Cold Welding and Data Protection in Suborbital Flight

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Abstract

Cold welding, the phenomenon in which two adjacent metals spontaneously join in a vacuum, presents both a potential hazard as well as an opportunity for aerospace endeavors. Most data regarding cold welding is derived from post-incident observations of mechanical failures rather than controlled experimentation. Thus, the mechanisms governing cold welding remain poorly characterized. The likelihood and strength of cold welding bonds are expected to depend on the presence of surface oxidation and the ability of contact methods to disrupt or remove this oxide layer. This experiment evaluates the probability of cold welding and the strength of resulting bonds between both similar and dissimilar metal pairs under three different contact conditions in the vacuum of space. The metal pairs are gold-gold, gold-aluminum, and aluminum-aluminum. The contact conditions are pressure, impact, and friction. The gold-gold pairs are expected to cold weld under all three contact conditions, whereas the aluminum pairs are expected to require friction to initiate bonding. Outcomes for dissimilar metal pairs are uncertain; however, cold welding has been demonstrated between dissimilar metals in a laboratory setting. To validate the results, sensors will collect data on environmental conditions during the experiment, including temperature, pressure, and g-force. To ensure that the sensor data returns intact, two different insulating materials will be utilized to protect the microSD cards from re-entry heat (450°F). A novel, cost-effective material known as Starlite, which can be produced from readily available ingredients, will be subjected to side-by-side tests against an industry standard insulation material (aerogel insulation padding) to assess heat shielding capabilities on data integrity. Starlite is expected to perform comparably to AeroGel insulation in heat shielding capability. Results from the cold welding investigation will improve understanding of vacuum metal bonding in aerospace environments, while the data-protection study may provide a low-cost thermal protection strategy for future RockSat payloads.

1. Introduction

1.1 Cold Welding Background

Cold welding is a solid-state joining process in which two metallic surfaces bond without the application of heat. Unlike traditional welding methods that rely on elevated temperatures to fuse materials, cold welding occurs when two clean, flat metal surfaces come into intimate contact under sufficient pressure, allowing the two surfaces to bond.

The phenomenon was first formally recognized in the 1940s [1], when researchers observed that metals brought into contact in controlled environments could adhere strongly without thermal input. Under ideal conditions, where surface contaminants such as oxides, gases, or oils are absent, the atoms at the surface of each metal can interact directly. When the separation between these surfaces becomes sufficiently small, the distinction between the two materials diminishes, and a continuous metallic bond can form.

In practice, cold welding is often inhibited by the presence of surface films, particularly oxide layers, which act as barriers to atomic contact. Most metals readily form stable oxide coatings that prevent bonding unless those layers are disrupted. In contrast, noble metals like gold do not form significant oxide layers under normal conditions, making them especially susceptible to cold welding.

As a result, cold welding is highly dependent on both material properties and surface conditions, including cleanliness, roughness, ductility, and applied force. These dependencies make the process difficult to predict in uncontrolled environments and motivate further experimental investigation under well-defined conditions.

1.2 Cold Welding in Space

Cold welding is of particular concern in space environments, where conditions can significantly enhance the likelihood of metallic bonding. One of the primary contributing factors is the presence of a high vacuum [2]. In terrestrial environments, metal surfaces are typically covered by thin layers of gases, oxides, moisture, and other contaminants that inhibit direct atomic contact. In contrast, the vacuum of space reduces or eliminates these surface films, increasing the probability that clean metal surfaces will come into intimate contact.

While a vacuum is not strictly required for cold welding to occur—certain metals, such as indium, have been shown to bond in non-vacuum conditions [3]—the absence of atmospheric interference in space allows for greater effective contact area between surfaces. This increases the likelihood of adhesion between two metals.

Mechanical conditions in space also contribute to the risk of cold welding. Components in spacecraft are often subject to repeated contact, vibration, or sustained pressure, all of which can promote bonding between metal surfaces, particularly if the oxide layer of the metals is disrupted. In the absence of lubricants or protective coatings—both of which may degrade or behave unpredictably in vacuum—these interactions can lead to unintended adhesion between moving parts.

The combined effects of vacuum conditions, reduced surface contamination, and mechanical interaction make cold welding a persistent challenge in spacecraft design. Understanding how these factors influence bonding behavior is critical for both preventing mechanical failures and exploring potential applications of cold welding in space-based manufacturing.

1.3 Engineering Relevance

Cold welding presents both a significant risk and a potential opportunity in space engineering, depending on how it is managed. While unintended adhesion between metal components can lead to mechanical failure in critical systems, the same phenomenon offers a possible method for joining materials in environments where traditional welding techniques are impractical.

One of the most notable examples of cold welding contributing to a spacecraft malfunction is the NASA Galileo mission. Launched in 1989 to study Jupiter and its moons, the spacecraft experienced a partial failure of its high-gain antenna, which did not fully deploy as intended. While multiple factors likely contributed to the malfunction, cold welding has been identified as a possible mechanism by which metallic components became adhered, preventing proper movement. This failure significantly limited the spacecraft’s data transmission capability and forced reliance on a lower-bandwidth antenna, reducing the overall scientific return of the mission [4].

Incidents such as this highlight the importance of understanding and mitigating cold welding in the design of spacecraft mechanisms, particularly those involving moving parts or deployable structures. Engineers must account for material selection, surface treatments, and environmental exposure to minimize the risk of unintended bonding.

At the same time, cold welding may offer valuable applications in space. Because it does not require external heat or energy-intensive processes, it presents a potential method for joining materials in orbit or on planetary surfaces, where conventional welding techniques are difficult to implement. This could be especially relevant for in-space manufacturing, repair, or assembly of structures, where minimizing energy consumption and equipment complexity is critical.

The dual nature of cold welding—as both a hazard and a tool—underscores the need for controlled experimental data. A deeper understanding of the conditions under which cold welding occurs, and the strength of the resulting bonds, is essential for improving the reliability and adaptability of future space systems.

1.4 Gaps in Existing Research

Despite decades of awareness, cold welding remains insufficiently characterized in terms of its predictability and practical impact on engineered systems. Much of the existing knowledge is derived from post-incident analyses, in which cold welding is inferred as a contributing factor after a mechanical failure has occurred. While these observations are valuable, they often lack the controlled conditions necessary to isolate specific variables or quantify the mechanisms involved.

Laboratory studies of cold welding have been conducted [5], but many are limited in scope, focusing on idealized conditions or small-scale interactions. In particular, a significant portion of experimental work has been performed at the micro- or nano-scale [6], where surface forces dominate and materials can be prepared with near-perfect cleanliness. While these studies provide insight into the fundamental physics of adhesion, they do not always translate directly to the macroscopic, mechanically complex systems used in spaceflight.

Additionally, there is limited comparative data examining how different contact mechanisms—such as sustained pressure, sudden impact, or frictional interaction—affect the likelihood and strength of cold-welded bonds. These modes of contact are all relevant in spacecraft environments, yet they are rarely studied together within a single experimental framework. Similarly, there is a lack of systematic comparison between material pairs with differing surface properties, such as oxide-forming versus non-oxide-forming metals, under consistent environmental conditions.

As a result, there is a need for controlled, repeatable experiments that investigate cold welding at a scale and under conditions more representative of real-world space systems. Quantifying both the occurrence of bonding and the strength of those bonds across different materials and contact modes would provide valuable data for both mitigating risks and exploring potential applications of cold welding in space.

1.5 Research Objectives – Cold Welding

The primary objective of this study is to experimentally investigate the conditions under which cold welding occurs in a suborbital spaceflight environment, with an emphasis on both bond formation and bond strength across different material pairs and contact methods.

To achieve this, three metal pairings were selected based on their surface properties and relevance to aerospace applications: gold–gold, aluminum–aluminum, and gold–aluminum. Gold was chosen due to its resistance to oxidation, allowing for relatively clean metallic surfaces that are more conducive to bonding. Aluminum, in contrast, readily forms a stable oxide layer that can inhibit direct atomic contact. By comparing these materials, the experiment aims to evaluate how the presence or absence of oxide layers influences cold welding behavior. The inclusion of a dissimilar metal pairing (gold–aluminum) provides an additional opportunity to explore whether cold welding can occur across materials with differing surface chemistries, extending beyond the more commonly studied same-metal cases. While prior studies have demonstrated cold welding between dissimilar metals at the micro- and nano-scale [7, 8, 9], its behavior under macroscopic and mechanically dynamic conditions remains poorly understood.

In addition to material selection, this study investigates the role of contact mechanics in facilitating cold welding. Three distinct modes of contact were chosen: sustained pressure, sudden impact, and frictional interaction. These modes represent a range of mechanical conditions relevant to spacecraft systems, including static loading, deployment events, and sliding interfaces. By examining these contact methods within a single experimental framework, the study seeks to determine how different forms of mechanical interaction influence both the likelihood of bond formation and the resulting bond strength.

The central research question guiding this portion of the experiment is: How do material properties and modes of contact affect the formation and strength of cold-welded bonds in a spaceflight environment? Addressing this question will contribute to a more comprehensive understanding of cold welding.

1.6 Data Protection Background

Reliable data collection is essential to the success of any spaceflight experiment, as the ability to interpret results depends directly on the availability and integrity of recorded environmental and system data. In the context of suborbital missions such as RockSat, this presents a significant challenge due to the extreme conditions experienced during flight and recovery.

Previous RockSat missions conducted by this team have encountered difficulties in successfully retrieving onboard data. These failures have been attributed primarily to two factors: the intense thermal environment during re-entry and exposure to saltwater during ocean recovery. Elevated temperatures can damage or destroy electronic components and storage media, while saltwater immersion introduces risks of corrosion, short-circuiting, and long-term degradation of hardware.

Initial design considerations for this experiment assumed that saltwater exposure posed a direct threat to data storage devices such as microSD cards. However, preliminary testing using a seawater analog demonstrated that submersion alone did not compromise the integrity or retrievability of stored data. This finding suggested that the primary risk associated with saltwater exposure lies not in the storage medium itself, but in the potential for powered electronic systems to short circuit during or after splashdown.

As a result, the data protection strategy for this mission shifted away from full waterproofing—which presents additional challenges due to material outgassing in vacuum environments—and toward mitigating electrical failure. In particular, emphasis was placed on ensuring that power to sensitive components would be disabled prior to water exposure, reducing the likelihood of damage while preserving stored data.

For experiments investigating phenomena such as cold welding, the loss of environmental data presents a critical limitation. Measurements such as temperature and mechanical conditions are necessary to contextualize experimental outcomes and determine the conditions under which bonding does or does not occur. Without this information, it becomes difficult to draw meaningful conclusions or validate hypotheses.

As a result, ensuring the survivability of data through all phases of the mission—from launch to recovery—is a key engineering challenge. Addressing this issue requires not only an understanding of the environmental hazards involved, but also the development of practical and effective methods for protecting sensitive electronic systems and preserving recorded data.

1.7 Existing Data Protection Approaches

A variety of strategies have been developed to protect onboard data in spaceflight systems, ranging from passive shielding methods to active data transmission and recovery techniques. The selection of an appropriate approach often depends on mission constraints, including budget, payload capacity, and the expected environmental conditions.

One common method involves incorporating thermal protection at the structural level of the vehicle. Launch systems are often designed with heat shielding that reduces the thermal load experienced by internal components during re-entry. However, smaller payloads and experimental platforms, such as those used in suborbital missions, may not benefit from the same level of integrated protection, leaving onboard electronics more directly exposed to extreme conditions.

Another approach involves transmitting data in real time during flight, under the assumption that onboard storage may not survive the full mission profile. While this method can reduce reliance on post-recovery hardware integrity, it requires reliable communication systems and sufficient bandwidth, both of which may be limited in small-scale or student-led missions. Telemetry was not available for this RockSat mission.

At the high end of available solutions, specialized systems such as Reentry Breakup Recorders (RBRs) are designed to survive extreme thermal and mechanical conditions and continue transmitting data during vehicle disintegration [10]. While highly effective, these systems are complex and costly, making them impractical for many small-scale experimental missions.

Together, these approaches illustrate the range of available strategies for data protection, each with its own advantages and limitations. For missions with constrained resources and increased environmental exposure, there is a need for alternative solutions that balance effectiveness, simplicity, and cost.

1.8 Mission Context and Constraints

The data protection component of this experiment is designed within the specific constraints of a suborbital RockSat mission, where payloads are intentionally exposed to harsh environmental conditions. Unlike larger spacecraft, which often incorporate substantial structural shielding and environmental control, this payload is configured to allow direct interaction between experimental systems and the spaceflight environment. This design choice is essential for the cold welding investigation, but it also increases the vulnerability of onboard electronics and data storage systems.

As a result, conventional approaches to data protection—such as heavy shielding or fully sealed enclosures—are not always practical or compatible with the goals of the mission. In particular, the need to minimize mass, avoid materials that may outgas in a vacuum, and maintain exposure of experimental components limits the feasibility of traditional protective strategies.

The purpose of this experiment is therefore to evaluate lightweight, accessible methods of protecting critical data systems under these constraints. By testing insulating materials and implementing targeted electrical protection strategies, the experiment seeks to determine whether reliable data recovery can be achieved without relying on complex or high-cost solutions.

This approach reflects a broader objective of developing practical engineering solutions for small-scale space missions, where resource limitations and experimental requirements often necessitate innovative trade-offs between protection and exposure.

1.9 Research Objectives – Data Protection

The objective of the data protection component of this study is to evaluate the effectiveness of lightweight, cost-accessible strategies for preserving onboard data during suborbital spaceflight and recovery. Specifically, this experiment investigates whether a combination of passive thermal protection and targeted electrical safeguards can ensure the survivability and retrievability of data stored on onboard systems.

To assess passive protection methods, two insulating materials were selected for comparison: aerogel-based insulation padding and an approximation of the proprietary ablative material known as Starlite. The commercially sourced aerogel insulation padding consists of silica aerogel integrated within a flexible fiberglass matrix, providing low thermal conductivity while maintaining structural durability and ease of handling. Aerogel-based materials have been widely used in aerospace applications due to their strong insulating properties [11]. Starlite, while less commonly characterized in open literature, has been reported to exhibit strong resistance to high temperatures [12, 13]. By testing these materials under identical flight conditions, the experiment aims to compare their effectiveness in mitigating thermal exposure to sensitive electronic components.

In addition to thermal protection, this study examines strategies to reduce the risk of electrical failure during post-flight recovery. Based on preliminary testing indicating that saltwater submersion does not inherently compromise data stored on microSD cards, the experiment emphasizes preventing damage to powered electronics rather than attempting full waterproofing. This includes ensuring that power to critical components is disabled prior to splashdown, thereby reducing the likelihood of short circuiting and preserving stored data.

A further objective of this experiment is to evaluate the effectiveness of redundancy in data logging. By recording data from multiple sensors to multiple storage devices, the system is designed to maintain data integrity even in the event of partial hardware failure. This approach aims to increase the probability of successful data recovery under uncertain post-flight conditions.

The central research question guiding this portion of the study is: Can low-cost, low-mass protection strategies ensure reliable data recovery in a suborbital spaceflight environment characterized by thermal stress and water exposure? Addressing this question will contribute to the development of practical data protection solutions for small-scale and resource-constrained space missions.

Together, these two experimental components form a coordinated investigation into the behavior of materials and systems under suborbital spaceflight conditions. The cold welding experiment focuses on understanding material interactions and bonding mechanisms, while the data protection experiment addresses the practical challenge of preserving the data necessary to interpret those interactions. The following sections describe the design, materials, and methods used to implement these experiments within the constraints of the RockSat payload environment.

2. Materials and Methods

2.1 RockSat Payload Overview

The experiment is designed as part of the 2026 RockSat program, scheduled for launch from NASA's Wallops Flight Facility in Virginia aboard a Terrier–Improved Malemute sounding rocket. This platform provides a suborbital flight profile that enables short-duration exposure to the space environment, including vacuum conditions and microgravity.

The rocket is projected to reach a nominal apogee of approximately 189.9 km, with a total flight duration of approximately 856.5 seconds (14.3 minutes). The payload is expected to cross the Kármán line at approximately 79 seconds after launch and re-enter the atmosphere at approximately 363.5 seconds, resulting in an estimated 284.5 seconds (4.74 minutes) of exposure to vacuum conditions. During descent, the payload is anticipated to experience significant thermal stress, with external temperatures during re-entry estimated to reach approximately 450°F, followed by ocean splashdown and recovery.

The payload is housed within an unpressurized section of the rocket, allowing direct exposure to the space environment. This configuration is essential for the cold welding experiment, as it enables interaction between test materials and vacuum conditions, but it also increases the vulnerability of onboard electronics and data storage systems to thermal and environmental stress.

The experiment occupies a quarter payload section, with strict mass and volume constraints. The total mass budget for the system is 7.5 pounds +/- 0.25 pounds. Within this limited space, the payload integrates two primary experimental components: a cold welding test assembly and a data protection system. The cold welding apparatus, which includes three distinct contact mechanisms, comprises the majority of the payload volume, while the remaining space is allocated to data protection test modules and supporting electronics.

The data protection system consists of multiple independent storage configurations to evaluate survivability under flight and recovery conditions. These include two insulated test enclosures—one utilizing Starlite-based insulation and the other aerogel-based insulation padding—as well as a sealed enclosure (Hammond box) providing an additional layer of protection. In addition, a fully unshielded microSD card is included as a negative control to assess the baseline survivability of unprotected data storage. The launch is scheduled for June 25, 2026, and the results presented in this paper are therefore based on pre-flight design and expected performance.

A schematic representation of the payload structure and component layout is provided in Appendix Figure A.

2.2 Cold Welding

2.2.1 Materials

The cold welding experiment investigates bonding behavior across three material pairings: gold–gold, aluminum–aluminum, and gold–aluminum. These materials were selected based on their differing surface properties, particularly with respect to oxide formation. Gold, which does not readily form an oxide layer, provides a relatively clean metallic surface, while aluminum (6061, non-anodized) rapidly forms a stable oxide layer that can inhibit direct atomic contact.

All samples used in the pressure and impact tests consist of square contact surfaces approximately 0.48 in × 0.48 in (≈0.23 in^2). The gold samples are fabricated from stainless steel

(CPM 154) and coated with a thin electroplated layer of soft 24K gold to promote ductility and facilitate plastic deformation at the contact interface. The friction test utilizes cylindrical geometries, consisting of rods approximately 0.25 inches in diameter and sleeves approximately 0.5 inches in height, machined to allow close but mobile contact between surfaces. In this configuration, rods are composed of either aluminum or gold-plated stainless steel, depending on the material pairing.

Gold plating for the pressure and impact samples is performed professionally to ensure consistent surface quality, while friction test samples are plated in-house. A relatively soft, ductile gold layer is used to increase the likelihood of surface conformity during contact. Aluminum samples are used in their raw, uncoated form to preserve their natural oxide-forming behavior.

The test assembly is constructed primarily from aluminum in order to meet payload mass constraints. To mitigate the risk of unintended cold welding between moving components of the impact mechanism, a graphite-based coating is applied to selected contact surfaces. This coating serves to reduce direct metal-to-metal interaction and minimize the likelihood of unintended adhesion during operation.

2.2.2 Surface Preparation and Handling

Surface condition is a critical factor in cold welding. To maximize the likelihood of bond formation, all samples are prepared to achieve smooth, flat contact interfaces with minimal contamination. Gold-plated samples are handled exclusively with nitrile gloves and wrapped in nonabrasive laboratory tissues to prevent scratching or contamination prior to integration.

To minimize surface damage during system testing, analog samples are used when validating mechanical components, including the impact mechanism. Final test samples are only installed once system functionality has been verified. Prior to launch, surfaces are cleaned using compressed air where possible, and protective coverings are maintained until final integration to reduce exposure to particulate contamination.

Aluminum samples are mechanically polished to reduce surface irregularities. Throughout handling and integration, efforts are made to minimize exposure to contaminants that could inhibit atomic contact at the interface.

2.2.3 Contact Mechanisms

Three distinct contact mechanisms are used to evaluate the effect of mechanical interaction on cold welding: sustained pressure (static loading), impact, and friction. Each mechanism is designed to isolate a different mode of contact relevant to spacecraft systems.

Pressure (Static Loading) - In the pressure test, paired samples are secured together prior to launch using a bolted assembly. The system is designed to apply a constant compressive force, estimated at approximately 7.2 psi[1] [see footnote] to each of the sample pairs, which is maintained throughout the duration of the flight. The force is limited by material constraints, as stainless steel fasteners are used within an aluminum structural assembly.

The design constrains lateral motion to prevent unintended frictional interaction, ensuring that the test isolates the effects of sustained pressure alone. All material pairings (gold–gold, aluminum–aluminum, and gold–aluminum) are tested simultaneously within this configuration.

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[1] This value is a preliminary engineering estimate based on current design and is subject to change pending further testing.

Impact - The impact test utilizes a sled mechanism that accelerates into a stationary sample platform, bringing paired surfaces into sudden contact. The sled carries three samples corresponding to the three material pairings, which align with matching samples on the opposing platform.

The mechanism is triggered by a shape-memory release actuator (Dcubed nD3RN release nut), which enables precise timing of the impact event. The release is scheduled to occur approximately 23.4 seconds prior to apogee, maximizing exposure to near-vacuum conditions at the time of contact. Preliminary engineering estimates indicate an impact energy on the order of 20 ft-lbf[2] [see footnote], followed by a sustained contact force of approximately 7.2 psi[3] [see footnote] for the remainder of the flight. This configuration allows for evaluation of whether rapid, high-energy contact under vacuum conditions enhances the likelihood or strength of cold-welded bonds.

Friction - The friction test consists of cylindrical sleeves that slide along stationary rods, generating surface abrasion through passive mechanical motion. Each material pairing is tested using a separate rod–sleeve assembly. Motion is driven entirely by launch-induced vibration and acceleration, without active actuation.

This design introduces mechanical disruption of surface oxide layers, particularly for aluminum samples. However, a key limitation of this approach is that the majority of frictional interaction is expected to occur during ascent, prior to sustained exposure to vacuum conditions. As a result, disrupted oxide layers may partially reform before the payload reaches near-vacuum, potentially reducing the likelihood of cold welding.

Additionally, the cylindrical geometry results in a larger and less well-defined contact area compared to the pressure and impact tests. While the nominal contact surface of the sleeve is approximately 0.78 inches squared, the dynamic nature of the interaction makes precise quantification of effective contact area difficult. CAD models of the Cold Welding test assembly are shown in Appendix Figures B and C.

2.2.4 Experimental Considerations and Limitations

Several factors introduce uncertainty into the cold welding experiment. Applied forces in both the pressure and impact tests are estimated and may vary due to material constraints and manufacturing tolerances. The thickness and uniformity of the gold plating layer are also not precisely quantified, which may influence bonding behavior.

Surface contamination remains a potential limitation despite precautions taken during preparation and handling. In addition, the friction test design introduces uncertainty due to its reliance on passive motion and its limited exposure to vacuum conditions during active surface interaction.

To support the experimental approach, preliminary testing was conducted using indium samples, which are known to readily cold weld under appropriate conditions. These tests demonstrated measurable adhesion between samples and provided validation for the planned post-flight evaluation methods, including force-based separation testing.

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[2] This value is a preliminary engineering estimate based on current design and is subject to change pending further testing.

[3] Preliminary engineering estimate

Following recovery, all samples will be analyzed to assess bond formation and strength. Evaluation methods include visual and microscopic surface inspection, pre- and post-flight mass measurements, and tensometer testing to determine the force required to separate bonded samples.

2.3 Data Protection

2.3.1 Materials

The data protection experiment is designed to evaluate the effectiveness of lightweight, low-cost thermal protection strategies for preserving onboard data during suborbital flight and recovery. Two insulated enclosures are used to enable a direct comparison between materials: one utilizing aerogel-based insulation padding and the other a Starlite-based composite.

Both configurations are implemented as small, 3D-printed enclosures (PLA), which serve primarily as structural housings for internal electronics rather than as primary thermal barriers. The aerogel configuration consists of a single layer of insulation padding approximately 0.39 inches thick, composed of silica aerogel embedded within a fiberglass matrix. This material provides low thermal conductivity while maintaining flexibility and structural integrity.

The Starlite-based insulation is formed as a molded outer layer approximately 0.25 inches thick. The formulation consists of a mixture of borax, powdered sugar, cornstarch, baking soda, all-purpose flour, and water. The original formulation of Starlite is proprietary and not publicly available; therefore, the material used in this experiment is an approximate reconstruction based on publicly available descriptions of its composition and properties. Relative proportions were adjusted through iterative testing to optimize thermal resistance and structural stability. During fabrication, a fiberglass mesh is embedded within the material to improve cohesion and reduce cracking or fragmentation.

Both insulation systems are enclosed with a fine stainless steel mesh to mitigate the release of particulates, as both materials exhibited minor flaking or dust generation during preliminary testing. This precaution is particularly important to prevent contamination of nearby cold welding test surfaces.

2.3.2 Electronics and Data Logging

Each insulated enclosure contains a microSD card for data storage and a thermocouple for measuring internal temperature during flight. The two configurations are designed to be functionally identical aside from their insulation materials, enabling direct comparison of thermal performance and data survivability.

Data logging is designed to occur continuously throughout the flight, with sensor data recorded to onboard storage. In addition to actively recording, all microSD cards used in the experiment are preloaded with known data prior to launch. This allows for evaluation of data integrity and recoverability even in the event of sensor or power system failure.

Power to the primary data logging systems is planned to be disabled prior to splashdown in order to reduce the risk of electrical short-circuiting during saltwater exposure. Based on the projected flight timeline, rocket power is expected to be terminated at approximately 377.1 seconds, well before splashdown. As a result, the electronics within the data protection modules are expected to be inactive during water exposure, significantly reducing the likelihood of damage to onboard storage devices.

The Hammond enclosure operates on an independent internal battery and is designed to continue recording throughout the duration of the flight. A timed shutdown is implemented for this system, with deactivation scheduled to occur shortly before splashdown. This configuration provides an additional layer of redundancy by maintaining active data collection beyond the main system power cutoff while still mitigating the risk of post-flight electrical failure.

2.3.3 Redundancy and Control Configuration

To increase the likelihood of successful data recovery, multiple storage configurations are implemented. The experiment includes insulated enclosures utilizing aerogel-based insulation padding and Starlite-based insulation, as well as an additional sealed enclosure (Hammond box) serving as a secondary protective system. This enclosure provides a more conventional level of environmental isolation and acts as a failsafe in the event that the experimental insulation materials do not provide sufficient protection.

In addition to these protected configurations, a fully unshielded microSD card is included as a negative control. This card is not actively recording data during flight but is preloaded with known data prior to launch. This configuration allows for direct assessment of the effects of the spaceflight environment on unprotected storage media. Comparisons between protected and unprotected devices provide a baseline for evaluating the effectiveness of the insulation strategies.

A minimum success criterion for the experiment is the successful recovery of at least one readable microSD card following flight. A more comprehensive success condition includes full functionality of onboard sensors and successful data recording throughout the flight, in addition to post-recovery data retrieval.

2.3.4 Environmental Testing and Design Considerations

Preliminary testing was conducted to evaluate the performance of the Starlite-based material under conditions analogous to those expected during flight. Thermal testing using direct flame exposure demonstrated that the material functions as an ablative heat shield, with improved performance observed after standardizing thickness to approximately 0.25 inches. Earlier tests indicated cracking at edges, which in some cases resulted in localized heating of underlying structures; this issue was mitigated through controlled fabrication and reinforcement with embedded fiberglass mesh.

Additional testing included vibration exposure, vacuum conditions, and low-temperature testing at approximately −112°F. Across these tests, the material maintained structural integrity with no major failures observed. However, minor crumbling and particulate generation were noted, motivating the inclusion of stainless steel mesh containment within the final design.

Saltwater exposure testing was also conducted using a seawater analog to evaluate the survivability of microSD cards. Results indicated that submersion alone did not compromise the integrity or retrievability of stored data. These findings informed the decision to prioritize electrical isolation—specifically, disabling power prior to splashdown—over complete waterproofing of components.

A representative dataset from Starlite thermal testing is provided in Appendix Figure D, and saltwater exposure results are summarized in Appendix Table A.

3. Expected Results

The following expected results are based on pre-flight design, preliminary testing, and established material behavior. As the launch has not yet occurred, all outcomes described in this section represent hypotheses that will be evaluated following post-flight recovery and analysis.

3.1 Expected Results – Cold Welding

Cold welding behavior is expected to vary based on both material pairing and contact mechanism. Gold–gold samples serve as a positive control and are expected to exhibit cold welding under all three contact conditions: pressure, impact, and friction. Due to the absence of a surface oxide layer and the ductility of gold, bonding is anticipated to occur readily when sufficient contact is achieved in a vacuum environment. Among the three mechanisms, frictional interaction is expected to produce the strongest bonds due to continuous surface disruption and increased effective contact area. Impact is expected to produce moderate bonding through high-energy contact followed by sustained compression, while static pressure alone is expected to produce weaker, but still measurable, adhesion.

Aluminum–aluminum samples are expected to demonstrate more limited cold welding behavior due to the presence of a stable oxide layer. Bonding is most likely to occur in the friction test, where mechanical abrasion may disrupt the oxide layer and expose fresh metallic surfaces. Impact may produce limited bonding if sufficient deformation occurs at the interface, though this is less certain. The pressure test is not expected to produce significant bonding for aluminum–aluminum samples.

Gold–aluminum samples represent an exploratory case involving dissimilar metals. Bonding behavior in this pairing is less predictable; however, cold welding is considered unlikely under static pressure or impact conditions. As with aluminum–aluminum samples, frictional interaction is expected to provide the greatest likelihood of bonding due to disruption of the aluminum oxide layer, though any resulting bonds may be weaker or inconsistent.

3.2 Cold Welding Evaluation Methods

Cold welding will be evaluated using a combination of macroscopic observation, microscopic surface analysis, and quantitative measurements. A primary indicator of bonding will be the presence of adhered sample pairs upon recovery. If samples remain bonded after flight, this will serve as direct evidence of adhesion. To distinguish cold welding from thermally induced bonding, environmental sensor data will be used to verify that recorded temperatures remained below the melting points of the materials involved (approximately 1947°F for gold and 1080–1205°F for 6061 aluminum). Bonding observed under these conditions would provide strong evidence of solid-state (non-thermal) processes.

In cases where samples are not adhered upon recovery, additional analysis will be performed to detect evidence of prior bonding. Pre- and post-flight mass measurements will be compared to identify potential material transfer between samples. Surface morphology will be examined using microscopy to identify features consistent with cold welding, such as localized deformation or material exchange at the interface [14]. Mechanical testing will also be conducted where applicable to quantify bond strength, using tensile or separation force measurements for samples that remain adhered.

Preliminary testing using indium samples—known to readily cold weld without requiring a vacuum—demonstrated measurable adhesion and provided validation for the planned evaluation methods. A summary of these results is provided in Appendix Table B.

3.3 Expected Results – Data Protection

The data protection experiment is expected to demonstrate varying levels of effectiveness across the different protection strategies. The aerogel-based insulation system is expected to provide the most predictable thermal protection due to its well-characterized low thermal conductivity. Potential failure modes are anticipated at seams or stitching interfaces; however, the use of high-temperature Kevlar thread and minimized stitch spacing is expected to reduce this risk.

The Starlite insulation is less well characterized but is expected to perform comparably to aerogel based on preliminary testing. Prior experiments demonstrated effective thermal resistance and ablative behavior, though structural vulnerabilities such as cracking or flaking were observed in earlier formulations. These issues have been largely mitigated through standardized thickness and reinforcement with embedded fiberglass mesh, and no major structural failures are expected under flight conditions.

The Hammond enclosure serves as a conventional protective baseline and is expected to provide reliable data preservation. The inclusion of aerogel padding within the enclosure provides additional thermal insulation and mechanical cushioning. Due to the hydrophobic properties of the aerogel material, some resistance to saltwater exposure may also be provided. The unshielded microSD card, included as a negative control, is expected to experience significant thermal damage and complete data loss.

3.4 Data Interpretation and Validation

Successful recovery of environmental data is critical for interpreting the results of the cold welding experiment. Temperature and acceleration data provide the necessary context to determine the conditions under which bonding occurs or does not occur. While observations of adhesion alone may suggest cold welding, the ability to correlate these outcomes with environmental conditions significantly strengthens the validity of the conclusions.

The combined results of the cold welding and data protection experiments are intended to provide insight into both the mechanisms of material interaction in space environments and the practical challenges of preserving experimental data under those conditions.

4. Discussion

4.1 Limitations

Several limitations of this study should be considered when interpreting the results, particularly given the constraints of a suborbital platform and the pre-flight nature of the experiment.

One of the primary limitations is the design of the friction test. The mechanism relies on passive motion induced by launch vibration and acceleration, which does not allow precise control over the magnitude or timing of frictional interaction. In particular, the orientation of the rod–

sleeve assemblies—with the axis of motion aligned parallel to the direction of launch acceleration—may cause the sleeves to be driven toward one end of the rods, limiting sustained sliding interaction during flight. As a result, the amount of friction generated between surfaces may be insufficient or inconsistent across samples.

Additionally, a significant portion of the frictional interaction is expected to occur during ascent, prior to sustained exposure to vacuum conditions. This introduces the possibility that oxide layers disrupted during early motion may partially reform before optimal conditions for cold welding are reached. A motorized or actively controlled friction mechanism would allow for more precise timing and repeatability of surface interaction and represents a preferred design for future iterations, though such a system was not feasible within the mass, volume, and time constraints of the current payload.

Uncertainty in applied forces also represents a limitation. The pressure and impact tests rely on estimated force values, with load distribution assumed to be approximately uniform across sample pairs. In practice, variations in manufacturing tolerances, alignment, and mechanical constraints may result in non-uniform contact pressures. Additionally, the impact mechanism is characterized by an estimated energy input rather than a directly measured force, limiting the ability to precisely quantify peak contact conditions.

Material properties introduce further variability. The thickness and uniformity of the electroplated gold layer are not precisely quantified and may influence bonding behavior, particularly in the friction test where surface wear may occur. Surface contamination remains a potential source of error despite careful handling procedures, as even minor contamination can inhibit atomic contact.

Finally, as this study is based on a pre-flight design, all results remain hypothetical until validated through post-flight analysis. The ability to draw strong conclusions will depend on the successful recovery of both physical samples and environmental data.

4.2 Future Experimentation

Future work will focus on refining both experimental design and measurement precision. For the cold welding experiment, improved quantification of applied forces—particularly during impact—would enable more rigorous analysis of the relationship between mechanical conditions and bond formation. Redesign of the friction mechanism to allow controlled actuation under vacuum conditions would also improve the reliability and interpretability of results.

Additional studies may expand the range of materials tested, including other metals commonly used in aerospace applications, as well as further investigation of dissimilar metal pairings.

Following recovery of the payload, a post-flight analysis will provide the opportunity to validate the hypotheses presented in this study and refine both experimental methods and design approaches for future missions.

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Appendix

Figure A – CAD model of fully integrated payload in quarter experiment space, showing Cold Welding test assembly (front), Hammond box (center), and Data Protection test modules (rear)

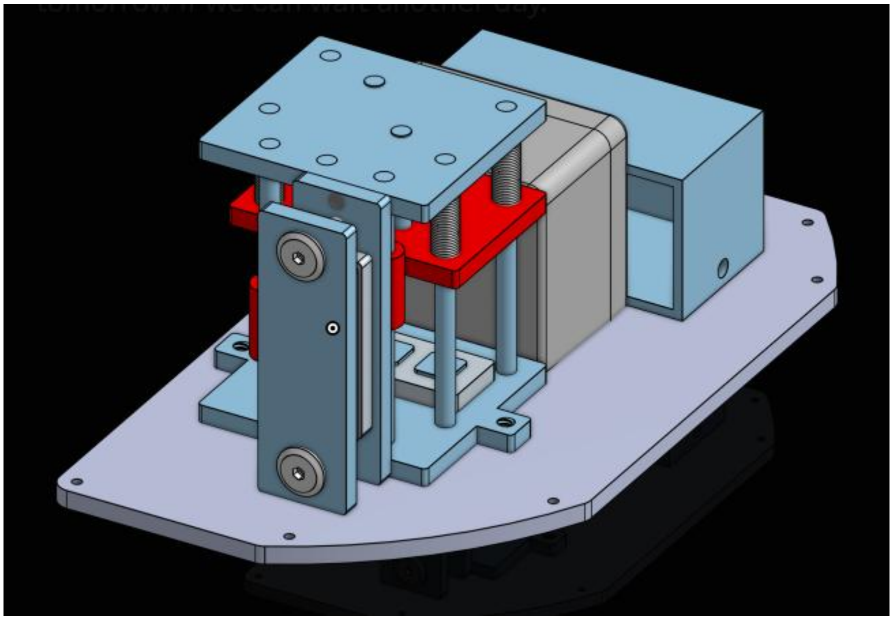


Figure A

Figure B – Side view of Cold Welding test assembly CAD model, showing Impact Test (left), Friction Test (center-right), and Pressure Test (right)

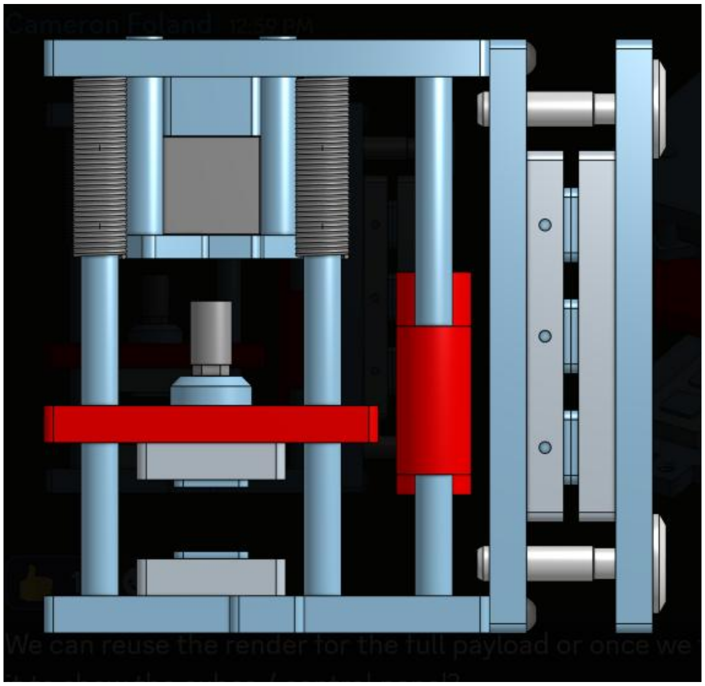


Figure B

Figure C – Alternate view of Cold Welding test assembly CAD model, showing Impact Test (left, with lower test samples visible), Friction Test (with cylindrical sleeves visible), and Pressure Test (right)

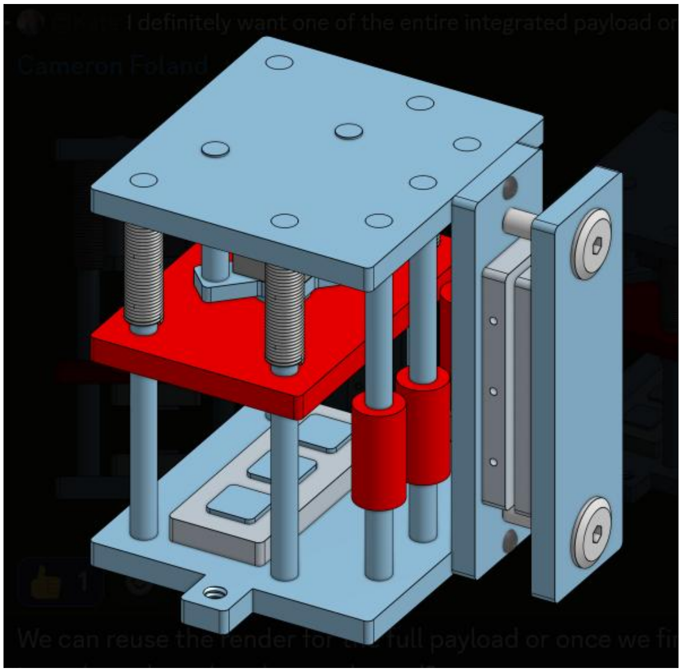


Figure C

Figure D – Starlite Heat Test; results showing the internal temperature sensor readings did not exceed 110.3 degrees Fahrenheit despite the outer Starlite coating being subjected to temperatures in excess of 1000 degrees Fahrenheit for over 5 minutes.

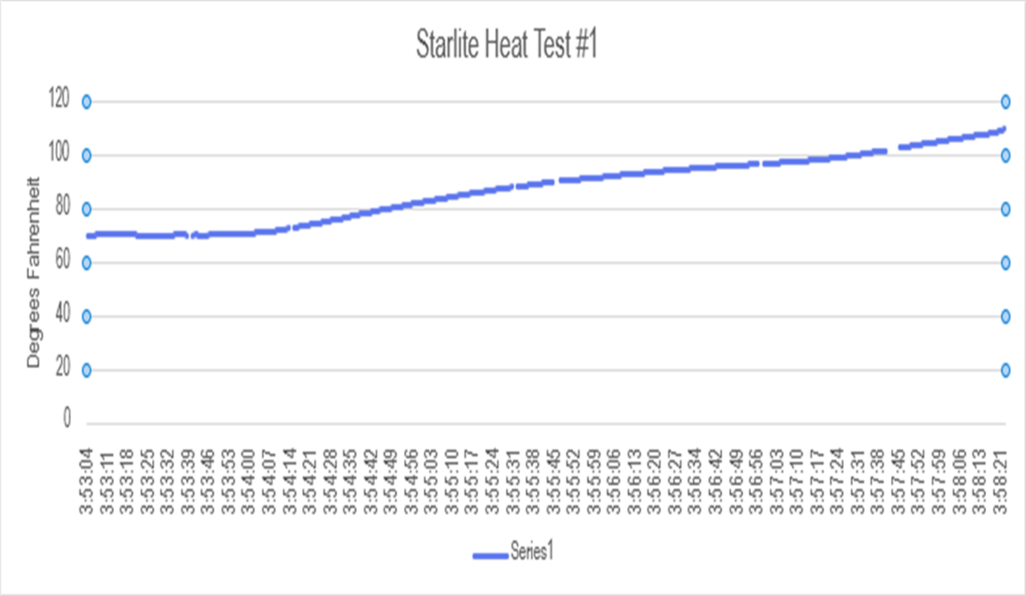
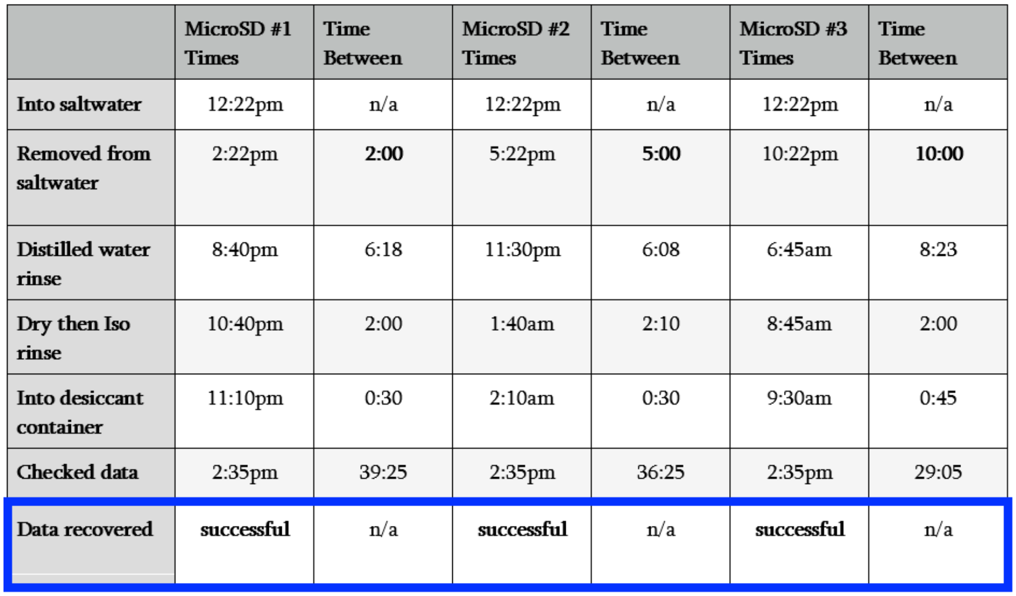


Figure D

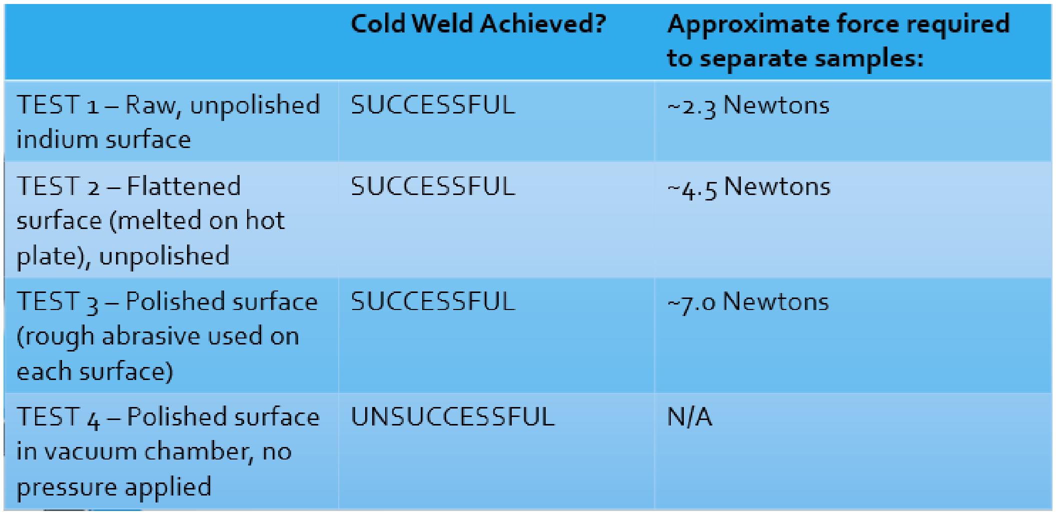
Table A – Results of Saltwater Analog Test with microSD Cards; showing that saltwater exposure alone was not damaging to data retrievability of microSD cards



	MicroSD #1 Times	Time Between	MicroSD #2 Times	Time Between	MicroSD #3 Times	Time Between
Into saltwater	12:22pm	n/a	12:22pm	n/a	12:22pm	n/a
Removed from saltwater	2:22pm	**2:00**	5:22pm	**5:00**	10:22pm	**10:00**
Distilled water rinse	8:40pm	6:18	11:30pm	6:08	6:45am	8:23
Dry then Iso rinse	10:40pm	2:00	1:40am	2:10	8:45am	2:00
Into desiccant container	11:10pm	0:30	2:10am	0:30	9:30am	0:45
Checked data	2:35pm	39:25	2:35pm	36:25	2:35pm	29:05
Data recovered	**successful**	n/a	**successful**	n/a	**successful**	n/a

Table A

Table B – Indium Cold Welding Test Results; showing the force required to separate indium samples cold welded after varying surface preparation methods, using an analog spring balance



	Cold Weld Achieved?	**Approximate force required to separate samples:**
TEST 1 – Raw, unpolished indium surface	SUCCESSFUL	~2.3 Newtons
TEST 2 – Flattened surface (melted on hot plate), unpolished	SUCCESSFUL	~4.5 Newtons
TEST 3 – Polished surface (rough abrasive used on each surface)	SUCCESSFUL	~7.0 Newtons
TEST 4 – Polished surface in vacuum chamber, no pressure applied	UNSUCCESSFUL	N/A

Table B