ACIS Door Failure Investigation: Technical Details and Mitigation Procedures

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Abstract

NASA's Chandra X-ray Observatory (formerly AXAF) was launched on July 23, 1999 and is currently in orbit performing scientific studies. Chandra is the third of NASA's Great Observatories to be launched, following the Hubble Space Telescope and the Compton Gamma Ray Observatory. One of four primary science instruments on Chandra, and one of only two focal plane instruments, is the Advanced CCD Imaging Spectrometer, or ACIS. The ACIS focal plane and Optical Blocking Filter (OBF) needed to be launched under vacuum, so a tightly sealed, functioning door and venting subsystem were implemented. The door was opened two and one-half weeks after launch (after most out-gassing of composite materials) and allowed X-rays to be imaged by the ACIS CCD's in the focal plane. A failure of this door to open on-orbit would have eliminated all ACIS capabilities, severely degrading mission science. During the final pre-flight thermal-vacuum test of the fully integrated Chandra Observatory at TRW, the ACIS door failed to open when commanded to do so. This paper provides a somewhat technically expanded description of the efforts, under considerable time pressure, by NASA, its contractors and outside review teams to investigate the failure and to develop modified hardware and procedures which would correct the problem. Although, despite considerable effort, the root cause of the test failure was never explicitly identified, the expanded technical information and factors presented here may prove of use to others working the details of door design. On ACIS our efforts ultimately became focussed on hardware and procedures designed to mitigate the effects of the potential, but unproven, failure modes. We describe a frequent real-world engineering situation in which one must proceed on the best basis possible in the absence of a complete set of facts.

Introduction

The Advanced CCD Imaging Spectrometer (ACIS) is one of the four primary science instruments on the Chandra (formerly AXAF) X-ray Observatory and one of only two focal plane instruments. A picture of the ACIS instrument is shown in Figure 1. In this view, the X-rays would be imaged by the X-ray mirrors, located far above the instrument, and directed downwards into the detector housing, where the CCD imaging chips are located. The ACIS door is shown in the open position in the picture. Due to the presence of a fragile optical blocking filter over the CCD's and the need for extreme cleanliness, the ACIS focal plane must be kept in an evacuated detector housing and launched under vacuum. The blocking filter essentially "blocks" any visible or ultraviolet light from entering ACIS's aperture. Acoustic loading during the launch environment due to presence of air in the detector housing would destroy the delicate filters. The ACIS door seals the detector housing during ground operations leading up to launch. STARSYS™ paraffin (wax) actuators are used as components in a rotary actuator, to open and close the door for ground testing and on-orbit operations.

The ACIS door mechanism, designed and built by Lockheed-Martin Co., was fully qualified and life tested (on an engineering model) and the flight unit had been actuated at least 23 times during component testing and during system assembly and test operations. However, during the final Chandra Observatory level thermal/vacuum test at TRW, the door failed to open when commanded to do so. This failure occurred in June of 1998, at a time when the Chandra launch was scheduled for early CY 1999. A similar failure of the door to open on-orbit would eliminate the use of the ACIS instrument and thereby greatly degrade mission science capabilities.

Needless to say, this failure at such a critical time in the Chandra Integration and Test cycle was extremely distressing and generated an immediate, overwhelming and ultimately successful response from a combined team of NASA-MSFC, contractor and independent review team personnel[1-2].
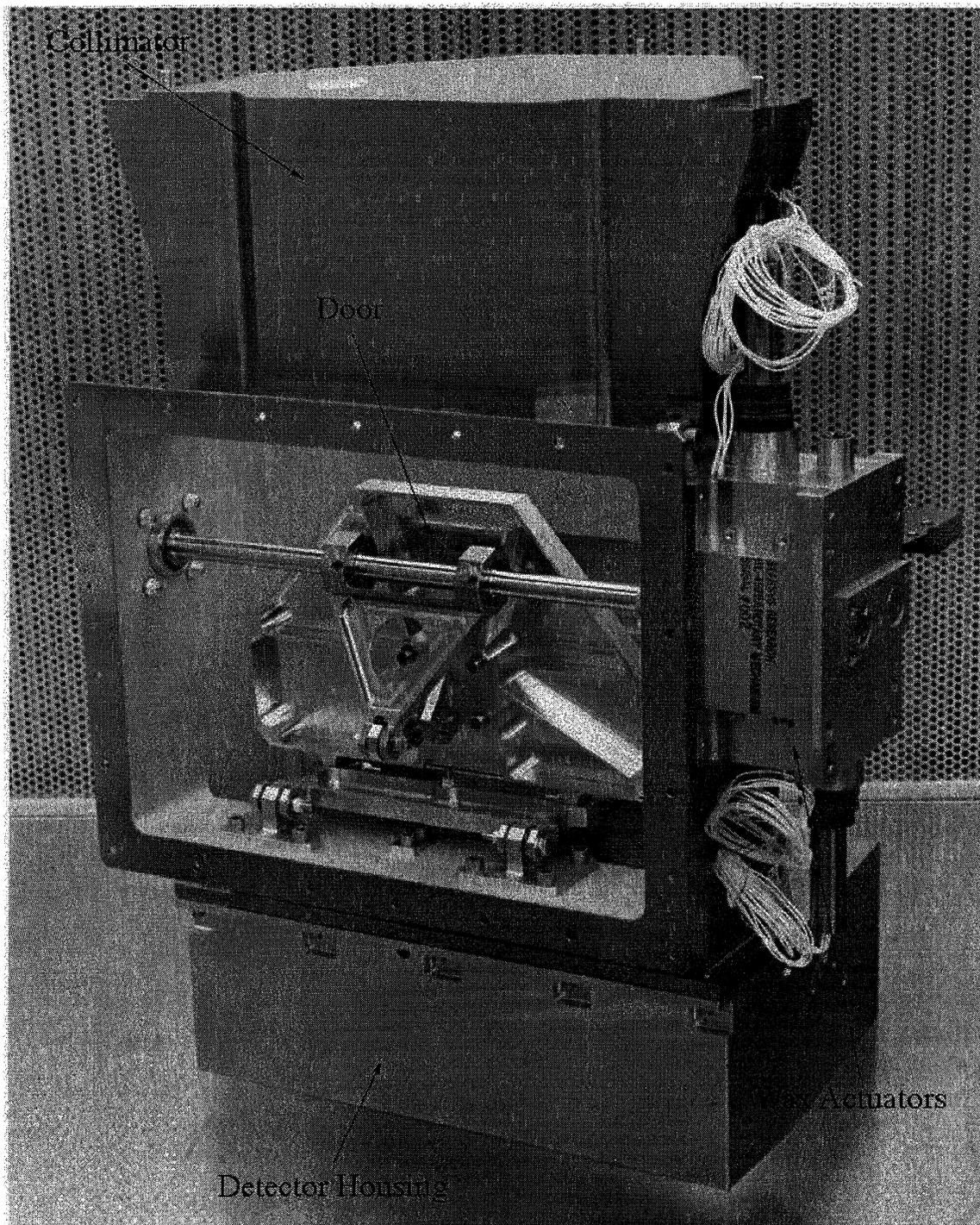
Figure 1 - ACIS Instrument

ACIS Door Mechanism Design

<u>Design Requirements</u>

The design of the ACIS Detector Assembly was performed by Lockheed-Martin Astronautics under contract to MIT (contract # SC-A-124624), who in turn was under contract to NASA-MSFC for the ACIS Instrument. Design work started in 1994 with a prototype unit built prior to Preliminary Design Review (PDR). A qualification unit was built and tested in early 1995 with the flight build and test starting in early 1996. An Engineering Unit was also built and was delivered to MIT in early 1995. There were many requirements which contributed to the final design of the ACIS Detector Assembly Door Mechanism. The key ACIS door requirements are listed below:

1.	Design Life	253 Cycles
2.	Operating Temperature Range	-60°C to +45°C (Qualification)
3.	Flight Operating Temperature	20°C
4.	Survival Temperature Range	-76°C to +45°C
5.	Operating/non-operating Pressure	800 TORR to 0 TORR
6.	Operating Voltage Range	24 Volts DC to 36 Volts DC
7.	Actuator Min. Operating Torque	> 5.1 Nm (45 In-lbs)
8.	Actuator Min. Stall Torque	> 6.8 Nm (60 In-lbs)
9.	On-orbit Operation	One open cycle
10.	Ground Operation	< 100 Cycles
11.	Cleanliness Requirements	Class 100A and meet the Requirements of MSFC-SPEC-1238 and MIL-SPEC-1443
12.	Internal Vacuum	Up to one atm Pressure difference Across Door
13.	Seal Capability	< 1 Torr leakage per Day

Contamination control was a significant design driver for the door mechanism assembly and so parting compounds were not utilized and materials and components were selected which were known to be compatible with these requirements. The requirement for an internal vacuum (in the detector housing) for all ground processing and launch environments, combined with the very low allowable leak rate for such a small instrument volume, demanded a nearly perfect hermetic door seal. An unlubricated Viton ® O-ring was chosen as the sealing material because of its vacuum compatibility and low outgassing properties. The torque requirements for the door actuator were derived from some early development tests which showed a requirement for at least 2.3 Nm (20 in-lbs) of torque capability from the actuator when using a dry Viton O-ring. Actuator trade studies performed early in the PDR design phase resulted in a decision to proceed with a Rotary Paraffin Actuator built by STARSYS Research to drive the door mechanism open and closed. This actuator (Part # HL4570B), based on a design from a previous NASA program, had redundant built-in limit switches and heaters with a positive latch at both extremes of travel. The minimum stall torque capability for this actuator was 6.8 Nm (60 in-lbs), which was a factor of 3 greater than required.

<u>Door Mechanism Actuator and Linkage</u>

The rotary actuator uses two linear paraffin actuators, one for each rotational direction. Upon actuation, heaters inside a cartridge warm the internal paraffin. As the paraffin changes phase at around 70°C its volume increase forces a steel pin outward; this linear travel is converted into rotary motion of the output shaft and coupled ACIS torsion driveshaft. The driveshaft and a folding two-bar linkage rotate the door approximately 92 degrees and out of the field of view upon opening; in the other direction the linkage is driven to a nearly straightened locking position when the door is closed. The linkage contains an adjustable turnbuckle, set to provide a calibrated force against the Viton O-ring. This force, determined through development testing, provides adequate sealing for evacuation of the instrument without additional applied forces. A "swing link" supporting the door hinge axis allows the door to seat fully on the O-ring so that O-ring compression is uniform upon preload and evacuation. An internal shear disk in each actuator prevents excessive pressure inside the actuator from causing a catastrophic failure of the paraffin actuator cartridge & protects the other components in the device from damage. However, a shear disk rupture does render the actuator permanently disabled. Figure 1 shows the ACIS door mechanism in the open position, with the access cover removed and the

<u>Door Mechanism Actuator and Linkage, Concluded</u>

STARSYS actuator on the right side of the photograph. The linear actuators are the cartridges extending from the top and bottom of the rotary actuator case.

<u>Actuator Torque Requirement</u>

The output torque required from the door actuator was almost entirely driven by the expected stiction that could develop in the O-ring door seal. A cross-section of the mechanism is shown in Figure 2 and shows the open and closed door configurations. The two bar linkage applies around 222 N (50 lbf) of force (1.8 Nm or 16 in-lbs) output torque from the rotary actuator) to the O-ring seal when in the straightened position. This force is required to compress the O-ring sufficiently so that the detector assembly can be evacuated. The mechanism itself consists of the aluminum door, dry Torlon ® bushings in all rotating joints, titanium/aluminum linkages, a titanium collimator, aluminum seal retainer and the 15-5ph stainless steel linkage driveshaft. The slip-fit Torlon bushings all have redundant moving interfaces which would nominally still allow rotation if one of
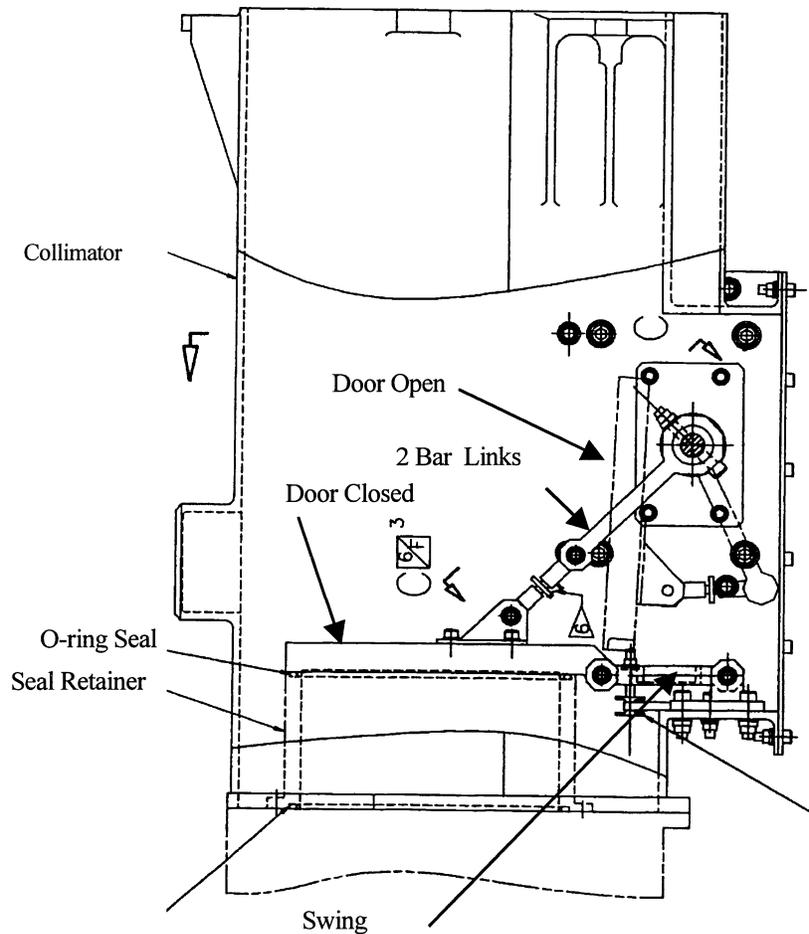

Figure 2 – ACIS Door Mechanism

Actuator Torque Requirement, Concluded

the surfaces were to bind. Running torque for the mechanism was very low, even in 1G environments, since the door weighs only about 0.11 kgm (0.25 lbs). The total running torque for the drive train was only around 0.5 Nm (4.5 in-lbs), which was mostly the frictional and spring losses inside the rotary actuator. The frictional losses in the Torlon bushings were minimal. Analysis and testing showed that there was not an issue with clearance changes that could result in any binding of mechanism components, even at the most extreme temperatures. Additionally (post-failure), the mechanical advantages at all joints were re-computed allowing for worst case angular positions (as loose tolerances can sometimes lead to unfavorable piece-part mechanical positions). This analysis showed no positions resulting in abnormal forces or restraints.

Design Redundancy

As is the case with most mechanisms or structures, the door mechanism drive train components connecting the rotary actuator to the door (driveshaft, linkages, etc.) were not redundant. Rotation joints in all linkages were intended to be single fault tolerant due to the inclusion of floating Torlon bushings. Adding a second rotary actuator would have significantly complicated the mechanism. The paraffin actuators themselves contained dual sealing O-rings and redundant heaters. The rotary actuator also contained redundant limit switches. Return springs inside the rotary actuator were designed to low operating stress levels to avoid redundancy concerns. During the design phase, a single paraffin actuator with redundant heaters was deemed to be adequate for a one-time on-orbit actuation requirement. These actuators had significant flight heritage with extremely high reliability, and required only 28 volt input power to one of the redundant heaters to perform as designed. All of the electronics required to power the actuators were fully redundant and met the single fault tolerance requirement.

Paraffin actuator shear disk rupture from high internal pressure was considered a potential single point failure resulting in loss of mission. During operation, the actuator reaches a temperature considerably above the paraffin melting point. If the case temperature becomes too high before heater shutoff, internal pressure is relieved by shear disk rupture. STARSYS research data showed a disk rupture threshold temperature of 154°C; the design team concluded that a shut-off of 135°C left acceptable margin for door operation, based on our development testing. To protect against failure, redundant temperature sensors were installed onto the actuator case and were monitored autonomously by the ACIS Power Supply and Mechanism Controller (PSMC). Power was removed if the actuator ever reached 133-135°C. The subject of shear disk rupture will be discussed in more detail later in the paper.

Pre-Flight Testing

Qualification Testing

Pre-flight testing was performed per NASA procedures to fully qualify the mechanism for flight. These tests included a 253 cycle thermal/vacuum mechanism life test on a special life-test unit (CAMSIM), O-ring stiction tests, acoustic tests, and random vibration tests. Initially it was felt that there were no significant issues that were not addressed in the final flight design for the door mechanism. One of the minor problems addressed was the burn-out of one of the life-cycle test heater elements. The root cause of this failure was a process change in a Minco heater that led to a delamination of the heater and subsequent burn-out as paraffin worked its way into the heater and fatigued the element. For flight, new heaters were fabricated with the original process and were re-qualified and life-cycle tested. A second problem occurred during the life-cycle test due to 1 G affects and rapid cycling of the mechanism and paraffin actuators. Convection inside the hot wax (only present in 1 G) resulted in a non-uniform re-freezing of the paraffin as it passed through the phase-change temperature. Since the paraffin froze at the bottom of the actuator first, the actuator output pin was prevented from fully retracting. This problem was addressed by procedural changes, a new retraction spring which had a higher spring constant, and an additional limit switch capability which would alert operators if the shaft was not fully retracted after a close cycle. There was a procedure in place, which never had to be used, to re-set the actuator should this problem repeat. These qualification tests showed that the mechanism was ready for flight build with no major design changes.

Flight Unit Testing

The flight unit Detector Assembly door was opened and closed at Lockheed-Martin at least 12 times as part of the component level Protoflight Test program under various test conditions prior to delivery to MIT. Testing included pre and post environmental exposure performance tests, random vibration tests, and thermal vacuum tests. The flight unit Detector Assembly was delivered to MIT in early 1997 and the flight focal plane and optical blocking filters were installed in April of 1997. The door was cycled open and close 11 more times in system level testing as described below.

An ACIS system level Thermal Vacuum test of all of the flight hardware was conducted at MIT Lincoln Labs. The door was cycled two times as part of the long and short form functional testing of all ACIS hardware, at hot and cold temperature extremes, with nominal results. At the completion of this test, the integrated ACIS was delivered to MSFC for an additional one month calibration test in the MSFC X-Ray Calibration Facility (XRCF) thermal/vacuum chamber. During X-ray calibration, several additional door operations cycles were performed under flight-like operating conditions with nominal performance. After calibration activities were complete, the unit was vibration tested as part of the final acceptance test by MSFC. Pre and post test mechanism performance, which included door cycling, was nominal, thus adding four more door open/close cycles. The integrated ACIS was then shipped to Ball Aerospace in Boulder for integration onto the Integrated Science Instrument Module (ISIM). The Detector Assembly was kept under vacuum for 5 months until the ISIM was fully integrated. ISIM level thermal/vacuum testing started in October 1997. During these tests the door was opened and closed two more times under flight-like conditions. One additional successful door opening occurred at ambient temperature and pressure in January of 1998. The ISIM was then shipped to TRW for integration onto the Chandra telescope. Periodic pump downs of the ACIS Detector kept the internal pressure between 0 and 10 torr for all system integration and test activities (including system Acoustic test).

Related Testing

Another STARSYS HL4570B rotary actuator (same model as for door) was used in the ACIS Large Vent Valve mechanism. A failure of this actuator occurred during the ACIS system thermal vacuum test at MIT Lincoln Labs in April of 1997. This failure was due to an operator error which caused both the open and close actuators to be powered simultaneously. Under this condition, one of the shear disks ruptured and required the removal and replacement of the Large Vent Valve rotary actuator with a flight spare actuator. Corrective action was to follow procedures to prevent simultaneous powering of open and close actuators. The large vent valve was cycled hundreds of times during test and integration and was never an issue before or after this event. However, this failure on the large vent valve pointed to a potential weakness in the actuator design. As discussed earlier, disk rupture will normally occur at a case temperature of about 154°C, and the PSMC will cut-off power when the actuator temperature reaches about 135°C. However, it was discovered that this 154°C rupture temperature was based on a linear actuator in which the output pin is allowed to extend normally to full extension. Therefore, the rotary actuator must operate with stall torques less than 6.8 Nm (60 In-lbs) on the rotary output shaft. If the output pin is restrained from extending, then there is no additional volume for the paraffin to expand into and the shear disk will rupture at a much lower temperature if power is not removed promptly. Thus, in the case of a restrained actuator, the temperature sensors do not provide protection from rupture except at end-of-stroke.

As it turns out, instead of a constant temperature shut-off point, each paraffin actuator could be protected by a variable shut-off temperature dependent on the amount of linear extension of its output shaft (transformed into rotary actuator shaft rotation). At zero degrees of rotation for the rotary actuator mechanism, the shut-off temperature should have been around 90°C rising to 150°C at full rotation or end-of-stroke. However, since a normal operation of the door or large vent valve would result in an actuator temperature of 105-110°C, we could not simply lower the shut-off temperature without affecting the ability to operate normally. It was also too late in the program to re-design the electronics to provide a variable shut-off temperature. It was evident, however, that in the case of a bound actuator shaft early in the stroke, we would not achieve our goal of opening the door. This potential new protection would have allowed us to try opening the door many times

rather than just once. The decision not to implement this protection was based on our high confidence in our ability to open the door, since we had never observed a stiction torque above 2.3 Nm (20 in-lbs) in over 3 years of testing.

To summarize the component and system level testing: the ACIS flight unit door was successfully cycled at least 23 times prior to the opening attempt at TRW under various operating temperatures and pressures. The ACIS team had confidence in the door mechanism performance for system level thermal vacuum test and for flight. There had been no anomaly in any of the previous door opening attempts. In fact, closing the door had always been of greater concern since the door was closed against a frozen (stiff) O-ring several times during these tests. Measured paraffin actuator case temperatures were always higher when closing against a frozen O-ring, but the unit was qualified to perform under these conditions so it was never an issue.

Door Opening Failure in System Thermal/Vacuum Test

Door Opening Failure

The fully integrated Chandra X-ray Observatory was subjected to over one month of thermal/vacuum testing at TRW (Chandra prime contractor). The final test planned for this period was a stray light test, in which the ACIS door would be opened and the ACIS used as a sensor to measure stray light levels within the telescope (lamp banks simulating the sun were installed in the T/V chamber). Test conditions prior to the stray light test were nominal for the telescope, with the ACIS running at cold temperatures as would be normal for observations in flight. Since there had been several past door openings with ACIS cold and a warm-up would have taken extra time, it was decided to open the door in the cold condition. At the time, there was no objection from anyone on this point.

The ACIS door opening procedure was run at 5am PDT on June 18, 1998, but the door did not open. The information available at the time was as follows: 1) Door Open Actuator exceeded its power shut-off temperature at 133°C with autonomous removal of power by the ACIS electronics (PSMC), 2) using X-ray measurements from a door mounted calibration source, it was determined that little to no motion of the door had occurred, 3) STARSYS actuator limit switch operation indicated less than 20 degrees of rotation had occurred, 4) ice had been observed on external surfaces of the Observatory, indicating the presence of at least some water in the T/V chamber, 5) the ACIS door and camera body were at —60°C, and 6) the STARSYS Actuator was at -42°C at the start of the procedure.

Post-test Failure Recovery and Analysis

Initially Suspected Failure Modes

As is usual in such cases, a small "tiger" team was formed to determine an immediate course of action. Even at this early stage, the team believed there was a high probability that the ACIS would have to be removed from the Observatory. A full stall of the mechanism with no door movement would more than likely have ruptured the shear disk inside the Paraffin Actuator based on experience with the Large Vent Valve Mechanism. A fault tree was created to help determine possible causes of the anomaly. The final form of the fault tree is shown in Figure 3. The first three (non italicized) items were those which were initially considered.

Initially Suspected Failure Modes, Concluded

A. **Door/Seal Retainer Bound**
- **Cold weld**
- *Ice*
- *Seal Adhesion*
  - *Electrostatic*
  - *Diffusion*
  - *van der Waals*
  - **Chemical Bonding**

B. **Rotary Actuator Bound**
- **Parts Bound**
- **Mismatched parts**
- **Contamination**

C. **Paraffin Actuator Bound or Failed**
- **Heater failed**
- **Wax leak**
- **Start low temp**
- **Low lube**

D. **Rotary Actuator Shear Disk Previously Ruptured**
E. **Test Procedure not followed**
F. **Retarding Torque > 6.8 Nm (60 in-lbs.)**
- **Over-center**
- **Seal Separation**

G. **Linkages Bound**
- **CTE Mismatch**
- **Bushing/Linkage bending**
- **Ice**
- **Contamination**

Figure 3 - ACIS Door Failure Fault Tree

Ideally, the team would have liked to see the unit left undisturbed to prevent the loss of information that could ultimately lead to determination of the failure mode. However, the MIT and Lockheed-Martin team concluded that there was too great a risk of damage to the focal plane and OBFs from contamination if the door were not fully closed prior to re-pressurization of the chamber. The door provides a nearly hermetic seal which would protect the focal plane and OBF's from contamination as the shrouds and spacecraft were warmed up and the chamber re-pressurized.

Recovery from Failure in Thermal/Vacuum Test

The decision was made to warm the detector assembly and door to 25°C using heaters that were designed for baking off contamination on-orbit. To protect the instrument and get the door closed, the open actuator had to be heated to soften the paraffin. With a warm open actuator, there was a higher probability that the close actuator could re-set the mechanism and latch the door closed again. The procedure was performed at 7pm PDT without success. Neither the open nor the close limit switches changed state, and the close actuator went over-temperature at 133°C as the PSMC autonomously removed power. A nominal opening or closing would normally result in an actuator temperature of around 105°C at limit switch shutoff. Now the question was whether or not the door was sufficiently sealed to allow for chamber re-pressurization. As dry nitrogen was bled into the chamber, the differential pressure transducers on the detector assembly quickly confirmed that the door was sealed, since a vacuum was measured within the detector housing. The focal plane and OBF were in a safe condition, since one atmosphere of pressure differential provides about 500 pounds of

Recovery from Failure in Thermal/Vacuum Test, Concluded

closing force on the door. Therefore once the door sealed, a positive latch was not necessary and the instrument could be handled safely without the fear of damage to the focal plane and OBFs.

During the next several days Chandra was removed from the chamber, the ISIM was removed from the optical bench and partially disassembled, then the ACIS was removed for shipment back to Lockheed-Martin. Initial external inspections at TRW looked normal except that the door did appear to have metal to metal contact with the seal retainer. This metal-to-metal contact could support the cold welding hypothesis but later inspections and testing would discount this failure mode. The ACIS detector was then shipped back to Lockheed-Martin where inspections and disassembly could occur in a class 100 clean room.

Initial Inspections at Lockheed-Martin

Failure investigation efforts centered on closing branches of the fault tree shown in Figure 3. Initial inspections of the door mechanism at Lockheed-Martin did not reveal the cause of the failure. All linkages appeared to be free and the two bar link was slightly over-center, which explained why the door was able to seal. It *appeared* that the door was metal to metal with the seal retainer, but until the detector was re-pressurized, we would not know if the door and seal were bound to one another. Since there was still a vacuum inside the detector, as measured with the Vacuum Ground Support Equipment (VGSE), we elected to remove the STARSYS actuator prior to detector housing re-pressurization, so that it could be inspected independently of the rest of the mechanism.

Door Seal/Retainer Bound (For the Non-Italicized Fault Tree Item A)

Since cold welding of the gold plated door to the aluminum seal retainer was a possible failure mode, extreme care was taken as the detector assembly was re-pressurized. Dial indicators were mounted above the door to measure movement of the door as dry nitrogen was allowed back into the camera body. The door slowly rose off of the seal retainer as the internal pressure was equalized to the ambient pressure in the clean room. The O-ring was still compliant and relaxed as the external pressure was removed from the door. Cold welding and/or galling was ruled out both because the O-ring and its gland had been sized to preclude line-to-line metal contact after a compressive set, and because the as-built O-ring had enough spring force to push the door away from the seal retainer. Close inspection revealed no signs of cold welding, metal burnishing, or metal-to-metal oxide/contaminant adhesion. This also would have been the case when the TRW thermal vacuum chamber was initially evacuated since the pressure differential across the door would been reduced in a similar manner.

With the differential pressure equalized, the door could be opened and running torque and seal adhesion could be measured. Using a torque wrench to drive the door open, the seal adhesion plus running torque was measured to be 2.6 Nm (23 in-lbs) which was near the expected value. Seal adhesions had never been measured above 2.3 Nm (20 in-lbs) and with a running torque of around 0.5 Nm (4 in-lbs), the seal adhesion was 2.2 Nm (19 in-lbs). The full capability of the STARSYS actuator as measured in subsequent testing, was around 10.2 Nm (90 in-lbs) which gave a factor of safety of over 4 above what was measured. With running torque within normal specifications, no problems were found with the mechanism. Further disassembly and inspections showed all dimensions for bushings and other components to be within specifications at room temperature. No binding or interference was found which could have contributed to the failure. Additional testing on the Torlon® bushings showed that the coefficient of thermal expansion was as expected and that analytically there were no concerns with the mechanism binding at low temperatures.

The over-center torque on the door mechanism was also found to be within specifications at about 1.9 Nm (17 in-lbs). Since this flight mechanism was set up in an over-center condition, due to normal rotational and machining tolerances, there was concern that if the over-center torque was too high then it could have combined with another failure mode to result in excessive retarding torque. This was shown not to be the case with testing on other engineering units even for an incompressible O-ring. Conservatively, the flight unit was re-assembled with the mechanism adjusted in a slightly under-center condition by building a new adapter bracket.

STARSYS Actuator Inspection and Test(Fault Tree Items B and C)

Failure of the STARSYS rotary actuator was one of the failure modes identified on the fault tree. X-ray inspection of the unit did not show any anomaly. As was expected, the open actuator shear disk had ruptured due to excessive pressures inside the actuator. The open actuator output shaft was slightly extended which explained why the latch and limit switches were not engaged. Some drive shaft rotation was also observed in the X-rays of the actuator. There was no evidence of any foreign material or debris that could have jammed the mechanism. The open actuator cartridge was then removed from the actuator assembly. As the actuator was removed, the latches and limit switches fell into place. The slightly extended output shaft, which was frozen in the paraffin, had prevented the actuator from re-setting completely. The shear disk looked like a normally ruptured disk with no signs of any material weakness. Material properties were measured for the shear disk and were as expected. There were no signs of wax leakage and internal inspections of the wax cartridge were nominal. Force measurements were made to determine the running torque for the rotary mechanism and were nominal at both room temperature and at –45°C.

Prior to total disassembly, the close actuator cartridge was removed and installed onto the open actuator side of the rotary mechanism assembly. At STARSYS, the unit was tested to failure with a full stall to characterize the performance of the actuator and shear disk under these conditions. This full stall test, performed at -45°C, simulated the condition where the door mechanism did not rotate and all bushings and linkages were frozen solid. The temperature profiles were similar to those which were measured at the time of the failure up until the actuator reached a temperature of around 129°C, at which time the shear disk ruptured. This is slightly lower than the estimated failure temperature of 132°C at TRW, but would be expected with this more severe test condition. The door mechanism linkages and torsion shaft would have allowed more rotation of the rotary actuator and thus a higher temperature at shear disk rupture. It is interesting to note that both shear disks were nearly protected since the PSMC shut-off temperature was set at 133-135°C. The peak torque at shear disk function was 10.4 Nm (92 in-lbs) vs. the 6.8 Nm (60 in-lbf) specification. Material testing showed that both the open and close shear disks were similar in thickness and shear properties, so it is likely that the STARSYS rotary actuator output was around 10.2 Nm (90 in-lbs) at the time of the failure at TRW. Complete disassembly and inspection of the mechanism and actuators did not reveal a problem. Nothing was obstructing the mechanism and the only discrepancy was the ruptured shear disk. This closed out numerous branches on the fault tree since everything appeared and functioned nominally.

The shear disk rupture point varies linearly depending on the amount of extension of the actuator linear output shaft, which can be anywhere from 0 to 19 mm. At 0 mm of linear extension, test data showed the actuator would reach an equivalent pressure to achieve 6.8 Nm (60 in-lbf) on the output shaft at around 90°C. The rupture temperature would be higher at an equivalent output torque of 10.2 Nm (90 in-lbs). For an extension of 19 mm, the shear disk would rupture at an estimated 154°C. Subsequent discussions will show that we believe the flight unit shear disk ruptured at around 132°C which also supports the evidence that the door mechanism had rotated 20-25 degrees (5.7 mm of linear extension) at the time of failure and was not locked up. The clearances in the bushings and the windup in the mechanism components could allow the actuator linear output pin to extend as much as 5.7 mm even with a stuck door.

NASA/Industry Team Formation and Failure Investigation Approach

Failure Investigation Team

The small team of Lockheed-Martin, NASA-MSFC and STARSYS personnel as discussed above initiated door mechanism failure diagnostics. Their goal was to determine the cause of the failure, fix the problem, and then return the ACIS detector to flight configuration so that it could be reinstalled on Chandra and still meet the (then projected) January 1999 launch schedule. This team was initially given two weeks to complete these activities, based on the (optimistic) assumption that the failure mechanism would be easily identified and rectified. As it eventually became clear that the failure was not going to be quickly resolved, NASA-MSFC formed a larger ACIS Door "Tiger" team which included members from NASA-MSFC, selected members the Chandra External Independent Readiness Review (EIRR) Board (from Optical Research Associates & the Aerospace Corporation), MIT, Lockheed-Martin, STARSYS, TRW and SAO. The team's function was to oversee and facilitate the ongoing ACIS door failure investigation and the decision making process. In the end, the team was to operate for almost one year, as circumstances dictated, with weekly telecons and meetings as necessary.

Failure Investigation Team, Concluded

The situation at the time the larger team was formed, in early July 1998, was not a promising one. As described above, initial work by the smaller team had ruled out many of the proposed failure mechanisms. Also, program schedule pressure was large, even though the launch date had been slipped to mid-summer 1999 due to other factors. The expanded team, along with senior NASA and program management, decided to pursue parallel paths of off-line failure investigation along with the re-build and re-test of the ACIS detector and then re-integration with the Chandra Observatory. It was believed that the re-test effort would also supply valuable data to the failure investigation team. As a further backup possibility, NASA-MSFC even developed an alternate actuator that could have been substituted into ACIS should subsequent problems with the above paths occur downstream closer to launch.

With more resources available now, many activities could proceed in parallel, even though the primary activity remained at Lockheed-Martin. These activities included the expansion of the fault tree to include a more detailed examination of the italicized items some of which were not initially considered, further investigation into the issue of ice formation, more detailed investigations into the stiction properties of Viton, a search of the prior test data to look for a possible inadvertent powering of the door actuator, development of a detailed finite element model of the door mechanism and O-ring to provide additional design verification and, of course, the re-build of the flight ACIS detector for a re-test at TRW in August of 1998.

Further Failure Investigations (Italicized Items, Section A, Figure 3), Changes, and Launch Liens

The expanded review team briefly reinvestigated a large number of fault tree branches that had been previously closed by analysis, test, and inspection. Possibilities reviewed included considerations that slow voltage ramp-ups in testing could have inadvertently produced a condition that might burst an actuator, as well as microscopic effects of ice/water, &/or Viton cold-flow. Additional tests and analyses were conducted in each of these areas, and selected design and operational changes were made to address each open fault tree branch. Mitigation schemes were implemented and verified by tests &/or FEM techniques including: (a) the use of a controlled energy slug and potentiometer to allow multiple opportunities to open the door on-orbit (reducing any paraffin actuator shear disk operational risk), (b) the previously noted elimination of "over-center" torque so as provide additional margin, and (c) use of door grounding to eliminate concerns relative to any stiction induced by electrostatic forces. Although a few KV were initially computed (given an Ion 55 source which was attached to the door for later use in on-station telescope calibrations), this value was later reduced to low levels as both further analysis and testing showed that the small gap at the seal interface can't support a significant level of charge build up. Regardless, the grounding strap was added for safety.

It was believed that a warm door opening on-orbit would close all open fault tree branches, but a launch constraint was imposed requiring a successful KSC open/close cycle. Further, an additional defacto launch constraint was imposed which required successful Engineering Unit testing using flight-like timelines for door closure. Here, the Engineering Unit (EU) testing incorporated both expected vibration & acoustic loading as well as use of selected on-station heating as part of a thermal "mitigation sequence" (this sequence will be discussed shortly). It was decided that the launch would be scrubbed if EU door opening required over 45 in-lb of torque (laboratory testing showed 19 in-lb to be a nominal stiction value, with worst-case test data of 44 in-lb achieved only once at -60°C after 28 hours). Recall that 90 in-lb was needed to cause the actuator to fail, so in constraining torques to 45 in-lb there would still be about 2X torque margin. While assessing a value to use as an EU toque limit, we also linearly added all the identified non-seal-surface-based stiction sources, and determined that only 55 in-lb of seal-based resistance might be sufficient to fail an actuator.

The cracking of the door seal at KSC would reset the stiction clock, but this was not without some risk of its own. Though the contamination effects of a KSC opening were evaluated and found to be acceptable, there existed the possibility that a *never-seen ambient-only* open failure might occur given the potential of van der Waals forces. (Recall how difficult it is to pull apart two mating microscope slides, especially with an intermediate thin film of water. Further, try and remove an ice-cube from a countertop after the cube has begun to melt. This type of stiction ties to the electrical polarization induced by surface particles; forces go

inversely as the seventh power of intermolecular distances involved.) Since ambient open forces were generally 2X those in vacuum, there seemed to be reason for suspicion. Also, since van der Waals forces can climb to 20-30 Ksi and the door-seal is approximately 20 inches in overall length by 0.1 inch in compressed-cross-section, stiction forces had the potential to overcome the available torque, even if only 1/20% of the mating surfaces were involved. The Team recognized that should a water-film based stiction actually occur at KSC, the case that the door would open on-station, despite the closure of fault tree branches, would be further weakened, and the launch might well be jeopardized. Moreover, any such ambient failure would be hard to "mitigate" at KSC as adequately dehumidifying the area would be quite difficult. Also, only small thermal changes could be introduced at ambient conditions, and small changes were determined to be insufficient to provide effective stiction mitigation. The Team decided to accept this risk, and press-on.

In parallel to firming-up KSC plans, the team developed procedural details & a flow-chart for a warm on-station opening that incorporated torque relationships as a function of time and temperature, and which accounted for all possible hardware tolerances (including issues of timing errors, temperature read-out anomalies, etc.). Also, a simulator (the CAMSIM) was used to check cold torque's, and this unit was configured to act as a Flight Unit Shadow. The CAMSIM would then be able to act as a realistic test-specimen should on-station difficulty eventually be encountered.

Transfer function calculations and tolerancing of all linkages were reworked, and all build-books were reviewed. No toleranced positions yielded sufficiently high torque to produce failure, even given the potential mechanical interferences in worst-case error stack-ups. These stack-ups accounted for temperature changes under differential expansion (Torlon/H_2O testing gave 36-37 ppm/°C matching vendor data of 30 ppm/°C), as well as relative humidity swelling and changes in the Torlon bushings (where creep effects were also measured). A detailed review of displacements Vs angles Vs joint mechanical advantages confirmed that iced/bound joints give insufficient restraint to cause a failure ($\approx$ 2 in-lbs of change). This was further confirmed by additional CAMSIM iced-Up testing. This work, taken together with our analysis, helped to eliminate linkage binding as the root cause of the failure.

Our new on-orbit operating procedures utilized the application of pulsed power to help prevent functioning/bursting of the shear disk. This allowed repeated attempts to be made to open the door. This new approach was verified on the Flight Unit (8 times), and actuator temperature/torque performance was fully characterized so we would know what to expect on-station. Also, telemetry rates were increased during door operation so as to allow for real-time interaction and possible intervention during flight door opening. Flight opening temperatures were set at ambient levels, but mitigation plans were included as a formal part of our door opening procedure. Here the plan was to rapidly thermally cycle the seal interface from 20-25°C to -60°C and back to 20-25°C, as ground testing showed that this type of cycling resulted in a 90% reduction in O-ring stiction.

The ACIS instrument operates with the detector housing at -60 °C. Bakeout heaters are supplied to temporarily raise the detector housing temperature to 25 °C in order to remove molecular contamination collected by the cold surfaces in the detector housing. Under normal conditions the radiators can cool the ACIS detector housing from 25 °C to -60 °C in about 11 hours. In contrast the bakeout heaters can raise the detector housing temperature to 25 °C in about 4 hours. For the sake of mitigation these temperature slopes constitute a rapid temperature cycle. On orbit, the bakeout heaters were on when the ACIS door was opened, raising the door seal to 20-25 °C. Should the door have failed to open, the heaters would have been turned off and the temperature of the ACIS detector housing allowed to fall to about -60 °C. Immediately after reaching low temperature, the heaters would then have been turned back on and the detector housing warmed back up to about 25 °C. After reaching high temperature, the door would then have again be commanded to open, as experiment has shown that for adhesions formed at 25 °C, this technique reduces residual adhesions to insignificant levels.

As work on the opening sequence proceeded, testing and forensics continued. Black "lines" were seen on the parted sealing surfaces. Surface reflectivity shifts due to changes in the stociometry of the gold surface coating were initially suspected, but forced O-ring extractions and IR Spectroscopy resulted in identification of the potential that a compressed baked Viton seal (two 3-4day 40+ °C cycles) could give rise to small amounts (<1% by weight) of a viscous Viton liquid (potentially dependent on the full completion of Viton curing). Interestingly, this "goo" (which was quite difficult to identify as wipes and photomicrographs were initially inconclusive), was found to act as a release agent. However, it may also have helped to catalyze the seal surface promoting cold flow, and dependent on the local morphology of the surfaces involved, it was felt that this Viton based goo might diffuse across the interface and "freeze" into the opposing face of the sealing surface. We also observed several unbaked O-rings and found that they oozed a liquid. Here the liquid, which differed in viscosity from the "goo ", increased stiction.

Nominal ice strength has been reported to be 114 Psi in shear, 200 Psi in tension, 500 Psi in compression, and 240 Psi in bending. Values depend on E-fields, entrapped air, loading speed, surface conductivity's, and surface temperatures[3-11]. Maximum ice strength is generally achieved once temperatures drop below -13°C. Note that multiple thermal cycles can raise 200 psi levels to 640 Psi. In the failed Chandra test there were 6 full thermal cycles & 3 smaller cycles, though not all of these cycles were under door-closed conditions where pressure loadings would be maximized. With shearing forces varying from over 200 psi for water-ice to potentially 2,000 psi for various types of Viton-based ice, once again not much of the sealing surface would need to suffer this type of indignity to overcome the available opening torque. (It is interesting to note that under hot conditions water & Viton can combine to produce powerful seals. Diesel engines with blown Viton gaskets generally can only have their seals removed under great difficulty.)

Initially the Team speculated that water couldn't possibly be present given the temperatures and pressures involved in on-station opening conditions, but this computation is rigorous only in an open area, and doesn't apply in a microscopic entrapped zone where the Viton seal mates with its sealing surface. In fact, this is analogous to the ice particles seen locally trapped within MLI layers, despite global conditions which would suggest ice could not be present. Depending of the temperatures involved and the shapes of these small "craters" (which here were 10 microns wide by a few microns deep over ≈ 1% of the interface, a favored size for ice-crystal expansion and bonding), the Team speculated that any water venting at an irregularity at a crater boundary might freeze at the contact point, binding the Viton seal to it's mating surface. Of course a similar bond might form should a wet crater-base be compressed sufficiently to contact the sealing surface. A rigorous analytical model of this possibility was sufficiently complex and uncertain that it wasn't attempted, but the potential appeared real enough to be a definite failure mechanism. To further complicate and aggravate the possibilities for freezing, we determined that a side-product of Viton curing is actually the production of water. (This has been noted in vacuum chambers used in optical coating. The presence of water has, at times, been traced to Viton curing /out-gassing, and later the chemistry was worked to confirm test results. MgO is an acid receptor and removes free HF molecules in curing: $MgO + 2\ HF \rightarrow MgF_2 + H_2O\uparrow$).

As part of our work we also examined both wet & dry O-rings, and monitored their behavior when compressed (as pressure is released, the O-ring "rounds-up" Vs "elevators-up"). This work was done both at TRW and at MSFC. Here a microscope was used to examine the sealing surface and O-ring shape as viewed through clear plates under various temperature & pressure conditions. SEM techniques showed no differences in the test samples used relative to the flight hardware with respect to gold plating morphology. A 70°C change loosened a "free" pressed ring but no rolling of the ring was observed. Likewise, Optical Research Associates investigated the effects of a temperature change on an O-ring compressed into a gland using FEM techniques (see Figure 4). The O-ring/gland combination was sized so as to preclude line-to-line contact of the gland and the mating sealing surface, even with the O-ring fully compressed into the gland (with compressed O-ring spring forces compatible with launch loads so as to preclude "burping" at the seal interface). The O-ring was found to "cup" like an under-inflated tire (consider the fact that the Viton has high thermal expansion, and is pinched into an aluminum gland such that on cooling the Viton shrinks into the gland). If the temperature of the sealing surface could be rapidly changed (via the bakeout heaters, as noted earlier), the Team reasoned that the resulting differential change in temperature between the opposing faces of the seal might also help shear any bond. This is because, dependent on the temperature differential between the O-ring/gland and the

opposing sealing surface, the two surfaces would move laterally relative to each other by an amount greater than the average size of any surface pits that might be frozen in place. Allowing for Viton's cold elasticity and strength, it was speculated that, given this limited FEM analysis, the net effect of these thermally induced axial and lateral motions would result in a pulling apart and shearing of any bond formed at the interface by Viton or water ice. This proved true even with cold Viton peel forces & strength up by 1.5X to 3X, based on limited testing.

O-ring Finite Element Model
assumed fixed, relative to gland,
at sides and bottom;
door effects excluded

O-ring Motion Based on ΔT = -80 $^\circ$C
Lateral Motion X-Dir = 2 μm w/r/t door
Vertical Motion Z-Dir = 8 μm w/r/t door

O-ring Motion Based on Temp Gradient of
20 $^\circ$C between Door and Gland
Lateral Motion X-Dir = 35 μm

Combo of Effects May Break Stiction
Pit Size: ~ 10 μm wide; ~ 2 μm deep
8 μm Z-Disp due to Soak is > 2μm
35 μm X-Disp due to Gradient is > 10 μm

Figure 4. AXAF Door: O-ring Motions
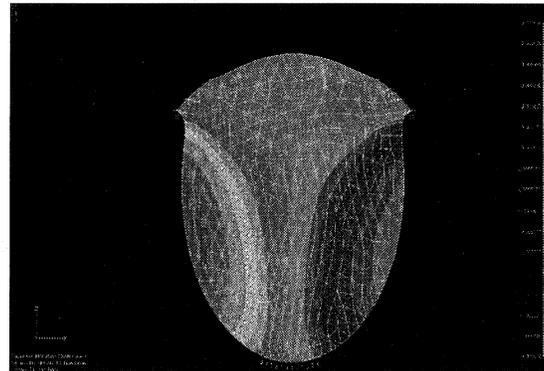
Relative O-Ring X - Disp; ΔT = -80 $^\circ$C

Z

X
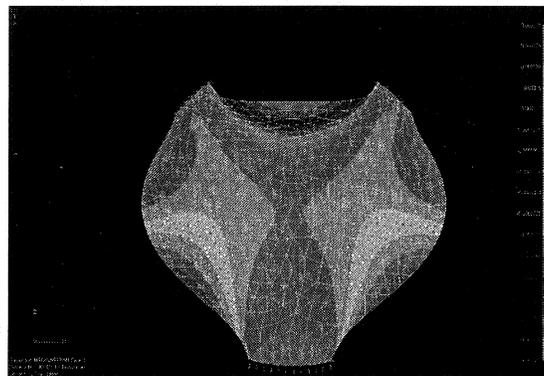
Relative O-Ring Z - Disp; ΔT = -80 $^\circ$C
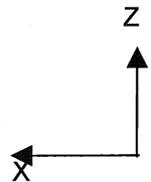
Beyond these factors, our Team also looked in detail at the specific fabrication processes used to make Chandra's 2-162 Viton 747-75 seals. In preparing Viton it is usually advisable to avoid alcohol wipes, though Viton is less damaged than many epoxies (e.g. Kapton has been rumored to experience apparent changes in surface texture). We also measured the material's diffusion and off-gassing rates (boiled O-rings absorbed $\approx$ 3.8% water by weight Vs 0.38% for standard unboiled O-rings). Viton (Vinylidene Flouride & Hexafluoropropylene Copolymer in a formulation referred to as V747-75) contains carbon black, high activity Magnesium Oxide (3%), & Calcium Hydroxide. Hydrated MgO has the formula $Mg(OH)_2$, and there are some Indications that MgO & $Mg(OH)_2$ also stick to metals (especially the later). Chandra's seals were injection molded, which results in a higher molecular orientation than compression molding. It also adds mold contaminants and release agents into the mix. However, testing showed all these factors to be unlikely as root causes of the failure.

We also surveyed other polymer bonding models Vs temperature in development at the Argonne National Laboratory, Georgia Tech., U. Cal. Santa Barbara, Pitt., Berkeley, Unitei Mixte de Recherches CNRS - Elf Atochem (France), and others, as well as tribology studies on friction and wear. However, no additional potential root causes surfaced as a result of these reviews.

ACIS Detector Rebuild and Re-Test

In the rebuild of the ACIS detector, much attention was given to possible ways to gain information on performance of the door actuator. Instrumentation to monitor door mechanism performance was added prior to the re-test which started in August, 1998. This instrumentation included non-flight strain gages to measure actuator output torque, a potentiometer on the torsion shaft (flight) and an additional temperature sensor to be used for "pulsed heating" of the paraffin actuator. This pulsed heating technique, in conjunction with potentiometer readings, would prevent the heating of the paraffin actuator so as to rupture the shear disk. Finally, a rapid warm-up and cool-down procedure was developed and demonstrated to reduce O-ring stiction (one of the possible causes of the failure) in case the pulsed heating technique did not initially open the door.

The re-test of the ACIS door mechanism (August/September 1998) was intended to re-qualify the door mechanism under flight conditions. It was decided to re-test the ACIS door as mounted to the ISIM only, not the entire Observatory. This would greatly simplify the testing and also allow work on the Observatory to proceed in parallel with ACIS/ISIM re-test. A key decision of the failure investigation team and program management was that the test would take place with the detector housing warm, as was planned for the on-orbit opening. This would eliminate any issues of ice during the re-test, but since water itself was an issue due to possible van der Waals forces, water was to be injected into the thermal/vacuum chamber to simulate the outgassing of the complete Observatory's composite materials. Some team members would have preferred to duplicate all test conditions at the time of failure (including detector temperature), but there was concern that another failure, even under non-flight conditions, would jeopardize program schedule.

The re-built ACIS detector was shipped back from Lockheed-Martin to TRW in early August 1998, and was then integrated onto the ISIM. The ISIM with both Chandra focal plane science instruments (ACIS and HRC) was then moved into the TRW thermal vacuum chamber. The subsequent test then simulated as closely as possible the projected on-orbit door opening scenario. The predicted temperature profile was closely followed. The ACIS detector housing was kept cold until about 14 days into the test, at which time the door was opened. Prior to door opening, the detector housing temperature was raised to 25°C using the ACIS bake-out heaters.

The door was opened (and then closed) a total of five times during the ISIM re-test, all using the pulsed heating technique. The first three openings were done with a bus voltage of 28 volts and the last two at 32 volts. The door angle potentiometer and driveshaft strain gages were monitored during these openings. All of the data from these openings was nominal. This successful re-qualification of the ACIS door mechanism allowed the program to proceed towards launch, but the fact that the cause of the earlier failure was still not exactly known was troubling to everyone. The ACIS failure investigation team would work for many more months, still attempting to discover the root cause of the earlier failure.

It should also be noted that there were additional door openings in an ambient condition scheduled and executed to gain confidence in the door opening mechanism prior to launch. This was accomplished through the use of the VGSE to re-pressurize the ACIS detector housing cavity with nitrogen to equalize the pressure prior to opening. This was not originally planned due to the risk of contamination entering the cavity and of inadvertently damaging the thin spectral filters. However, a more detailed look showed that if procedures were carefully followed, these risks were small enough to be acceptable, given the circumstances.

Ongoing Failure Investigations

The expanded ACIS door fault tree is shown in Figure 3. This tree evolved over the course of the investigation and guided our efforts to identify the failure mechanism. As mentioned above, early post-failure inspections and tests addressed some of the branches of the tree.

Pre-ruptured Shear Disk (Fault tree Item D)

One possible failure mechanism which had not yet been ruled out, was an accidental activation of the open actuator under ambient pressure conditions prior to the TRW test. This would have taken place after the last opening at Ball (January 98) and before the opening attempt during Observatory Thermal/Vacuum testing. With a vacuum inside the detector, the shear disk would have ruptured if the open actuator were powered

Pre-ruptured Shear Disk (Fault tree Item D), Continued

when the Observatory was in an ambient environment, since the mechanism does not have enough torque margin to overcome one atmosphere of pressure against the door. Chandra flight telemetry was monitored anytime that Chandra or the ISIM were powered up. An investigation of the available telemetry data showed no time at which the actuator temperature had exceeded ambient. However, a potential failure mode was discovered when it was determined that when the spacecraft voltage was ramped up slowly, the ACIS mechanism controller could power up without receiving a command to do so. The team was able to duplicate this condition on the ACIS test hardware and was able to show that the mechanism could have been powered up inadvertently. However, the temperature profile and limit switch actuation measured at TRW during the door open failure did not match the characteristics which would be obtained for a pre-ruptured shear disk. (When the actuator is stroked, the expansion of the paraffin gives an additional tell-tale; it produces a 2 °C to 3 °C thermal inflection point in valve time-temperature traces.) This conclusion is based on extensive testing with non-flight hardware and also the actual flight actuator used in the failed opening attempt.

As part of this work the timing accuracy's of all commands were also reexamined (data logging within major & minor data frames), and this too was cleared as a potential failure source. Commands go to the controller at the start of major frames (within 3 - 4 seconds), while both door actuator and valve temperatures are recorded later, in minor frames. This type of signal timing initially made the door actuator appear to rise in temperature before data-tell-tales showed that the actuation command was actually sent.

Figure 5 shows a typical torque curve. The strain gauge amplifiers were zeroed prior to opening even though this measurement contains significant zero offset. This offset is caused by the strain in the shaft required to maintain the 50 pound preload on the closed door. When the actuator unlatches (at ~85 seconds in Fig 5) the forces from the preload back-drive the actuator until the running torque of the actuator arrests this motion. This exhibits itself as a level portion of the curve where the linear wax actuator "catches up" to the back-driven output shaft. During this time the limit switch picks up showing that the actuator is unlatched. As the wax actuator continues its stroke what remains of the 50 pound preload is removed as shown in Figure 5 by steadily declining torque. Eventually, the preload torque is completely relieved, which removes the compression on the door linkage. At this time the linkage travels through a dead band caused by the clearances in the various mechanical components. This too is exhibited by a second, level segment of the curve (~100 seconds) and represents the true zero torque value at the shaft. As rotation continues, the linkage begins to pull on the door and the shaft torque curve in Figure 5 continues to decline. At this point the linkage is in transition from compression to tension and so represents a change of sign for the shaft torque. From this point on the torque measured is the torque caused by the adhesive forces between the O-ring and the door and any small running torque caused by bearing friction and gravitational loads. As can plainly be seen this continues until the torque curve discontinuously jumps. This discontinuity has been visually correlated with door first motion on all of the tests performed. A small residual strain remains after the discontinuity and is a result of the now freely hanging door with gravity pulling it open and any residual torque in the mechanism.

For the purposes of this analysis the second plateau caused by the unloading of the door mechanism is used as zero. The minimum reached just prior to the discontinuity was used as the opening torque. Thus, in the example shown in Figure 5 the opening torque is about 6.5 in-lbs.

Microswitch triggering tests were also conducted (positions; effects of energy stored in the linkage, etc.). These tests showed that energy stored in the linkage can move switch positions by up to 0.05", effecting the apparent timing of critical mechanical events (the shaft rotates from 10° to 20° under 60 in-lb of torque).

## Pre-ruptured Shear Disk (Fault tree Item D), Concluded

CAMSIM Opening Torque
45.5 Hour Vacuum Compression

Legend:
- Drive Shaft Torque (in-lbs)
- Switch 1
- Switch 3
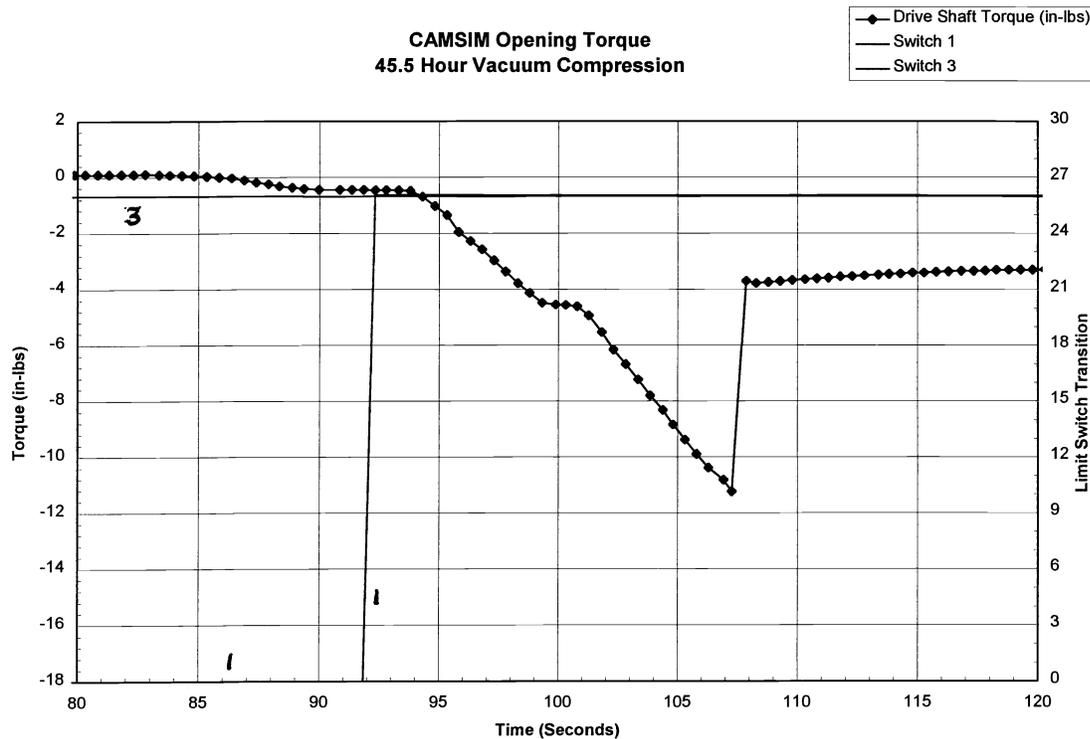
Figure 5. Typical Torque Curve for Opening ACIS Door

Ice on Mechanism (Items A and G of Fault Tree)

Icing of the mechanism (as opposed to the door seal itself) was thought to be a promising failure mode since the failure occurred when the door was opened cold and frost was seen on the Observatory optical bench prior to the opening failure. However, analysis showed that ice could not have caused the problem with the door mechanism. At the time of the failure, several different pressure monitors inside the chamber showed the pressure to be in the 10^{-6} Torr range. At this temperature (-60°C) and pressure, the sublimation rate for water/ice is greater than the collection rate and it was unlikely that enough ice could exist on surfaces at -60°C to cause a problem. Colder surfaces at, -90°C or less, did have visible ice because the collection rate was higher than the sublimation rate. Some water/ice was probably present on mechanism components since there were increases in pressure when the heater was turned on to warm the housing to +25°C. However, the thickness of water/ice would have been angstroms and not the millimeters which would have been required to block the mechanism. A pressure increase was also observed with the on-board Chandra vacuum monitor when the heater was turned on. However, even small amounts of water/ice could result in increased pressure at vacuum levels of 10^{-5} to 10^{-6} Torr. The local pressure around the mechanism would have had to been an unlikely 10^{-3} Torr in order for enough ice to collect to cause a problem. On a *global* basis then, the presence of ice was analytically shown to be non-credible. (However, as we have noted, locally, in a trapped interstitial space, the conditions can differ sufficiently to allow an iced-up *seal* to remain as a viable potential failure mode.)

To further investigate the water/ice failure mode, an engineering unit door mechanism was purposefully iced up by cooling it with liquid nitrogen in ambient pressure. The mechanism and STARSYS actuator were covered with ice from relative humidity condensation but the running torque increase was barely measurable. Other tests and studies were performed, but all of our test results failed to show icing as a failure mechanism.

<u>Further Commentary on O-ring Adhesion Mechanisms</u>

During the course of this investigation various O-ring adhesion mechanisms have been proposed as possible causes for the failure. Although none have been shown conclusively to occur under the failure conditions of the flight hardware, several remained viable possibilities. This is especially true if two or more adhesion mechanisms acted together synergistically. All possibilities focused on the properties of Viton adhering to the gold surface of the door seal under various conditions. Although this failure mode is believed to be the most probable failure mode, no test or analysis could conclusively prove that enough adhesion could have existed at TRW to prevent the door from opening. Lockheed-Martin conducted many tests with engineering hardware that duplicated the environmental conditions, but not the 7 months that existed before and during the failure. (Exponential curve-fitting of stiction values Vs time asymptote to 12.1 in-lbs, and logarithmic fits predicted 18.3 in-lbs, tantalizingly close to the 19 in-lb of torque measured when the flight door was first opened after the failure. Neither of these predicted values would create any difficulty for the ACIS actuator and mechanisms.) The team was unable to reproduce the failure under any simulated circumstance.

Plans for Flight Opening

An immense effort was expended to identify the failure mechanism prior to launch, but despite the best efforts of many able people, we were not able to conclusively identify the failure mechanism. In fact, it sometimes seemed as if the failure could not have occurred, but it had. As time went on and we approached the launch date without a clearly identified root cause, the team's (and program management's) approach was to eliminate or "mitigate" all possible remaining failure modes. The decision to open the door warm, which had always been the plan, would eliminate any potential issues with icing, however unlikely.

Since O-ring stiction seemed to be the most likely failure mechanism, even though it could not be proven, plans were developed to deal with it in the flight situation. First of all, it appeared that the stiction level would build over time, starting out at a low value when the door was initially closed, and reaching an asymptote at some later time. To minimize the potential stiction build-up, it was decided to open the flight door as late as possible in the integration process.

Another stiction mitigation technique was developed by the Team and confirmed by Lockheed-Martin in their testing using engineering models of the door mechanism. It was determined that thermal cycling of the detector housing would lower stiction levels. Mitigation testing on the CAMSIM test unit showed that a rapid temperature cycle to 25°C would virtually eliminate any O-ring adhesion which was present prior to the cycle. Two tests were preformed after a room temperature dwell with 1 atmosphere of pressure on the door for 21 and 172 hours. Using a prediction based on previous O-ring adhesion testing, one would estimate seal adhesion of 0.6 and 1.2 Nm (5.8 and 10.5 in-lbs), respectively. After the mitigation thermal cycle (described above) was performed, only 0.1 Nm (0.7 in-lbs) of adhesion were measured in both cases.

In preparation for flight, the Chandra Flight Operations Team (FOT) developed a procedure which was essentially identical to the multiple-heating-cycle ground procedure, and modified the telemetry decommutation software and display pages to utilize the new information available on the door mechanism.

A full end-to-end test of the new door procedure was executed on September 27, 1998 from the Chandra Operations Control Center in Cambridge, MA, controlling the Observatory at TRW. The ISIM was installed on the Observatory, which was in ambient conditions. The flight procedure utilized a library of command sequences that contained the actuator heater-on command, a fixed time delay, and the actuator heater-off command. These sequences were built with time delays of 50s to 200s in 5s intervals, and additionally in 250s and 300s intervals. The operator could then select the command sequence with an appropriate time interval based on the starting temperature of the actuator, the spacecraft bus voltage, and the results of the previous heating cycle. On September 27, 1998 the door opened nominally in five heating cycles. The heating cycles used were of 70, 85, 100, 110, and 250 sec. and reached maximum actuator temperatures of 61.2, 68.9, 74.1, 76.6, and 99.9°C. The spacecraft bus voltage was 31.5 V and the input voltage at the PSMC was 30.9 V.

The final pre-flight door opening took place on May 10, 1999, before Chandra was integrated with the orbiter Columbia. The opening went smoothly, after equalizing the pressure with the VGSE, with all data perfectly nominal. The instrument was commanded from the ACIS EGSE at KSC. The Observatory was in ambient

Plans for Flight Opening, Concluded

conditions in the Vertical Assembly Building. The door was opened with 4 heating cycles of 90, 100, 110, and 180 sec. duration's, and the actuator reached maximum temperatures of 63, 68, 72, and 100 C. The spacecraft bus voltage was 30 V.

On-Orbit Door Opening

The Chandra X-ray Observatory was launched from KSC on July 23, 1999 in the orbiter Columbia. On August 8, 1999 the ACIS door was opened as planned, 16 days after launch. The door opening sequence is shown in Figure 6. The same procedure was used to open the door in flight as had been used on the ground test at TRW.   The only difference was the timing of the individual heating pulses.   The door was opened with 5 heating cycles of 90, 110, 125, 140 and 200 sec. and the actuator reached a maximum temperature of 56.1, 68.9, 79.2, 87.0, and 110.3°C. The spacecraft bus voltage was 31.0 V and the input voltage at the PSMC was 30.4 V.   Actuator temperature, door angles and limit switch transitions were all as expected and are shown in the figure. With the successful door opening, the Chandra X-ray Observatory planned calibration observations were completed and scientific studies are now being performed as intended. The stiction mitigation technique we developed was essential to allow us to proceed through launch, but the actual stiction values seen by the Flight Unit were sufficiently low (with the KSC re-setting of our stiction-"clock") that its use was not required.
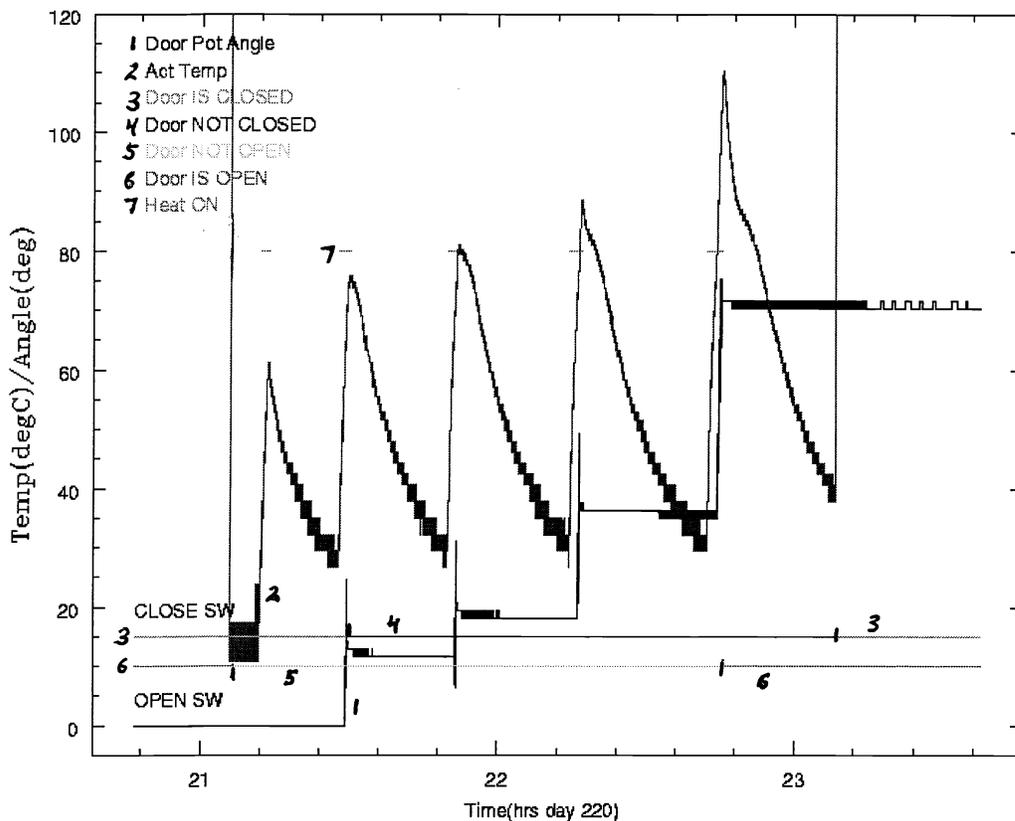

Figure 6 – On-Orbit ACIS Door Opening

Lessons Learned

If there is one lesson to be learned, it is to always "test as you plan to fly" and not push the limits of a mechanism to facilitate schedule, logistics or to reduce other potential impacts to the test program. On-orbit, it was always planned to open the door with the camera body and O-ring at 25 °C. During testing, if we had operated the door mechanism as planned, the door may have opened and we would not have had to deal with the long and involved failure investigation. If it had failed during test, the fault tree would have been much simpler since we would not have to deal with issues related to cold operation. One positive contribution, however, was the development of a much safer, more reliable operational procedure that ultimately would contribute to a successful door opening on-orbit.

Another lesson is that either the mechanism design or operational procedure should allow for a prolonged stall condition to occur, due to possible binding or stiction, without mechanism component failure. In the ACIS door application, due to the late occurrence of the failure, the program successfully adopted an operational technique to preclude a failure due to a stalled condition, and also developed a technique to remove the cause of the stall.

The results of the ACIS door failure investigation ultimately were inconclusive and thus very frustrating. The specific cause of the test failure was never positively identified, although several potential causes were left open as possible. As it became clear that the specific cause might not be identified, much effort was put into "mitigation procedures". These procedures were developed to "mitigate", or to reduce the effect of, possible failure mechanisms such as O-ring stiction. These procedures were extensively tested on ACIS door engineering models, and later on the flight unit itself.

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