# CLOSED-LOOP NEUTRON PARTICLE EFFECTS TESTING ON A RECOVERABLE FLIGHT CONTROL COMPUTER

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## Abstract

This paper describes a Single Event Upset (SEU) experiment performed at the Los Alamos National Laboratory. A closed-loop control system consisting of a Recoverable Flight Control Computer (FCC) and a Boeing 737 simulator was operated while the FCC was exposed to a neutron beam. The purpose of this test was to analyze the effects of neutron bombardment on avionics control systems operating at altitudes where the occurrence of neutron effects is 100 or more times more probable than at sea level. The neutron energy spectrum produced at the Los Alamos National Laboratory is similar in shape to the spectrum of atmospheric neutrons but much more (at flight altitudes up to a million times more) intense. The higher intensity results in accelerated life tests that are representative of the actual neutron radiation that a FCC may receive over a period of years.

## Introduction

Most testing of avionics electronics is done at the chip level where bits are of interest. The results presented in this paper are novel in that the FCC is tested as a system and the phenomena of interest are the effects of SEUs on the 737 flight. The FCC used here is that used in a Recoverable Computer System (RCS). Along with the FCC, the RCS included additional computers which provide the simulated 737 airplane around which the FCC closed the loop. The RCS implemented an automatic landing function (during ILS beam tracking) with a single FCC (single thread) system. The FCC incorporates a rollback recovery scheme and is comprised of modern digital avionics technology [1]. There is considerable interest in observing whether the fault tolerant features of the RCS FCC provide closed-loop robustness in the presence of neutron radiation. This paper is the first of several presenting the results of experiments at Los Alamos. Presented is an overview of the experimental data and closed loop system effects of the rollback recovery scheme. Results concerning the occurrence of neutron effects on the RCS are presented as well as the experimental setup and procedure. Additionally, single event effects are identified and classified according to system effects. The results described in this paper provide a base for considering particle effects on avionics systems and will be further developed in subsequent papers to classify possible effects on flight critical and other avionics systems. For flight controls the papers to follow will describe stability analysis, closed loop perturbations due to SEUs, modeling and simulation results based on data described in this paper, and present probability estimates for particle effects on performance of systems for commercial flights.

The objectives of this research are to: (1) investigate the effects of SEU on closed-loop systems, (2) develop SEU closed-loop system test methods and capability, (3) develop design and analysis methods to mitigate and assess SEU closed-loop system effects, and (4) investigate the applicability of recoverable computing techniques to mitigating SEU effects. The expected benefit of this research will be the development of design and validation guidelines for the achievement of aircraft system performance in the atmospheric neutron environment that provides the degree of safety needed. Particular focus is on aircraft functions critical to safe flight.

The remainder of this paper is organized as follows. In the next section background information concerning upset testing is given along with information about the RCS. This section is followed by information about past SEU experiments and the neutron environment. Next, the experimental set up is described followed by an overview and preliminary analysis of the experimental data.

Finally, the conclusion section summarizes the main results and proposes future research.

## Background

The NASA Langley Research Center (LaRC) has been characterizing atmospheric environmental threats, such as lightning and High-Intensity Radiated Fields (HIRF), and investigating their affect on flight critical systems for many years [2-8]. *These investigations have been conducted* independently and in collaboration with the FAA. The first SEU experiment was conducted in December 2002 and used a Quad-Redundant FCC representing 80's digital technology [9]. In this past experiment, the older electronics had large operating voltages and geometries that offered immunity to neutron effects. More recently, another generation of FCC has been tested for SEU's.

NASA Langley, in collaboration with Honeywell International Inc., developed and assessed a recoverable computer architecture for mitigating soft faults caused by transient disturbances [1, 10]. This computer used a new approach to achieve fault tolerance called "rapid recovery". Using the dual-lock-step processing architecture developed for the Aircraft Information Management System on the Boeing 777, a prototype computer incorporating "rapid" recovery was developed. The dual-lock-step computing platform has hardware monitoring active on every CPU clock cycle. All computing resources are lock-step compared on a processor cycle-by-cycle basis. All feasible soft or hard faults in the hardware are detected. In this approach, if a soft or hard fault event occurs, the processing (FCC) platform is immediately trapped to service handlers. The FCC has two copies of processor fundamental "state data" in the self-checking pair. Unlike "traditional" systems where the single thread processor may be so defective it cannot record any data, the hardware (hardware monitors that are independent from the CPU) and software checking of the FCC self-checking pair should be successful. Thus, the process of diagnosing hardware errors involves comparing each half of the pair. If the self-checking pair miscompare (one-half of the pair is faulted or both-halves are faulted but not identically), the hardware and software checking associated with fault detection and response can easily isolate errors down to processor address, control, or data bits. Dual-lock-step computing was an enabling technology for the implementation of a rapid recovery approach that involves a rollback to "state data" stored during a previous processing cycle. On the surface, the monitoring associated with dual-lock-step computing would appear to be a more sensitive approach than conventional fault tolerance monitoring methods. However, the rapid automatic recovery approach provides the computing platform with a compensating recovery element that result in robust operation even in "harsh" environments.

In 1997 this computing platform (referred to as a rapid recoverable computer) was delivered to NASA LaRC as the FCC in the RCS. Results of experiments performed on the RCS in the HIRF facility showed that any electromagnetic energy induced loss of computing could be recovered rapidly enough that, essentially, there was no substantive effect [1]. The interest in HIRF threats has recently extended to ionizing radiation such as neutron particles.

### *SEU Background*

Single Event Upset phenomena have been documented since 1979 [11]. In 1992, it was established that atmospheric neutrons are the cause of SEUs in avionics [12]. This was confirmed by further studies in 1996 [13]. A survey of SEU phenomena and research was developed by a NAVAIR Avionics Working Group in 2000 [14]. The issue of atmospheric induced SEU is particularly vexing for electronic systems for commercial aviation. Such systems are based upon the application of commercial off the shelf electronic devices. These types of devices are designed for the large consumer (personal computers, cell phones, etc) market where, currently, there is no qualification requirement for operation in a radiation environment. Many SEU studies that have been performed to date have focused on the effects on integrated circuits. However, it is known [14, 9] that SEU phenomena can affect and have affected operation of the overall aircraft electronic system. It is believed that the analytical methods developed by Old Dominion University researchers and the analysis techniques developed for HIRF effects can be extended to include SEU phenomena.

A research partnership was established in 2002 to study the effects of neutrons on flight critical systems for commercial aviation. Participants in this research partnership are the NASA Langley Research Center, the Federal Aviation Administration (FAA), the Los Alamos Neutron Science Center (LANSCE), Honeywell International Inc., and Old Dominion University. The Los Alamos Neutron Science Center at the Los Alamos National Laboratory contains a neutron source that can produce a neutron spectrum similar to the neutron spectrum produced by cosmic rays in the atmosphere. Since 1992, dozens of companies, including Honeywell International Inc., have established facility user agreements to determine failure rates of electronic components in the neutron environment. However, the approach presented in this paper is at a systems level.

Since it is not economically feasible to shield or harden commercial aircraft avionics from neutron induced SEU, mitigation strategies that include a combination of recovery and redundancy could potentially provide a cost effective approach to achieve required performance reliability in the neutron environment. It should be noted that other mitigation strategies would have to be applied for Single Event Latch-up (SEL) or other neutron induced effects resulting in electronic device damage. At the system level, failure (Mean-Time-Between-Unscheduled Removal/ Mean-Time-Between-Failure: MTBUR/MTBF) rates of system elements at the Line-Replaceable-Unit/Line-Replaceable-Module are the key metrics of interest and not SEU, SEL, etc rates of electronic devices. In the FAA regulated market, system level failure rates would be in the sense of the Code of Federal Regulations: XX.1309 (Parts 23, 25, etc) and accompanying Advisory Circulars: XX.1309. Of course, the device rates can roll up to MTBUR/MTBF rates.

The process being developed for determining the effects of neutron particles on flight critical control systems is a combination of analysis, simulation, and tests. This process will address the following issues: (i) closed-loop operation of the controller under test, (ii) stability of the closed-loop system with controller malfunctions caused by neutron particle effects, and (iii) single event effects on aircraft performance relative to the stage of flight and flight conditions. The experiments described in this paper were performed in the Irradiation of Chips and Electronics (ICE) House at LANSCE. The ICE House is located on the 30° left flight path of the high-energy neutron source at the Weapons Neutron Research Facility, and is shown in Figure 1.

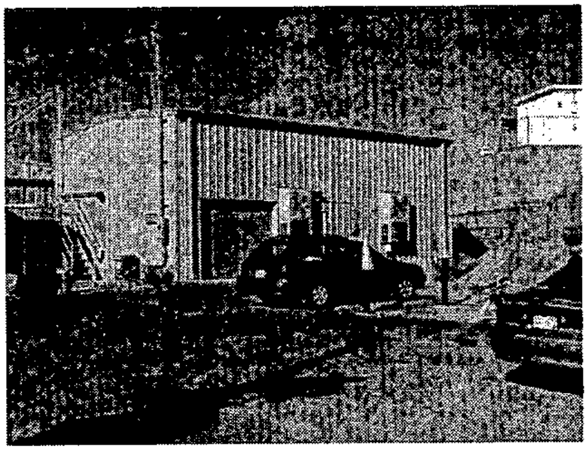

**Figure 1. LANCE ICE House**

### *Neutron Environment*

Using a relatively intense neutron beam to irradiate the FCC in a single thread flight control system, the objective of this test was to determine the system level effects during accelerated neutron exposure of the FCC. Figure 2 shows that the energy spectrum of the neutron source is similar to a normalized energy spectrum of atmospheric neutrons at 34,000 ft and 45° latitude. A model of the flux for the atmospheric neutron normalized energy spectrum is given in [15]. This model asserts that the flux of significance for neutron induced effects is in the 1-10 MeV range. The model was calibrated so that the integrated flux in the 1-10 MeV range was 0.56 n/cm$^2$-sec. If flying at the desired altitude and latitude (34,000 ft and 45° latitude used in the experiment), this is the value that would correspond to that needed for experimental data interpretation. To superimpose the atmospheric model and ICE House experimental fluxes, the atmospheric flux model was multiplied by $2.62\times10^5$. This number is the ratio of the integrated flux from 1.25 MeV to 800 MeV of the experiment to the atmospheric model flux. Thus, a 25 minute run in the neutron beam corresponds to $1.09\times10^5$ equivalent flight hours at 34,000 ft.

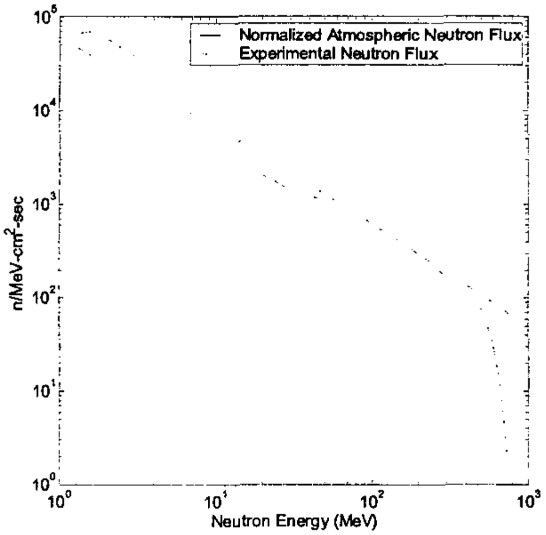

**Figure 2. Energy Spectrum**

## Experimental Setup

The flight control computer in this setup runs a control program which processes outputs from a Boeing 737 flight simulation system running on a separate host computer. The simulation consists of an aerodynamics model of the 737 airframe and actuators. The equations of motion are integrated in both the aircraft frame of reference and an earth-fixed frame of reference to locate the aircraft. Wind gusts are simulated using the Dryden gust model. The flight control computer executes control laws that generate the appropriate control signals to maintain straight and level flight at a cruising altitude of 34,000 feet. The wind gusts and control inputs act on the airframe plant dynamics model. The 737 emulation is based on Sperry Corporation's Advanced Transport Operating System (ATOPS) 737 FORTRAN code that was converted to C. This code was run in a VME Power PC platform with the VxWorks operating system.

The interconnection between the flight control computer and the flight simulation host computer constitutes a closed-loop feedback control system, which is the unique feature of these experiments. The flight control system is single thread (no redundant elements in the system architecture).

The data acquisition system is maintained on a third computer system. It collects the flight data from the aircraft emulation computer, the FCC, and measurements from the flux sensor for off-line analysis. The flux sensor is a fission ionization detector that produces pulses [16] that are proportional to the neutron flux. Should the aircraft deviate from the nominal flight path at any time; it is possible to determine the total number of neutrons that reached the FCC per unit area during the last and previous computation frames.

In this experiment, the Recoverable FCC (representing 1990's digital computer technology; with corresponding feature sizes of circuit cells within electronic device) was subjected to the neutron beam, see Figure 3. During the exposure, the RCS was executing 737 aileron and elevator control laws and was interfaced to the 737 simulation with the option of applying 1 ft/sec wind gusts. Real-time monitoring of the control commands was executed during exposure. Data was collected for each 50 ms calculation frame.

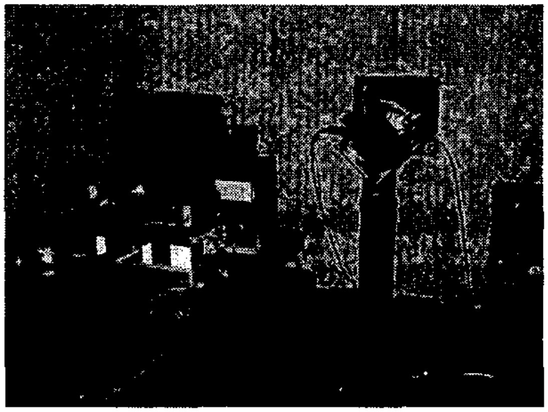

**Figure 3. Recoverable FCC Aligned in Beam**

The Recoverable FCC is a prototype computer based on the Airplane Information Management System (AIMS) technology which is used in the 777 to handle several avionic tasks such as flight management, displays, airplane condition monitoring, thrust management, digital flight data, and engine data interface. AIMS uses a reliable fault-tolerant architecture based on dual lock-step processors with high speed comparison. To execute multiple tasks in a single fault-tolerant computing unit, Application-Specific Integrated Circuits (ASICs) with robust software partitioning were implemented. Most of theses ASICs have been previously neutron tested at the chip level therefore providing background data for the susceptibility analysis of the FCC. The Recoverable FCC adds automatic rapid correction of soft faults to the AIMS architecture. The correction is done using rollback recovery. The information management system software was replaced with basic 737 aileron and elevator control algorithms. For closed-loop testing in the high intensity radiated fields chambers at NASA Langley Research Center, the AIMS ARINC 629 I/O board was replaced with an optical ARINC 429 interface. For the test in Los Alamos, the power supply Circuit Card Assembly (CCA) was replaced with four external current-limited power supplies. These power supplies were connected to the RCS via a 20ft cable and a printed wiring board. The purpose of the current-limited power supplies was to avoid damage to components that might latch-up during the experiment. If current exceeds the limiting threshold, the power supplies would shut down before component damage occurred in the Recoverable FCC.

By visually examining the CCAs in the FCC, several targeting objectives were determined based on chip set locations. To align with these targeting objectives, five beam alignment positions on the Recoverable FCC were determined as follows:

1 T1 – Maximize beam exposure to the RAMs on the Scratchpad Data Memory CCA and miss all the large chips on the Processor CCA. (2 inch neutron beam diameter)
2 T2 – Maximize beam exposure to one CPU on the Processor CCA but miss the LSI chips on the Instruction Memory. (2 inch beam)
3 T3 – Maximize beam exposure to the flash on the Instruction Memory but miss the LSI on the Processor CCA. (2 inch beam)
4 T4 – Expose a single CPU on the Processor CCA, as much flash as possible on the Instruction Memory, and as many RAMs as possible on the Scratchpad Data Memory CCA, but miss the protected rollback area. (2 inch beam)
5 T5 – Use the same objectives as T4 but widen the beam to hit the protected rollback area. (3 inch beam)
6 T2p – Same as T2 but target the alternate processor on the Processor CCA. (2 inch beam)
7 T4p – Same as T4 but use a 3 inch beam.
8 T2pp – Same as T2 but use a 3 inch beam.
9 T2D1 – Center beam on the first processor. (1 inch beam)
10 T6 – Target the processor and miss all other chips on the Processor CCA. (1 inch beam)
11 T6p – Target the LSI chip next to the processor and miss the processor on the Processor CCA. (1 inch beam)

Approximately 100 baseline runs were performed prior to neutron exposure and between exposure runs. Approximately 100 exposure runs were completed. These runs were logged together, forming a data based of 200 runs. For each target there were recoverable fault events. For most targets there were also unrecoverable faults. Overall, the number of recoverable faults was significantly greater than that for unrecoverable faults.

## Data and Results

From the neutron-exposed runs, experimental results are presented for two selected runs. The first is run number 151 that had many recoveries, and the second is run 114 which had the recovery mechanism turned off. A full run consist of 72,000 data frames containing a variety of performance parameters for the control system. A full run takes 60 minutes. Shown in Figure 4 are plots of some important signals. In the upper left is the Fault Count. This signal is a cumulative count of the rollback recoveries verses the frame number. As can be seen, there were 31 recoveries before the RCS stopped. The plot in the center left is of the recovery delay in green and the number of labels received in blue. These signals were used to check RCS/host communication. At the bottom left is a plot of the voltage supply output powering the RCS. This was monitored for anomalies during the experiment. At the upper right is the cumulative beam count in blue that gives a measure of the neutron exposure during the run. Also shown on this same plot is the altitude. As can be seen from the green line, the airplane remained at 34,000 feet until the RCS stopped. The plots in the center right are the pitch (blue) and roll (green) in degrees. For this run the wind gusts were set to 1 ft/sec, which accounts for the non-zero values. When the RCS stopped, the plane went out of control as can be seen. Finally, the bottom right plot is of the elevator (blue) and aileron (green) control commands produced by the RCS. Due to winds, these control surfaces stayed active during the test until the RCS stopped.

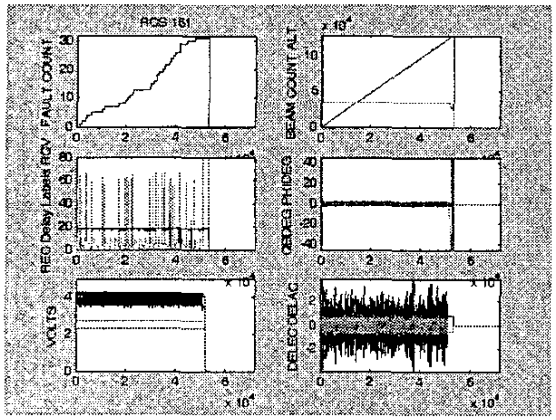

Figure 4. Plots for Run 151

A closer look at the elevator and aileron control signals is warranted. Since the value of these commands during a recovery is of interest, a close-up plot where a recovery occurs is shown in Figure 5 for the elevator and Figure 6 for the aileron.

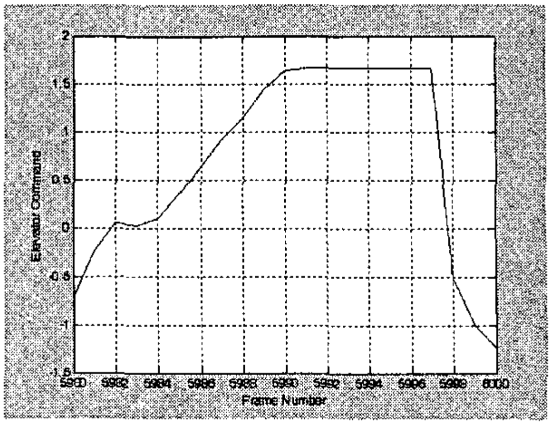

**Figure 5. Close-Up of Elevator Command during a Recovery, Run 151**

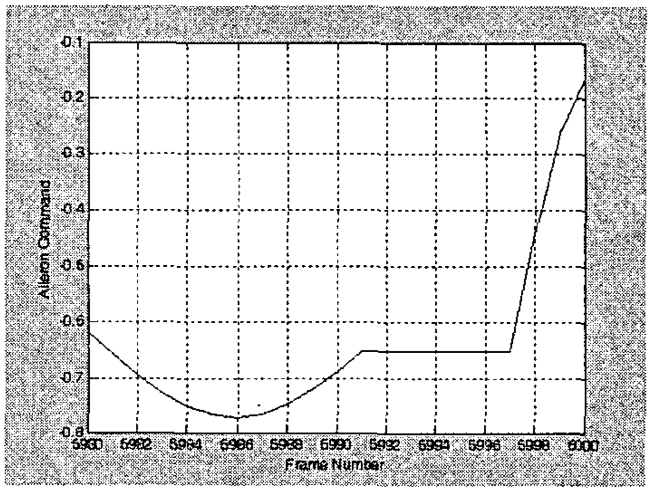

**Figure 6. Close-Up of Aileron Command during a Recovery, Run 151**

As can be seen from Figures 5 and 6, the RCS holds the commands constant for seven frames, which results from a miss-compare between the two microprocessors. This constant value may be seen starting at frame 5991 and ending at frame 5997. An examination of the aircraft flight dynamics shows no noticeable deviation as a result of the rollback. This seems to be the case for all runs examined thus far, showing that the rollback recovery introduces no noticeable perturbations in the flight dynamics while compensating for the neutron induced error in the control command calculations.

It is of interest to examine the effect of a neutron-induced fault response where recovery was turned off. The two control commands are shown in Figures 7 and 8 for run 114. With the recovery feature off, the control commands were reset rather than loaded to a previously known state when a miss-compare occurred because of fault response handling techniques employed by the legacy resident software associated with 777 AIMS technology. For this run the wind gusts were set to zero so the oscillations shown are due to the natural Dutch roll of the aircraft. A close look between frames 59600 and 59700 will reveal the reset. When the aircraft dynamics were examined in this case, no noticeable perturbations were seen. This can be explained because of the very small change in the control commands for this run. From only one run it would be not possible, with an acceptable degree of confidence, to project how robust the legacy AIMS technology would be to atmospheric neutron induced soft faults. However, millions of hours of existing field data from the AIMS product indicate a very high robustness to atmospheric neutron induced soft faults.

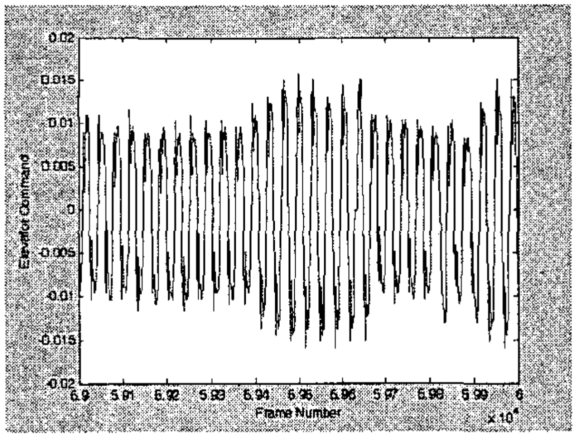

**Figure 7. Close-Up of Elevator Command with Recovery Off, Run 114**

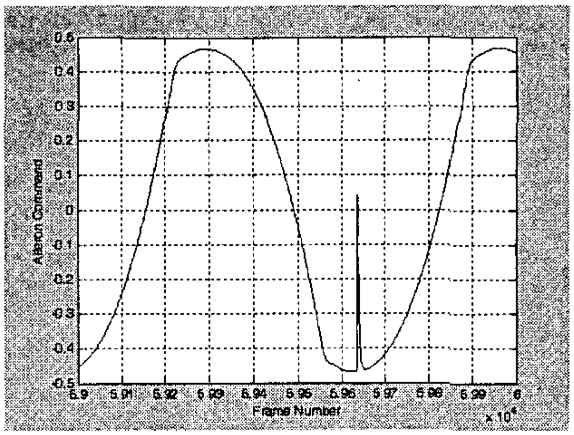

**Figure 8. Close-Up of Aileron Command with Recovery Off, Run 114**

In summary, the rollback recovery mechanism was triggered for many runs during the neutron exposure. For those runs without neutron exposure, no recoveries occurred and all flights finished successfully. Therefore, it is thought that the recovery is being triggered due to a miss-compare between the two processors resulting from a Signal Event Effect (SEE). The rollback recovery appears to offer robustness in the neutron particle environment. Cases in which the RCS stopped operating are currently being studied. However, it is evident that this is due to some effect produced by the neutrons, since it never occurs without neutron bombardment. For all cases in which the RCS stopped, the power had to be recycled to resume normal operation.

Table 1 is a summary of experimental observations when the neutron beam was on and the run length was 60 minutes. The first column describes the observation. In the second column, F stands for Fault and R stands for Reboot. The faults are due to a miscompare that triggers a rollback recovery, while a reboot reloads the operating system and restarts the application software. The third column contains the total number of runs where the action was observed for the given target and in parentheses the target location. The last column contains the total number of all runs where the action was observed, and the sum of the time for the runs.

**Table 1. Experimental Observations**

| Observation | F (R) | Number of Runs (Position) | Totals: Runs (Time) |
|---|---|---|---|
| No Effects | 0 | 7(T1),<br>8(T3),<br>1(T6),<br>6(T6p) | 22<br>(22 hours) |
| Normal Rollbacks | 2,<br>5,<br>34,<br>14,<br>7,<br>9,<br>11 | 2(T1),<br>1(T2),<br>4(T2p),<br>3(T4),<br>2(T4p),<br>4(T5),<br>2(T2D1) | 18 runs<br>(18 hours) |
| No Rollbacks "Reboot" | 0(1),<br>0(1), | 1(T4),<br>1(T6p) | 2 runs<br>(2 hours) |
| Rollbacks and "Reboot" | 2(1),<br>1(1) | 1(T5),<br>1(T6) | 2 runs<br>(2 hours) |
| Rollbacks with "Reboot" and Stop | 6(2),<br>6(3),<br>26(7) | 2(T2),<br>3(T2p),<br>7(T2pp) | 12 runs<br>(~2 hours) |
| Rollbacks and Stop | 19,<br>20,<br>4,<br>5,<br>114 | 4(T2),<br>3(T2p),<br>2(T4),<br>2(T5),<br>11(T2pp) | 22 runs<br>(~8.5 hours) |
| Stop Only | 0,<br>0,<br>0,<br>0,<br>0,<br>0 | 1(T2),<br>1(T2p),<br>1(T4),<br>1(T4p),<br>2(T2pp),<br>1(T6p) | 7 runs<br>(~2.5 hours) |

The rows of Table 1 correspond to the specific observations. The first row describes the column contents. The second row is a summary of the runs that contain no neutron phenomenon. Here there where no faults or reboots. As can bee seen, there where 7 runs in target position T1, 8 in T3, 1 in T6, and 6 in T6p. When all runs are added for the "No Effects" observation, a total of 22 runs results. Since each run is 60 minutes and all runs finished successfully, the total number of hours is 22. The third row is a summary of all runs that completed successfully, but the recovery mechanism was triggered. Since the recovery was never triggered in any of the neutron free runs, it is certain that these triggers were due to SEUs. The forth and fifth rows contain the runs where an operating system reboot occurred. These runs finished successfully, however at some point in the run the system rebooted and reloaded the application software. The sixth row contains those runs where rollbacks occurred, the system rebooted, and the run did not finish because the RCS stopped communicating. It is unknown whether the communication loss was due to a strike counter or an SEU, such as a latch up, from which the RCS was unable to recover. The seventh row contains those runs where recoveries occurred and the RCS stopped communicating at some point. However, for these runs the RCS never rebooted. In the last row the RCS simply stopped communicating with no noticeable faults.

In characterizing the observations it is critical to consider the RCS firmware. The application executing in the FCC consists of a partial set of flight control laws for the 737 (aileron and elevator), ARINC 429 interface software, and recovery control/management software. In addition to the application software, there is resident software which is a collection of Power-up-Bite tests, Initialization/boot, Operating System, Data Load support, and Fault Response. Some of the functions of the resident software are to halt, restart, perform Built In Test (BIT), or reboot the operation of the lock-step pair processors if the fault conditions warrant such activity. While such functions are not part of the application and simple operating system developed for the RCS FCC, they are resident in the FCC and are artifacts of the 777 AIMS technology that was adapted to implement the recovery architecture of the FCC. As part of the AIMS fault response design, there is a capacity to "gracefully" recover 777 AIMS functions. "Retry monitors" are part of this graceful recovery capability and are referred to collectively as "strike counters." These strike counters probably account for some of the results in Table 1.

In interpreting the observations, it is also critical to consider the neutron beam path through the FCC. The effected area for a given run can be seen by considering the neutron path across each board for a given targeting position. Table 2 shows the relative positions of the Circuit Card Assemblies (CCA). At the top is the I/O Client and the bottom CCA is the RCS Data Memory Backup.

**Table 2. Position of CCA in RCS**

| |
|---|
| I/O Client |
| BIPM CCA |
| Power Supply (Removed) |
| Processor CCA |
| Instruction Memory |
| Scratch Pad Data Memory |
| RCS Data Memory Backup |
| RCS Data Memory Backup |

Depending on the neutron beam size and location, parts of the boards in Table 2 were hit and others were missed. As an example, consider target position T2. Figures 9-11 show the neutron beam path across the three cards that were hit for this particular target setting. Shown in Figure 9 is the Bus Interface Power Monitor (BIPM) CCA. The yellow path on the cards represents the neutron beam. To get an idea of the exposure, consider the colored cross section shown in the lower part of the yellow path. This is the cross section of the neutron beam as it enters the FCC. The red is the most intense, then yellow, green, and blue. The black sections represent areas with virtually no neutrons. At the top of the yellow path is the exit profile. Like the entry profile, this section shows a cross section of the neutron beam intensity at the edge of the card. As can be seen, the beam intensity has decreased some due to neutron absorption and scattering from the FCC. Likewise, Figure 10 shows the neutron path across the Processor CCA and Figure 11 the Instruction Memory CCA. Here again the colored sections at the entry and exit locations show the cross section (perpendicular to the CAA) of the neutron beam. The beam profiles are the intensity distributions. In comparing the entrance and exit beam profiles, one should keep in mind that very few neutron were actually absorbed by the FCC, most neutrons simply pass through. The beam profile coloring differentiates slight variations.

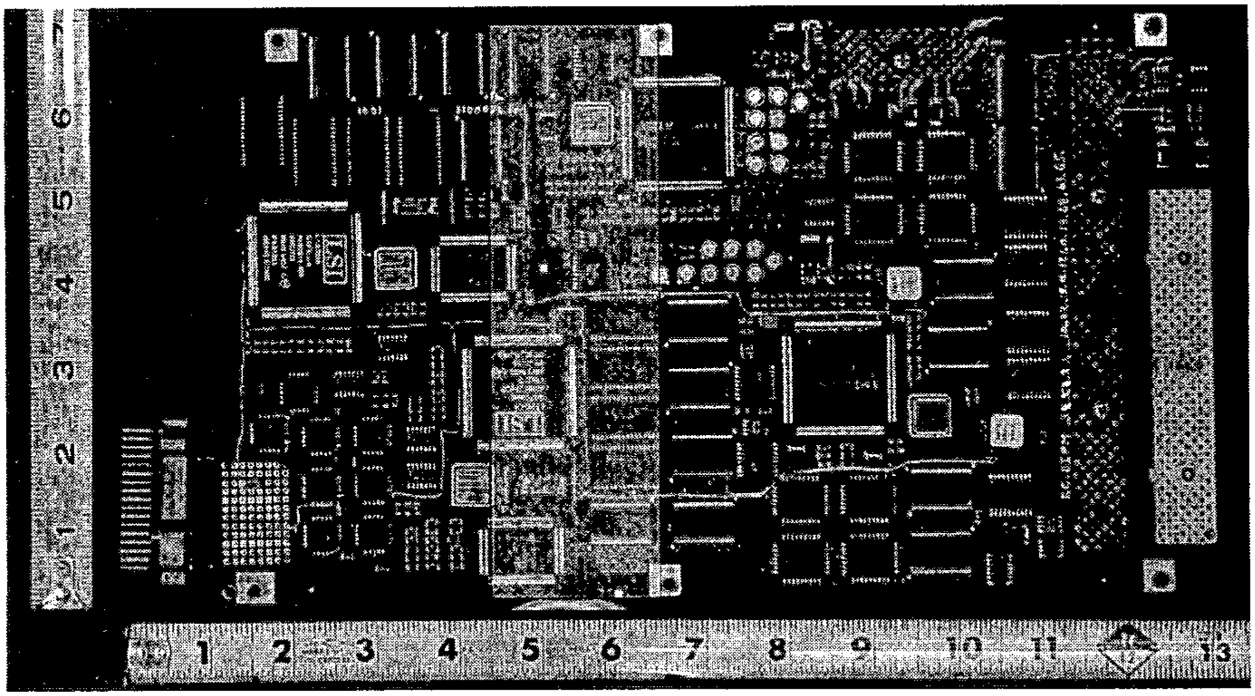

Figure 9. Beam Passage through BIPM CCA

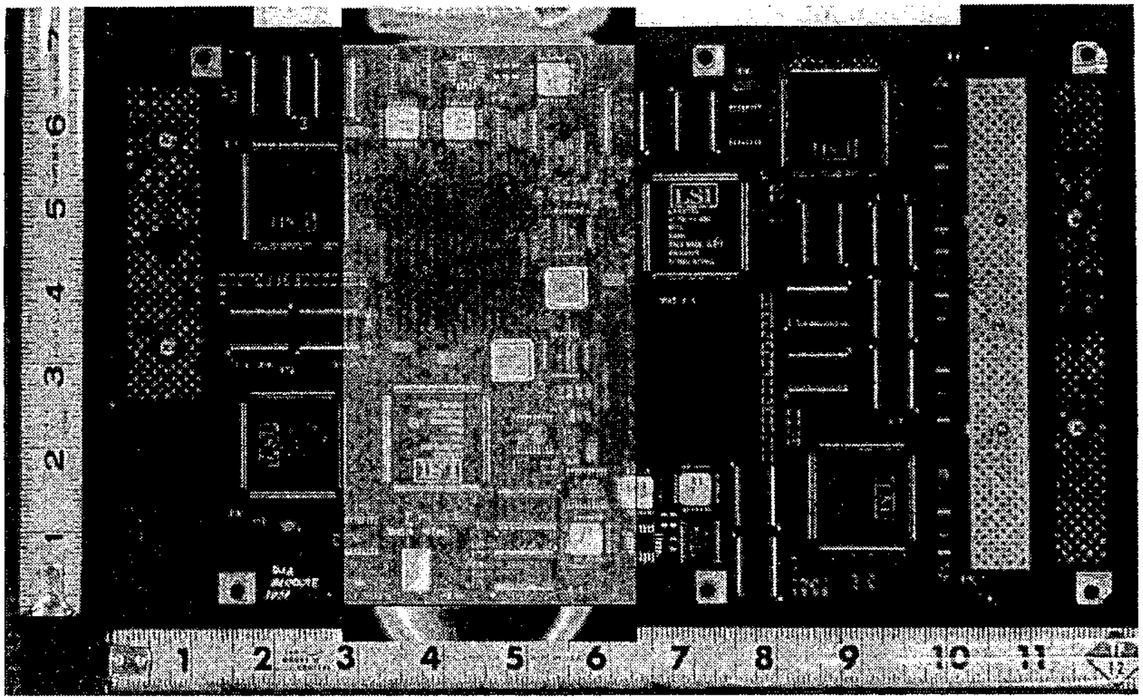

Figure 10. Beam Path through Processor CCA

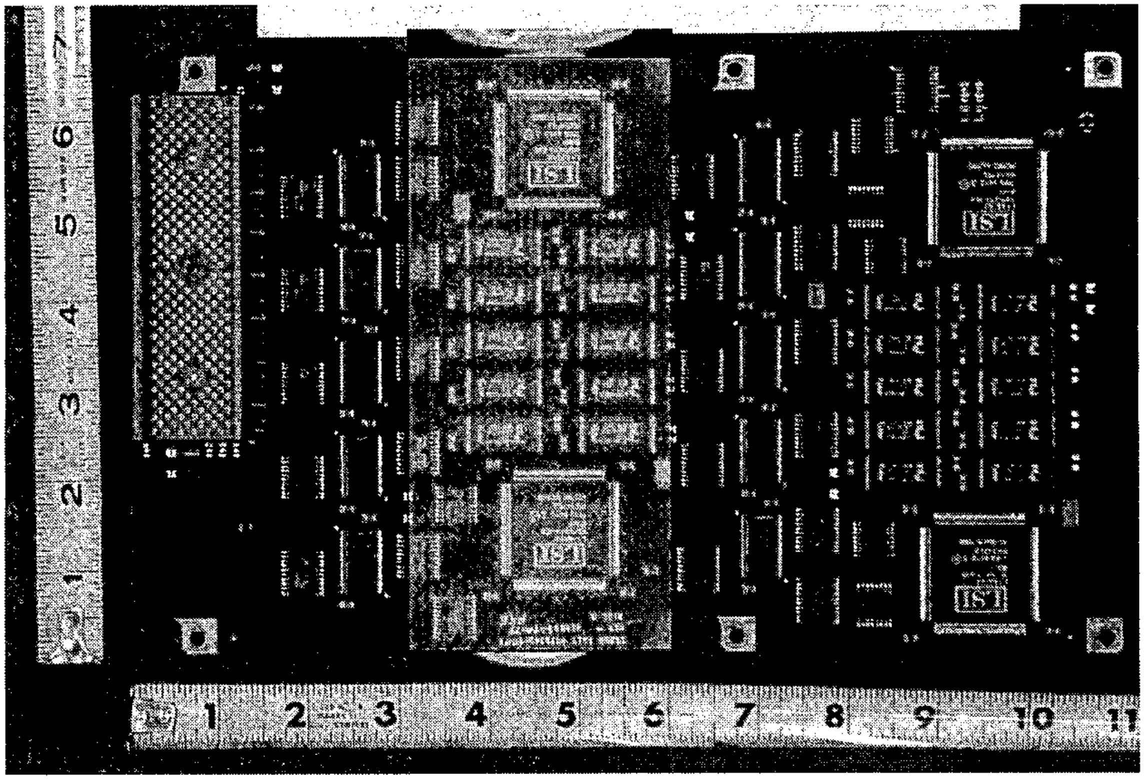

Figure 11. Beam Path through Instruction Memory CCA

## Conclusions and Future Work

The recoverable flight control computer tested in this experiment demonstrated an ability to be robust in an adverse particle environment. The recovery scheme resident with AIMS technology provides a measure of tolerance to single event effects. Dual lock-step processors with the additional architecture elements for rapid rollback recovery provide a fault tolerant methodology for flight critical systems in harsh particle environments. When neutron effects assessments are performed on electronic systems, it is the "complex"/highly integrated electronic devices (microprocessors, ASICs, FPGAs, etc) upon which attention is focused. Never the less, it is suspected that most of the unrecoverable failures observed during testing were due to strike counters (normally not part of a flight control system fault response) disabling the recoverable computer processing. There were, however, instances were neutron induced phenomenon did cause failures which were both unrecoverable and can not be attributed to the action of resident AIMS legacy software.

Future research will involve further analysis of the effects of rollback recovery on closed loop stability as well a further test on the recoverable FCC to isolate suspected chips and chip sets. This identification of neutron susceptible components and subsystems could have implications for fault tolerant design strategies if similar components are currently being used, or will be used, in flight critical systems.

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