

Major Design Choices and Challenges that Enabled the Success of the Ejectable Data Recorder System

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Abstract

The Ejectable Data Recorder (EDR) subsystem was added to the Crew Module (CM) of the Ascent Abort 2 (AA-2) test flight due to a risk that the communications architecture would be insufficient to downlink all the data to the ground during the test flight. Since the EDR subsystem was a secondary system for data collection, AA-2 management enabled the team to take a different approach to hardware development that was more agile-like. This paper discusses key design decisions, technical challenges, and lessons learned that enabled the success of the EDR system during its flight on July 2, 2019.

Background

The successful Ascent Abort 2 (AA-2) test flight on July 2, 2019 demonstrated the Orion Launch Abort System (LAS) performance during the maximum dynamic pressure phase of the launch (Figure 1). In order to reduce costs, the test used an aerodynamically and structurally representative boilerplate substitute for the Orion spacecraft Crew Module (CM), which was not equipped with a parachute recovery system. Rather, the CM was discarded several miles off shore at the conclusion of the test. Although data from the developmental flight instrumentation (DFI) system was returned via high data rate telemetry link, the risk of interruption in the telemetry justified the development of a backup data recording system. The CM splashed down into the ocean after the launch and was not intended to be recovered. Thus, the data recorders were ejected after completion of the LAS test phase of the flight, but prior to water impact of the CM. Then, the data recorders were independently retrieved via water recovery operations.



Figure 1: AA-2 launch.

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The Ejectable Data Recorder (EDR) subsystem had three major functions: record the data, eject the payloads, and provide the location of the payloads so that they could be retrieved. These functions were implemented through a dual string redundant system that consisted of a US Air Force AN/ALE-47 flare and chaff dispenser system, a breakout box that contained the computer for the recording capability and routed power and data, and a payload (Figure 2) with a memory device and a beacon. The details of this design will be presented at the IEEE Aerospace Conference in March 2020¹. This paper expands upon the previous paper with focus on key design decisions and a non-traditional development process at NASA that enabled success of the EDR subsystem, within the constraints of limited resources and a compressed schedule.



Figure 2: Six of the twelve flight payloads near completion.

Aggressive cost and schedule limits for the AA-2 program, exacerbated by the late addition of the EDR subsystem, forced development to proceed along an accelerated path with resource limitations that did not allow for a typical process of developing requirements, defining environments, and analytically validating design solutions. With an incomplete set of requirements, engineering judgment guided the identification of design parameters with the most uncertainty, and/or highest risk of not converging on an acceptable solution. These parameters were pursued with demonstration testing as early as possible in the development process, which provided the necessary evidence regarding those requirements with the highest sensitivity to the design parameters. Requirements definition matured concurrently with testing progress. Design was explicitly driven to maximize potential for large margins in parameters with high uncertainty and low sensitivity. The design also allowed for radical redundancy – twelve data recorders were flown, but only one needed to be recovered to obtain the full flight data set.

Unique Challenges

The principle challenge was to determine how to eject a recorder from the CM. Detailed knowledge of the local environments at the time of ejection was not available, but the ejection system needed to ensure confidence in successful retention and separation of the data recorder payloads during the anticipated tumbling of the CM during uncontrolled flight. Due to the cost and schedule constraints of the project, making use of an off the shelf solution was preferable to a new development. Early on it was recognized that the US Air Force AN/ALE-47 flare and chaff dispenser system had many features that seemed to be congruent with the EDR objectives.

The standard ALE-47 dispenser system required an enhanced capability in two critical aspects. The anticipated flight vibration environment of the CM during the test flight greatly exceeded certified limits of the ALE-47 system. In addition, the ALE-47 system was designed for dispensing passive decoy payloads and did not have provisions for separable power and data connections between the payloads and host vehicle. Thus, modifications to the ALE-47 system were required to meet these needs for the AA-2 test flight.

Bounded by the standard capabilities of the ejection system, the defined characteristics of the payload data storage and beacon electronics, and the requisite operational environments, the dominant aspect of the payload design was the balance of packaging the components into the available mass and volume limits of the standard ALE-47 cartridge, while still maintaining adequate robustness. Not only did multiple electronics need to fit within the volume allotted by the cartridge, but the mass was constrained by the need for sufficient buoyancy to ensure the payloads would float in the ocean with adequate stability for antenna pointing, yet

have sufficient structural integrity to survive the water impact at a terminal velocity of approximately 150 mph.

Ejection System Concept

In the ALE-47 system, the payloads were packaged into cartridges that function similar to a mortar tube (Figure 3). Crimping of the open end of the aluminum cartridge case restrains an aluminum closeout plate (cap) that retains the payload in the cartridge until ejection. A specially designed machine performs the crimping operation, which guarantees that the payload has no residual gap and cannot move within the cartridge. An electrically initiated pyrotechnic squib installed in the base of the cartridge provides the propelling gas that forces the payload and closeout plate through the restraining crimps and out of the cartridge. A plastic piston assembly installed in the bottom end of the cartridge ensures that the combustion gasses from the squib do not leak past the payload and negate the propelling force, analogous to the function of the wadding in a shot gun shell.

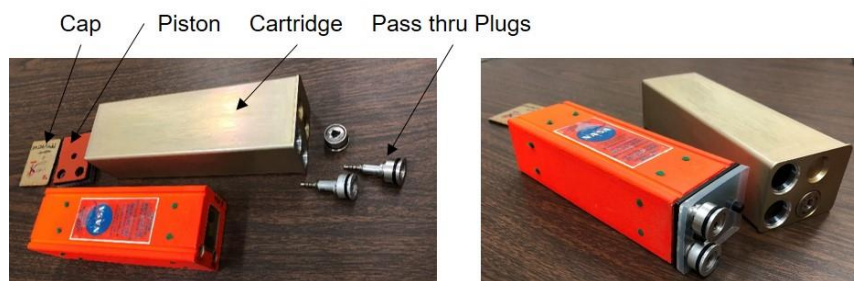


Figure 3: The figure on the left shows the components for assembling the payload into the cartridge and the figure on the right shows the pass thru plugs installed into the payload interface.

The cartridges were packaged into a magazine that constituted the operational load element of the system, and were installed on the vehicle by sliding into the muzzle of the ALE-47 dispenser after installation of the pyrotechnic squibs (Figure 4). The modularity of the dispenser and magazine system enables installation of as many as 30 cartridges of varying sizes with payload cross sections ranging from 1" x 1" up to 2" x 2.5". Only six of the largest size cartridges required for the AA-2 EDR payload can fit in each dispenser, which leaves 24 of the electrical squib contacts in the dispenser breech plate unused and dead faced against the cartridge bases.

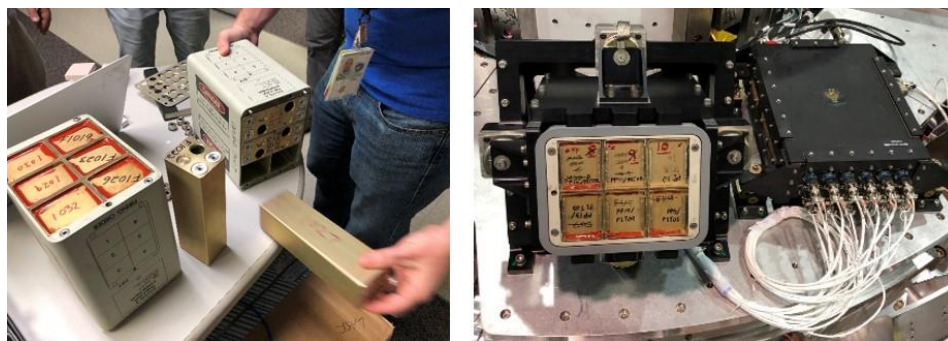


Figure 4: The figure on the left shows the payload packaged inside the cartridge and the cartridge being installed in the magazine. The first on the right shows the assembled dispenser next to the breakout box installed in the forward bay area of the CM.

Two independent ejection systems were mounted in the forward bay parachute compartment of the AA-2 CM, pointing in opposite directions (Figure 5).



Figure 5: EDR ejections. Figure on the left is an artist rendering and the first on the right is an image from the actual flight.

Risk Definition

Risks were based on perceived probability and consequences, but also ranked according to the expediency or difficulty of accomplishing closure. Tests that could be conducted rapidly and efficiently received schedule preference in order to identify pitfalls as soon as possible. The principle risks identified were as follows:

- Functionality of the COTS ejection system and EDR unique payload
- Adequate separation performance of the ejection system in the poorly characterized post-test flight environment
- Mechanical survival of the payload during flight, ejection, and impact environments
- Recording of the data stream and storage of the data in the payloads
- Separation of the power and data connections of the payload through the ejection system
- Packaging of the payload elements
- Buoyancy and stability of the payload
- Location and recovery of the payloads
- Survival of the system in the flight vibration and shock environment
- Payload battery performance and survivability
- Beacon activation

Critical Developmental and Risk Reduction Testing

Project resource limitations drove testing concepts to prioritize low-cost approaches using existing or readily available, and often non-traditional, assets to the fullest possible extent. One of the earliest tests was performed using an aircraft and recovery boat to drop and recover inert simulated payload shapes into open water. The simulated payload shapes were constructed from a prototype syntactic foam mixture and were dropped from an altitude well in excess of that necessary for the payloads to reach terminal velocity. This testing proved that syntactic foam provided sufficient protection to the payload. This test was followed by an ejection from the ALE-47 dispenser using inert simulated payloads. With the data from this initial testing and multiple iterations of design and 3D printing, the team began to close on a payload design that encompassed the volumetric, buoyancy, and structural constraints.

The next payload prototype included an early generation, functioning locator beacon and recording computer, contained within a 3D printed plastic payload shell (Figure 6), as opposed to an aluminum shell used in the initial design. Ultimately, this shell printing process proved vital to the frequent and rapid iteration of the payload design, the extremely low production costs, and quick fabrication times. 3D printing also enabled the project to construct the numerous development and replacement payload units needed to work through many test failures, as well as the large number of flight units for redundancy purposes. The ejection performance test was repeated with this enhanced payload, and showed that the ejection system could

adequately eject a functionally complete payload with sufficient velocity, and that the payload could survive the ejection forces.

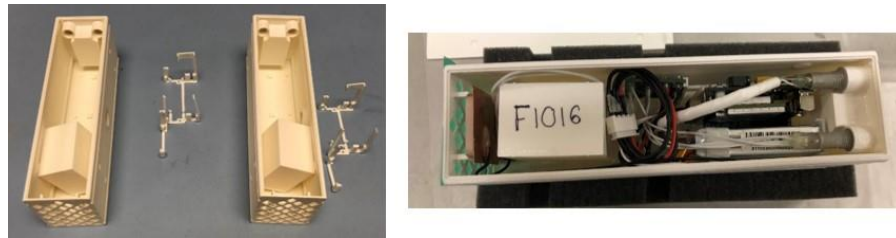


Figure 6: The image on the left is a set of 3D printed payload shells and scaffold. The image on the right is an assembled payload that is prepared for foam pouring.

Collaborative use of a NASA-owned Gulfstream III aircraft equipped with an instrument package deployment capability allowed for early demonstration of water impact survivability and recoverability of prototype active payloads. Five payload prototypes of varying configuration were dropped from approximately 5000 feet above sea level and approximately 50 miles off shore from Galveston, Texas. Beacon signals were received from all units, although two units failed to send proper GPS coordinates. These discrepancies were thought to be due to unsuitable antenna configurations or assembly defects. The other three units were recovered and their simulated data retrieved (Figure 8).

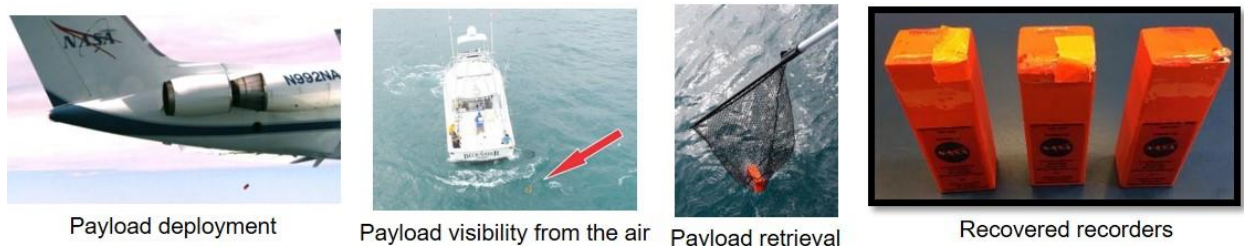


Figure 7: Early drop testing and retrieval operations.

Following were data writing tests, initial demonstrations of payload power and data harness separation, vibration testing of the ejection system elements, tests of data writing during vibration, increasingly complex payload recovery operations, thermal exposure followed by ejections (Figure 8), ejection system performance with fully active payloads, payload beacon battery failure margin testing, and recovery beacon activation tests.



Figure 8: Ejection testing of a data recorder mass simulator.

Dispenser Vibroacoustic Mitigation

The expected vibroacoustic environment during the abort sequence of the AA-2 mission greatly exceeded the rated capabilities of the ALE-47 dispenser (Figure 9). The system specifications of the off-the-shelf dispenser accommodated a lower amplitude vibroacoustic environment, but for a much longer duration than the abort sequence (3 hours for the benign rated environment, as opposed to 5 seconds of the AA-2 abort environment).

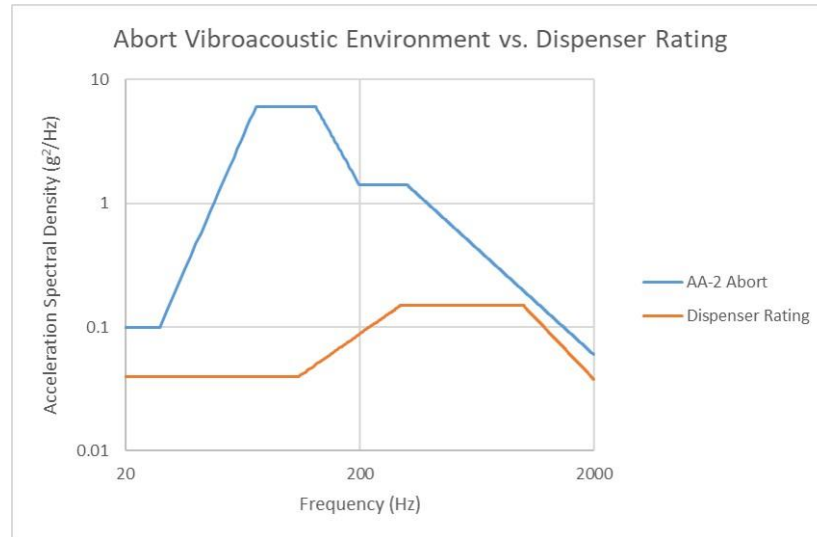


Figure 9: Dispenser rating compared with the AA-2 abort environment.

Several mitigation strategies were necessary to produce a design that could reliably withstand the extreme environments induced by the abort motor. These strategies included using additional structural attachment points to the dispenser and mounting the dispenser on cup-style elastomeric isolators (Figure 10). Notably, the dispenser with its custom mounting interface was tested to the extreme abort environments while mounted on hard mounts (i.e. solid aluminum stand-ins for the isolators) and survived. However, with the dispenser in the hard-mounted configuration, data transfer to the data recorders loaded inside was unsuccessful.

The off-the-shelf dispenser provides four attachment points near the muzzle of the dispenser to attach to vehicle structure (Figure 10). The center of mass of the dispenser is not in plane with these attach points, resulting in a cantilevered arrangement. To avoid this cantilevered arrangement, the AA-2 custom design made use of the subassembly fasteners near the breech of the dispenser to affix plates and brackets such that the custom dispenser mounting interface was nearly coplanar with its center of mass.

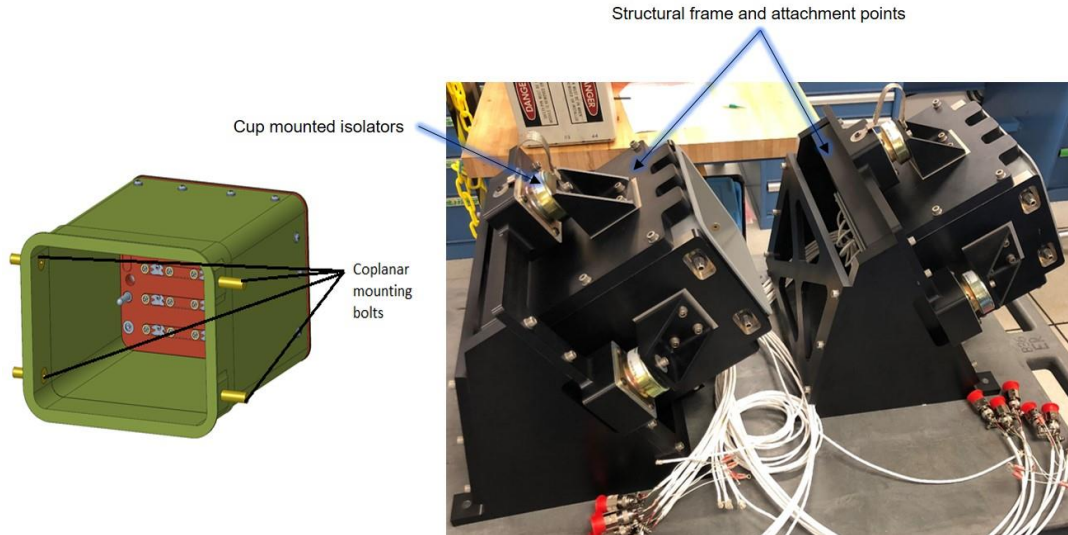


Figure 10: The image on the left shows the four attachment points. The image on the right shows the suite of dispenser modifications.

These additional brackets were located in such a way that when mounted on isolators, the center of mass of the dispenser was near the centroid of the isolators. This design eliminated rotational coupling (i.e. swaying motion) of the dispenser when exposed to vibrational environments, keeping the resulting motion almost entirely translational.

The isolators themselves were selected such that the natural frequency of the isolated mass would be approximately 32 Hz, providing vibroacoustic attenuation for frequencies above 45 Hz. Figure 11 shows the frequency response of the isolated dispenser based on the theoretical transmissibility of the selected isolators. Even with the isolators, the dispenser experienced a vibroacoustic environment above its rated values for frequencies below 200 Hz. However, with the customized mounting arrangement of the dispenser and brief exposure to the abort loads, the system design passed qualification testing and was ultimately successful in the AA-2 Mission.

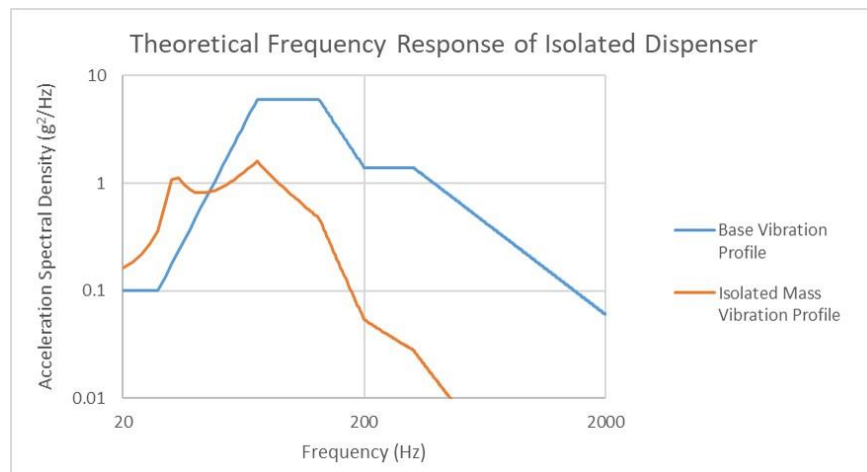


Figure 11: Theoretical Frequency response of isolated dispenser.

Lessons Learned During Vibroacoustic Testing

Cartridge Crimp Failure

An early vibration test had a failure of the crimped cartridge to contain the ejectable data recorders. Ideally, the contents of the cartridge would be preloaded in a manner that resulted in no backlash or motion of the contents of the cartridge. However, an error in the crimping procedure resulted in a free displacement of the recorder between .007 and .044 inches within the cartridge. Even this small motion was enough to produce significant impact loads on the crimp feature, which was defeated. During the test, the lids came off the cartridges, and due to the asymmetric friction resistance of the piston seal (i.e. higher force needed to push seal in than to pull out), the vibration motion “ratcheted” the piston and data recorder out of the enclosed cartridge. Recalibration of the crimping machine at the cartridge loading vendor’s facility, along with inclusion of a felt spacer and a bead of RTV sealant as used in the standard cartridge configurations, resolved the loose fit issue such that this failure did not reoccur (Figure 12).

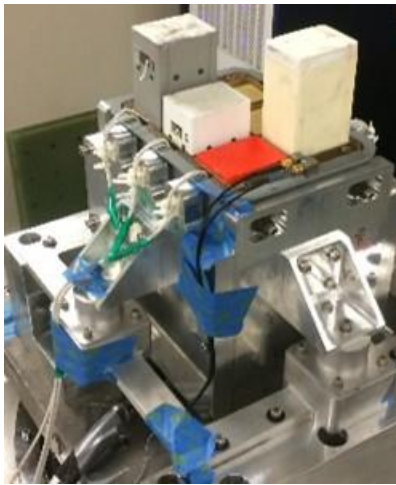


Figure 12: Cartridge crimp failure during vibration testing.

Dispenser Isolator Failure

Another test failure occurred on the dispenser when an erroneously entered test profile was programmed to the shaker table, which resulted in the destruction of the isolators. After the failure occurred, it was determined that the erroneous profile differed from the intended profile as shown in Figure 13. The 32 Hz frequency is notable since that is the system’s natural frequency based on dispenser mass and isolator stiffness.

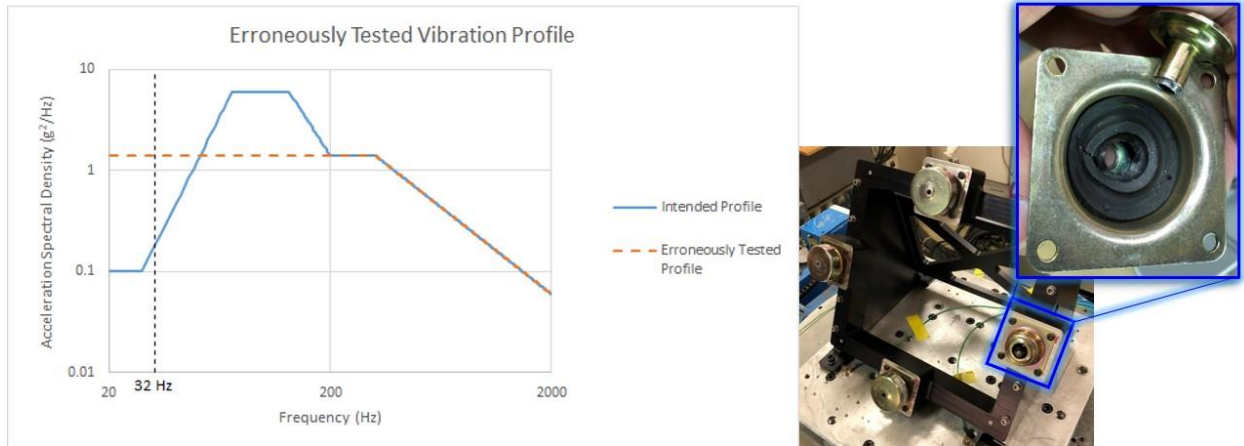


Figure 13: Figure on the left shows the erroneously tested vibration profile. The images on the right show the resultant cup isolator following the test.

Curiously, the g_{rms} value of the erroneous profile that destroyed the isolators was 17% lower than the g_{rms} value of the intended profile (29 g_{rms} vs. 35 g_{rms}), even though the isolators were proven to survive the intended profile when tested on a later date.

In this case, the erroneous profile exceeded the intended profile in the most crucial frequency range, the low frequency domain, which included the system's natural frequency of 32 Hz (Figure 14). Applying the isolators' transmissibility to calculate the frequency response of the isolated dispenser creates a clearer picture of why the erroneous profile was an over-test.

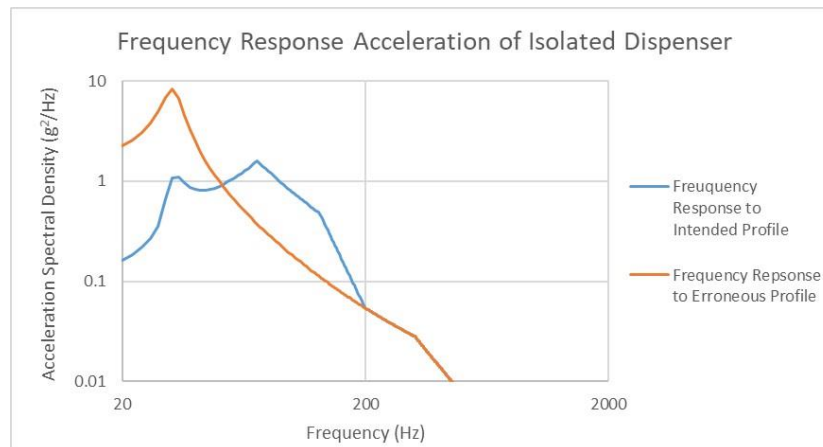


Figure 14: Dispenser frequency response to erroneously tested vibration profile.

As before, the g_{rms} value does not tell the full story. The frequency response of the isolated mass shows only a slight increase in g_{rms} when comparing the erroneous profile to the intended one (12.1 g_{rms} and 10.9 g_{rms} , respectively). The true significance of the exceedance in the low frequency is not apparent until examining the rms displacement, instead of the rms acceleration.

Acceleration values resulting from oscillating motion are linearly proportional to displacement amplitude and proportional to the square of the oscillation frequency. This means, for example, that for a body experiencing a given rms acceleration from sinusoidal motion at 400 Hz, the peak-to-peak displacement when experiencing the same rms acceleration at 40 Hz is 100 times greater. Thus, given the two acceleration profiles, with similar g_{rms} values, shown above, it is expected that the profile with a higher acceleration spectral density in the low frequency domain, namely the erroneously tested profile, will have a greater rms displacement.

Indeed, when comparing the dispenser's frequency response displacement from the erroneous profile, with its response displacement from the intended profile, it becomes clear that the erroneous profile was much more severe. Figure 15 shows the comparison on a non-logarithmic plot.

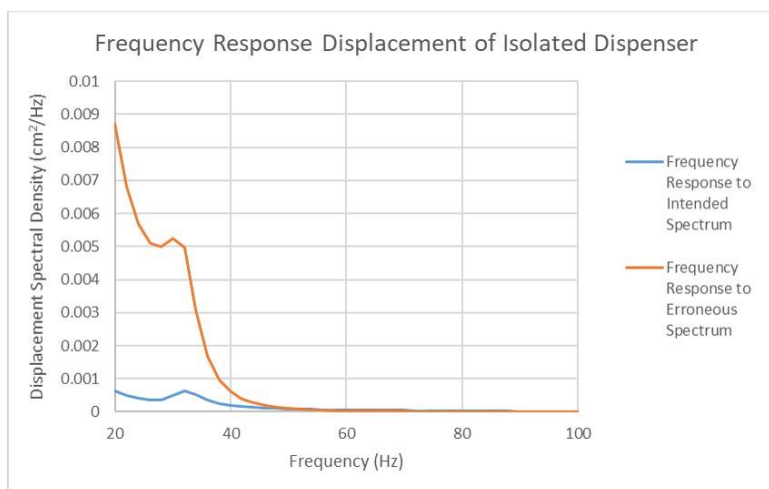


Figure 15: Dispenser frequency response displacements to erroneously tested vibration profile.

The rms displacement of the intended profile is 0.107 cm, while the rms displacement of the erroneous profile is 0.299 cm. The test failure that occurred was a result of excessive displacement of the isolators. It is notable that although the erroneous test profile indicated a 17% more benign acceleration value (g_{rms}), the resulting displacement that the isolators experienced was almost triple the intended value.

Data and Charging Link Challenges

The standard ALE-47 system dispenses only passive payloads and does not include any provision for data or power interfaces between the host vehicle and the payloads, as required by the AA-2 EDR application. The power connection served only to charge the EDR batteries prior to launch and therefore did not function during the flight environment, but the data connection had to maintain integrity of the 20 Mbps real time data stream between the local data controller and the USB solid state memory embedded in the EDR throughout the full flight load, vibration, and EMI environments. Additionally, these connections had to be separated upon ejection in a manner that preserved the data connection for use after recovery. Each of the two connections required four independent conductive paths. The field installation nature of the ejection system pyrotechnic devices required that the payloads be installed and thus these connections be made for the final time only during the later stages of the launch preparation process, long after the EDR system had been built and installed in the host vehicle.

There were two concepts traded to sever the data and power lines between the vehicle and the payload. The first concept employed a blade in the cartridge that would cut the wires as the payload ejected, similar to a guillotine. The other concept routed the power and data lines through connecting plugs between the payloads and dispenser, oriented with their axis of separation aligned to the axis of payload ejection. After several different tests and trade discussions, the concept that employed a connecting plug interface was selected due to the ability to easily insert and remove the populated magazine from the dispenser multiple times. Ejection of the payload pulled the plugs from their associated jacks. Routing of the cables to the external interfaces took advantage of the excess pyrotechnic squib electrical interface locations in the dispenser breech plate not required for use in the six payload configuration, such that installation of the loaded magazine into the dispenser accomplished engagement of the plug. Because the gas expansion chamber formed by the piston and the base of the cartridge case fully encompassed the end face of the payload perpendicular to the axis of ejection, the umbilical connections had to pass through both sides of the gas expansion chamber without introducing an excessive leak path. Due to the imprecise nature of the

EDR construction, the positioning of the connecting jacks within the payload were not tightly controlled. The relative positioning of the payload connectors to the cartridge base, the cartridge base to the dispenser breech plate, and the connector location to the piston seal constituted three independent alignment challenges, each with six degrees of freedom, that had to be accommodated by a separable umbilical connection routing through the cartridge base and dispenser breech. The connection was required to prevent separation or electrical chattering of the plugs under all conditions prior to payload ejection.

The design solution employed four conductor, coaxial mini-phono connectors as the separable plugs due to their axisymmetric nature in eliminating the need to accommodate rotational alignment constraints, self-alignment of plug insertion, robust connection strength, compact size with high conductor density per cross section area, and low cost. The precise fit nature of these connectors required compliance for each plug to follow the unique lateral, axial, and angular alignment of its corresponding jack. In order to simplify the combined alignment challenges, each separable plug connection was split into two different plug and jack pairs, with one pair constituting the mating interface for the loaded magazine installation function and the other pair constituting the demating interface for the payload ejection function. Due to the nature of the payload assembly within the cartridge, it was necessary to have a separable connection at the payload to cartridge interface, and another one in series at the cartridge to dispenser interface. The results was the “pass through plug” (Figure 16), which consisted of a mini phono plug on the payload mating end linked to a mini phono jack on the dispenser mating end.

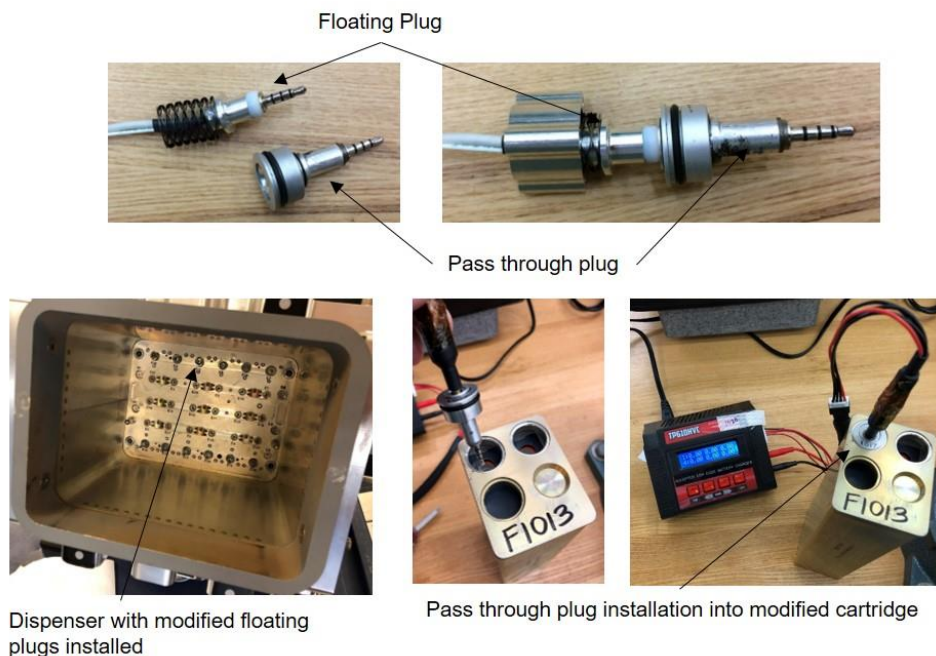


Figure 16: Pass through plug and floating plug installation.

The connectors of each pass through plug were embedded in a two-part shell capable of accommodating the compliance necessary to ensure alignment of the assembly, such that the plug was fully seated and the shell adequately aligned, in order to seal in the ejection gas generated by the pyrotechnic charge. This plug and jack pair constituted the demating interface for the ejection function of the connectors. Oversized holes in the piston and piston seal accommodated alignment compliance between the installed pass through plug assembly and piston assembly. A layer of compliant seal material (rubber sheet), sandwiched between the upper surface of the piston and the lower end of the payload, provided a seal against leakage of the expansion gas without requiring a tight fit between the pass through plugs and associated holes in the piston and piston seals. Phono plug assemblies (the “floating plug”) installed in the dispenser breech plate, in place of the squib electrical interface pins, constituted the mating interface for the magazine installation function of the connectors (Figure 16). Within the dispenser, a compression spring at each connection

provided enough force to guarantee full insertion of the connections once the payloads were fully seated, and allowed for flexure of the connectors to accommodate any misalignment (Figure 17).

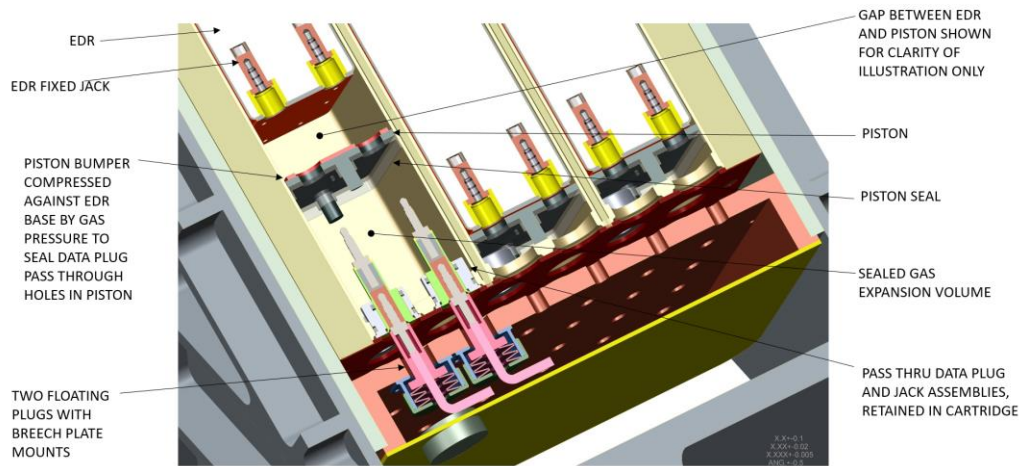


Figure 17: Dispenser to payload pass through plug interface.

The original intent was to limit the payload installation into the vehicle to a single cycle, but unanticipated challenges with the software of the data recording and payload beacon activation forced an extended test campaign with numerous installation and removal cycles. The environmental test plan of vibration, thermal, and ejection tests also required a larger number of payload installation and removal cycles than originally envisioned. The repeatable and simple nature of this connector concept proved both vital to testing, but also problematic. The inherent nature of the coaxial plugs caused a variety of adverse connector pin shorting conditions during insertion and removal that required development of detailed and rigorous operational procedures to avoid damage to the payloads.

Although initial data integrity testing appeared successful at the component level, early development tests of data writing during vibration encountered anomalies with data integrity. Initial diagnostic efforts focused on the apparent association with the vibration environment, but further testing revealed that intermittent data writing failures existed when using the fully integrated system configuration in any environment. Signal diagnostic testing uncovered that although data had been successfully transmitted and the combined connection had excellent conductivity on all lines, when operating at the high frequency and low signal strength of the USB 2.0 standard, the fully assembled data connection had a net impedance sufficient to cause intermittent failure of the data signal. Upon comparison of the coaxial phono plug connector with traditional USB connectors that have individual, parallel signal paths, it was realized that the closely spaced concentric geometry of the coaxial contacts in the phono plug created a capacitance between adjacent connector rings. With the positive and negative high frequency data channels placed on adjacent rings, this capacitance resulted in an impedance at the high frequency of the data signal sufficient enough to block the low voltage signal when combined with other losses in the complete system. By reordering the USB channels through the connector such that the ground channel of the USB DC power bus was placed on the ring between the two data channels, the capacitance effect was disrupted and the impedance problem eliminated.

Beacon Activation and Battery Maintenance Challenges

Since it was necessary to avoid premature emission of radio signals and draining of battery capacity, the locator beacon was not activated until the payload was ejected. Due to the extended period of dormancy from final battery charge until payload ejection, it was necessary to minimize the power draw of the ejection detection system in the payload. The EDR payloads included a custom designed activation circuit for the ejection detection and battery charging functions. The coaxial nature of the phono plugs was susceptible to brief shorting between adjacent conductors during insertion and removal, which in combination with

peculiarities in the activation circuit design, led to a couple of challenging problems uncovered during later phases of testing.

Early versions of the activation design involved means of detecting severance of the USB data connection circuit via cross connections to the battery charging circuit. This cross coupling resulted in numerous permanent failures of the payloads during testing, particularly to the COTS flash drives used for data recording. Eventually it proved impossible to eliminate the failures with the original concept. A new system of detecting payload ejection was developed. This method sensed the severance of a short circuit between terminals protruding from the side of the payload and shorted through contact with the wall of the aluminum cartridge prior to ejection. This late design change succeeded in eliminating the flash drive failures due to problematic coupling of the charging and data circuits.

Due to inadequate voltage specification of certain components in the activation circuit, another consequence of crossing conductors during coaxial plug insertion and removal was a propensity to damage the activation circuit or battery, which accumulated over repeated cycles. Delayed understanding of the issue precluded redesign for properly sized components. Thus, the vulnerability was mitigated through procedural safeguards and rigorous monitoring.

A final redesign was undertaken to completely replace the activation circuit with an optically sensed circuit for detecting payload ejection. While this completely resolved all of the remaining risks for operational damage or premature battery drain of the payloads, the very late introduction in the schedule precluded the opportunity for full adequate testing of this design. In the end, a mixture of both redesigned versions of the payloads was flown in order to balance these conflicting risks without disrupting the flight schedule.

Conclusions

The most challenging development issues were related to the custom designed payload activation circuit and the software for writing data to the flash drives. Ironically, neither of these had been considered noteworthy risk items at the beginning and had assumed to be within the scope of routine developments. In hindsight, the one noteworthy improvement to the development process would have been earlier acceptance of the need for a change of design concept for these two items and better integration between mechanical and electrical aspects of the design process in the crucial early phases.

In operation, the EDR system performed almost flawlessly. It met all critical schedule milestones up to and including flight, and without disruption to the overall AA-2 development and launch preparation schedule. During the mission, all 12 data recorder payloads ejected exactly as planned and were successfully recovered ahead of the anticipated timeline. Data was successfully retrieved from all units and ultimately proved to be a perfect recording of the telemetry stream on 11 of the units, with the only flaw being limited disruption of the data on one of the payloads. The data loss was an intermittent issue with one of the data channels of the breakout box noted during testing, but accepted due to the impracticality of repair and protection of massive redundancy.

Other than the noted issues with early versions of the payload beacon activation circuit and data writing software, the programmatic and operational performance of the system fully validated the selected design choices and development philosophy of the EDR subsystem.

References

1. Rojdev, K., Hagen J., Burlone, M., Petri, D., Jackowski, A., et al., "An Ejectable Data Recorder Subsystem for the Ascent Abort-2 Test Flight of the Orion Launch Abort System," Proceedings of the IEEE Aerospace Conference, Big Sky, March 7-14, 2020.

