Chandra Flight Note

FLIGHT NOTE NO.	441
SUBJECT	HRC -Y Shutter Failure (OCCcm06110): FDB Closeout
DATE	22 October 2004
AUTHOR	Michael Juda for the HRC Team

1 Summary

This flight note documents the results of the investigation launch in response to the failure of the HRC -Y shutter to insert on day 2003:269 as part of the configuration for ObsID 3831. The failure has been traced to a failure of the -Y shutter select relay. This failure of the -Y shutter select relay first appeared (but was not noticed) during a SCS-107 activation on day 2001:308 and was persistent for all subsequent attempts at relay selection. The mechanism of the relay failure is most likely to be caused by particles; the particles being generated as a result of oxidation of the copper elements of the contact assembly during long-term storage in an oxidizing environment. The same type of relay is used to select the HRC door for operation. Given the nature of the relay failure, all HRC mechanism use in normal operations has been stopped and the HRC instrument safing SCSs have been patched to stop mechanism use. There is an unknown potential for long-term degradation of the HRC UV/Ion shield from low-energy (E = 0.1-0.2 MeV) protons during radiation zone passages which is being routinely monitored with periodic observations of a bright, celestial UV source.

2 Background

The SEP2203 schedule contained an observation of the Crab pulsar (ObsID 3831) which required a special configuration of the HRC in order to accomplish the science goals of the observation. The request was for the HRC to be configured to use the HRC-S in its high-precision timing mode and for the +Y and -Y shutters to be inserted so that on-axis X-rays from all but one quadrant of the HRMA would be blocked. The configuration of the shutters was requested so that the total HRC event trigger rate from this bright source would be below the telemetry saturation rate of ~ 184 counts s^{-1}. All commanding to establish the configuration was to be done via the weekly command loads.

The motion of the HRC door, shutters, and door mounted calibration source are all controlled by a single set of circuits within the primary or redundant electronics. The motor to be controlled by the circuits as well as the motor's thermistor and the mechanism's associated limit switches are selected by a serial-digital command. Other serial digital commands specify whether to use particular limit switches to stop the mechanism motion and initiate a particular mode and direction of motion. In building the weekly schedule, the OFLS uses a set of command sequence definitions to insert the commands into the command loads. A review of the approved SEP2203B load products showed that all of the required commanding to the mechanism controller was present to perform the insertion of the +Y and -Y shutters on day 2003:269 and to later retract the shutters on day 2003:271, as part of the steps needed to configure the HRC for its next observation (ObsID 3675).

There was no communications pass during the shutter insertion starting at ∼2003:269:19:55; however, a portion of the Crab pulsar observation occurred within the 2003:269:21:30–22:30 pass. The total HRC rate that was observed during this pass was above telemetry saturation, contrary to the goal of the requested configuration. This could have been taken as an indication that the HRC was not properly configured but the charged particle background could lead to telemetry saturation as well. What was not checked at this time, or on the subsequent passes prior to the scheduled shutter retraction, was the state of the -Y shutter "Home" limit switch, which would have shown that the shutter did not insert (i.e. the "Home" limit switch was active). The shutter retract commanding occurred during the 2003:271:03:45–04:45 communications pass starting at ∼04:30; no HRC personnel were monitoring the telemetry in real-time.

Martin Weisskopf, of the observer team, notified Michael Juda via e-mail on 2003 September 30 that an initial examination of the data lead them to suspect that only one shutter blade had been inserted during the Crab pulsar observation. M. Juda verified that this was indeed the case and alerted the HRC IPI and FOT engineering teams of the problem to start the anomaly investigation. There were no scheduled HRC mechanism operations for the next week, so no immediate action or decision was required.

3 Analysis

The SEP2203B command loads contained the necessary commands for the HRC shutter insertion; so, an on-board hardware problem was the immediately identified reason for the anomaly. Figure 1 shows the top-level fault-tree for the shutter insertion failure; while figure 2 shows the HRC motor controller branch where, as we describe below, the fault occurred.

3.1 Telemetry Review

Rich Logan and Dan Shropshire reviewed the telemetry from the SI-RCTU command counter and verified that the command to select the -Y shutter was received making the most-likely origin for the anomaly within the HRC. A review of the HRC motor controller telemetry indicated that the HRC received and acted on the serial-digital command to select the -Y shutter mechanism but that the motor was not selected. Figures 3–6 display much of the motor controller telemetry around the period of the +Y and -Y Shutter insert on day 2003:269. The +Y shutter is selected during the time between the HRC commands 2PYMTASL (+Y Shutter Motor Select) and 2ALMTADS (All Motors Deselect); similarly, the -Y shutter motor should have been selected during the time between the HRC commands 2NYMTASL (-Y Shutter Motor Select) and 2ALMTADS. Figure 3 shows that the "-Y Shutter" bit remained at zero while the "None" bit remained at one during the time the -Y shutter was commanded to be selected. Figure 4 shows that the close ("Home") primary limit switch stayed active during this interval. Figure 5 suggests that the HRC bus current showed a slight increase (on the order of one telemetry step or ∼68 mA) during this time, similar to the slight increase at the start of the +Y shutter commanding interval. However the bus current did not show the increase expected for driving the motor after the motor drive was enabled (command 2MDRVAEN) as is seen for the successful +Y shutter insertion. Figure 6 shows that the motor thermistor was selected by the controller. The telemetry shows that the HRC exhibited a response

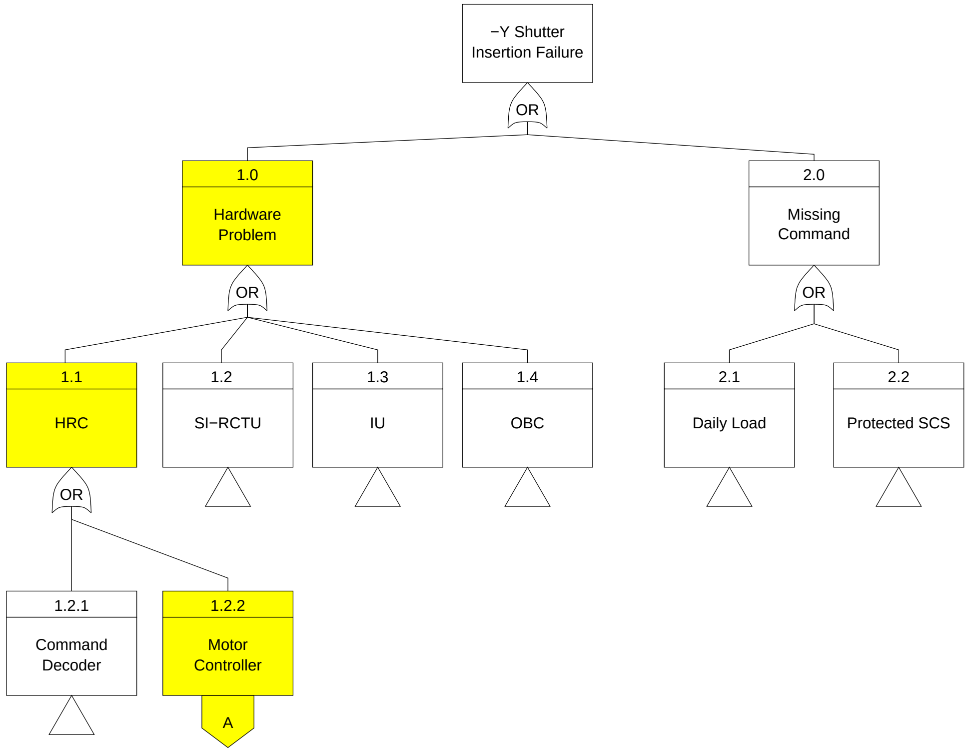

Figure 1: Top-level fault-tree for the HRC -Y shutter insertion failure

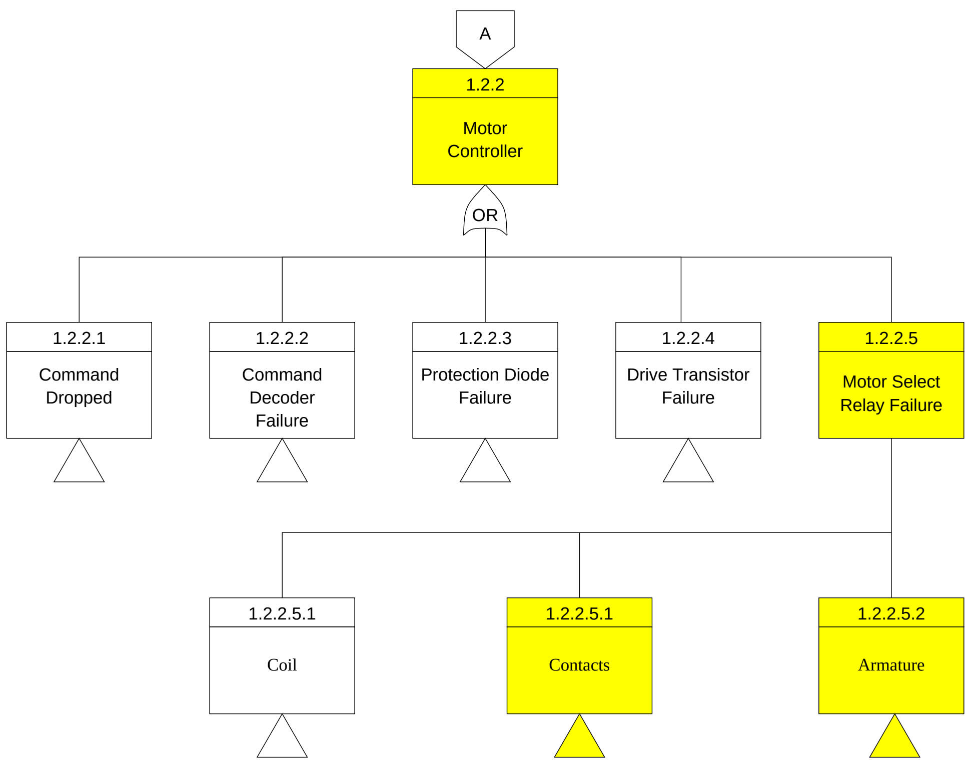

Figure 2: HRC motor controller branch of the fault-tree for the HRC -Y shutter insertion failure

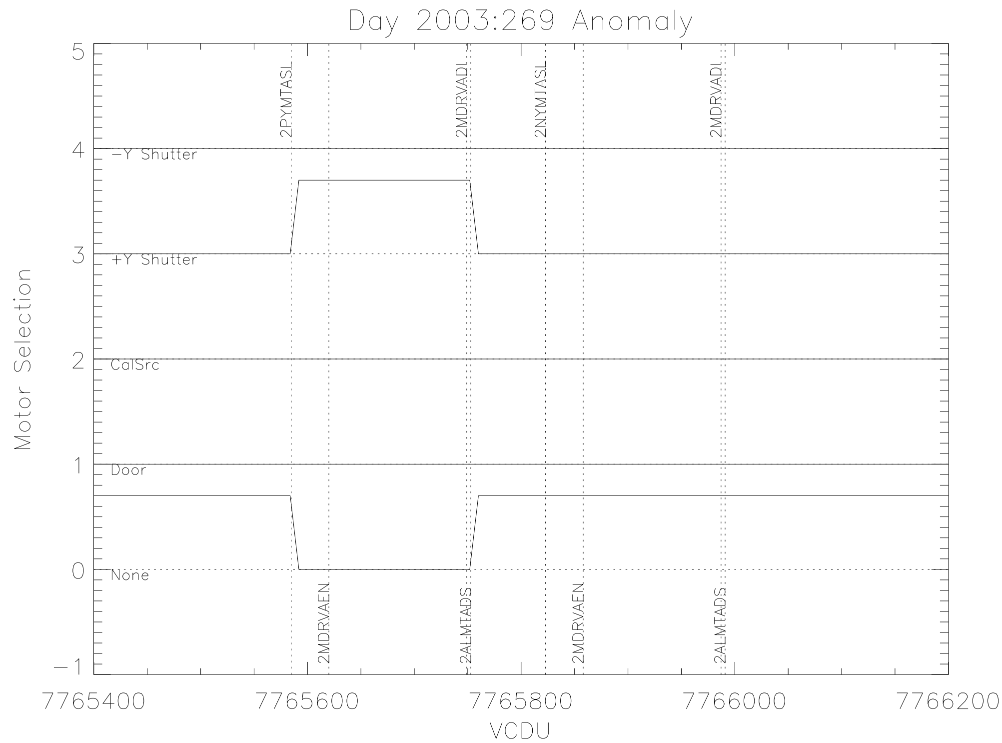

Figure 3: Motor selection bit telemetry during the shutter insert commanding on day 2003:269. The vertical text and dashed lines are the HRC command mnemonics and scheduled times.

to the the command to select the -Y shutter but that the shutter did not move from the home limit switch because the motor itself did not get selected by the controller. A similar telemetry response was apparent during the day 2003:271 shutter retraction interval. This isolates the fault to within a small portion of the motor controller circuit.

The shutters are rarely used during normal operations. They were used during the orbital activation and check-out phase to perform instrument focus and HRMA tilt-alignment measurements. The last scheduled use of the shutters was day 2000:349, during which time they inserted and retracted as expected. Historically the shutters get commanded at unscheduled times whenever SCS-107 is activated. Analysis of the -Y shutter motor selections during SCS-107 runs indicate that the -Y shutter selection failure first occurred during the SCS-107 run on 2001 November 4 and that selection has never succeeded since that time.

3.2 Schematic Review

The HRC mechanism that gets selected or de-selecting all mechanisms is accomplished by serial digital command. Table 1 lists the 16-bits of command hex that are used by the HRC, the command mnemonic, and the description for each of the five commands that cover motor selection. The HRC serial command decoder electronics essentially interprets these five commands as a motor select active command in bits 12–15 (with a value of 0x7 generating an internal signal MOTSELWR) and data that describes which motor to select in bits 8–11 (with only the three lowest ever being set). Figure 7 shows the portion of the motor controller schematic (HRC-5222) that buffers the three interesting serial-digital motor select command bits (bits 8, 9, and 10 as BCMDB08, BCMDB09,

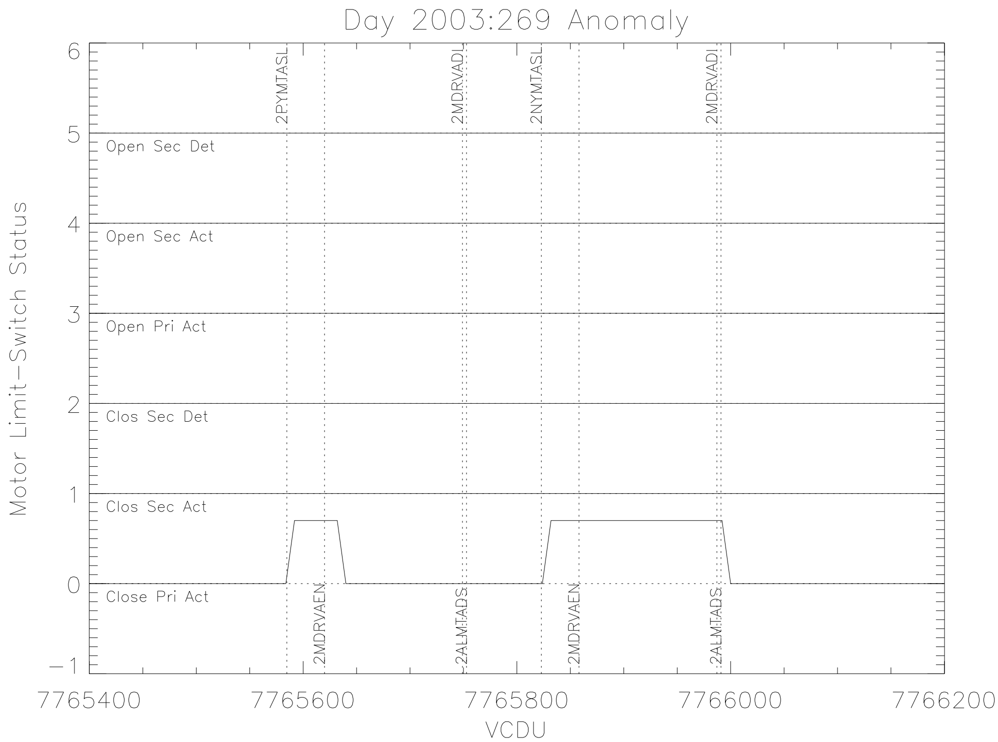

Figure 4: Motor limit switch bit telemetry during the shutter insert commanding on day 2003:269. The vertical text and dashed lines are the HRC command mnemonics and scheduled times.

Table 1: HRC Motor Select Commands

Command Hex	Mnemonic	Description
70XX	2ALMTADS	ALL MOTORS DESELECT
71XX	2DRMTASL	DOOR MOTOR SELECT
72XX	2CLMTASL	CALSRC MOTOR SELECT
73XX	2PYMTASL	+Y SHUTTER MOTOR SELECT
74XX	2NYMTASL	-Y SHUTTER MOTOR SELECT

XX = don't care about bit value - set to 00 in the command

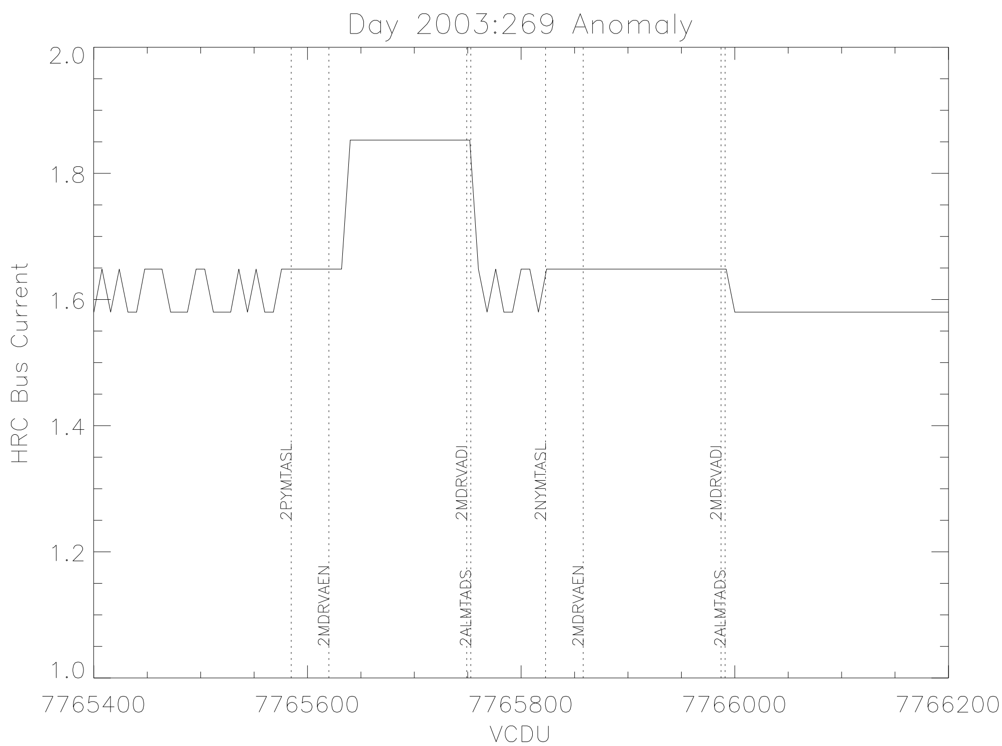

Figure 5: HRC bus current telemetry during the shutter insert commanding on day 2003:269. The vertical text and dashed lines are the HRC command mnemonics and scheduled times.

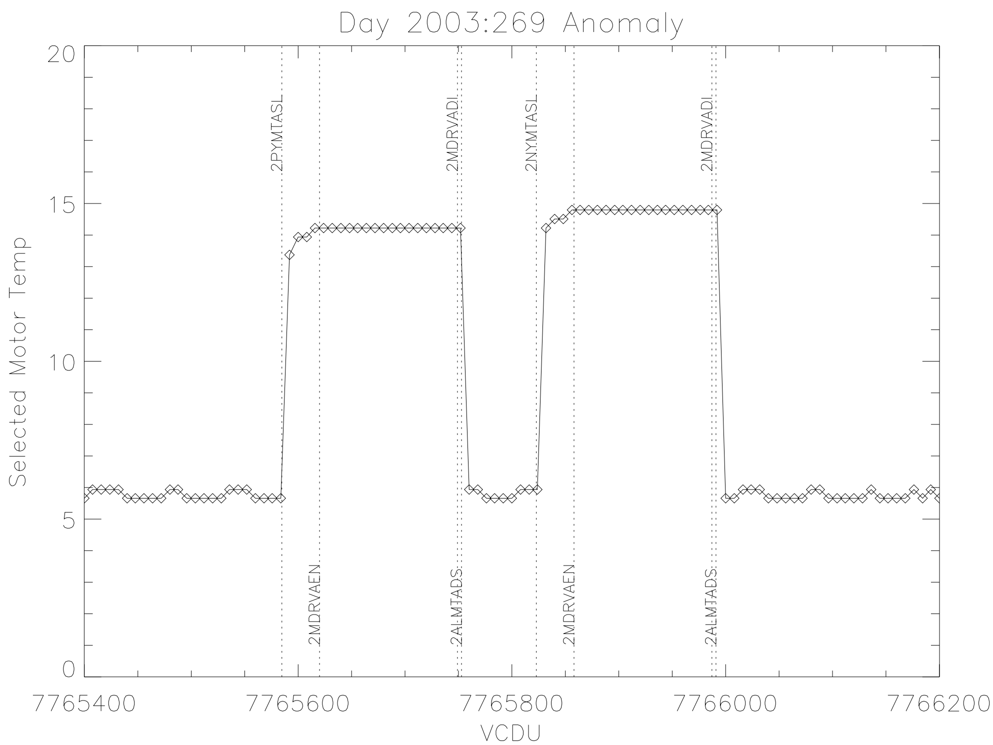

Figure 6: Selected motor temperature telemetry during the shutter insert commanding on day 2003:269. The vertical text and dashed lines are the HRC command mnemonics and scheduled times.

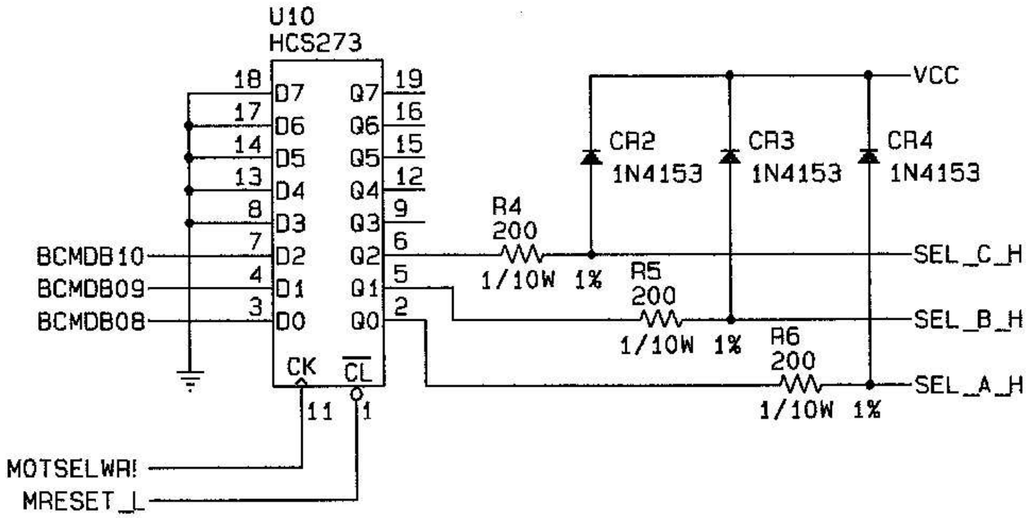

Figure 7: Buffer circuit for serial-digital command bits of the selected motor from motor controller schematic HRC-5222.

and BCMDB10) into internal signal bits (SEL_A_H, SEL_B_H, and SEL_C_H) that hold the selected motor information. These internal signals are used to select the portions of the motor control electronics associated the the selected mechanism. The bit SEL_C_H is only set when the -Y shutter is selected; the fact the the thermistor and limit switches associated with the -Y shutter were selected demonstrates that the serial-digital command is being processed correctly. Figure 8 is a portion of the motor select schematic that shows how these signals are used to generate the four motor select signals. The signal EN_MOTOR_4_H is used to select the -Y shutter motor and is not used anywhere else. Figure 9 is a portion of the motor select schematic which shows where this signal is used to switch the transistor that energizes the relay-coil to select the motor; identical circuits are used for the other three motors. The signal MOTOR_4_ON_H in figure 9 provides the telemetry indicator that the motor has been selected. Since the telemetry indicated that the -Y shutter selection bit did not change when the motor was selected and the motor did not turn when the motor drive was enabled then at least two of the relay contacts did not close. This outcome could have resulted from:

- damage to the contacts in the relay
- damage to the relay armature
- damage to the relay coil
- failure of the drive transistor
- failure in the protection diode
- the signal EN_MOTOR_4_H is missing

The slight increase in bus current when the motor is selected is an indication that the coil was energized which eliminates all but the first two of these as the cause of the anomaly.

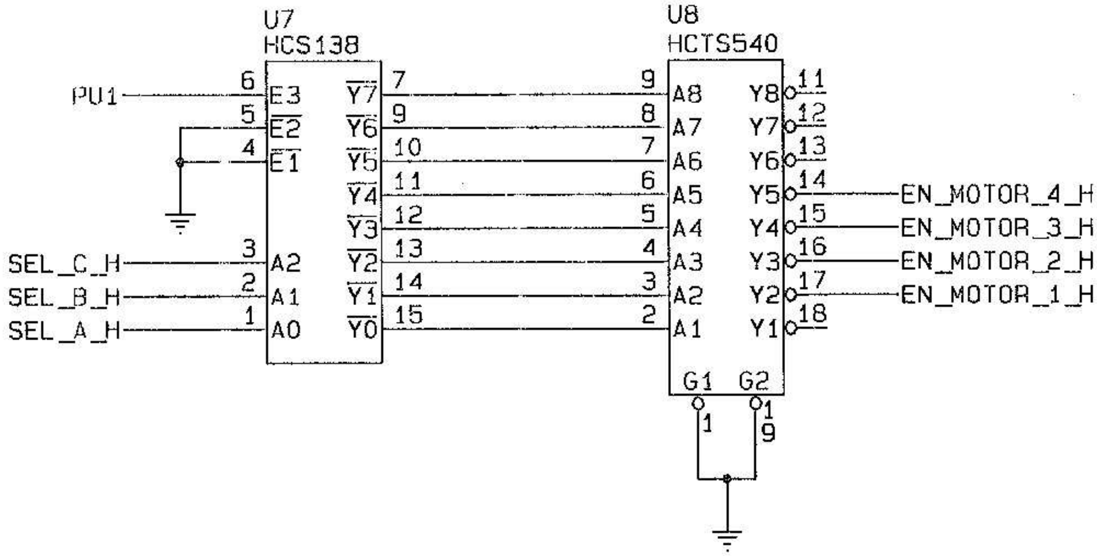

Figure 8: Schematic of the motor select command bits decoder

3.3 Laboratory Tests

The HRC team has a set of "Proof-of-Concept" (POC) electronics in the laboratory that are built to the flight design. Measurements of nominal performance of the motor control electronics on the POC indicate that issuing the motor select command causes a 33 mA increase in the output of the internal +24 V supply. Unfortunately, the current of the +24 V supply does not appear in telemetry. The slight increase in the HRC bus current when the -Y shutter motor is selected is consistent with what we would expect from a 33 mA increase in the +24 V supply with power-supply efficiencies taken into account. Given this rough consistency it appears that the relay coil is being energized and the most likely cause for the anomaly is either the armature not moving or the armature does move but the relay contacts do not close.

The relay that is the most likely cause of the anomaly was produced by Genicom: part # S311P754/09/003 with a date code of DC9536; nine relays were purchased. Eight of these relays are used in the flight instrument (four each in the A-side and B-side electronics), all in the motor select circuits; one was placed in bonded stores and has been subsequently used in diagnostic tests. The POC uses four similar relays but these were not purchased to the GSFC flight specification. Sixteen similar relays have been purchased, again not to the GSFC flight specification, for use in laboratory tests. Details of the laboratory tests performed on the remaining flight and flight-like relays are in appendix A. The result of laboratory testing identifies the most-likely cause for the relay failure as particles, generated as a result of oxidation of the copper elements of the contact assembly during long-term storage in an oxidizing environment.

4 Options and Risks

There is nothing in our knowledge of reason for the failure of the -Y shutter motor select relay that suggests it is unlikely to happen to any of the remaining relays. Several operations options are available, each with its own risks:

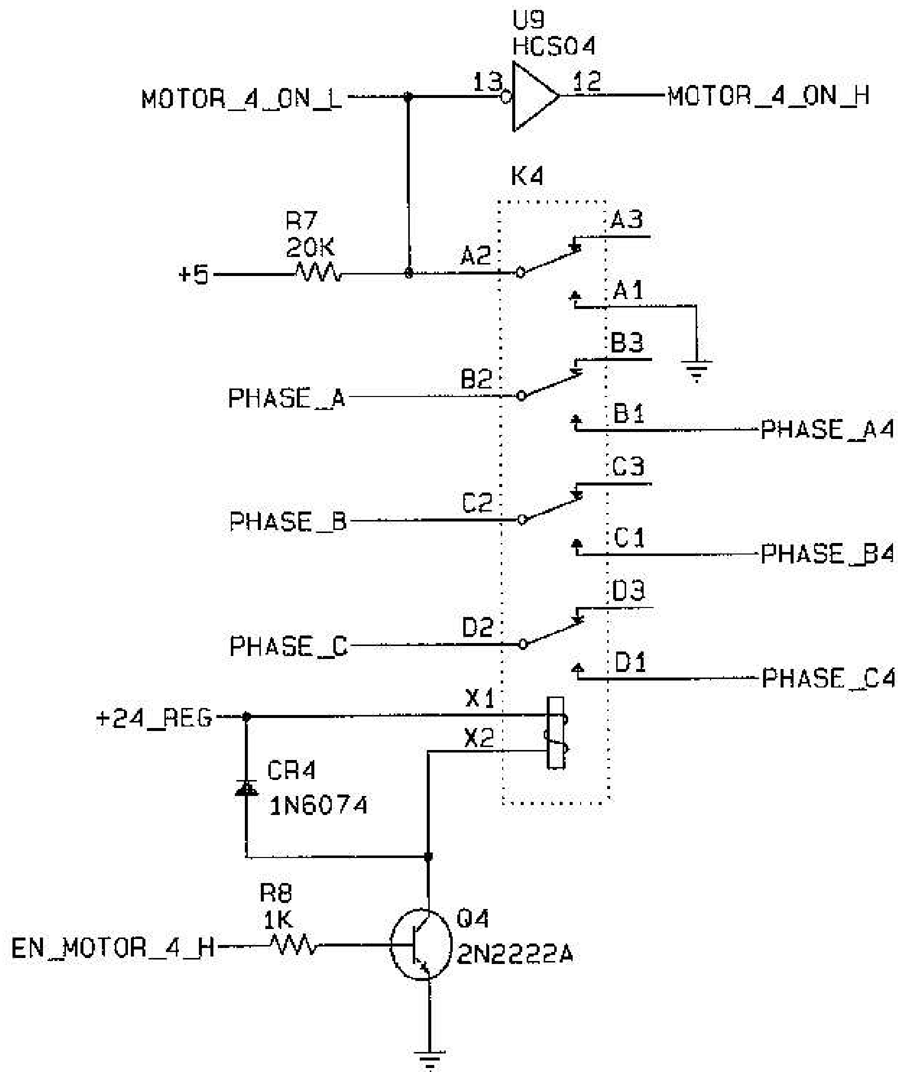

Figure 9: Schematic of the motor select relay and drive circuit.

- Stop using all HRC mechanisms
- Continue to use the HRC door and +Y shutter and try to recover the use of the -Y shutter
- Continue to use the HRC door and +Y shutter but never use the -Y shutter
- Continue to use the HRC door but stop use of the shutters
- Stop using the HRC door but continue to use the shutters
- Switch to the B-side electronics to re-gain full function

Stopping the use of the calibration source mechanism has no impact as the ^{55}Fe source intensity has decayed to a level much lower than the background.

Continued use of some combination of the HRC mechanisms leaves us open impacts from a potential failure of another relay. The position that we have taken since the anomaly has been to stop using all HRC mechanisms. Upon opening the HRC door for an observation scheduled in the OCT1303 week, the command sequence definitions used to put HRC activities into the command loads were modified to remove all door commanding. The stored command sequence used for HRC safing that contained the commands to partially close the HRC door (SCS-105) was also disabled to prevent a safing event from selecting the HRC door. The shutters could still be selected for commanding during safing actions until SCS-104 was patched on day 2004:025 to remove the commanding to them. The concern with this approach is that we had been moving the HRC door to a mostly-closed position during radiation zone passages and safing events as a prudent measure to avoid an unknown potential for damage to the aluminized polyimide UV/Ion shield from low-energy protons that scatter through the HRMA. However, studies of the effects of high radiation on polyimide windows for propotional counters showed no mechanical degradation for doses up to 5 MRad[1], and a study performed on the radiation effects on Chandra HETG grating facets, which use a polyimide substrate, that showed no evidence for changes to the grating properties (diffraction efficiency) nor to mechanical propoerties (resonant frequency of membranes)[2]. In addition, observations of Vega, a bright UV source, on 2004 February 05 and on 2004 August 28 show no change in the response of the HRC[3]; there is no evidence for degradation in the UV/Ion shield during the $\sim$120 radiation zone passages with the door mostly open that occurred prior to the August observation. The lack of evidence from the literature for degradation of polyimide and our on-orbit experience of no degradation in the UV/Ion shield removes much of the concern with leaving the HRC door open during radiation zone passages.

If the door and shutters were both allowed for use, a relay failure at the wrong time could potentially leave a shutter in the volume of space that the door sweeps through in going from the mostly open to the mostly closed position; this is a violation CARD constraint HRC-C-001 and could lead to the loss of the HRC science instruments. Continuing to use the HRC door but not the shutters would provide protection against the possibility of damage from low-energy protons during radiation zone passages; however, a failure of the door select relay when the door is in the mostly closed position would prevent the use of the HRC for science observations until the door could be opened. Unfortunately, in this door stuck closed scenario the only way to re-open the door would be to switch to the B-side electronics in order to use the redundant motor control electronics. There is no fail-safe mechanism to open the door. Switching to the B-side electronics entails some risk and there is still the possibility that the B-side door motor select relay will have suffered a similar failure.

Shutter use with the door permanently left in the mostly open position could continue with or without making an attempt to restore the -Y shutter to operation. Failure of another relay could leave a shutter partially blocking an HRC detector. As with the door, the shutter might be retracted by switching to the B-side electronics; alternatively, the shutters do have a fail-safe mechanism that will retract them back to the "Home" position. Using the fail-safe is not reversible. Procedures for operating the fail-safe have not yet been developed and tested and considerable effort would be required for this development and test. The fail-safe uses a Starsys wax actuator to release the shutter blade from its motor. Such wax actuators are subject to failure during operation due to burn-out of the heater prior to full actuation. A failure of the fail-safe would leave the shutter partially blocking the HRC detectors, resulting in a permanent degradation of the HRC science capabilities.

5 Recommendations and Actions

The HRC team recommends that we stay with the current operations strategy of not using the HRC mechanisms. The potential risk of damage to the UV/Ion shield for low-energy protons during radiation zone passages is still a low-level concern that we are monitoring. The HRC team recommends the following actions:

- The frequency of Vega monitoring observations should be increased from one set per year to four per year. This will allow for more prompt detection of the onset of any degradation in the HRC response. This has already begun and should continue.
- The potential for using the mid-point of the SIM translation range for radiation zone passage and safing should be explored. Can both the ACIS and HRC instruments be safe from low-energy protons at this position?

The effects of low-energy protons on the UV/Ion shield material could be measured in the lab, to determine the amount of degradation expected in a 15-year mission if we leave the HRC detectors exposed during radiation zone passages. Given our knowledge of radiation effects on polyimide and our on-orbit experience, the HRC team believes that such tests are not needed at this time. If the monitoring observations (or lab measurements, if performed) indicate that we have a problem with the low-energy protons and going to the mid-point of the SIM translation does not provide the required protection, then we should consider resuming moving the HRC door to the mostly closed position for radiation zone passages and safing.

Suspending the use of the shutters has some impact on the science that can be performed with the HRC; resuming the use of the +Y shutter will have an impact should its motor-select relay fail while the shutter is inserted.

- The HRC team should determine the proceudres that must be developed and tests that must be completed prior to the resumption of the use of the +Y shutter such that there would be minimal impact to the science mission in the event of a failure of its motor-select relay.

References

[1] "X-ray windows for spaceborne detectors", Viitanen, V.-P. et al. 1992, SPIE Proc. 1743, 245.

[2] "Rad-exposed Grating Analysis", http://space.mit.edu/HETG/rad_anal/rad_anal.html

[3] "Monitoring the UV/Ion Shield Health",
http://hea-www.harvard.edu/ juda/memos/uvis_monitor/index.html

A Failure Analysis of HRC Flight Relay

A.1 Introduction

Following the determination that the -Y shutter motor select relay failed, a failure analysis was initiated to determine the cause of the failure. The intent was to provide a basis for deciding if it was possible to recover the proper operation of the relay, as well the impact of the failure on the continued use of the other motor select relays.

A.2 Background

The Genicom relays (S311P754/09-003; DC9536) used for the Flight HRC motor selection were qualified to GSFC specification S311P754 including PIND test per MIL-R-83536 for detection of fine particles. These relays have an excellent reliability history in space programs with no failures. A review of the documentation received with Chandra relays showed that the lot for Chandra was selected from a lot of 24 relays that had two failures during processing (1-vibration, 1-seal).

The relays have "gold plating over nickel underplate" on contacts; such contact coating has no history of flaking and causing particles. Particle contamination is one of the major causes for relay failure.

The Proof of Concept (POC) HRC electronics utilize the same relays except for additional screening imposed by GSFC S311754 requirements. The POC system has been in operation since 1994.

A.3 Preliminary Failure Analysis

Unfortunately there was only one "flight" relay in spare stock. So preliminary analysis was conducted on POC relays and MIL GRADE relays from Genicom and Tyco.

A.3.1 Residual Gas Analysis (RGA)

An RGA was performed on a POC relay (3SBH1347A2, Genicom) to determine contamination levels in the relay package. The data is presented below (A-1).

Element	%
Nitrogen (N)	99+
Carbon Dioxide (CO_2)	0.113
Moisture (H_2O)	0.177

Table A-1: Residual Gas Analysis results

A.3.2 Decapping

The relay was decapped by grinding, taking care not to introduce particles within. The decapped relay failed a switching test in a similar mode as observed in the flight HRC. The failure was found to have been caused by distortion of the assembly during decapping. After repair the relay was found to operate normally.

A particle contamination was simulated by inserting a .002" thick piece of paper in the contact mechanism. It produced the failure mode observed in orbit. Particle contamination was thus established as one of the possible failure modes in orbit.

A.3.3 High Humidity (50% RH) and Temperature Extremes (75C, -40C)

POC and Genicom MIL GRADE relay were subjected to extremes of temperature (75C, -40C) and high humidity (50% RH) for varying periods of time. No failures were observed.

A.3.4 Oxidizing Environment

The RGA suggested the possibility of an oxidizing environment within the relay package, consisting of H, N, and O (constituents found in nitric acid fumes). A decapped POC relay was subjected to 5% nitric acid fumes at 25C for 12 hours, resulting in a failure similar to that observed in orbit. Six consecutive switching attempts were required to correct the relay operation. (Extended exposure to fumes (∼300 hours) caused heavy oxidation of copper elements — a worst-case scenario). Thus oxidation in gaseous environment within the relay package was established as a source of particles and a possible failure mechanism.

A.3.5 Preliminary Conclusions

The analysis suggested the following factors as probable cause for the HRC failure in orbit:

1. Particle contamination
2. Oxidizing environment in the relay package as the primary source for particles.

A.4 Failure Analysis

On the basis of the findings of preliminary analysis, failure analysis was conducted on following relays:

Relay	Part No./Date Code	Manufacturer	Status
1	S311P754/09-003/9536	Genicom	Flight
2	3 SB145134K / 9452	Genicom	MIL GRADE
3	3SBH1665A2 / 2002	Genicom	MIL GRADE
4	3 SB145134K1 / 2003	Tyco	MIL GRADE

Table A-2: Relay Identification

A.4.1 Residual Gas Analysis (RGA)

The results of the RGA are shown in Table A-3.

The data confirmed the previous finding of an oxidizing environment. In addition, it showed significant moisture content within the flight relay.

Elements	Relay 1	Relay 2	Relay 3	Relay 4
Nitrogen (N)	98	99	86	98
Argon (Ar)	.032	.032	.185	.029
Carbon Dioxide (CO2)	.058	.063	.63	.083
Moisture (H2O)	.92	.258	12.10	.75
Hydrogen (H)	.32	.174	.161	.167

Table A-3: RGA Analysis

A.4.2 Moisture Content and Relay Operation

To study the effect content (up to 12.1%), a measured amount of moisture (0.87 cc), determined from the RGA data and dimensions of the relay package was introduced in decapped relays (#1, 3 and 4). These relays were selected because of their high moisture content. The relays were tested at 25C and were found operational.

The relays were then stored at -45C in quiescent state for 22 hours. At the end of 22 hours, the relays operated normally at -45C. Relays were then stored at -60C in quiescent state for 2 hours. Tests at -60C, -40C and 10C showed normal operation.

It was therefore concluded that moisture content up to 12% had no effect on relay operation under normal humidity condition.

A.4.3 Particle Contamination

Siltek, a diamond powder with particle size of 0.5 μm was used for contamination of two relays (#3 and 5). Three particles were deposited on top of the decapped relays, and the relays were then tapped lightly to allow random, free fall of the particles into the contact assemblies. Both relays failed in a similar mode as observed in orbit. Relay #3 was then stored in quiescent state at -40C for 150 hours in an oven that tended to vibrate whenever the blower fan was energized. At the end of 150 hours, the relay exhibited the same failure mode. So particle contamination as a source of relay failure was established.

A.4.4 Oxidation

The objective of the oxidation tests was to simulate the long-term storage condition experienced by the failed -Y shutter motor select relay in Chandra, and to prove oxidation as the primary source for particles within the relay package.

Two relays, #2 and 4, were exposed to nitric acid (5%) fumes after initial switching tests in a quiescent condition for 24 hours. The switching test at 24 hours showed normal operation, with the appearance of thin oxide layers. The relays were then subjected to nitric acid fumes for 150 hours. At the end of the 150 hours relays were found to be heavily oxidized — worst case situation in long-term quiescent storage. The oxide layers are shown in the attached photographs.

This strongly suggested the growth of oxides on copper elements of the contact assembly over a long period of exposure to oxidizing environment and the oxidation as the primary source of particles in the relay.

A.5 Conclusions

The RGA of the Chandra flight relay showed significant moisture content (0.92%) in the relay package. Such an environment at room temperature is considered ideal for oxidation of copper and copper alloys.1

The possibility of particles from external sources (such as gas supply, processing) was discounted because the relays were processed and tested per GSFC S311574 specification including PIND test. Additionally, the documentation received with the relays showed no anomalies.

The failure analysis concluded that the relay failure in orbit was likely caused by particles; the particles being generated as a result of oxidation of the copper elements of the contact assembly during long term storage (4 years) in oxidizing environment. This failure mechanism suggests that all the HRC motor select relays on- orbit have the potential to fail in a similar fashion.

A.6 Recommendations

The HRC door mechanism should not be exercised. The door requires the its motor select relay to operate properly to both close and open the door. The door does not have any failsafe features in the mechanism in the event that the door was closed and the motor select relay failed at that time. This would leave the HRC door permanently closed and render the HRC useless for the remainder of the mission.

The HRC shutters do have a failsafe mechanism to remove the shutter blades from the field of view in the event that a motor relay fails. (Note that the failsafe mechanism is a one-shot, non-resettable mechanism). At the current time, the -Y shutter relay has failed and is presumed to still be failed. Periodic attempts to select the -Y shutter motor could be done without actually deploying the shutter to see if the relay can be recovered. There is no known problem with the +Y shutter. The only drawback to the use of the shutters and reliance on the failsafe features to overcome a relay failure is the use of Starsys wax actuators in the failsafe mechanisms. Actuator of a similar type experienced failures due to burn-out of the heater prior to full actuation. Such a failure would result in the shutter blade still in the field of view, again rendering the HRC useless. This problem with the wax actuators was known prior to launch, but a decision was made not to replace them, but to overcome any potential problem operationally. The plan was to develop a procedure whereby the actuator would be turned on for brief intervals to allow the wax to heat up slowly without having to leave the heater on continuously. Heater elements of the type used in the HRC actuators were obtained from the manufacturer of the actuators for use in laboratory testing to determine the proper heater duty cycle. These tests were never conducted and no procedure was ever tested on the flight instrument. There is, therefore, some risk that the failsafe function of the shutter mechanisms could fail to function properly in the event of a shutter motor relay failure.

The HRC calibration mechanism is of no interest as the strength of the ^{55}Fe source has diminished to the point that it is no longer useful.

A.7 References

1. Handbook of Materials and Techniques for Vacuum Devices, Walter H. Kohl, Rheinhold Publishing.

A.8 Relay Photographs

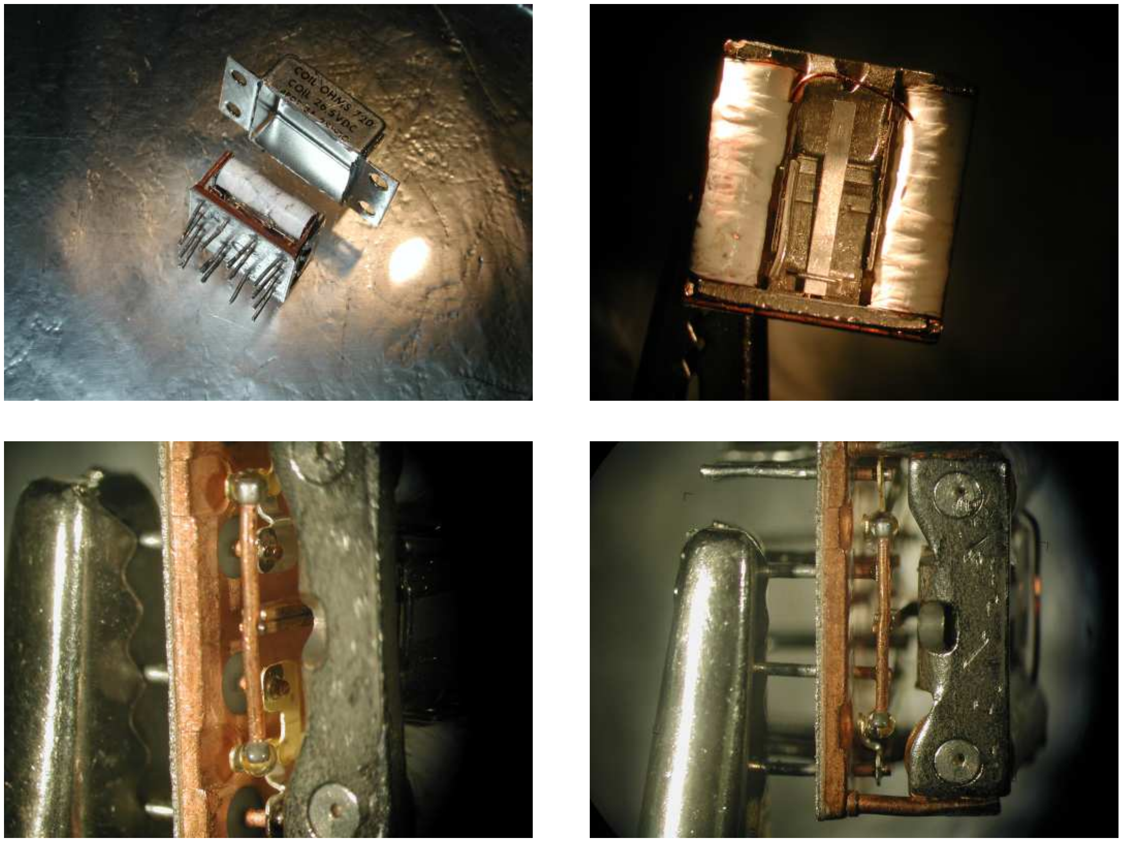

Figure A-1: Relay Views