>1E10
4	290	2521	1.00	EA	4	BEARING, THRUST, AXK2035	STEEL	>1E10
4	300	2522	2.00	EA	4	WASHER, THRUST, AS2035	STEEL	>1E10
4	310	1158	2.00	EA	4	WASHER, HIGH-STRENGTH MCMASTER CARR #9826a035	STEEL	>1E10
4	320	1535-03-001	2.00	EA	4	SHIM, PLASTIC, 3.7x2.76x.001	POLYESTER	1E7
4	330	1535-03-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	340	1535-03-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	350	1535-04-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	360	1535-04-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	370	1535-04-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	380	1535-10-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	390	1535-10-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	400	1535-10-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	410	1535-09-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	420	1535-09-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	430	1535-02-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	440	1535-02-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	450	1535-02-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	460	1535-05-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	470	1535-05-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	480	1535-05-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	490	1535-01-001	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	500	1535-01-002	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	510	1535-01-005	2.00	EA	4	SHIM, PLASTIC	POLYESTER	1E7
4	520	1126	1.00	EA	4	HEX NUT, M61.0	STEEL	>1E10
4	530	1134	4.00	EA	4	SCREW, SET, SOCKET	STEEL	>1E10
4	540	1144	1.00	EA	4	SCREW, SET, SOCKET	STEEL	>1E10
4	550	1119	2.00	EA	4	BOLT, HEX-HEAD, ZINC PLATED	STEEL	>1E10
4	560	1138	12.00	EA	4	SCREW, SOCKET HEAD, CAP	STEEL	>1E10
4	570	1122	16.00	EA	4	SCREW, SOCKET, CAP	STEEL	>1E10
4	580	1121	3.00	EA	4	SCREW, SOCKET, CAP	STEEL	>1E10
4	590	1123	2.00	EA	4	SCREW, SET, SOCKET, CUP POINT	STEEL	>1E10
2	600	3013-2	1.00	EA	4	BEARING, PINION, CARTRIDGE, BOTTOM, K3A	STEEL	>1E10
4	610	1125	3.00	EA	4	SANDWICH MOUNT, j-4624-618 (LORD)	RUBBER	1E6
4	620	1535-09-002	2.00	EA	4	SHIM, PLASTIC,	POLYESTER	1E7
4	630	3013-1	1.00	EA	4	BEARING, PINION CARTRIDGE, TOP, K3A	STEEL	>1E10
4	640	1536-08	2.00	EA	4	KEY, L.H. PINION SHAFT, K3A	STEEL	>1E10
4	650	2518	2.00	EA	4	WASHER, THRUST, as4565	STEEL	>1E10

APPENDIX C -- PAPERS:

Sias, Fred R., Jr., "Special Requirements for Electronics to be Used in Robots in Space", *Proceedings, 42nd Conference on Robotics and Remote Systems,* American Nuclear Society, 1994, Vol. 1. Removed for seperate processing - H Hill

Sias, Fred R., Jr., and James S. Tulenko, "Update on Radiation-Hardened Microcomputers for Robotics and Teleoperated Systems", *Proceedings, 41st Conference on Robotics and Remote Systems,* American Nuclear Society, November, 1993. Removed for separate processing

Sias, F.R., J.S. Byrd, D.M. Dawson, R.O. Pettus, and R.J. Schalkoff, "Design Considerations for an Intelligent Mobile Robot for Mixed Waste Inspection", *Proceedings of the Second International Mixed Waste Symposium,* Baltimore, MD, August 17-20, 1993. Removed for separate Processing HH

Sias, Fred R., Jr., Selecting Microprocessors Suitable for Robotic Applications in Radioactive Sites, *Proceedings of the Fifth Topical Meeting on Robotics and Remote Systems,* American Nuclear Society, Knoxville, TN, April 1993. Removed for separate processing

Sias, Fred R., and Robert M. Fox, Selecting Radiation-Resistant Semiconductors for Robots and Teleoperated Systems, *Remote System Technology Division Proceedings,* American Nuclear Society, Chicago, Nov. 1992.

Sias, Fred R., Jr., and David A. Williams, Design of a Radiation-Hardened Embedded Microcomputer, *Remote System Technology Division Proceedings,* American Nuclear Society, Chicago, Nov. 1992.