THE ICE HOUSE

Neutron Testing Leads to More-Reliable Electronics

Bruce E. Takala

In 1992, scientist Steve Wender of the Los Alamos Neutron Science Center (LANSCE), working with a team from Boeing, Honeywell, and LSI Logic Inc., discovered that LANSCE's Target 4, the most-intense high-energy neutron source in the world, is an effective tool for testing the vulnerability of computer electronics to single-event upsets induced by cosmic-ray neutrons. That discovery was momentous. Today, companies are literally lining up for neutron beam time at the Irradiation of Chips and Electronics (ICE) House of LANSCE. The effects of neutron irradiation on electronics are not only real but also growing, as electronics become smaller and their vulnerability to neutrons becomes correspondingly higher. Putting electronic devices through their paces helps determine the limits of reliability.

Probably everyone has heard of cosmic rays, but not everyone is aware that cosmic rays affect everyday life. Indeed, secondary neutrons from cosmic-ray showers naturally present in the atmosphere can interact with the memory and logic in electronic systems and cause them to malfunction. Just imagine noticing that the million-dollar digit in your bank account has changed, especially if it has done so in the wrong direction, or traveling in a car or airplane in which the safety system has suddenly failed. Although designers and users of semiconductor electronics have taken steps to avoid potentially catastrophic events, the cause of such events is constantly present and is of increasing concern.

When cosmic rays collide with nuclei in the upper atmosphere, they create a shower of subatomic particles. By the time the cosmic-ray shower reaches aircraft altitudes and below, the uncharged neutrons present are the dominant source of errors in electronics. These neutrons pose little health hazard because the radiation dose is relatively low, but each neutron can interact with silicon and other elements in integrated circuits to deposit charge in localized regions, with potentially disastrous impact on memory and chip function. Such disruptions, potentially caused by a single neutron, are collectively known as single-event upsets (SEUs), and their rate is the largest single contributor to the soft-error rate of modern electronic integrated circuits. (For further information on how SEUs are created, refer to the box "The Origins of SEUs" at right.) Hardware is said to experience soft errors if it malfunctions temporarily and hard errors if it is damaged permanently.

What are the effects that can be so disastrous to electronics? The simplest SEU occurs when a memory or logic location changes its state because of charge deposited by an energetic

The Origins of SEUs

High-energy cosmic rays impacting the upper atmosphere generate a cascade of secondary particles that reach lower altitudes. In general, these high-energy particles are very penetrating and do not stop in exposed electronic devices. Since the energy deposited in the host device is small, the excess charge (electron-hole pairs) generated by electronic ionization is insufficient to cause soft errors. Even though the probability of a collision is very small, these secondary particles can collide with a silicon nucleus in the semiconductor device. When neutrons collide with a silicon nucleus, many different nuclear reactions can occur. Scattering reactions, elastic and inelastic, leave the silicon nucleus intact, but they cause it to recoil. The recoiling nucleus leaves an intense local ionization trail (see reaction 1). In high-energy cases, the collision may lead to a series of direct reactions (intranuclear cascade), whereby individual nucleons (protons or neutrons) or small groups of nucleons (say, an alpha particle, ${}^{4}He_2$—see reaction 2) are ejected from the silicon nucleus or the silicon nucleus may fragment. As the available energy becomes less, a compound nucleus (a neutron may be captured by a nucleus) may be formed that will "boil off" nucleons to reach stability. When the total number of ionization electron-hole pairs collected in a sensitive region of the device exceeds a critical value (which is a characteristic of the device), an SEU is born.

$$n + \mathrm{Si} \rightarrow \mathrm{Si} + n' + \text{ionization trail} \quad (1)$$

$$n + {}^{28}\mathrm{Si} \rightarrow {}^{4}\mathrm{He}_2 + {}^{25}\mathrm{Mg}_{12} \quad (2)$$

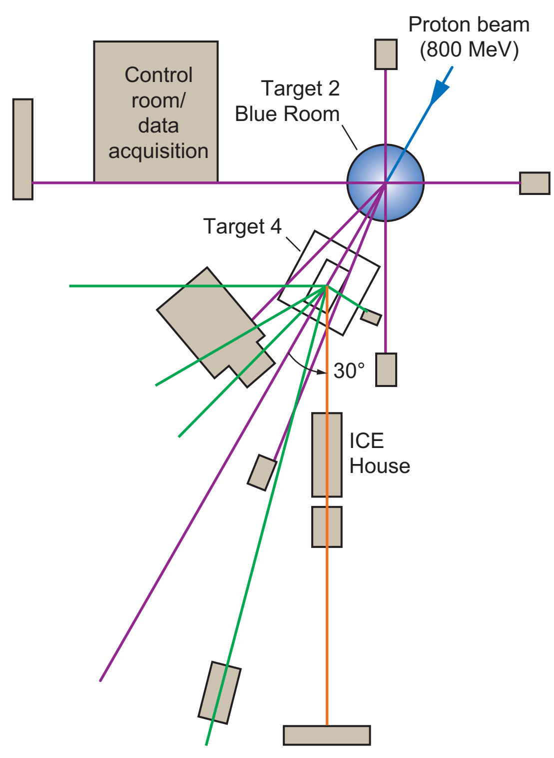

Figure 1. The Beam Lines at the WNR Facility

particle. Sometimes more than one memory location can be affected by a single particle. Latchup is another frequently encountered, although much more serious, soft error, whereby an electrical current arises in an unintended area. The device stops functioning until it is turned off and then on again. Finally, hard errors can permanently damage or even destroy devices by causing them to draw large currents.

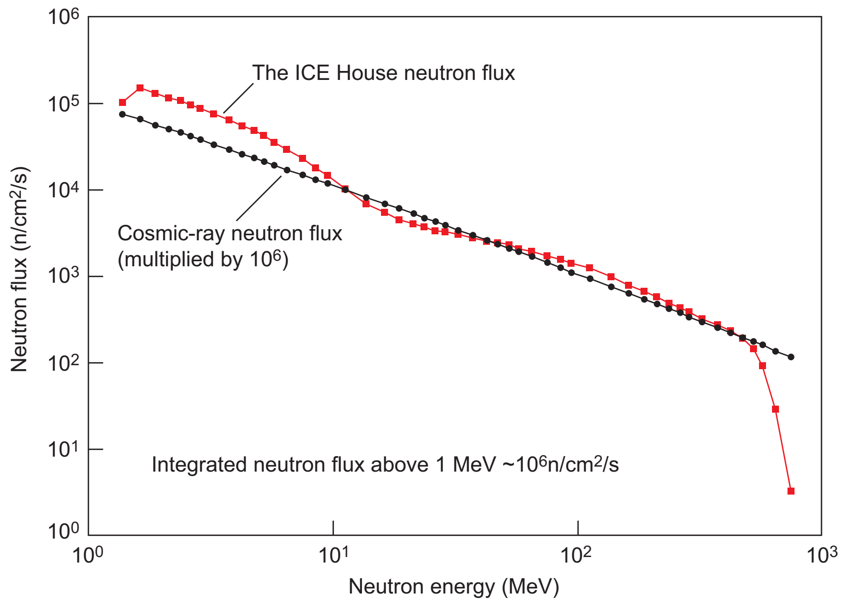

Figure 2. ICE House vs Cosmic-Ray Neutron Spectrum
This plot of neutron intensity vs energy illustrates the high degree of similarity between the ICE House neutron spectrum and the natural atmospheric neutron spectrum from cosmic rays. Significant differences show up only at energies close to 800 MeV.

History

Following up on what was mostly anecdotal information, Ziegler and Lanford (1979) showed that the products of cosmic rays striking the atmosphere were causing upsets in computer memory. Even though the authors considered those effects only marginally significant, they were quite prophetic in asserting that their observation would be important for future electronic circuits. By 1993, Taber and Normand concluded "that a significant SEU phenomenon exists at airplane altitudes, that it is most likely due to energetic neutrons created by cosmic ray interactions within the atmosphere (NSEU), and that memory error-correction coding is likely to be necessary for most high density avionics memory systems" (1993).

As the SEU phenomenon was increasingly recognized as a problem, a method for rapidly testing device susceptibility to neutron-induced errors was needed. In 1992, scientist Steve Wender of LANSCE, working together with a team from Boeing, Honeywell, and LSI Logic Inc., designed an experiment to demonstrate that neutrons generated at the Weapons Neutron Research (WNR) Facility (Figure 1) could be used as an effective SEU testing tool. The team had recognized that the spectrum of neutrons delivered on one of the beam lines from Target 4, the most-intense high-energy neutron source in the world, was quite similar to the neutron spectrum in the atmosphere. The first experiments consisted of small boxes taped to the end of an outdoor beam pipe. Despite the makeshift design, the experiment was highly successful in establishing the proof of principle. None of the participants could have imagined that this simple experiment would eventually result in the busiest beam line at the facility and so many publications at the forefront of the field.

Creating a Neutron Beam Line for Testing Chips and Electronics

The heart of LANSCE is the 800-million-electron-volt (MeV) half-mile-long linear accelerator producing a pulsed proton beam. Neutrons are produced at LANSCE by directing the pulses of the proton beam at high-*Z* neutron-rich targets. The impact of each pulse of protons causes a short burst of neutrons with a wide range of energies (up to 800 MeV) to be released from nuclei in the target and to travel down beam lines. The WNR Facility, first conceived in the early 1970s, is made up of two target areas, Target 2 and Target 4. Target 4 consists of a "bare" tungsten neutron-production target and six instrumented beam lines with detector stations ranging from 10 to 90 meters from the target and at angles of 15° to 90° with respect to the incoming proton beam. The neutron spectrum ranges from a hard (high-energy) spectrum at 15° to a softer (low-energy) spectrum at 90°.

The New Facility

The ICE House (ICE is short for Irradiation of Chips and Electronics)

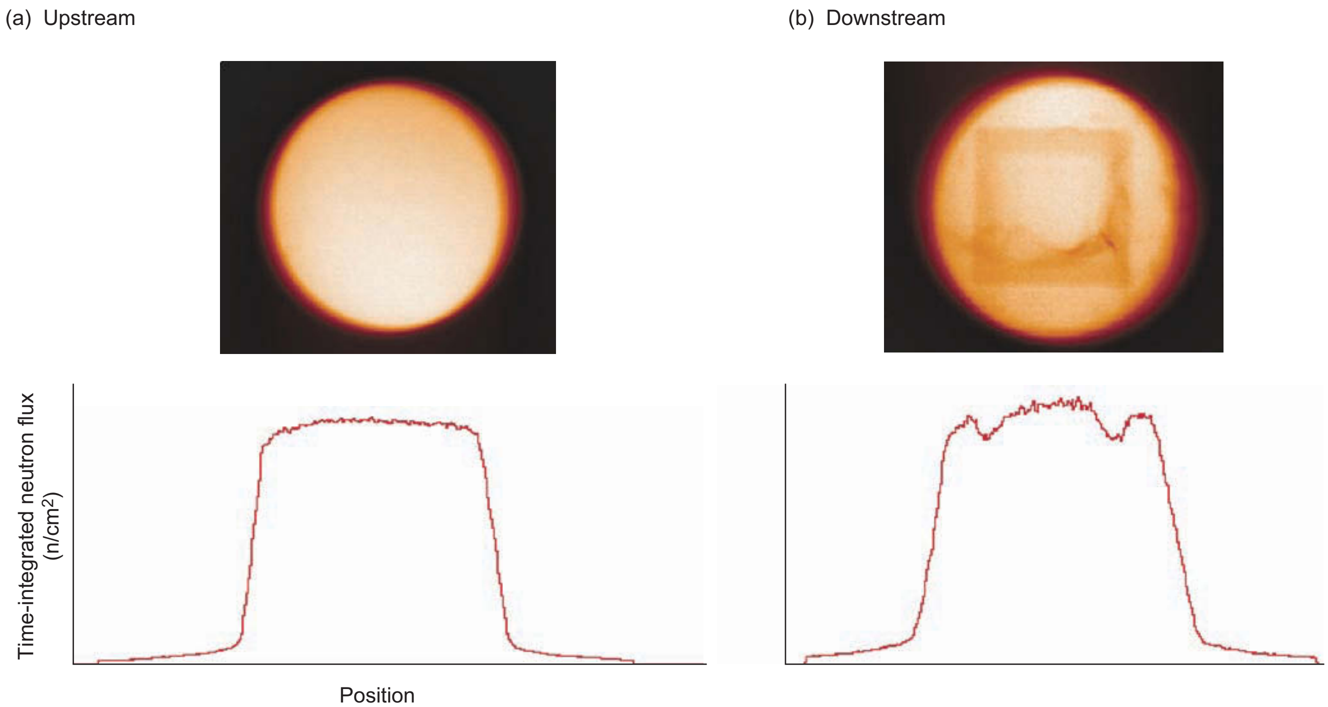

Figure 3. Neutron Radiographs of the ICE House Beam
Image plates of the ICE House neutron beam in (a) and (b) show uniform brightness and sharp edges. Note that the image downstream of the device is a neutron radiograph of the device. The radiographs measure neutron fluence (time-integrated neutron flux). The matching plots show line scans of the radiographs along the horizontal axis, which correspond to a cross section of the beam before and after the beam passes through the device.

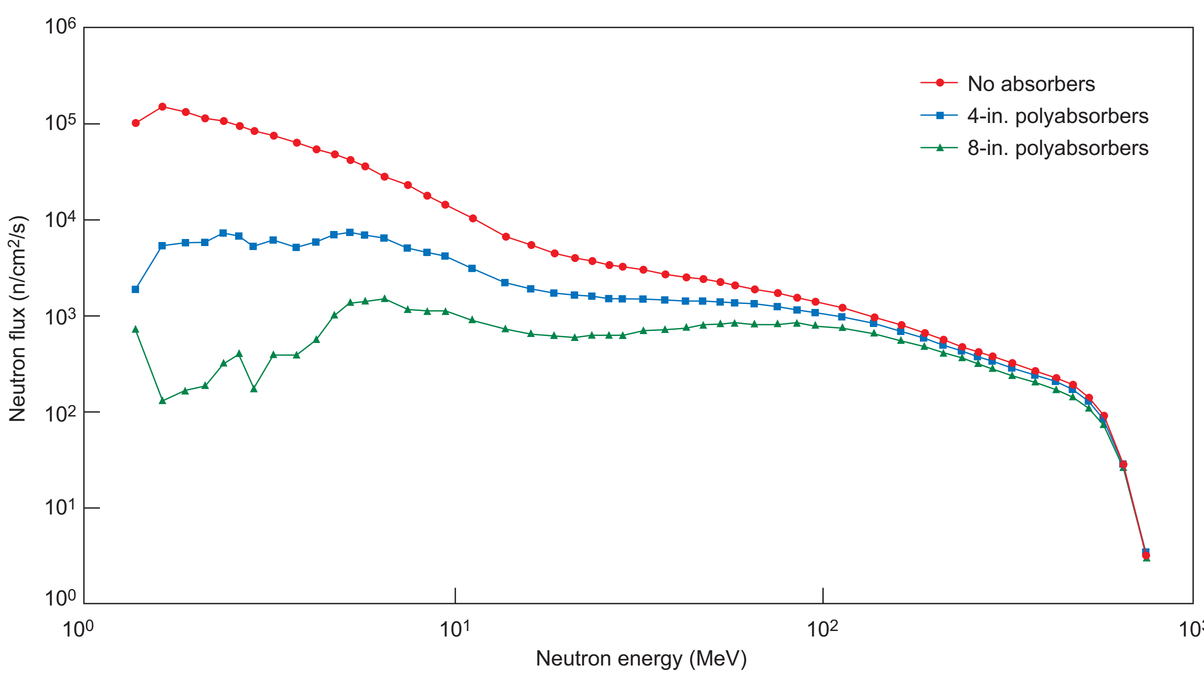

Figure 4. Altering the Neutron Spectrum
As polyethylene is added to the beam, low-energy neutrons are removed, leaving a beam with higher average neutron energy.

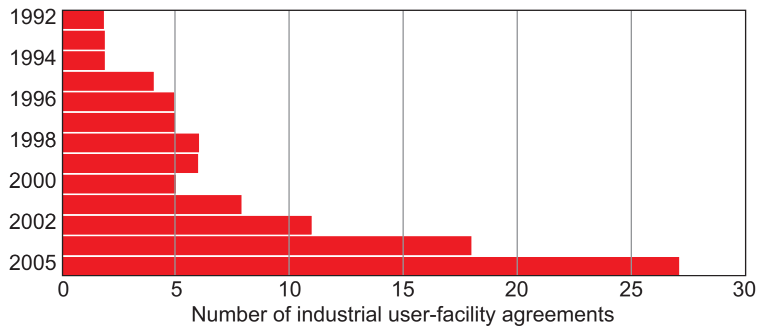

Figure 5. Use of the ICE House by Industry
A remarkable increase in user facility agreements is apparent between 2001 and 2005. (Note that 2004 is not included in this graph because of a Laboratory-wide shutdown.)

Figure 6. International Collaborators at the ICE House
Art Bridge and Bruce Takala (wearing hats) of LANSCE are pictured here with a large team of European and United States collaborators from STMicroelectronics, Commissariat à l'Energie Atomique, Hirex, Motorola, and Trinity Convergence.

is located on the 30° left beam line of the high-energy neutron source at the WNR (Figure 1). At this angle, the neutron spectrum is very similar to the spectrum of neutrons produced in the atmosphere by cosmic rays (Taber and Normand 1993), but the neutron flux at 30° is a million times higher (Figure 2) than the flux of neutrons produced by cosmic rays, depending on altitude. This large neutron flux allows testing of semiconductor devices at greatly accelerated rates, in which one hour of exposure is equivalent to more than 100 years of exposure at aircraft altitudes. By starting a timer when the proton pulse hits the target and measuring the time the neutrons take to travel the length of the beam line, the number and energy of the neutrons are measured.

No other facility in the world can offer this intensity with a spectrum whose shape matches that of the natural atmospheric spectrum so closely. Because this flux is composed of approximately 35,000 individual neutron pulses caused by the time structure of the accelerator proton beam, the results are still representative of atmospheric results because the probability of multiple neutron events is exceedingly low for individual pulses. The capability of the facility has been succinctly recognized by the Joint Electron Device Engineering Council (JEDEC), representing about 300 manufacturers and users of electronics. Its published memory-testing standard JESD89 mentions that "The WNR at Los Alamos is the preferred facility" for accelerated neutron-induced SEU testing.

Advantages. The ICE House approach to testing has several advantages over other testing methods. Unlike heavy-ion tests, during which a device must often have its case material removed and be placed in vacuum to permit particles to reach the sensitive regions of the chip, testing in the ICE House beam permits normal operation of the device in the open air. In fact, because neutrons are not strongly absorbed by the device tested, several devices may be placed in the neutron beam at once, one behind the other. At the experimenters' request, the diameter of the beam spot can also be changed by collimation. As the device under test is moved down the flight path, the beam spot on the device becomes correspondingly wider in diameter. One can choose almost any diameter for the beam spot within the range of 1 to 6 inches. In Figures 3a and 3b, images of neutron beam intensity taken at the ICE House before and after the beam hits the object tested show uniform brightness and sharp edges. The matching plots show line scans of the radiographs along the horizontal axis, which correspond to a cross section of the beam. The plot in Figure 3b clearly indicates that the device has scattered neutrons out of the beam.

In addition, the neutron spectrum can be altered if absorbing material is placed in the beam to reduce the low-energy intensity relative to the high-energy part. Figure 4 shows what happens to the shape of the neutron spectrum when different amounts of polyethylene are added into the neutron beam. By using this method,

Industrial Customers of the ICE House

ABB, Switzerland
Advanced Micro Devices, AMD, U.S.A.
AeroSpeciale, France
AerotechTelub, Sweden
Agere Systems, U.S.A.
Alpha Sciences, U.S.A.
Altera, U.S.A.
BAE, U.K.
Boeing, U.S.A.
Digital Equipment Corporation, U.S.A.
Dynex Technologies, U.K.
Eupec, Germany
Extreme Networks, U.S.A.
Fujitsu, Japan
Hewlett-Packard, U.S.A.
Hirex, U.S.A.
Hitachi, Japan
Honeywell, U.S.A.
Infineon Technologies AG, Germany
Intel Corp., U.S.A.
iRoc Technologies, France
Lockheed Martin, U.S.A.
LSI Logic, U.S.A.
Lucent Technologies, U.S.A.
MBDA Missile Systems, U.S.A.
Micron Technology, Inc. U.S.A.
Motorola, U.S.A.
NEC Electronics, Japan
Qinetiq Ltd., U.K.
Rockwell Collins, U.S.A.
Saab, Sweden
Samsung, Korea
Smiths Aerospace, U.S.A.
Sony Corporation, Japan
STMicroelectronics, Italy and France
Sun Microsystems, Inc., U.S.A.
Texas Instruments, U.S.A.
Trinity Convergence Limited, U.K.
Xilinx, U.S.A.

experimenters determine the relative contributions of higher- vs lower-energy neutrons to the error rate.

The Testers or Who's Who in Electronics

Customers who have brought electronic devices to LANSCE's ICE House make up a who's who of the global electronic and avionics industries. Testers represent the full spectrum of product manufacturers: from chip producers and board level integrators to consumer product companies. Circuit manufacturers understand the risk posed by cosmic-ray neutrons and try to design around it, so testing at the ICE House is increasingly becoming an international standard for putting new circuits through their paces. Figure 5 illustrates the sharp growth in the number of user facility agreements between 2001 and 2005. Eight experiments were conducted in 2001, twenty-one in 2002, twenty-eight in 2003, and the numbers of both proposals and industrial participants are continuing to increase at record levels in 2005. The year 2004 is not listed because a Laboratory-wide standdown delayed the start of the 2004 run cycle until 2005.

A large increase in the number of multicompany collaborations sharing beam time is also notable. Figure 6 is a picture of one of the recent large teams from Europe and the United States. Demand for the test bed has grown so much that we had to come up with a waiting list for beam time. The box "Industrial Customers of the ICE House" on the opposite page lists many of the companies that have so far tested electronic components at LANSCE. A strong international presence is evident. Clearly, the ICE House has developed into a valuable resource for the worldwide electronics community.

The Good News for Consumers and Industry

As more and more companies are testing at the ICE House, the good news for consumers is that their electronic systems end up being more reliable and more secure. Companies come to the ICE House because they must answer a very difficult question: How good is good enough? In general, a typical static-random-access-memory chip (referred to as an SRAM chip in the industry) will generate roughly 1200 soft errors per hour when subjected to the intense neutron flux at the ICE House, which can be as high as a million neutrons per square centimeter per second. For the devices they test, companies hold as proprietary information the exact number of errors per unit of testing time. The Laboratory supplies them with information on the number of neutrons per square centimeter that went through the device during the test. When they are done testing at Los Alamos, companies have data showing the number of errors per neutron. With this information and knowing the neutron flux in the environment in which the system will operate, they can predict the soft-error rate of the system in the field (an example of testing results is discussed in the accompanying article "Testing a Flight Control System for Neutron-Induced Disturbances" on page 104). Once they know the expected error rate from neutrons, chipmakers can decide if error correction, redundancy, or other protective measures are needed to compensate for the neutron-induced errors. This approach ensures that any unreliability at the device level is compensated for at the system level.

Failure to test has been a costly mistake for some companies. One instance involved a Honeywell component that was failing in the field, but the problem could not be duplicated in the lab. After several failed attempts to diagnose the problem, Honeywell experimenters made an urgent request for ICE House beam time. Their subsequent run in the beam confirmed the problem as a latchup vulnerability of one chip that had been designed with a new type of memory cell. Not only did it cost Honeywell millions of dollars to recall the devices and replace the chip, the company also had to redesign several items that were nearing production. Honeywell has been back to test every year since. According to the company, "The results of these series of experiments will, in large part, drive Honeywell's future memory architectures and fault-protection methodologies for the next generation of [a new product] now in development."

The Future

New issues continue to emerge from recent experiments. Neutron-induced effects on field-programmable gate arrays (FPGAs), one of the cutting-edge developments in microelectronics, are being widely studied. The relationship between failure rates and feature size is hotly debated. Indeed, there are those who believe that the smaller the electronic components, the higher the error rate and that keeping the error rate at tolerable levels could be the ultimate constraint on the size of electronic parts. Wide variations in latchup susceptibility have been observed. Variations depending on orientation (which side of the component is facing the beam), socket type (the type of mounting on the circuit board), and even circuit layout have been demonstrated. "No one's been able to make this problem go away for key electronic applications; in fact, even the codes people use to predict failure rates are becoming less accurate," Wender said. "But if somebody eventually comes up with a possible solution, the new design will have to be brought here and tested out." Neutron-induced SEUs remain a significant threat to semiconductor electronics. Through the new ICE House Facility, LANSCE is uniquely positioned to address this problem for the electronics industry, the nation, and the world.

Further Reading

Baumann, R. C. Accelerator Needs for Characterization of Radiation Effects in Commercial Semiconductor Technologies. To appear in *Proceedings of the 18th International Conference on the Application of Accelerators in Research and Industry*. (Ft. Worth, TX, October 10–15, 2004).

Taber, A., and E. Normand. 1993. Single Event Upset in Avionics. *IEEE Trans. Nucl. Sci.* **40** (2): 120.

Ziegler, J. F., and W. A. Lanford. 1979. Effect of Cosmic Rays on Computer Memories. *Science* **206** (4420): 776.