

The Failure Analysis, Redesign, and Final Preparation of the Brilliant Eyes Thermal Storage Unit For Flight Testing

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ABSTRACT

This paper describes the engineering thought process behind the failure analysis, redesign, and rework of the flight hardware for the Brilliant Eyes Thermal Storage Unit (BETSU) experiment. This experiment was designed to study the zero-g performance of 2-methylpentane as a suitable phase change material. This hydrocarbon served as the cryogenic storage medium for the BETSU experiment which was flown 04 Mar 94 on board Shuttle STS-62. Ground testing had indicated satisfactory performance of the BETSU at the 120 Kelvin design temperature. However, questions remained as to the micro-gravity performance of this unit; potential deviations in ground (1 g) versus space flight (0 g) performance, and how the unit would operate in a realistic space environment undergoing cyclical operation. The preparations and rework performed on the BETSU unit, which failed initial flight qualification, give insight and lessons learned to successfully develop and qualify a space flight experiment.

INTRODUCTION

After initial flight qualification vibration testing of the BETSU located inside the NASA Hitchhiker canister, significant damage was observed. Obviously, this experiment would not be allowed to fly until the cause of the failure was identified, corrected and the unit subsequently passed flight qualification testing. Following initial vibration testing, failures were identified and repaired, then the experiment was reintegrated and retested. Following the second vibration testing, less (but significant) damage was still observed. At this point a loose bracket was identified which was causing amplification during the vibration testing. Finally, the damage was repaired, the bracket was secured, and the experiment was vibration tested again. At this point, the BETSU was successfully qualified. Four months later the experiment was launched on STS-62 and performed exceptionally on orbit. This was only possible because of the intensive redesign and rework done during flight qualification.

INITIAL FAILURE ANALYSIS

The BETSU was deintegrated from the HITCHHIKER can and then taken from Goddard Space Flight Center to Grumman Aerospace Corp. (builders of the BETSU) to undergo any and all necessary repairs. Due to NASA flight schedules, the unit would have only 48 hours before either a retest occurred, or the experiment would not be permitted to fly. However, at this time Grumman and the Air Force were involved in sensitive contractual negotiations. As a result, the Phillips Laboratory sent a flight hardware qualified technologist to investigate the BETSU, analyze, repair, re integrate and oversee the remaining tasks necessary to achieve flight on board the Shuttle. The existing contract was amended to allow this individual access to Grumman's facilities and also to initiate any repairs necessary to make the failed unit operational. To further complicate the task, the person who had built the original unit was no longer working at Grumman.

Disassembly showed three failures: S-glass straps broken, Q-meter frayed, and mounting post bent. Figure 1 shows the original design and figures 2 thru 4 show the damage.

S-Glass

It was immediately apparent during disassembly at Grumman that the six S-glass straps, were completely destroyed. The straps are used to "suspend" the BETSU from the outside canister and to minimize thermal conductivity. The straps are about 1 1/2 " long, with a radius of about .140". Initial microscope examination indicated that the failure occurred at the apex of each radius. Analysis by the Phillips Laboratory representative on site, indicated the failure was consistent with the material "pulling apart" (Fig 2), and under the microscope one could see how the fiberglass was laid together and that it had delaminated at the apex of each S-glass strap radius. Later analysis indicated the vibration "modes" set up in the unit during testing were causing this delamination to occur.

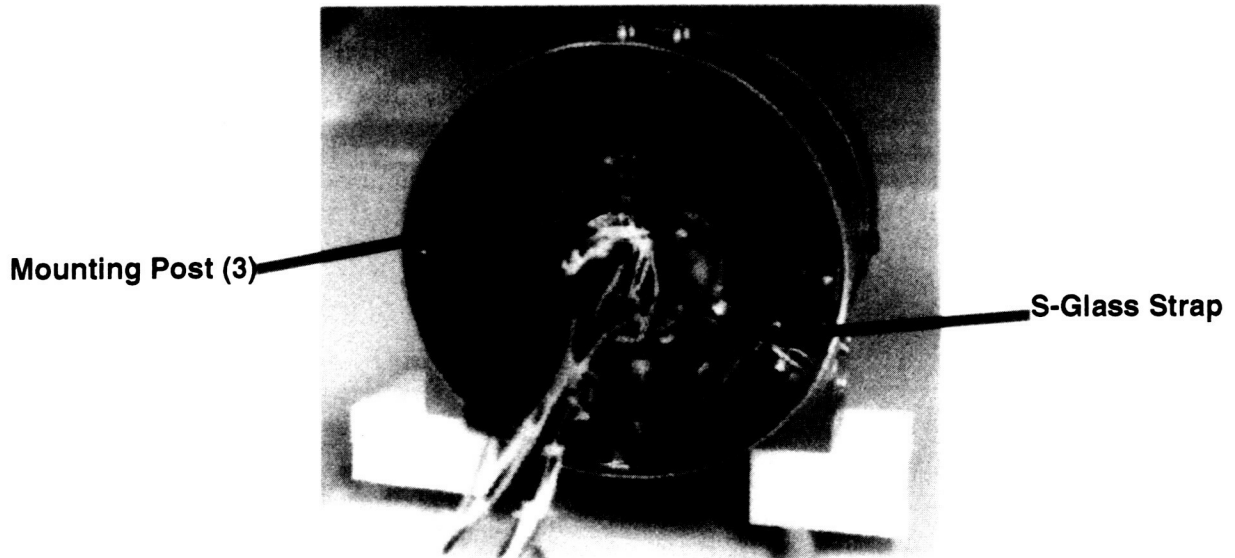


Figure 1: Original BETSU Configuration

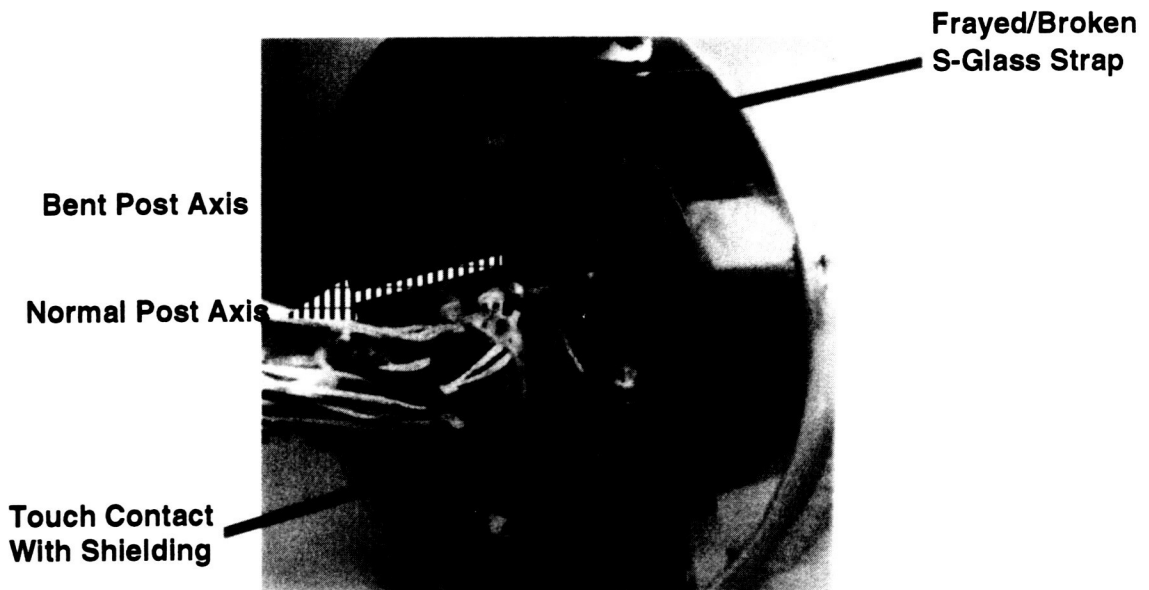


Figure 2: BETSU Damage

Mounting Post

After further disassembly and analysis, the clevaces on the three S-glass strap mounting posts (Fig 1) on the Q-meter side of the BETSU showed signs of failure. These three posts were integral parts machined into the top of the BETSU canister. It was discovered that two of the posts were cracked, about .150" up on the Q-meter side. The third post was bent almost completely over (40 deg) from normal. In addition, initial observation indicated one of the three posts on the opposite side of the BETSU (heater side) was also bent.

Q-Meter

Immediately after disassembly it was evident the Q-meter was frayed. The Q-meter is the calibrated mechanical link between the BETSU itself and the thermal shunt. It is braided steel (similar to a grounding strap), and the motion of the BETSU during vibration testing (postulated as a circular motion) had caused the attached Q-meter to literally fray apart. Since there was no Multi Layer Insulation on the unit for this test, this failure was identified by means of a bore-scope inspection.

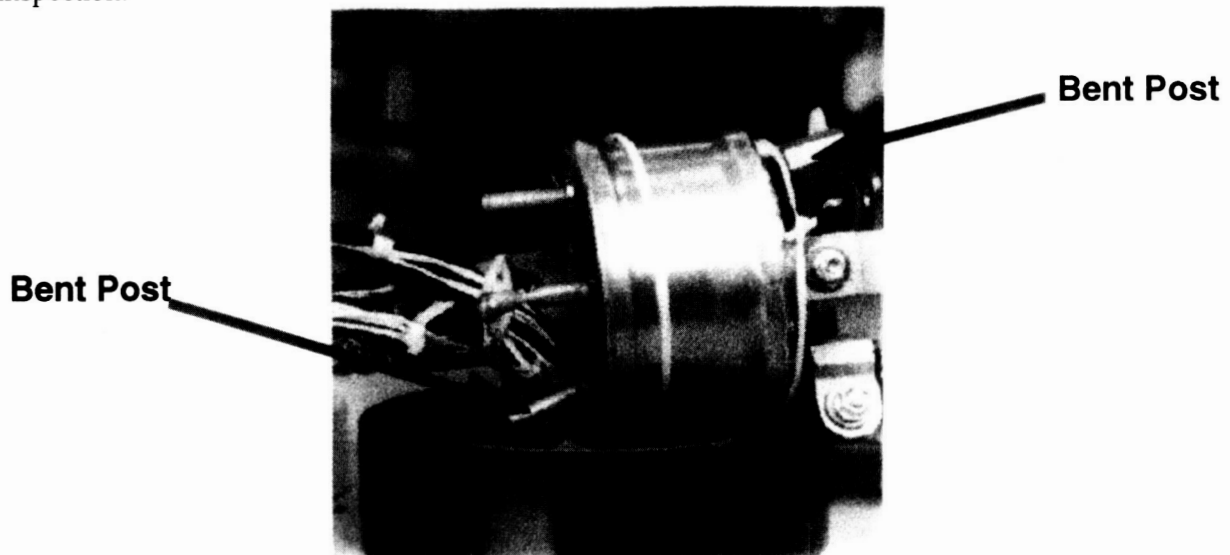


Figure 3: Mounting Post Damage

Sequence of Failure

After surveying the total damage to the unit, the Phillips Lab representative postulated that probably the front S-glass straps broke first. Since the Q-meter was bolted to the thermal shunt, with the other end attached to the "suspended" (but now free floating) BETSU, the "braided" portion of the Q-meter saw the brunt of the dynamic BETSU motion and this caused the massive fraying to occur (see figure 4). This also caused the Q-meter side posts to continually strike the outer canister and resulted in the bending and cracking noted in the post failure analysis. This hypothesis was confirmed when the inner gold shielding was examined and the "hit marks" discovered on the shielding were "reached" by physically seeing how much deflection the still attached BETSU would exhibit.

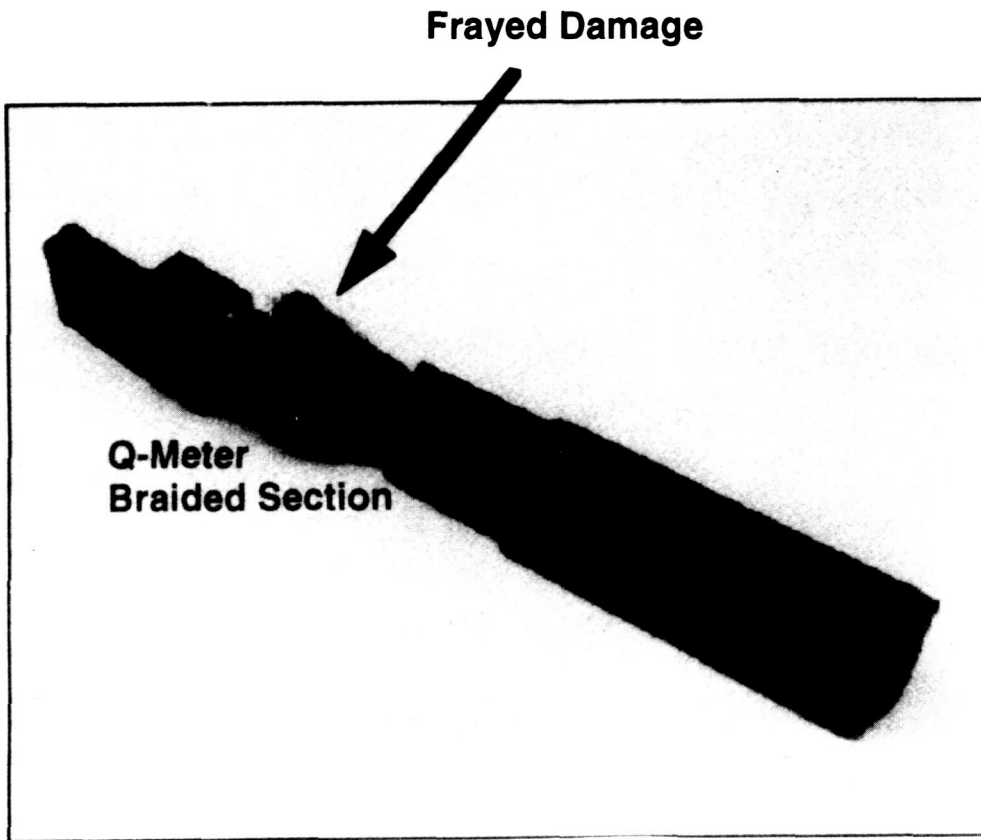


Figure 4: Q-Meter/Shunt Analysis

The "beat up" nature of the gold shielding confirmed that motion occurred at some point during the initial flight qualification testing, but whether it occurred during the 9.1g, 60 sec (each axis) random vibration test, or the 12.1g sine burst was unknowable. With only one unit in existence, this qualification unit was the actual flight unit. The qualification unit would need to be repaired and subjected to at least a repeat of the vibration testing before NASA safety would certify it flight worthy. Discussions with Grumman at this time centered on concerns with heat from any post welding operation being conducted into the BETSU canister with unknown consequences. The Phillips Laboratory tech suggested submersing the BETSU in water to keep it cold during the post welding operation and minimize thermal conductivity.

REPAIR/REINTEGRATION

S-Glass

As there was no way to repair the broken straps, they were replaced with flight spares.

Mounting Posts

A special tool was fabricated to straighten out the posts, but a penetrant test prior to straightening indicated more subtle problems existed with the two of the posts (see figure 3). These two posts exhibited numerous cracks, a typical crack being .050" long, with a .004 to .006" open gap and had a .020" to .060" depth. One post was on the heater side of the BETSU @ the 4 o'clock position, with the other one on the Q-meter side @ the 12 o'clock position.

The two posts which had multiple "cracks" were repaired in the following manner. Each crack was ground out about 1/4 of the post depth, and then welded by (TIG) process. Cold, wet rags were used as a heat sink, and finally the welds were ground and cleaned. However, the main, front Q-meter side post was a more challenging repair. This post was bent and cracked so bad that it

simply broke off about .070" from the bottom. After discussion with the Grumman machinist, the PL tech designed an L-shaped replacement post which utilized the main front Q-meter mounting point for stability. Figure 5 shows the redesigned post which replaced the broken one.

Q-Meter

As with the straps, the Q-meter was also non-repairable. consequently, it was replaced.

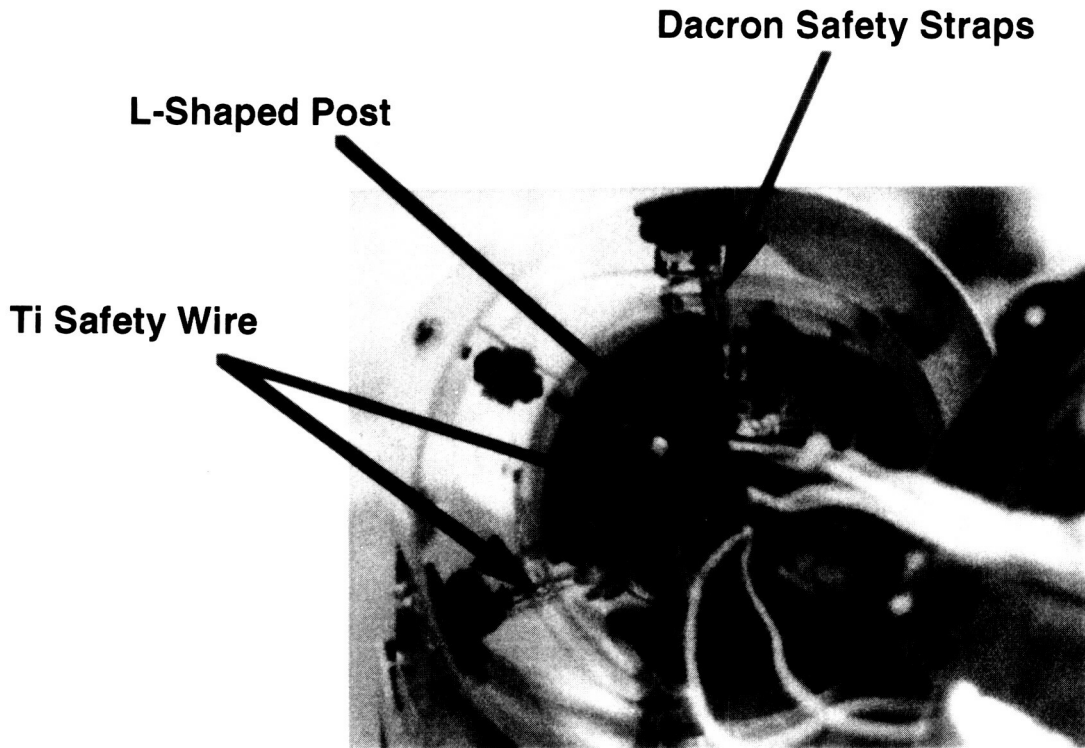


Figure 5: BETSU Repairs

As seen in figure 5, with the "base" of the L-shaped post was epoxied down, the "leg" inserted into the Q-meter mount, pinned and staked, all that was needed was to machine the vertical part to match the other existing posts. Most importantly, this solution involved no welding operations on the BETSU. At this point, repairs were basically complete on the BETSU, but still the "cause" of the failure was unknown, and thus the repaired unit would in all likelihood also fail if tested in it's present configuration. To attempt to strengthen the post "configuration" (since most of the posts had been through repeated welding and thus lost some tensile strength), the PL tech hand cut out a receiver groove (half round) in each post for use with flight safety wire. By "triangulating" safety wire around all three posts, any force was distributed across all three, and not potentially acting on only one post. This configuration was repeated on the three posts on the Q-meter end of the BETSU. Then all six posts had washers staked down on the can to give the clevice a little more strength. It was hoped that this would help the BETSU "survive" the qualification retest.

Additional Repairs/Reassembly

Besides the aforementioned mechanical/structural repairs, the qualification unit also needed to have the following repairs and/or replacements:

- a. Repair crushed heater wire near heater plate
- b. Repair Platinum Resistance Thermometer??? (PRT) #23 (on heater plate) wire in vicinity of Q-meter
- c. Install six new PRT's on Q-meter

- d. Rework daisy chain with six wires from new PRT's.
- e. Install aluminum tape over PRT #23 on heater plate
- f. Verification test the six thermocouples did indeed close when cooled (LN2 test)
- g. Re-epoxy one thermostat on inboard side of heater plate
- h. Replace one G-10 heater support angle from spares
- i. Clean gold plated thermal shields
- j. Re-stake hardware on heater plate and all other locations where appropriate.
- k. Replaced all fasteners per NASA flight hardware regulations

During BETSU reassembly, the PL tech discovered that although the unit was "secure" in a solely lateral or vertical direction, it was not as rigid when it comes to twisting or flexing about the unit's centerline. Since this was discovered during reassembly, and time was already running out, there was little to do except note the phenomenon. About this time, other players (namely people from the Aerospace Corp.) were beginning to work up models with the S-glass straps to see if they could really do the job. However, this was not finished in time for the reassembly timeline.

The unit was tightened "as solid" as the technologist felt was prudent, and this was greater than the original Grumman specifications called out.(12.72 lbs) However, tightening only to the Grumman specifications allowed too much torsional movement, and it was decided that this type of movement should be minimized if possible. The tech suggested that some sort of "safety strap" be used around the S-glass straps to minimize BETSU damage if another S-glass failure occurred during retest. This was purely a "damage mitigating" thought since it was felt the cause of the first failure was still unknown, and thus the same type of failure could occur. Safety strapping could thus help minimize internal damage and 1) reduce the amount of rework necessary and also 2) "protect" enough of the unit so that the "failure mechanism" may be more apparent. Thus, the tech added NASA flight certified Dacron as safety straps around the S-glass straps during reassembly.

NASA FLIGHT QUALIFICATION RETESTING

A little over 48 hours had passed when the repaired and reassembled unit was driven back to Goddard and reintegrated into the HITCHHIKER canister by the PL tech. The canister was vibrated again, and post-test inspection indicated another failure had occurred. The Q-meter was found to be loose, and the S-glass straps were broken again, the Q-meter was frayed, and the electronics were damaged. About this time, it looked as if an "amplification" was occurring inside the HITCHHIKER canister, and not just in the BETSU. This could be anything from a mass/location/inertia problem, to a faulty vibration test rig.

S-Glass

The straps had broken exactly as they had the first time the BETSU was shaken.

Q-Meter

The Q-meter was minimally damaged. It is believed that the safety straps had minimized the Q-meter damage

Electronics

The cryo electronic control module (CECM) package was found to be "broken.. Boards had come off their stand-offs, and even piece parts (chips, etc.) were "sheared" off the boards!

Loose Bracket

During disassembly/reassembly, the tech discovered a support structure mounting bracket for the CECM was loose. When this bracket was taken off, indications of motion was so severe that the plate it was attached to was gouged severely. This provided a possible explanation for the suspected amplification.

REPAIR AND REINTEGRATION

S-Glass

At this time, replacements for the S-glass straps were the number one priority. Various manufacturers and materials were tested for suitability. Kevlar was tested, but it was found that the elasticity characteristics were not suitable for the size and length of the attachment. In addition, the repaired posts would have to withstand whatever tension was necessary for the S-glass replacement material. It was later shown that the post redesign was three times stronger than the original, and had plenty of margin for the S-glass replacement material. In the end, the configuration tested and flown was titanium wire, with the "knot end" welded together and the Dacron safety wire as a backup. This necessitated additional repairs on the electronics control unit in addition to BETSU repairs and S-glass replacement testing.

Q-Meter

Clipping frayed edges was the only repair task necessary to the Q-meter. The repaired Q-meter could be used in space, and then "recalibrated" on the ground.

Electronics

The electronics were fully disassembled and inspected. All broken piece parts were repaired or replaced.

NASA FLIGHT QUALIFICATION RETESTING

NASA safety agreed that at this point a component level vibration of the BETSU alone would be acceptable. It must be remembered that this GAS can had already gone through flight qualification testing, flown on the shuttle, and been subject to two more flight qualification vibration tests. It was strongly felt this bracket was shaking inside the canister and setting up the amplification which was destroying the internal components. This part of the structure was repaired and then NASA safety was called in to make a ruling on what the vibration retesting would consist of. It was felt the canister and all the components inside it had seen two vibration tests, and only the BETSU had never "passed".

The BETSU was bolted on a plate, re-vibrated, and it PASSED!

CONCLUSIONS/LESSONS LEARNED

The entire BETSU failure analysis, redesign and flight acceptance highlights several important factors which anyone preparing to qualify hardware for space flight should consider.

First, NASA flight qualification standards are primarily geared towards preventing the unwanted, catastrophic failures of individual components which could damage/jeopardize the rest of the space vehicle. Proper operation of an individual subsystem after flight qualification testing is complete rests entirely with the manufacturer and/or hardware integrator. With this in mind, initial component design and analysis must ensure proper operation after flight qualification testing, not just enable the unit to "survive" this test. If the initial design is unable to operate after qualification testing, a redesign by personnel knowledgeable in the system/experiment, and familiar with the "host" spacecraft is essential. If that is not practical, the next best option, as demonstrated in this paper, is a flight hardware qualified technologist utilizing the best engineering practices in real time to rework the subsystem/experiment and enable the unit to complete the mission.

Second, a space hardware systems engineering thought process must enter into the initial design of any flight system/experiment. Without proper systems engineering design, a "black-box" which is designed to meet flight requirements may still experience failure when integrated into the rest of the spacecraft and tested as a complete unit. The structural rigidity of the spacecraft mounting, distributed power, thermal management, etc., are never fully certain until all the parts are fully assembled. As demonstrated by the BETSU failure, even a highly successful, seemingly well known environment like a NASA Hitchhiker canister can prove difficult to predict accurately. This highlights the fact that any piece of flight hardware must be treated as if it was being flown

for the first time and considered as a potential problem until proven acceptable. Thus, sufficient initial design margin and experienced hardware integrators can prevent a catastrophic failure which almost occurred with the BETSU.

Finally, failure analysis of any kind (not just during space flight qualification testing) should be considered from an overall systems perspective. Stopping a failure analysis just because the "broken" or "faulty" part is observed can cause you to zero in on the symptom and ignore or miss the cause of the failure. As observed with the BETSU, although it was expected that the original S-glass straps would have failed under normal vibration testing, this was not the only problem identified. Further inspection was required to identify the loose bracket which most likely was "amplifying" the vibration environment of the experiment. So, even if an obvious failure is identified, continue to completely examine the subsystem/experiment for other failures and also inspect the rest of the overall system for induced failure mechanisms.