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RADIATION-HARDENED CONTROL SYSTEM

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RADIATION-HARDENED CONTROL SYSTEM[a]

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ABSTRACT A radiation-hardened bit-slice control system with associated input/output circuits was developed to prove that programmable circuits could be constructed to successfully implement intelligent functions in a highly radioactive environment. The goal for this effort was to design and test a programmable control system that could withstand a minimum total dose of 10^7 rads (gamma). The Radiation Hardened Control System (RHCS) was tested in operation at a dose rate that ranged up to 135 krad/h, with an average total dose of 10.75 Mrads. Further testing beyond the required 10^7 rads was also conducted. RHCS performed properly through the target dose of 10^7 rads, and sporadic intermittent failures in some programmable logic devices were noted after ~13 Mrads.

INTRODUCTION

The Rad-Hardened Control System (RHCS) was developed to prove the feasibility of constructing an intelligent control system that would withstand a total gamma dose of 10^7 rads or greater.

Unlike the design of specific radiation-hardened integrated circuits (ICs), the design of a radiation-hardened circuit will focus on the careful selection of components (including those that are specifically designed to be rad-hard) to combine the needed function with the proper processing technology to maximize the probability that the overall circuit will be rad-hard. Foremost in the process of selecting suitable components is the irradiation and testing of prospective parts to determine which ones will (or will not) survive the anticipated radiation levels. If the component cannot be tested under actual operating conditions, the alternative is to test it passively (no dc bias—short the leads together during the irradiation and test the component afterward). In many cases for bipolar transistors, this can be a worst-case scenario for irradiation because the heat generated by the device during active biasing facilitates annealing. If even passive testing is not feasible, a phone call to the manufacturer can usually provide enough processing information to allow a rough estimation of the component's hardness. Passive irradiation, however, is not always a suitable method for selecting components, because our own experience has shown that some devices will survive a passive irradiation test but will fail while being irradiated in operation. As it turns out, this phenomenon is a function of monitoring during irradiation rather than biasing-dependent radiation tolerance: the passively irradiated ICs do, in fact, fail, but they regain their functionality soon after the irradiation is stopped. This phenomenon is believed to be the result of annealing by the IC after it has been removed from the radiation field and has been observed in both passively and actively irradiated chips. Thus, some devices that actually failed during passive irradiation annealed to functionality by the time they could be tested. The time between failed and annealed states probably varies considerably between individual devices, but annealing to functionality has occurred in less than one day. This process of annealing is significant because it implies that radiation damage can possibly be continuously "repaired" even while the device is being damaged by the radiation, and this in turn implies that device behavior in a radioactive environment is dose-rate related. In fact, limited experiments along these lines

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have shown that for some oxide-isolated devices, reducing the dose rate does in fact enable the devices to survive to higher total dose levels before initial failure. This does not imply that the device can withstand higher doses before complete (irreversible by annealing) failure, because it was not conclusively determined that the total dose at which complete failure occurred was different for other dose rates.

The processing technology decided upon for this design was junction-isolated Schottky bipolar, primarily because of the wide selection and availability of bit-slice components and other building-block logic functions, and also because of the strong indications from previous experimental programs (Kennedy and Wu, 1988) that indicated good radiation tolerance for this class of device. Bit-slice technology was used in lieu of a microprocessor because microprocessors are generally only available in one of the metal-oxide semiconductor processes, which have been shown to be radiologically delicate.

The specific family of devices selected for this design is the 2900 series of bit-slice components. These parts, in particular the 2901 ALU and the 2909, 2910, and 2911 microsequencers, were chosen because they are multisourced, they can be obtained in junction-isolated technologies, and they offer a clear migration path to the design of a GaAs-based design or GaAs custom IC. GaAs is the preferred technology from the rad-hardening perspective, but the limited selection of functions currently available and the difficulty of producing a new design in GaAs favor the use of more common and easily used technologies. These restrictions, however, are not as applicable to the design of a GaAs custom IC, so by basing the current design on the 2900-series bit-slice components, which are currently available in GaAs, the design offers the promise of eventually being transferable to GaAs. This in turn offers the promise of a controller capable of withstanding a total dose in excess of 10^8 rads.

The use of bit-slice components, although ostensibly a more cumbersome approach, has in fact a number of advantages over the use of a complete ready-made microprocessor. The primary advantage, of course, is from the rad-hardening perspective. Other advantages are

1. The controller and its associated circuits can be custom designed to best accomplish the tasks that they will be required to perform.

2. The system address, data, and control buses can be designed to most effectively augment the operation of the controller and its input/output (I/O) cards.

3. The instruction set can be minimized and optimized for the intended tasks, or the system can eliminate instructions altogether and operate entirely from microcode to increase speed.

4. Functions normally controlled via the system bus can be microcode controlled to increase speed and capability.

5. The entire system can be designed with the end use in mind, rather than trying to base a design on a component that may not be optimal for the intended use.

The bit-slice controller design selected for RHCS was configured to move data rather than perform computation. The final operational test was basically intended to exercise the controller and its I/O cards and to prove that the components used would in fact perform properly through 10^7 rads. The test consisted of having the controller communicate via a serial link with a personal computer to exchange I/O data with the controller. The exercise was controlled by the computer, which was essentially a "master" that sent a set of I/O settings to the controller to distribute the data to its I/O channels, read the data back, and send it back to the computer for comparison and display. Between interrogations, the controller remains in an idle state and monitors the communications hardware.

The RHCS prototype consists of seven circuit cards. The prototype circuits were hand-wired on standard printed-circuit cards, and the connections were made by point-to-point solder connections using Kynar-insulated 30-gauge wire wrap wire. The boards used were VME prototype cards. The VME cards were selected because of their physical dimensions; the irradiation container for the final operational test was a 2.1m-long, 23cm-ID watertight cylinder, and the VME cards would allow the most circuit area and still fit inside the cylinder.

SYSTEM OVERVIEW

The system block diagram for RHCS appears in Fig. 1. The controller itself consists of a central processing unit (CPU) board and a Micromemory board. The Micromemory board takes as its inputs the system clock and a microcode address from the CPU. The CPU board in turn takes as inputs the system clock, microcoded instructions from the Micromemory board, and various status signals from throughout the system. The CPU board controls the entire system, primarily via the Micromemory board, as the control signals and other controller outputs are microcoded. The output from the

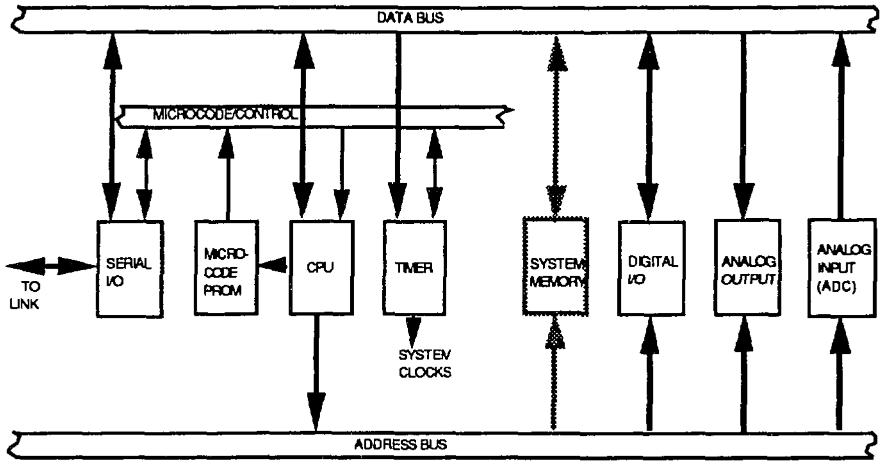

Fig. 1. System block diagram

Micromemory board is loosely termed a Microcode/Control bus.

The timer and serial I/O boards are also considered part of the controller but do not directly control the functions of the overall system. The serial I/O board allows the controller to communicate with the "master" computer. It is microcode controlled and is essentially a data encoder/decoder, using the standard biphase encoding format. The inputs include the encoded serial input, data from the system data bus, and control signals from the microcode/control bus. The outputs consist of the encoded serial output to the master computer and internal data and status signals. The timer board serves three system functions: it contains the crystal oscillator and clock generator circuitry from which the system clocks are derived, a reset generator, and two interval timers. It is controlled by microcode, and its status outputs go directly to the CPU, as do those of the serial I/O subsystem.

The system memory and the analog/digital I/O cards are all bus operated. The controlling functions of the system bus are a 16-bit address, I/O read and write signals, memory read and write signals, and the system clocks. The system bus also contains 16 bits of data. The bus protocol is simple and synchronous and is loosely based on the IBM PC-Bus format. The read/write operation according to the protocol requires three clock cycles, but because of the design of the I/O cards, the operation can in fact be completed in just one cycle if desired.

The system memory card contains both random access memory (RAM) and read-only memory (ROM). Part of the RAM addresses and the I/O addresses, which are memory mapped, overlap to allow faster storage of input and output data. This feature is especially useful when it is desired to send I/O data redundantly, because it permits the data to be stored in RAM at the same time it is being read from the I/O and transmitted to the master computer (or as it is being received from the master computer and written to the I/O). Additional RAM address space is also supported to allow RAM to be used in more conventional applications. Because of space limitations in the test vessel, this board was not included in the prototype irradiation-test system.

The digital and analog I/O cards are the interface to the controlled function, such as a manipulator. The current prototype has 16 bits of digital I/O and four analog I/O channels with 12 bits of resolution for each channel.

EXPERIMENTAL RESULTS

Because the RHCS was designed to withstand a total dose of 10 Mrads, it follows that the entire system should be tested to 10 Mrads, preferably by irradiating it in an operational mode. It should go without saying that operational testing is the preferred method, especially because it was shown in these tests that passive irradiation is not always worst case from the standpoint of detecting operational failures (as noted in the introduction). Operational testing also stresses the components in a realistic manner and best simulates the actual conditions that the system may encounter during operation.

Three tests were actually conducted on the RHCS. The first two tests were of limited scope and duration and were discontinued after accumulating a total dose of ~5 to 6 Mrads over some portions of the circuitry. In these tests, the CPU and micromemory cards both contained oxide-isolated devices that failed shortly after the tests began, hence the discontinuation of the tests before a full gamma dose could be accumulated. The two device types that failed (Am2910 and Am29116) had both been successfully tested after having been passively irradiated to 10 Mrads; unfortunately, in actual biased operation they survived for only a small fraction of that dose. This fact calls into question the reliability of passively irradiating oxide-isolated devices, including those with predominantly bipolar devices.

For the first operational test of RHCS, the dose rate was set at a peak rate of 75 krads per hour, with the dose rate at the CPU (which is where the failure occurred) at about 40 to 50 krads/h. The Am29116 failed after 8 h, and the Am2910 failed ~2h later. For the second test, the two devices were replaced with identical parts and the dose rate was reduced to a peak rate of 30 krads/h. Under these conditions, the two devices survived considerably longer but still failed before reaching 2 Mrads. It was at this point that the tests were suspended until the CPU and micromemory cards could be redesigned with devices that were more radiation-tolerant. The resulting design is the one described in this report.

For all three operational tests of the rad-hardened controller, the circuit cards were mounted longitudinally in a long aluminum watertight cylinder (Fig. 2). The cylinder was lowered to the bottom of a storage pool at the Oak Ridge National Laboratory Bulk Shielding Reactor, and a gamma source was then positioned alongside the cylinder to irradiate the contents. The source in this test was a 23,000-Ci ^{60}Co slug, contained in a steel vessel and suspended in the pool water by a steel cable. Because the cylinder was ~7 ft long and the source was essentially a single point, the source had to be moved to a number of positions along the vertical axis of the cylinder to more evenly distribute the radiation. The distance of the source from the cylinder remained constant, and for the third (and final) test corresponded to a maximum dose rate of ~135 kR/h adjacent to the source. The dose rate decreased rapidly with increasing distance from the source. On the basis of empirical measurements conducted just prior to the beginning of the final test, it was determined that the source would have to be rotated among nine positions along the cylinder to ensure a reasonably uniform exposure over the entire length of the circuitry. For this test, the average dose over the bulk of the circuitry was ~10.75 Mrads (as seen in Fig. 3), with variations not exceeding +0.65 and −0.3 Mrads. The total dose at each of the extreme ends of the circuitry was ~9.5 Mrads. These values do not include additional exposures that some portions of the system received from the earlier tests but rather are the minimum that the least-irradiated portions of the system received. The reduced doses at the extreme ends of the circuitry were inconsequential because the two end circuits were among those that were previously irradiated. The maximum dose for circuits that were included in all three tests was ~16 to 17 Mrads.

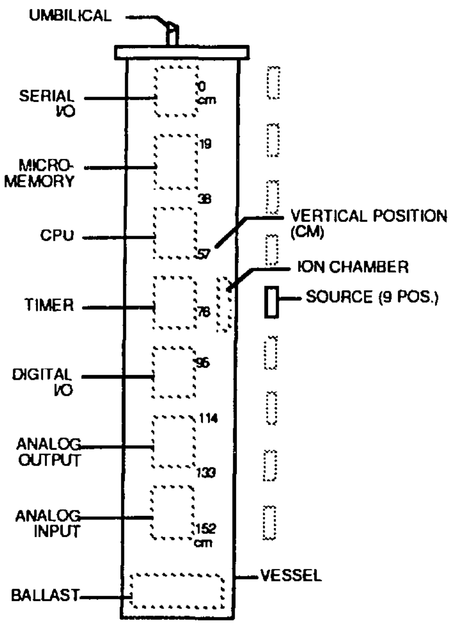

Fig. 2. Experimental setup

RESULTS

The results of the final test were quite encouraging. The junction-isolated components from which the prototype controller was constructed operated properly to doses well in excess of the 10-Mrad target and at their designed clock rates. There were no failures of any kind below the target dose of 10 Mrads; in fact, the only failures occurred in the analog input and output cards at dose levels well beyond the target dose. In these failures, one of the outputs of a programmable logic device occasionally ignored the inputs after receiving an accumulated dose of ~13–14 Mrads. The only other

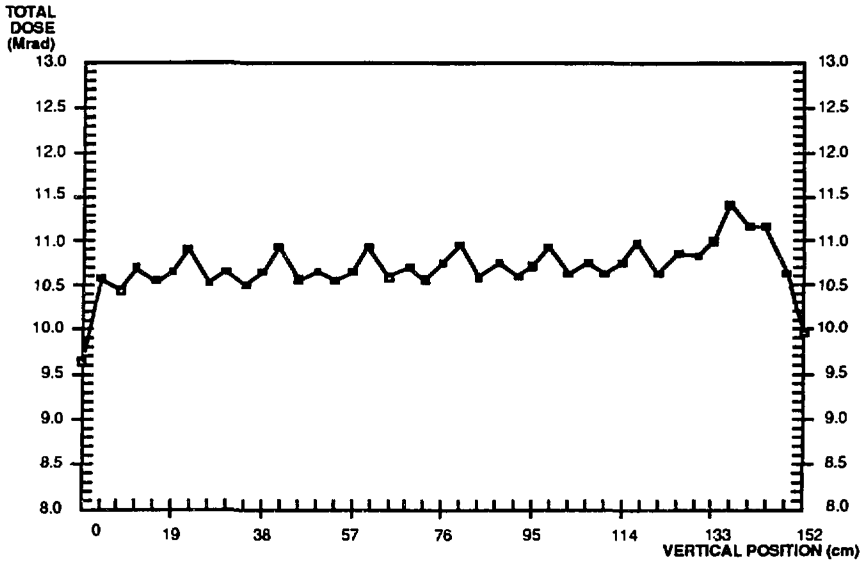

Fig. 3. Total accummulated dose for final operational test. Total dose averaged 10.75 Mrad for this test, with peak dose rate of 135KR/h.

anomaly in the system was an anticipated minor drift in the voltage reference for the analog cards. At the conclusion of the test, the analog input and output cards had accumulated a total dose >15 Mrads and, with the exception of the intermittent failure of some of the programmable logic devices, were still operating properly.

CONCLUSIONS

The results of this experiment indicate that it is possible to construct a radiation-hardened processor that can implement a useful degree of intelligence and computational power in a radioactive environment. The results of the radiation testing indicate that the most suitable TTL components from which a processor could be constructed are those fabricated with junction-isolated, as opposed to oxide-isolated, construction.

REFERENCE

E. J. KENNEDY and A. WU, "Electronics Irradiation Testing," *TR-EE/EL-19*, The University of Tennessee, Knoxville (1988).