Lessons Learned Designing a Spherical Satellite Release Mechanism

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Abstract

A low-cost mechanism, part of the CAPE ICU payload, was designed to contain and deploy two spherical satellites from the Shuttle in December 2006. Overall the system successfully placed the satellites into orbit but encountered an anomaly. This flight anomaly and subsequent investigation revealed several key design issues. This paper discusses the lessons learned from the inaugural mission.

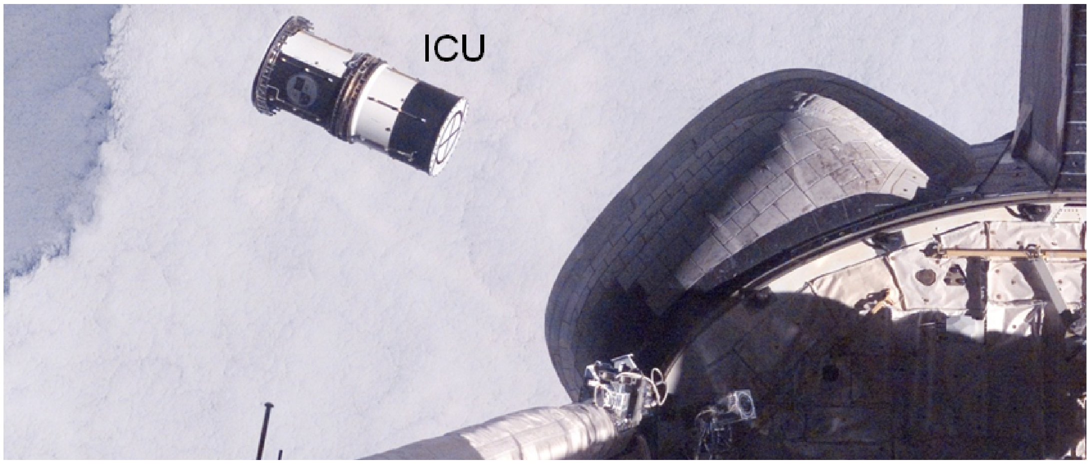

Figure 1. Ejection of ICU from CAPE aboard STS-116

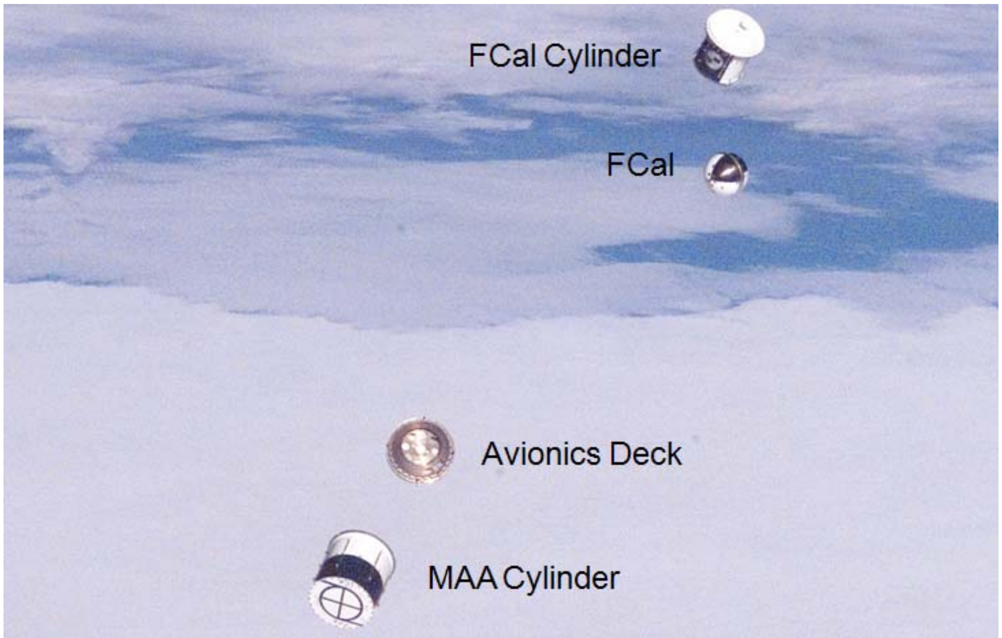

Figure 2. Separation of ICU, Releasing the Satellites

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Introduction

The goal of this project was to design a release mechanism for two spherical satellites. The mechanism was to fly on a risk reduction mission to verify the design and operation of the system for a future, more ambitious mission. Because of the need to maintain a constant drag coefficient under any orientation, the satellites had no external appendages or hard points for contact. The spheres and their release systems had to be enclosed within the Canister for All Payload Ejections (CAPE). CAPE is an aluminum cylinder 0.56m ID x 1.3m long. The Space Test Program-H2-Atmospheric Neutral Density Experiment Risk Reduction Mission (STP-H2-ANDE RR) flew aboard Space Shuttle mission STS-116.

The Naval Research Laboratory designed satellites were Mock ANDE Active (MAA) and Fence Calibration (FCal). MAA was 0.48m in diameter and 52 kg. FCal was 0.44m in diameter and 63 kg. MAA was desired to have a spin rate of 1-10 rpm upon orbit insertion. Each satellite was enclosed in its own cylinder. The cylinders were joined together by two Motorized Lightband separation systems (MLBs). When the MLBs separated, the satellites were simultaneously pushed out of the cylinders by compression springs. The name given to everything contained within the CAPE that separated from the Shuttle was the Internal Cargo Unit (ICU). At the end of one of the cylinders was a larger Lightband, CAPE Separation System (CSS). See figures 1-5

The ICU was ejected from the CAPE by means of the CSS, a diameter 0.59m NEA actuated Lightband separation system. Approximately 40 seconds later two diameter 0.50m MLBs, ICU Separation Systems (ISS), were to simultaneously separate at the center of the ICU. The lower haves of each Lightband with the motor mechanism were attached to the central Avionics Deck. The upper half of each Lightband was attached to the open end of each cylinder. Upon separation, each satellite ejected from the cylinders through the center of the upper ring.

ICU Design

The ICU consisted of five separable elements, the FCal Cylinder/ICU Lid, FCal, Avionics Deck, MAA and MAA Cylinder. The structural components had the following masses, FCal Cylinder 38.1 kg, Avionics Deck 18.5 kg, MAA Cylinder 13.4 kg resulting in a combined ICU mass of185 kg. Roller Guides on the outside of the cylinders ensured proper ejection from the CAPE. Conical pedestals held Viton o-rings. These o-rings compressed the satellites at +and – 45 deg latitude. The o-rings preloaded the satellites to minimize vibration during the launch environment. 6 Delrin sleeves ran axially along the inside of each cylinder to prevent marring of the satellites. Compression springs with Delrin guides were placed at + & - 36-40 deg latitude to aide in ejecting the satellites from the cylinders and overcoming any possible o-ring to satellite stiction. The upper portion of the spring guide held a radial ball bearing that contacted the satellite. Each satellite had two 10mm dia countersinks at 15 deg latitude nearest the Avionics Deck. The Avionics Deck Pedestals held accepting 90° conical tipped snubbers meant to engage the satellite countersinks. One snubber contained a magnet to activate an inhibit keeping the satellites turned off until ejection. The second snubber on each satellite acted as a back-up to prevent rotation of the satellite during launch incase the o-ring compression was insufficient. MAA contained a third snubber at its Delrin equator. This served as a temporary hinge point to impart rotation on MAA during its ejection from the cylinder. The entire structure of the ICU was 6061-T6 aluminum alloy. MAA had 6061-T6 hemispheres with a Delrin equator. Its surface comprised of alternating black anodized and gold irirdited quadrants. FCal had brass hemispheres with an aluminum equator. Its surface comprised of alternating nickel plating and white paint. See Figure 6.

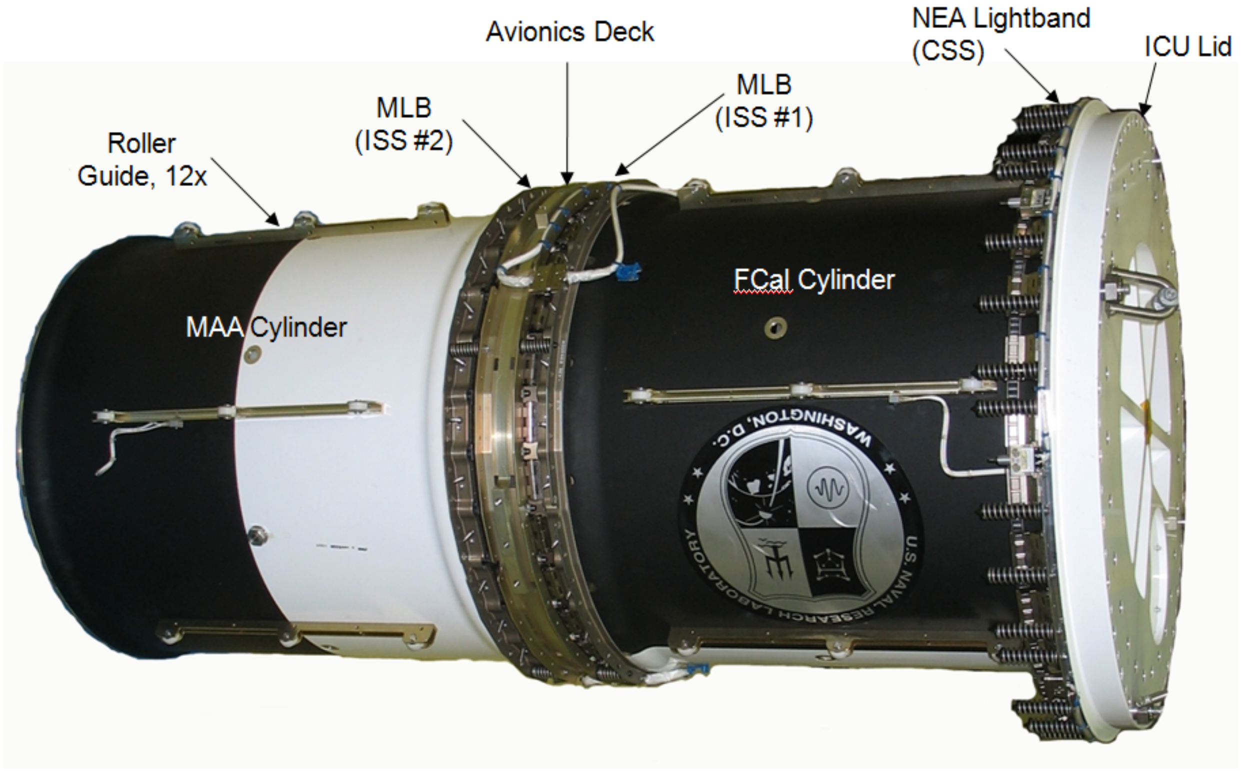


Figure 3. Internal Cargo Unit (ICU)

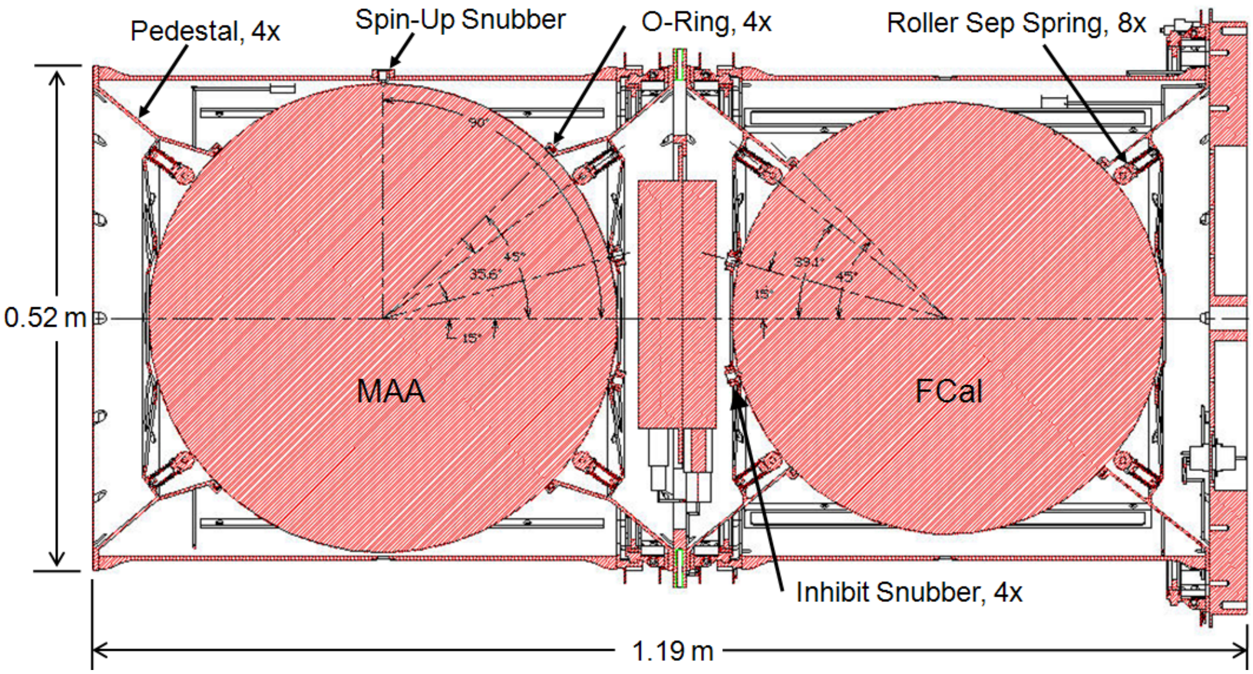


Figure 4. ICU Section, Stowed

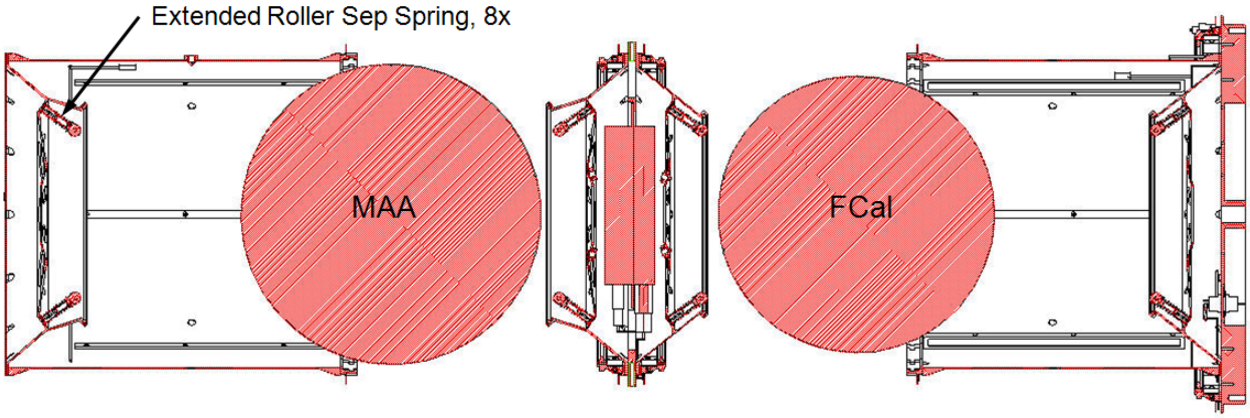


Figure 5. ICU Section, Deployed

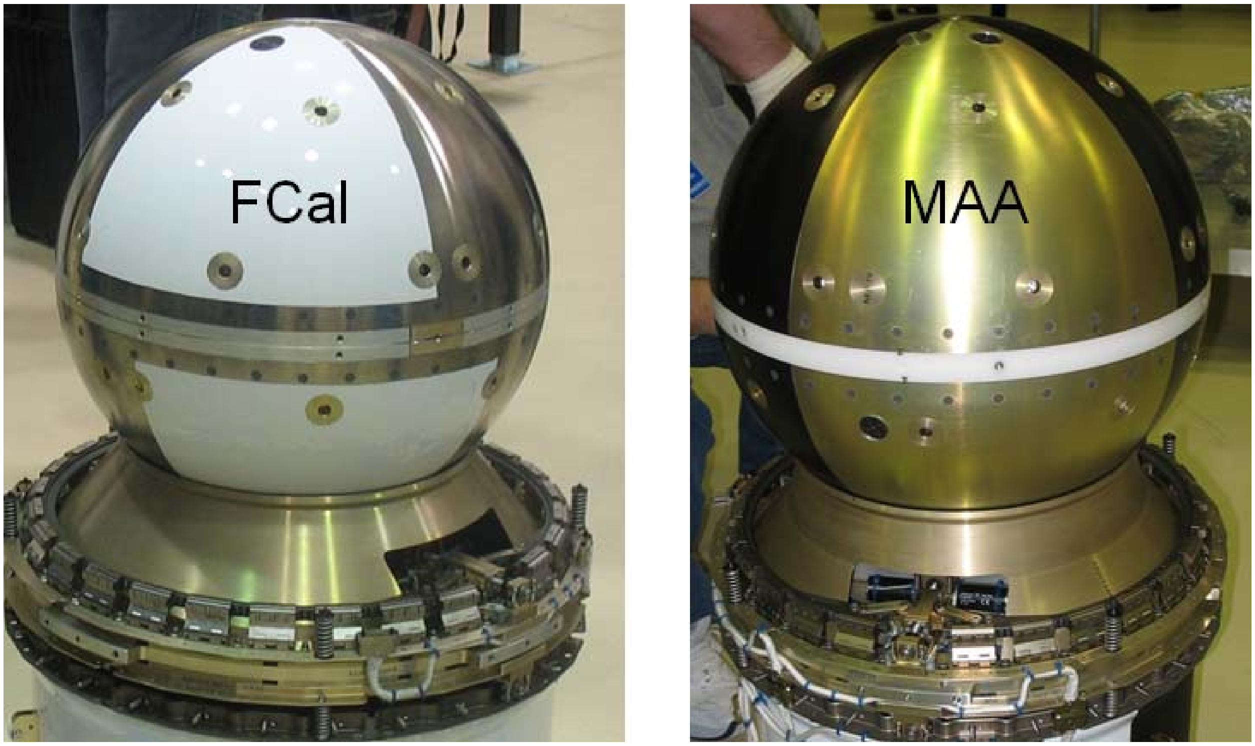


Figure 6. FCal and MAA Satellites Resting on the Avionics Deck

The Designed Separation Event

The ICU was designed to separate from the CAPE by means of actuating the NEA operated CSS Lightband. 32 compression springs on the CSS eject the ICU at a velocity of 0.52 m/s from the Shuttle. After 40 seconds, the timer in the Avionics Deck sends a signal to simultaneously separate ISS #1 and ISS #2, releasing the satellites from their respective cylinders. See Figure 7.

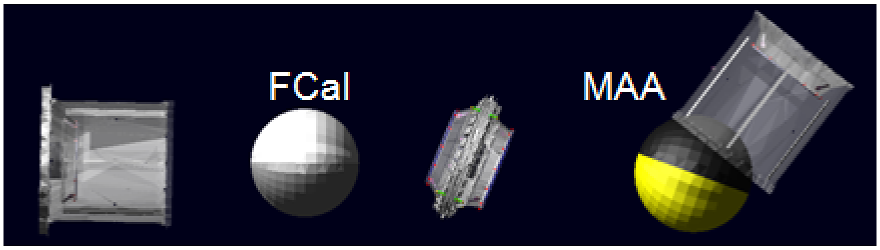


Figure 7. Anticipated ICU Separation Event

Flight Anomaly

By all accounts the ICU separated nominally from the CAPE. Video taken from the Shuttle shows the ICU ejecting smoothly with no observable rotation. Velocity appeared normal. See Figure 1.

The ISS separation event had an anomaly. The satellites did not simultaneously eject from their respective cylinders as expected. FCal separated from its cylinder. Its ejection rate was as expected except when the equator reached the end of the cylinder it temporarily “stopped” for a few seconds and then slowly continued out of the cylinder. The MAA did not come out of its cylinder. Instead of all bodies ejecting simultaneously away from the central Avionics Deck, the Avionics Deck “stuck” to the cylinder for a few seconds before slowly tumbling away. The Avionics Deck showed a noticeable rotation rate of 10-15 deg/sec while the MAA Cylinder had no observable rotation. MAA was not seen to eject for the entire 20 minutes that Shuttle video tracked the MAA Cylinder. Ground operations confirmed that MAA did finally eject approximately 1 hour after ISS separation. See Figure 8.

Figure 8. Actual On-Orbit ICU Separation Event

Flight Anomaly Investigation

Closer look at the flight video showed slight shadow movement of ISS #2 (MAA Lightband) one frame before ISS #1 movement was noticed. The theory was that when ISS #1 separated it pushed the Avionics Deck back against the MAA Cylinder causing the halves of ISS #2 to temporarily contact. Eventually it was believed that one of the roller separation springs on the Avionics Deck re-contacted MAA. This imparted a torque on the Avionics Deck, but since the spring force’s line of action bisects the center of MAA, the MAA/Cylinder received very little torque. This explains why the Avionics Deck spun-up and the MAA Cylinder did not.

Several ideas were also speculated in the days immediately following. Perhaps the MAA jammed on the spin-up snubber during ejection. MAA may have seized against the Avionics Deck snubbers when it attempted to rotate out. The o-ring stiction may have been so high that the springs could not overcome the force. The Lightband separation systems may not have separated cleanly.

Using dynamic simulation software, Matthew Eby of The Aerospace Corporation was able to model many variations of the separation event. This included simultaneous ISS separation and staggers of varying delay. He also adjusted the o-ring preload. In the end, the analysis confirmed the initial assumptions that ISS #2 separated 0.01 to 0.02 seconds before ISS #1. The halves of ISS #2 temporarily re-contacted and a roller separation spring re-contacted MAA, imparting the observed rotation on the Avionics Deck.

Since FCal ejected quickly it received far less scrutiny in the post flight investigation, however its anomaly is just as important to understand. FCal contained two antennas secured in a groove around its equator. These were to deploy several seconds after the magnetic inhibit was removed and the satellite ejected. These wires were noticed during assembly to slightly bulge out past the spherical surface near their root and initial bend into the groove. Also, the upper rings of the ISS Lightbands attached to the ends of the cylinders. The socket head cap screws used to attach them were secured with lock-wire. Great care was taken to keep the lock-wire close to the ring and out of FCal’s deployment path and staked to remain in place. It can only be assumed that one or a combination of the following occurred. First, FCal may have come off the inhibit during flight, causing FCal to power on and release the antennae. This scenario is unlikely since two snubbers penetrate the surface of the satellite. Second, the antennae could have broken free or come loose, bulging out of the groove. The antennae could then have temporarily snagged on the lock wire of the upper ring. Lastly, a section of lock wire may have broke and stuck out into the deployment path of FCal, forcing it to bend out of the way as FCal passed by.

History Leading to the Anomaly

Late in the design phase of the ICU it was determined that the ICU Lid lacked the required stiffness to prevent the ICU from contacting CAPE’s inner wall during launch. The designers lacked the necessary software to maximize the part’s specific stiffness. Thus as time was critical and the mass margin was high a design was made to simply “throw mass at the problem” to increase stiffness of the ICU Lid. The impact of this change to other aspects of the design was not fully understood until later in the test phase.

The unique design of the ICU makes it nearly impossible to test the flight separation event. The only possibility was to test on a KC-135 “vomit comet”. However the logistics and safety concerns of deploying and then restraining five separate bodies with a combined mass of 185 kg on a plane make it a difficult task. The program budget and schedule also did not allow for this. At the time, detailed dynamic analysis software was not available to the ICU designers. Therefore, an inexpensive 2D separation test was designed to simulate the flight event as closely as possible. The test consisted of 2D steel mock-ups of the 5 separable ICU components mounted on near frictionless planar air bearings. See Figure 9. The masses were fine tuned to match the expected flight masses. The test fixture itself worked well, allowing for verification and measurement of the separation velocities and satellite rotation rates. The spin-up snubber was present in the fixture; however the Avionics Deck snubbers were not present due to an oversight in the fixture design. Also, a simple means of implementing compressed o-rings could not be determined and thus they were also left out of the test.

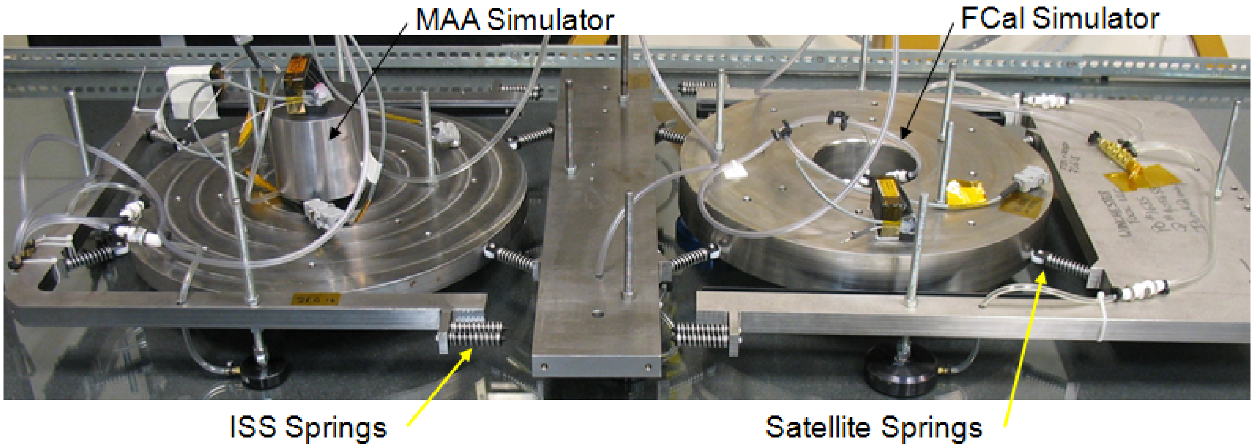


Figure 9. ICU 2D Separation Test Fixture

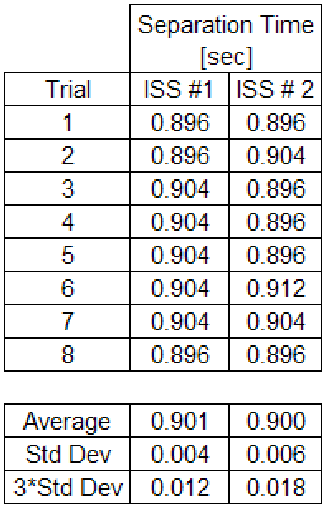
The 2-D separation test revealed that the separation velocities were too high. An imposed design requirement was that all components must separate from the Shuttle with a net velocity of 0.3 m/s. Energy had to be removed from the separation event to reduce the velocity of the MAA Cylinder. The required amount of energy removal was further impacted by the earlier decision to hastily increase the mass of the ICU Lid, effectively reducing the ICU separation velocity from the shuttle. It was deemed essential that the initial separating force from the springs remain the same to ensure proper operation of the Lightbands and overcome any possible stiction in the o-rings. It was thus decided to reduce the travel of all the compression springs from 20mm to 5mm. The final configuration consisted of 4 roller springs per satellite and 4 regular springs per ISS. The fully compressed force of each spring was 88 N.

The springs were modified and the test was re-run. Separation rates were within limits for all scenarios: simultaneous ISS separation, ISS #1 first and ISS #2 first. However, the test revealed a risk of the Avionics Deck re-contacting a satellite during staggered separations. It was deemed that tip-off of the Avionics Deck could not be controlled well enough to guarantee clearance. Thus it was decided that a simultaneous ISS separation was the best scenario for achieving proper separation of all 5 components.

Delayed ISS Separations

Because so much effort was put forth into meeting velocity and safety mission requirements no one fully considered the possible adverse effects of a near simultaneous separation. Care was taken to adjust the two Lightbands such that they separated as closely as possible. Repeatable separations within 0.01 seconds were achieved in ambient testing and the consensus off all involved parties was that this was “good enough”. The concept of re-collision was never considered. Table 1 shows data from the ambient testing to fine-tune the ISS separation times. It can be seen from the testing that a difference of 0.02 seconds was a distinct possibility as the post flight analysis presumes happened.

Table 1. ISS Separation Timing



	Separation Time [sec]	
Trial	ISS #1	ISS # 2
1	0.896	0.896
2	0.896	0.904
3	0.904	0.896
4	0.904	0.896
5	0.904	0.896
6	0.904	0.912
7	0.904	0.904
8	0.896	0.896

Average	0.901	0.900
Std Dev	0.004	0.006
3*Std Dev	0.012	0.018

Temperature was also a significant contributor to the flight anomaly. Based on initial on-orbit data taken from the satellites, it is believed the ICU was -25 °C or colder at separation. Although not out the theoretical flight limits this was significantly colder than realistically expected. ISS motion was first noticed from the Shuttle video 42 to 43 seconds after ICU ejection from CAPE. This means the ISS Lightbands took approximately 2x to 3x times longer to separate than at room-temperature. The avionics timer was verified through ground testing. None of its components are believed to be temperature sensitive. Assuming the avionics timer worked properly, the suspect component is the Lightband itself. The mechanism that initiates separation in the Lightband consists of worm gears, brush motors, ball bearings, and a ball screw all lubricated with NYETORR 5200 vacuum grease. At this low temperature the viscosity of the grease increases substantially and thus increases the torque load on the motor. Testing performed on several Lightbands at similarly cold temperatures has shown that an increase in separation time from 0.9 sec to 3 seconds is entirely possible. This rise in torque and separation time further increases the standard deviation and probability of a delay between the ISS separations relative to ambient delays.

Preloading the Satellites

The use of Viton o-rings to preload the satellites resulted in several unknown affects to the separation event. Viton was chosen because it has low outgassing properties and is readily available. However, the limiting factor of standard Viton is that its rated minimum temperature is typically only -23°C. The o-rings may have been below this temperature when the ICU actually separated. No testing was performed on the o-rings at this temperature so it is unknown what their stiffness or condition was at separation and how that may have impacted the separation event. At the time no data was available on the percentage of stored energy in a compressed o-ring that imparts kinetic energy upon instantaneous compression release. It was believed low, but at the time unknown. As mentioned earlier, the 2D separation test fixture did not accommodate o-rings.

Since the flight, testing has been performed to determine the energy ratio of Viton as a function of temperature. A 380mm diameter Lightband separation system was separated on a 5 degree-of-freedom air bearing fixture to obtain a baseline velocity. A 7mm thick, 180mm OD o-ring was then placed inside the Lightband and compressed to a known preload and distance. The Lightband was again separated and velocity measured. The change in kinetic energy due to the o-ring could then be calculated. The results can be seen in Figure 10.

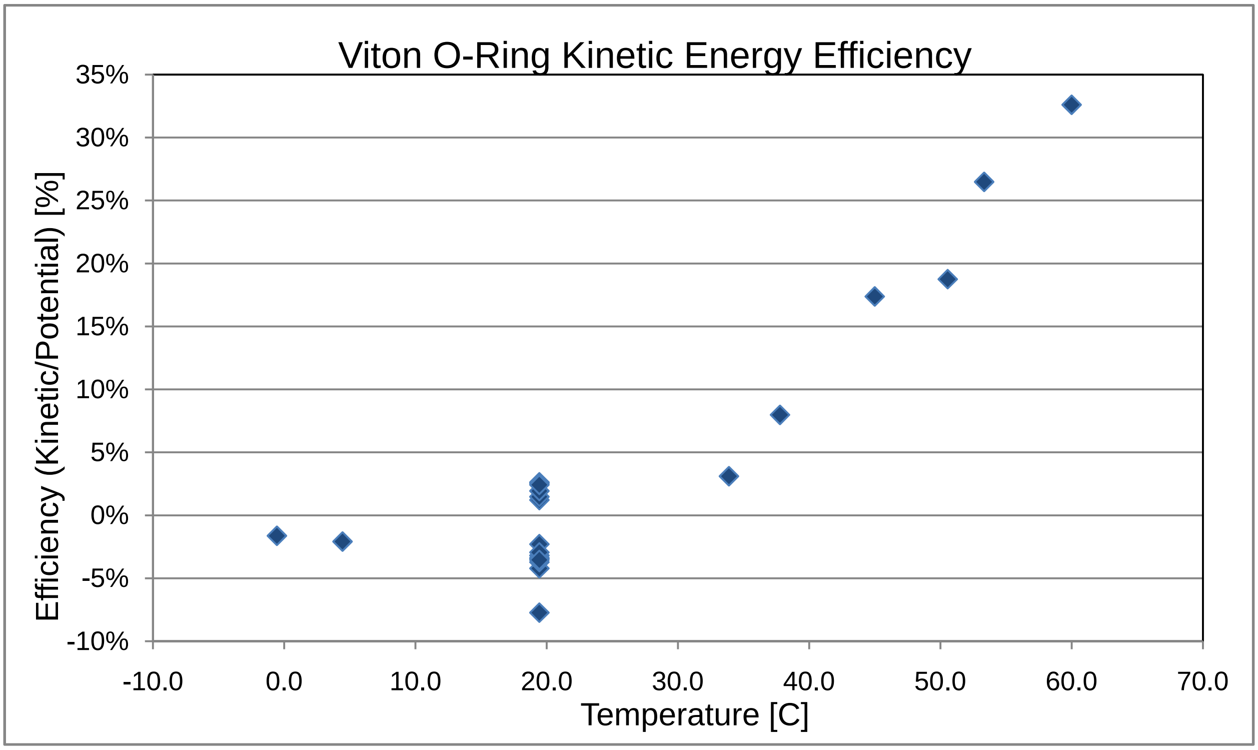


Figure 10. Ratio of Imparted Kinetic Energy to Stored Compression Energy in a Viton O-Ring

Several trials at various compressions were performed at room temperature, while only a few trials were performed hot and cold. This explains the scatter at room temperature and very little scatter elsewhere. However, from the data it is apparent that the energy efficiency of the o-ring increases with temperature. It was actually negative for some tests. The assumption is stiction between the Viton and aluminum rings decreased velocity. The test set-up and fixture limited the minimum achievable o-ring temperature to 0°C. It is still unknown how the o-ring would react at -25°C. If it follows the same trend however, it is likely that the preloaded o-rings had little effect on the separation event.

The other question that remained was the exact preload on the satellites at separation. Strain gages were bonded to the inside cylinder walls, transforming them into load cells. To keep them away from the satellites the strain gages were placed approximately 13 cm from the ends of the cylinders. These were calibrated by loading mock-up plates that simulated the interface of the satellites to the pedestals. Schedule and budget restraints prevented testing to correlate preload with respect to temperature. It also prevented the monitoring of preload over time to correlate creep in the o-rings and create a model to predict preload vs. time. The only data available was during a trial satellite installation where the satellites remained in the ICU for a few hours. See Figure 11.

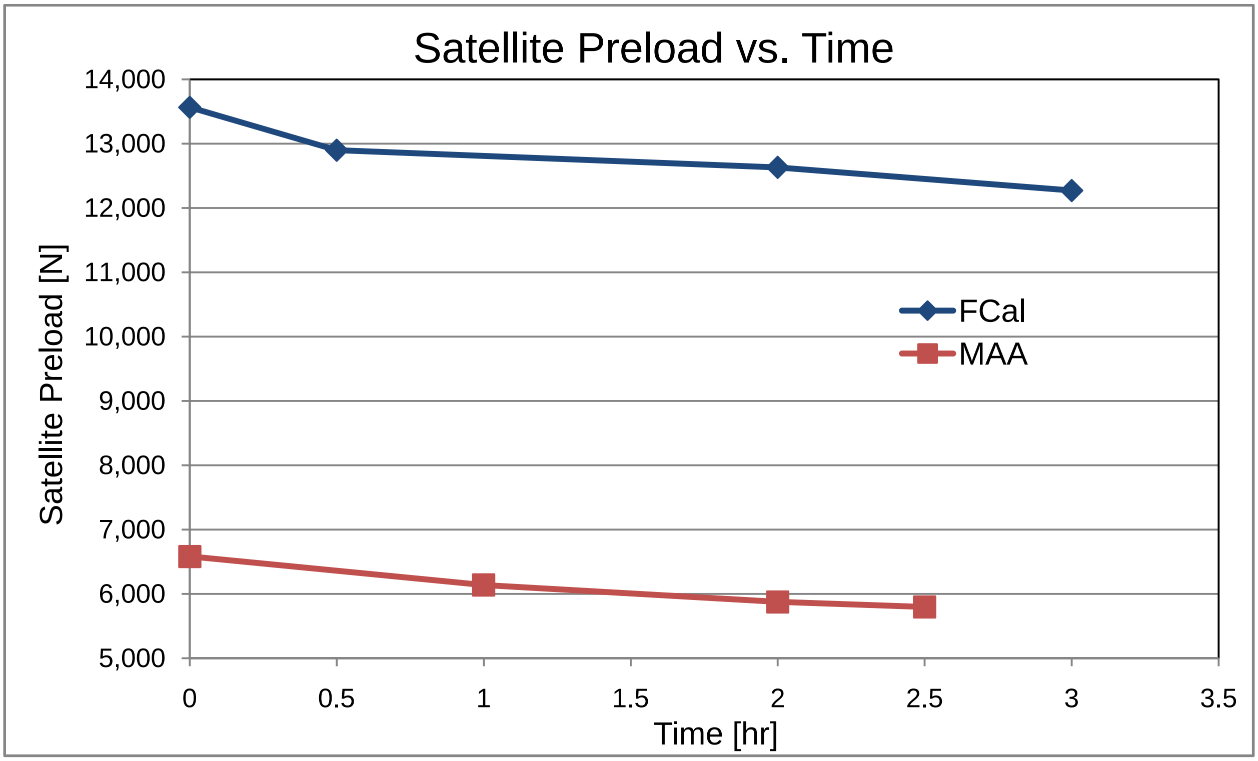


Figure 11. Decrease in Satellite Preload as a Result of O-Ring Creep

This short timeframe makes it difficult to predict whether the preload would continue dropping or eventually approach some asymptote.

The indicated preload readings were also subject to some skepticism due to the extremely low strain in the cylinders. Given the cylinders were 490mm in diameter and 2.9mm thick, the strain was on the order of 2E-5 to 4E-5. The indicator could measure this strain. The problem arose in bolting components together. Small variations in flatness often created localized stress increases that significantly changed the indicated preload. For instance, simply bolting the ICU Lid to the FCal Cylinder changed the indicated reading on FCal by 17,000 N. Because of this, care was taken to calibrate the load cells with everything fastened as in flight. However, the addition of preload shims could easily change the local flatness. With it being that sensitive, the preload on the satellites has a large tolerance. An improvement would be to put the strain gages on the outside of the cylinders so that they can be placed in the middle, as far away as possible from any localized interface stresses. Also, the flatness of all adjoining planes should be held as tight as reasonably possible.

Consideration was given to using something stiffer than Viton to contact and preload the satellites that would be non-marring. A Delrin strip was considered however this was too stiff. Since the shims can only be manufactured to 0.25mm thick, replacing one shim would result in a preload change of several thousand newtons. The cylinder walls cannot be made much thinner without affecting the overall stiffness of the ICU. An o-ring appears to be the best option. A consideration should be made to investigate the performance of either low-temperature Viton or Butyl rubber (IIR) for this application given.

Impediments to Proper Satellite Ejection

The ability to ensure full compression of the roller separation springs inside the Pedestals was difficult. Since they were on the inside of the Pedestals they were hard to inspect when the ICU was fully assembled. Fine tuning of the spring's compression was performed with the Pedestals simply pushed against the satellites on a table. Additional compression due to o-ring preload had to be analytically accounted for. It is unacceptable to bottom out the springs and risk damage to their Delrin guide components so some tolerance had to be added to prevent this. This tolerance, along with the possible variations in o-ring compression due to satellite preload is a significant percentage of the overall spring travel. This means the exact force and energy imparted by these springs in flight was unknown and likely lower than desired. This may have additionally contributed to the satellite ejection anomaly. Moving the springs outside the pedestals and more accurately predicting the o-ring compression would improve the accuracy of this spring compression.

The spin-up snubber used to impart rotation on MAA may have contributed to MAA not ejecting. During all 2D testing the snubber performed flawlessly. Post flight dynamic analysis of the separation event revealed that as MAA ejects its countersink rides up on the snubber, temporarily pushing the satellite against the opposite side of the cylinder. During normal ejection this is fine. As the Avionics Deck quickly separates from the MAA Cylinder, the roller separation springs are long enough to overcome the temporary rubbing of the satellite against the cylinder. However, the combination of the Avionics Deck not immediately releasing and the possible shortened spring travel may have combined to stop MAA on the snubber.

The implementation of the conical snubbers used as satellite inhibits and to prevent rotation unnecessarily complicated the integration process and separation event. The snubbers could not be seen during installation of the satellites onto the Avionics Deck. Thus, alignment marks were devised to ensure the snubbers were concentric to their accepting countersinks. However, even with these marks it was difficult to confirm the exact position of the snubbers. If not perfectly aligned they may have gouged the surface of the satellite as the o-ring was compressed during preloading. They also may have prevented MAA from properly rotating out of the cylinder during ejection. Since they are located on the Avionics Deck, as the sphere attempts to rotate out of the cylinder, the snubbers may have been in the way, temporarily jamming the satellite. Ideally these snubbers would be removed. Testing should be performed to verify that the sphere will not move during random vibration. It is expected that a sphere with its center of mass in the geometric center and proper preload during launch will not rotate during vibration.

Conclusion

Overall, the ICU was a great success and served its purpose as a risk reduction mission to test the separation system of spherical satellites for future missions. It proved its functionality as a low cost means of placing two spherical satellites into orbit. The ICU ejected smoothly from CAPE by means of the NEA Lightband and Roller Guides. The containment and ejection system for the spheres proved feasible. The main issue was the oversight of assuming a perfectly simultaneous separation. This however can be corrected by purposely staggering the ISS separations by several seconds. The inclusion of penetrating snubbers on the satellites complicated the separation event. Other means of imparting rotation to the satellite should be considered, including self spin-up after ejection. With the improved simulation software now at the disposal of the designers, the separation event can be accurately modeled to minimize the risk of re-contact and ensure proper satellite ejection. It will also enable the designer to account for many different scenarios.

The 2D separation test proved to be of limited benefit in predicting the flight event. The limitations of the fixture produced results that cannot be assumed realistic. Developing a detailed simulation model in software is a better allocation of resources.

A result of this mission and subsequent investigation is that it is crucial to test a mechanism throughout the extremes of the flight environment. Assuming the system would perform at flight extremes as it did under room temperature conditions was a significant oversight. The ability to predict the satellite preload and understand the effects of a compressed elastomer on the separation event at various temperatures is essential to create accurate simulation models.

Lessons Learned

The following is a summary of the lessons learned during the design, test, integration and flight of the ICU. These lessons will be applied to the follow-on ANDE mission.

- Stagger the satellite ejections. This reduces the degrees of freedom and interaction possibilities by decreasing the number of separating bodies from 5 to 3 for each event. It is also impossible to get a truly simultaneous separation of both Lightbands.
- Tighten the flatness and alignment tolerances on all mating surfaces. This will improve the accuracy of satellite preload determination. Flatness of 0.025mm may be necessary.
- Remove the penetrating conical snubbers from the satellites. They needlessly complicate the separation event.
- Perform tests to confidently predict the preload creep on the satellites over several months.
- Ensure the material properties, specifically stored energy, of an elastomeric o-ring are fully understood across the entire temperature range.
- Increase the velocity of the ICU from the CAPE. This increases the energy available to impart on the satellite ejection event.
- Make both satellites out of aluminum to minimize any thermal induced preload changes.
- Reduce the risk of snagging by eliminating lock wire near the path of satellites.
- Painting scheme and alignment marks are valuable when viewing and analyzing on-orbit video.

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