

Article

Launch and Recovery of a Hybrid Rocket Intended for Reuse

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Abstract

The objective of the project was to develop a hybrid rocket with a recovery system that would facilitate reuse. The rocket was successfully developed, launched and recovered. A two-stage parachute deployment system was developed and utilized, incorporating a non-pyro separation and a low-shock device. Notably, the non-pyro separation device plays a pivotal role in enabling the successful separation of a hybrid rocket, thereby ensuring its operation is free from explosive hazards. The launch took place on 14 December 2024, and all equipment was successfully recovered, except for the nose cones, the antenna-deployable GPS beacon and the motor case. The Ti-6Al-4V oxidizer tank, an important part that can be reused, was recovered with damage only to the outlet fitting. The tank was successfully repaired and passed a pressure test. This marks the first step in creating a reusable hybrid rocket.

Keywords: hybrid rocket; system design; low-shock separation device; separation nut; star fractal swirl fuel grain; ballistic launch experiment; telemetry; data logger



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1. Introduction

A hybrid rocket engine uses non-explosive, resin-like plastic fuel and a liquid oxidizer. Since it is free from explosive hazards, costs associated with handling explosive fuels are reduced. However, launch vehicles require a separation mechanism for stage separation and fairing opening, and the conventional separation mechanism is pyrotechnic, which prevents it from being free of explosive hazards. In addition, the pyrotechnic separation mechanism creates a high-level shock that can damage onboard electronic equipment and devices. Pyrotechnics are used in many areas of our daily lives, such as in airbags and seat belt restraint systems. These small pyrotechnic devices for separation are reliable, safe,

and have a low impact. However, these devices can only be used for a small pre-load. For high stiffness and high pre-load use in rockets, a higher holding load and high-energy pyrotechnics are required to induce high shock. Therefore, a non-pyrotechnic, low-shock separation device is required. Oh and Lee developed a separation nut that is fixed by a nylon cable. The separation nut separates by cutting the nylon cable with a nichrome burn wire [1]. However, the maximum holding load is smaller than the required holding load for launch vehicle applications because it depends on the tensile strength of the nylon wire. Bhattarai, Go and Oh [2] developed mechanisms for burning the wire and triggering hold-down mechanisms for CanSats. However, because these mechanisms were very small and compact, they could not be used to separate the launch vehicle. Zhang et al. [3] developed a shape memory alloy separation device. Sudick and Kaczynski [4] developed a nichrome burn wire separation mechanism. However, the maximum holding loads were lower than 1000 N, which is much smaller than required for launch vehicle separation. Downen et al. [5] developed a reusable low-shock clamp band for small spacecraft. The clamp band can be used for diameters ranging from 229 mm to 601 mm. This range exceeds the launch vehicle's diameter of 200 mm. Much more research can be found. For example, Niu et al. [6] analyzed the reliability of low-shock separation nuts. However, these studies were too specific and detailed to be applied to new designs. Similar separation mechanisms have been developed for commercial use [7–9]. However, they are too large for the peak altitude separation. Several types match the required holding load for the 1000 m altitude separation, but the cost and delivery do not. Thus, two types of lightweight novel separation devices with high holding loads and stiffness and low cost were developed. The first type is for peak altitude separation and the second type is for 1000 m altitude separation. These separation devices were used in the recovery system of a hybrid rocket and were launched.

During the 2021 launch test [10], the separation signal could not be received, so separation could not be confirmed based on the altitude and velocity data. Possible causes include condensation or malfunction of the nichrome wire drive circuit due to vibrations during launch and inadequate heating of the nichrome wire due to temperature drops during high-altitude flight. Therefore, improvements were made to address these issues.

2. The Peak Altitude and 1000 m Altitude Separation Modules on the Hybrid Rocket

Research and development of separation mechanisms for interstage separation and fairing opening applications is underway to achieve future satellite orbit insertion. The separation mechanism is currently used for deceleration and recovery of the rocket by deploying parachutes and releasing floats. Figure 1 shows the dimensions of the hybrid rocket, while Table 1 shows its major specifications. Figure 1 also shows the locations of the peak altitude and 1000 m altitude separation modules on the hybrid rocket launched on 14 December 2024. The rocket reached a maximum altitude of 10,055 m and a maximum speed of Mach 1.5.

The deceleration sequence begins when the rocket reaches its peak altitude. At this point, the peak altitude separation module separates and the streamers are released. Then, when the rocket descends to an altitude of 1000 m, the 1000 m altitude separation mechanism activates, deploying the parachute and floats. Figure 2 shows an overview of this sequence of operations.

The 1000 m altitude setting is an empirical value obtained by considering horizontal dispersion during descent and simulation errors. It is adopted as a reasonable operational standard to increase the recovery success rate.

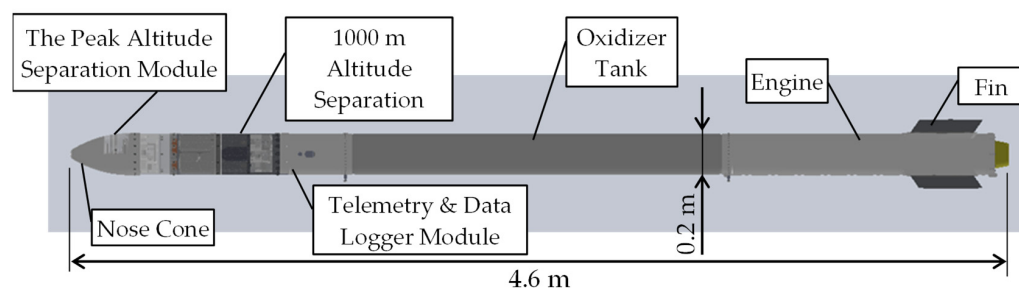


Figure 1. Positions of the peak altitude separation and 1000 m altitude separation modules.

Table 1. Major specifications.

Item	Unit	FY2024 Model, "Suzuki-Maru"
Gross liftoff mass, m_0	kg	93.1
Mass of the fuel before combustion, m_{f0}	kg	16.0
Mass of the fuel after combustion, m_{ff}	kg	7.28
Mass of the oxidizer, m_{ox}	kg	40.0
Mass of the propellant, $m_p = (m_{f0} - m_{ff}) + m_{ox}$	kg	48.7
Propellant mass fraction $\zeta = m_p / m_0$	%	52.3
Total impulse	kN-s	80.7

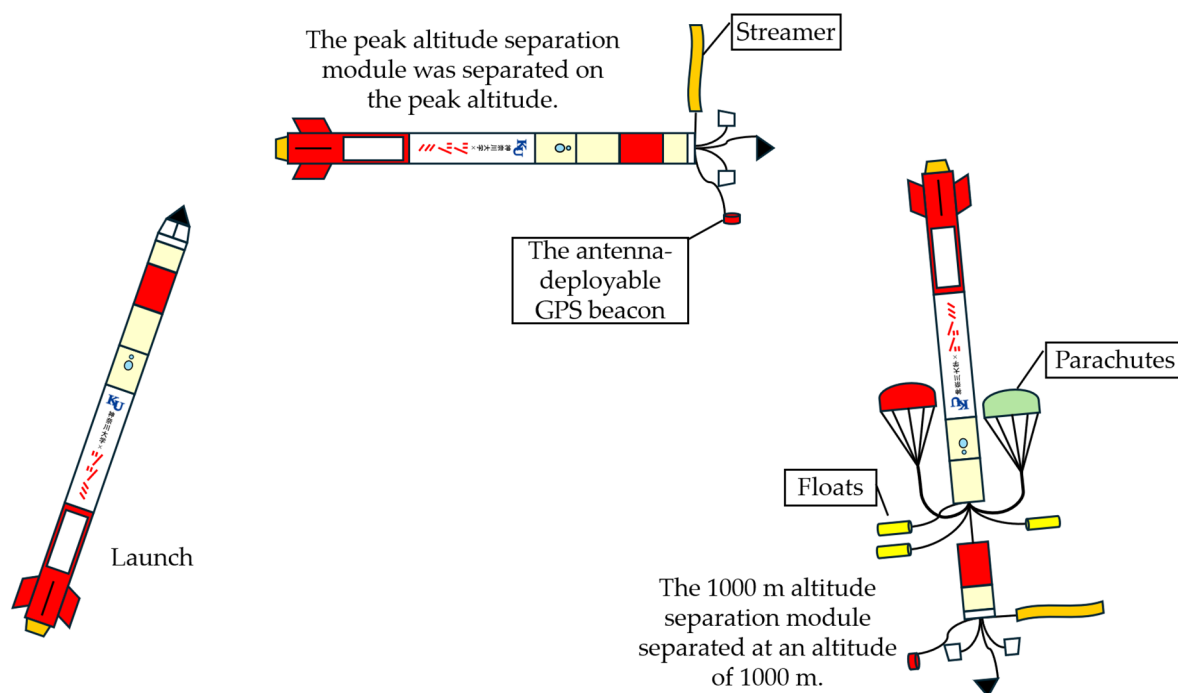


Figure 2. Separation sequence during decelerating descent.

Figure 3 shows the exact locations of the peak altitude and 1000 m altitude separation mechanisms. The first separation module contains a streamer and an antenna-deployable GPS beacon. The 1000 m altitude separation module contains two floats and a parachute.

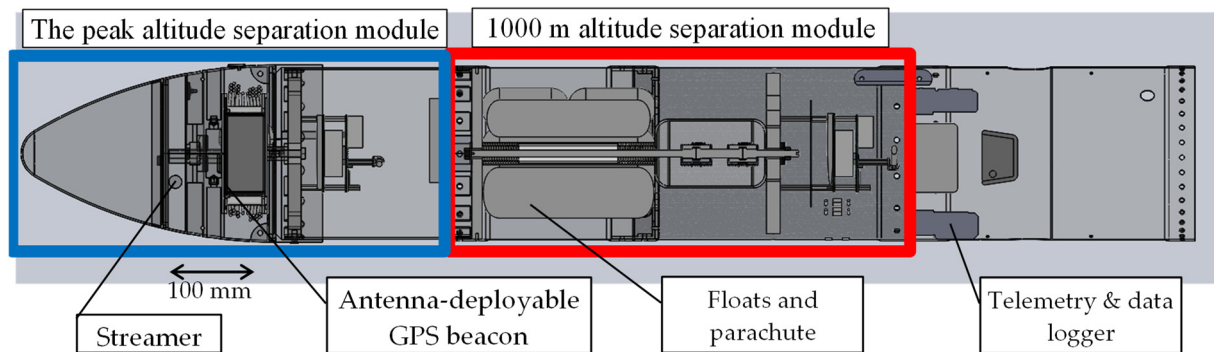


Figure 3. The peak altitude separation and 1000 m altitude separation modules.

3. Design of the Mechanisms for Peak Altitude and 1000 m Altitude Separations

To maintain the “non-explosive and high safety” characteristics of hybrid rockets, a non-pyrotechnic separation mechanism was developed. For the peak altitude separation mechanism, a nichrome wire method, as illustrated in Figure 4, is used to cut the resin rod. The rod is made by Reny, Mitsubishi Gas Chemical company, INC, Japan, from high-strength polyamide, which is a type of resin based mainly on polyamide MXD6. The maximum holding load of 2742 N is limited by the strength of the Reny rod. However, the required holding load of 125 N from the separation spring is much smaller. The nichrome wire with a diameter of 0.26 mm and 5 turns was used. The power was supplied by three 8.4 V, 800 mAh, 006P-type batteries connected in parallel, and the current was 2.4 A. As will be shown later, the nichrome wire cut the resin rod at room temperature in 3.6–3.9 s. Additionally, the module can separate after random vibration and at $-20\text{ }^{\circ}\text{C}$.

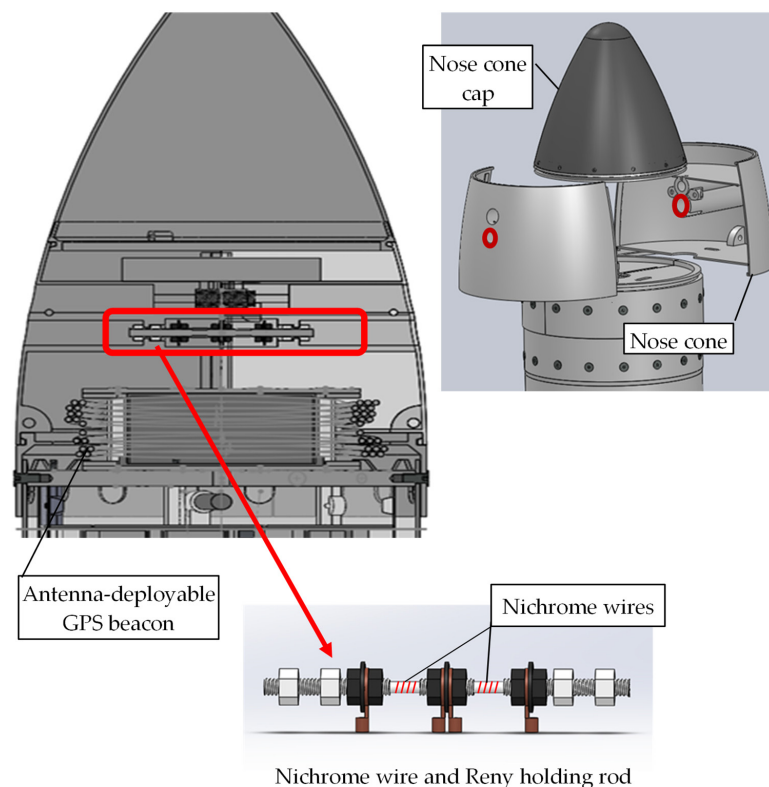


Figure 4. The peak altitude separation modules.

As illustrated in Figure 5, the 1000 m altitude separation mechanism uses aluminum separation nuts, which provide greater strength and stiffness. The shock load applied to the 1000 m altitude separation mechanism during the deployment of the peak altitude, as well as the risk of damage to the rocket due to aeroelastic instability such as flutter and divergence when the rocket reaches the speed of sound during high-altitude launch, are the reasons for this. The separation nuts are held in place by a polycarbonate band that is cut by a nichrome wire. One of the authors (A.T.) developed a half-cut internal thread separation nut; however, the maximum holding load of 4300 N was less than the required 5280 N holding load. Thus, a higher-holding-load separation nut was developed that uses a trapezoidal fitting nut instead of a threaded type.

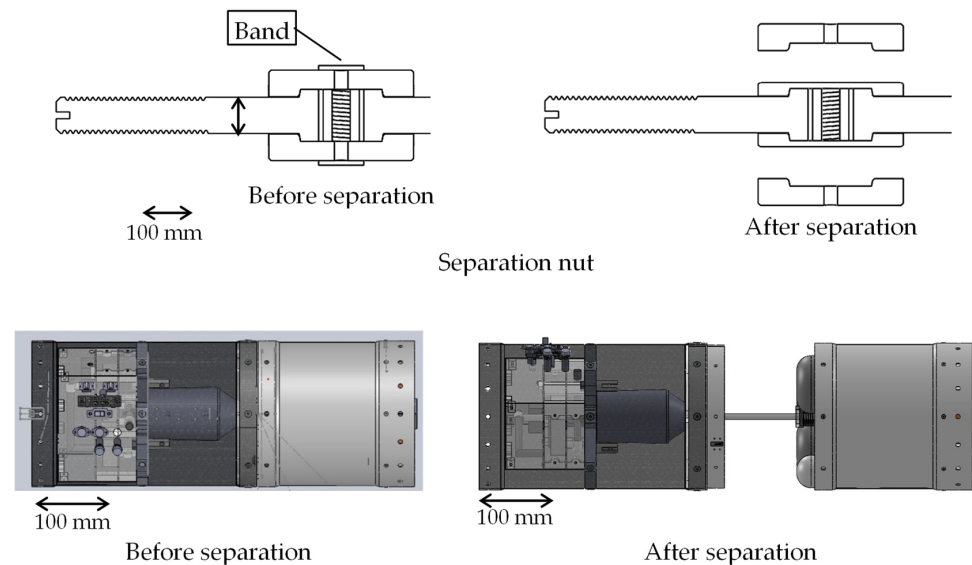


Figure 5. The 1000 m altitude separation modules.

Prior to 2022, the first type of trapezoidal fitting nut was developed. During pre-launch separation tests, separation failures occurred multiple times. One cause was the excessive localized load applied by the tip of the separation nut to the rod (shown in red circles in left of Figure 6) during separation, resulting in plastic deformation of the rod's surface and the formation of a depression. This prevented the separation process. To alleviate this problem, the shape and structure of the separation nut were improved to enhance reliability.

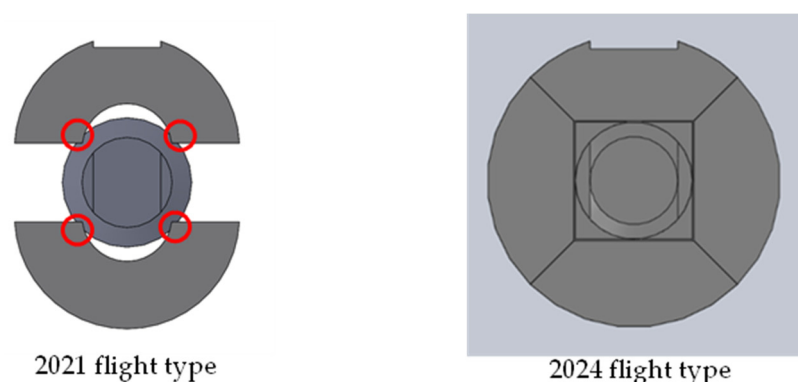


Figure 6. Types of the separation nuts.

Therefore, the load-bearing surface was changed from two surfaces to four, as shown in Figure 6 (right). The curved surface was also changed to a flat one to prevent biting into the rod. As a result, the maximum holding force was 5932 N (exceeding the required force

due to the shock load of the peak altitude separation) when the band width was 10 mm. In addition, stable separation was achieved by preventing the band from biting into the rod. Table 2 shows a comparison of previously published and commercial devices.

Table 2. Comparison of previously published and commercial devices.

Test Type	Present Separation Nut	Half-Cut Internal Thread Separation Nut [11]	LSRD-10K/C-2000 [7]	061-028 Medium-Duty HDRM [8]	E1000 ERM [9]
Mass [g]	101	30 (without housing)	350	—	—
Dimension [mm]	$\Phi 75 \times 130$	$\Phi 16 \times 30$	$\Phi 52 \times 43$	$\Phi 42.8 \times 67.6$	$\Phi 36.8 \times 50.8$
Bolt size	M8	M6	1/4-28 UNJF	No.10-32 UNJF	No.10-32UNF
Maximum holding load [kN]	5.9	4.3	—	11.1	4.4
Nominal holding load [kN]	3.0	2.0	10	—	—
Power [W]	25	17.5	108		8.1
Resistance [Ω]	3.0	1.9	3.0	0.5–2.0	1.6
Function time	2.4 s @23 °C 4.2 s @−20 °C	1.6 s @23 °C 2.5 s @−10 °C	<0.15 s	<0.05 s @3.5A	<0.4 s @4.0A, 23 °C

“—” denotes no data.

4. Tests on Ground

As mentioned in the Introduction, the separation signal could not be received during the launch test in 2021 [10]. This was possibly due to an anomaly in the nichrome wire drive circuit caused by condensation or vibration during launch. Therefore, the nichrome wire drive circuit was housed in a moisture-proof case. Furthermore, the peak altitude and 1000 m altitude separation modules were assembled to the same conditions as in flight, and random vibration tests and low-temperature separation tests were conducted.

Random vibration tests were conducted at the vibration levels shown in Figure 7. The effective value of acceleration was set to $G_{\text{rms}} = 235.8 \text{ (m/s}^2\text{)}_{\text{rms}}$. This value was set as the enclosure value of the measured random vibration level by an acceleration data logger attached to the combustion test stand on which the hybrid rocket engine used in this rocket was mounted during combustion testing. Figure 8 shows a comparison of the measured random vibration level during the combustion test with the enclosure value. Table 3 shows a comparison of the overall acceleration levels. Figure 8 and Table 3 show that the enclosure value is significantly higher than the measured random vibration level.

Furthermore, wireless communication with the nichrome wire drive circuit was confirmed to be functioning properly before, during, and after the vibration test. Finally, a separation test was performed after the vibration test.

The test duration of the random vibration test was 120 s; the test axis was the longitudinal axis. The specifications of the shaker are shown in Table 4.

As shown in Figure 9, all separation mechanisms operated normally after excitation and achieved successful separation. This confirmed that the mechanisms function under the expected vibration conditions.

Another possible cause of the 2021 separation failure was condensation on the Reny rod and nichrome wire due to the low-temperature environment at high altitudes during flight. Therefore, a low-temperature separation test was conducted to evaluate the operability of the separation mechanism under these conditions. The test aimed to verify that the

separation and wireless communication could function normally in a low-temperature environment and to measure the time it took for the nichrome wire to burn through the band from the moment the current was applied until separation was visually confirmed. For the low-temperature separation test, the peak and 1000 m altitude separation modules were placed in a freezer and cooled to target temperatures of $-20\text{ }^{\circ}\text{C}$ and $-10\text{ }^{\circ}\text{C}$, respectively. Figure 10 shows the temperature during the duration of the freezer soak.

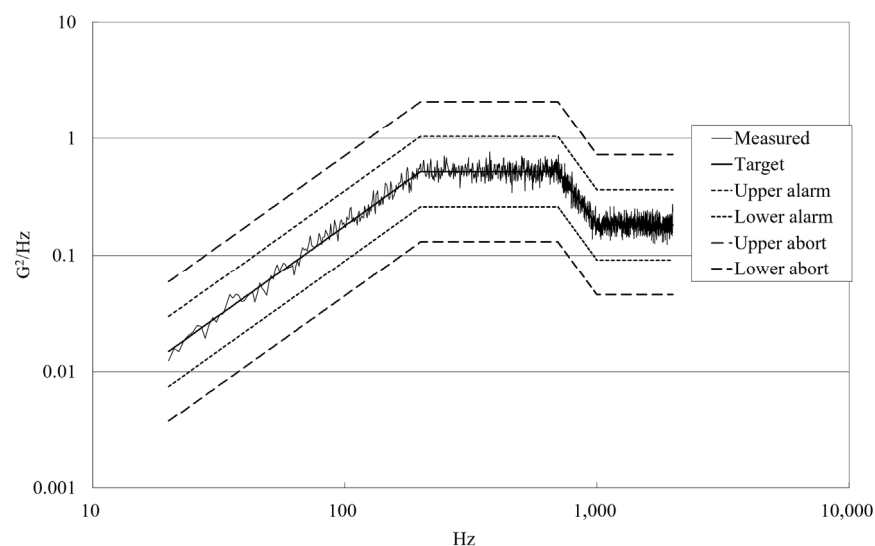


Figure 7. Random vibration test level.

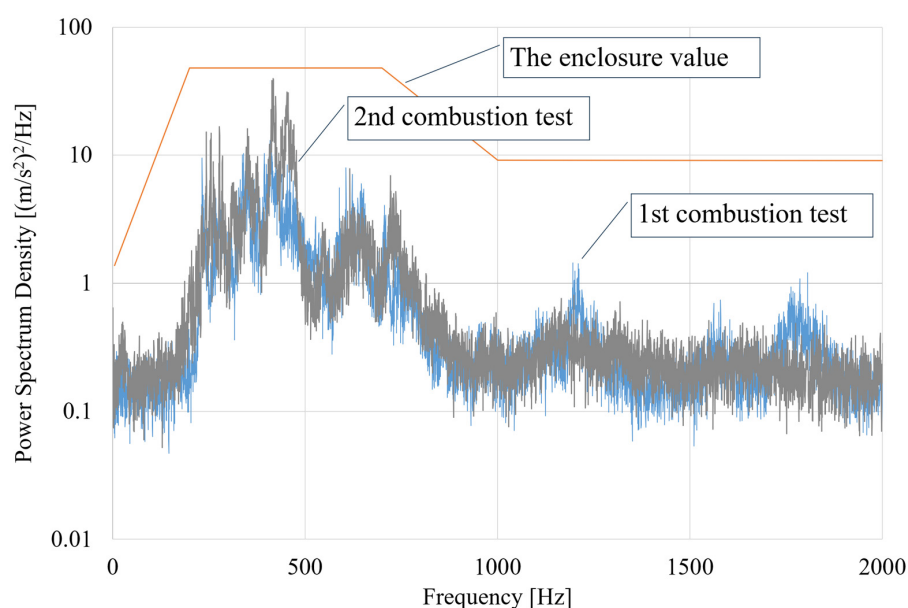


Figure 8. Random vibration level during combustion test.

Table 3. Comparison of the overall acceleration levels.

Test Type	Overall Acceleration Level $[(\text{m/s}^2)_{\text{rms}}]$
1st combustion test	37.89
2nd combustion test	44.44
Sample standard deviation	235.8 (24 G_{rms})
Qualification test level for onboard equipment on H-II rocket [12]	202.0

Table 4. Specification of the shaker.

Manufacturer	IMV corporation, Osaka, Japan
Model number	VS-2000A-140T
Type	Electrodynamic Shakers (voice coil type)
Specification	Excitation force: 19.6 kN (sine wave), 13.7 kN rms (random wave)
	Frequency range: 5–3000 Hz (unloaded)
	Maximum acceleration: 980 m/s ²
	Maximum velocity: 1.4 m/s Maximum displacement: 51 mm p-p

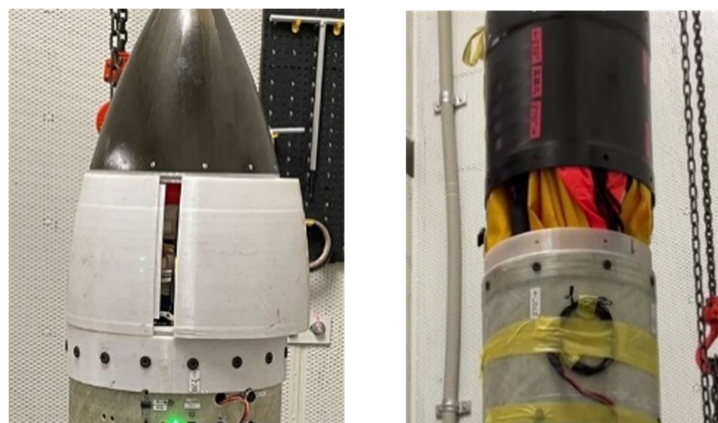
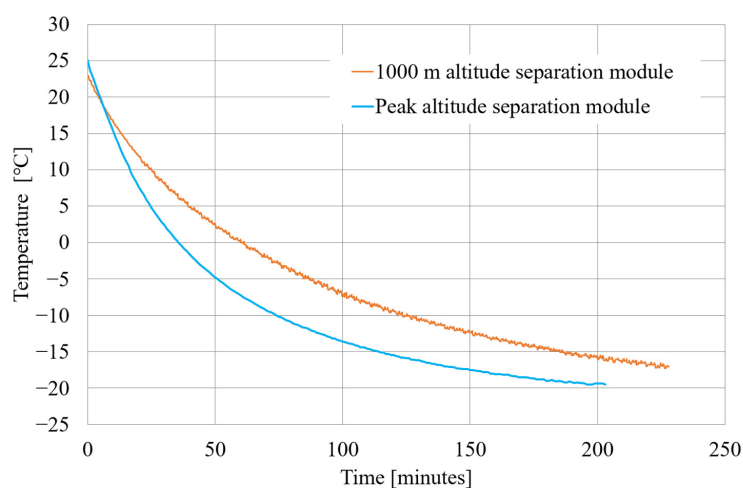
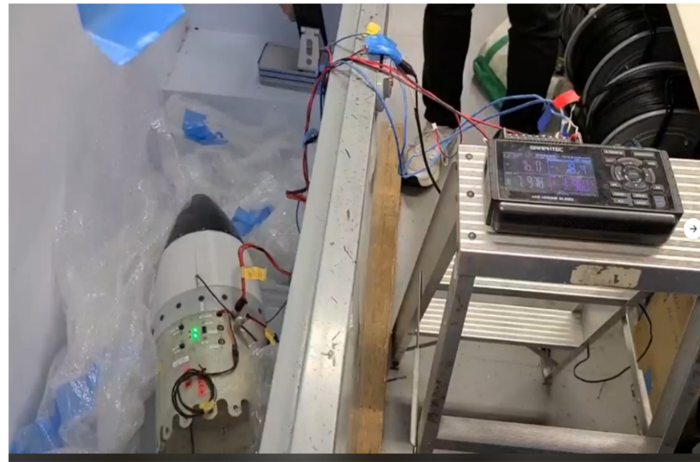
**Figure 9.** Separation test after random vibration test.

Figure 11 illustrates the configuration of the low-temperature separation test in a freezer. Tables 5 and 6 show a list of separation times for the separation tests on the room temperature and the low temperature. A repeat room temperature test was conducted to verify the workmanship. As the design and manufacturing of the first and second rockets were identical, the second rocket did not undergo a repeat room temperature test. For this reason, only a single rocket underwent low-temperature and random vibration tests. The results showed separation times of 4.3 and 6.3 s for the peak altitude separation and 4.2 s for the 1000 m altitude separation. The results were longer than the average values at room temperature, which were 3.6 and 3.9 s for the peak altitude separation and 2.4 s for the 1000 m altitude separation. These results confirmed that the separation mechanism operates normally in a low-temperature environment.

**Figure 10.** Temperature during the duration of the freezer soak.



Low-temperature separation test in a freezer.



After separation of the peak altitude separation module.



After separation of the 1000 m altitude separation module.

Figure 11. Low-temperature separation test configuration.

Table 5. Separation time of the peak altitude separation module.

Test Type	First Rocket [s]	Second Rocket [s]
Room temp. 1st	2.2	3.7
Room temp. 2nd	3.5	4.2
Room temp. 3rd	5.1	-
Average	3.6 ($n = 3$)	3.9 ($n = 2$)
Sample standard deviation	1.2 ($n = 3$)	0.3 ($n = 2$)
After random vibration test	5.3	-
Low-temperature 1st	-	4.3
Low-temperature 2nd	-	6.3
Average	-	5.3
Sample standard deviation	-	1

Table 6. Separation time of the 1000 m altitude separation module.

Test Type	First Rocket [s]	Second Rocket [s]
Room temp. 1st	2.1	2.6
Room temp. 2nd	2.7	-
Room temp. 3rd	2.4	-
Average	2.4 ($n = 3$)	-
Sample standard deviation	0.25 ($n = 3$)	-
After random vibration test	-	7.8
Low temperature	-	4.2

5. Launch Test and Results

On 14 December 2024, a launch test of a hybrid rocket equipped with the peak altitude and 1000 m altitude separation mechanisms was conducted in Minamisoma City, Fukushima Prefecture. The rocket successfully lifted off, as shown in Figure 12. The rocket body separated and was recovered successfully, including the Ti-6Al-4V oxidizer tank. The recovered rocket body is shown in Figure 13. The separation surface was detached from the body, and the stored parachutes and floats were deployed, as shown in Figure 14. Based on telemetry data, the 1000 m altitude separation was confirmed to have separated within a normal time frame after 171 s, as shown in Figure 15. However, the nose cones and nose cone cap were not recovered, as shown in Figure 16; thus the separation of the peak altitude separation could not be confirmed visually. Additionally, the timing of the peak altitude separation could not be determined from the telemetry data because only one data point was received at 45 s, which was earlier than expected, as can be seen in Figure 15. The expected peak separation time was 59.6 s, i.e., the sum of the 56 s set timer time and the 3.6 s average separation time of the peak altitude separation module, as shown in Table 5. A post-launch analysis of the telemetry data indicated that the nichrome wire drive circuit of the peak altitude separation was reset 16 s after launch. Thus, the actual turn-on time was $45 + 16 = 61$ s, and the peak altitude separation was performed normally.

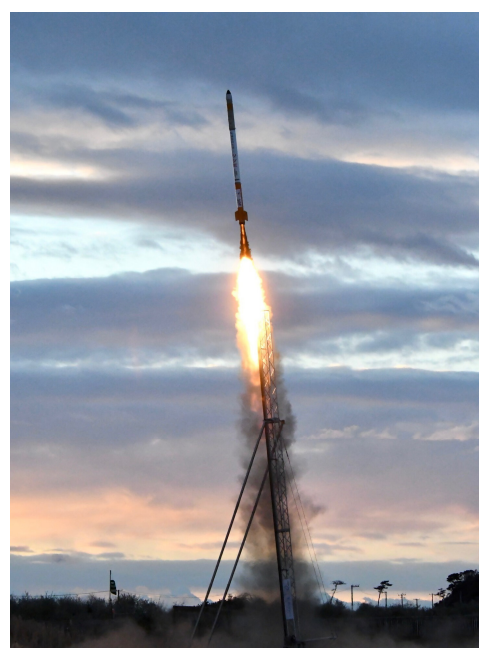
**Figure 12.** Launch test on 14 December 2024 in Minami-soma city. Copyright Naoto Michiura.



Figure 13. Recovery of the rocket.



Figure 14. Recovered parts of the rocket.

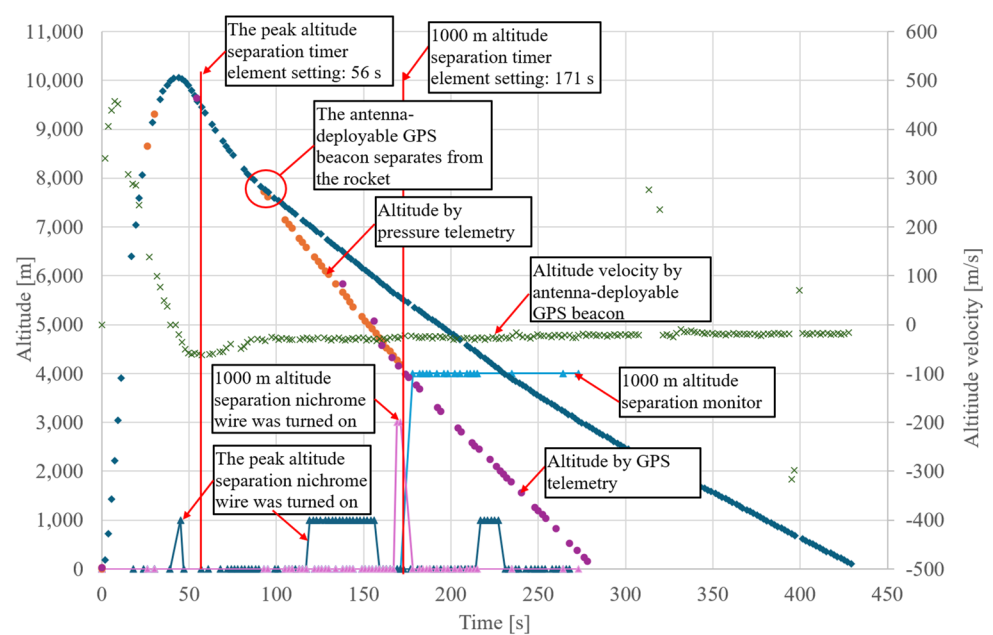


Figure 15. Telemetry data.

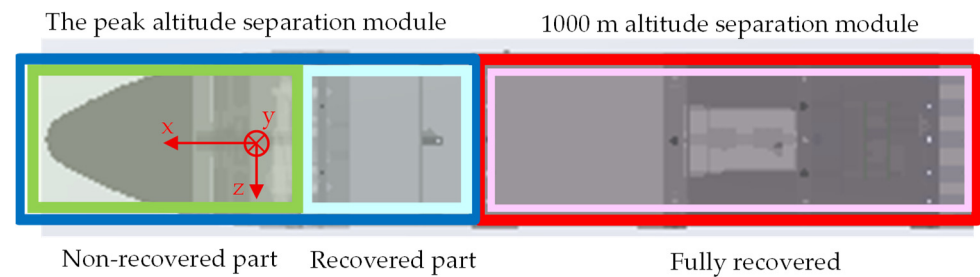


Figure 16. Recovered parts of the separation modules.

Figure 17 shows that the angular velocity around the x-axis increased from approximately 0 deg/s to -2000 deg/s over a period of 60 s. The 60 s matches the 56 s peak altitude separation timer setting plus the 3.6 s separation time shown in Table 5. The increase in angular velocity around the x-axis occurred due to the separation of the nose cones and caps connected by shock cords to the rockets, which created a moment around the x-axis. This indicates that the peak altitude separation was conducted as expected.

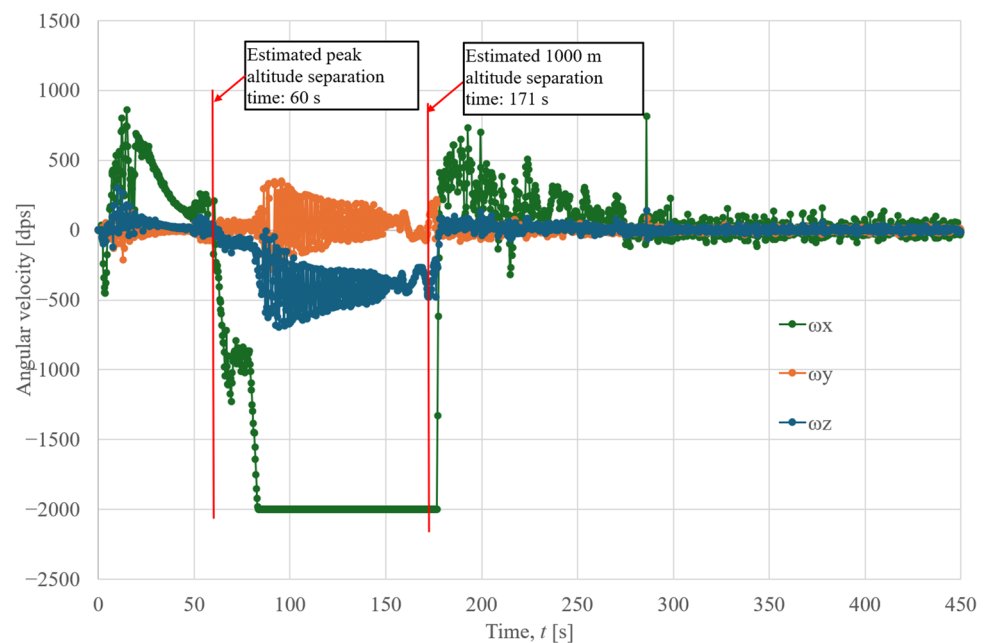


Figure 17. Angular velocities.

After the 1000 m altitude separation, the angular velocity around the x-axis decreases sharply. This is due to the deployed parachute and floats reducing the angular velocity. Figure 18 illustrates this concept by showing the entangled impact cords of the parachute and floats, which absorbed the angular momentum.

As shown in Figure 16, most of the components below the peak altitude separation module were recovered. However, the upper structure, including the nose cones, the nose cone cap, and the antenna-deployable GPS beacon inside the cap, could not be recovered. Figure 19 shows details of their scattering.

Figure 20 shows where the antenna-deployable GPS beacon landed. It was inside the nose cone cap. It is believed that the beacon was unintentionally released due to a break in the shock cord. Figure 15 shows that the altitude data of the antenna-deployable GPS beacon and the rocket indicate that the beacon separated from the rocket approximately 90 s after launch. It is possible that one of the following occurred approximately 90 s after reaching the peak altitude:

- The GPS transmitter was scattered after the peak altitude separation.

- The peak altitude separation mechanism was damaged during flight.

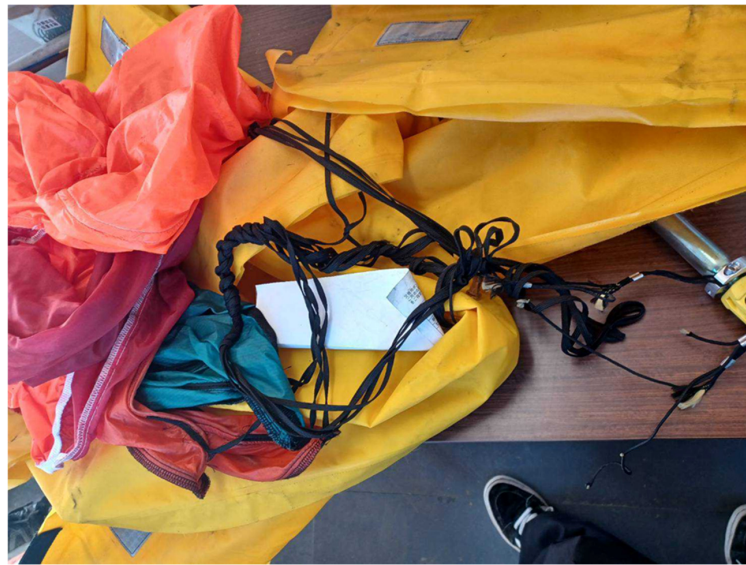


Figure 18. Entangled shock cords and parachutes.

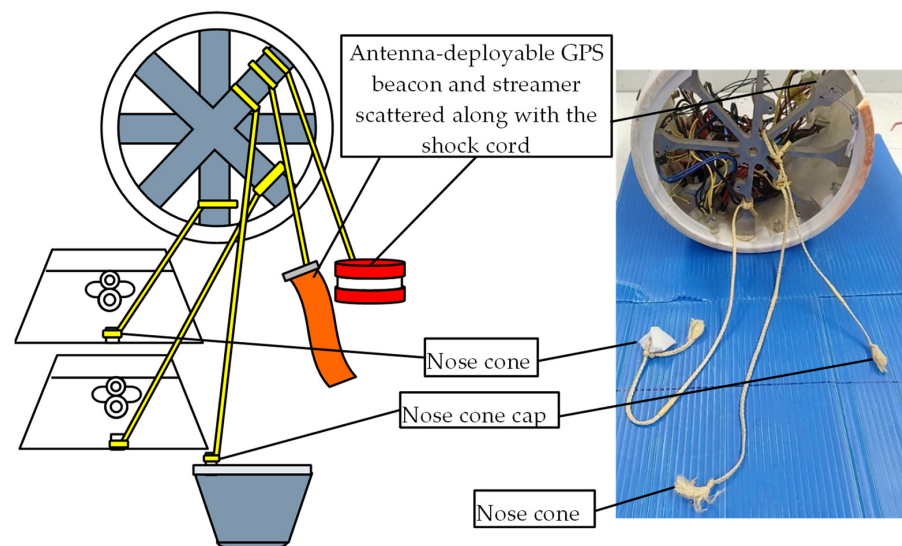


Figure 19. Scattering of shock cords and parachutes.

However, it is unlikely that an external force due to the separation shock was large enough to cut the shock cords on the peak altitude separation mechanism between peak altitude and splashdown because the shock cords and their attached fittings were designed to ensure the separation shock load. Therefore, this fracture of shock cords was thought to have been caused by rotation around the x-axis maximum of 2000 deg/s, as shown in Figure 17.

Based on the above analysis results, it can be concluded that the peak altitude separation mechanism functioned properly after reaching the peak altitude, and 1000 m altitude separations were successfully completed.

Figure 21 shows the recovered Ti-6Al-4V oxidizer tank with the outlet fitting dropped, and Figure 22 shows the repaired tank. The dropped outlet fitting was welded by fiber laser welding. The repaired tank was verified by a hydrostatic pressure test. Figure 23 shows the strain gage layout and Figure 24 shows the pressure–strain chart. The test pressure

was 7.5 ± 0.1 MPa at 3 min, which is 6 MPa of the maximum expected operating pressure (limit pressure) multiplied by an acceptance load factor of 1.25 [13]. The maximum strains within $7875 \mu\epsilon$ correspond to the yield strength, and the maximum residual strain within $\pm 2000 \mu\epsilon$ corresponds to the 0.2% offset yield strength. Thus, the tank was successfully repaired and passed a pressure test.

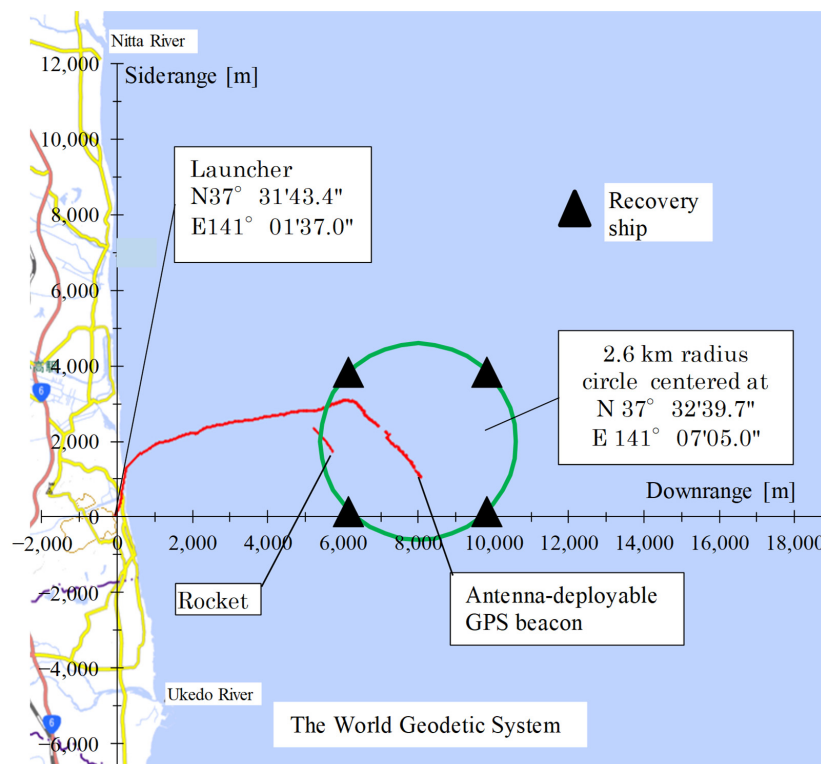


Figure 20. Flight path and landing point.

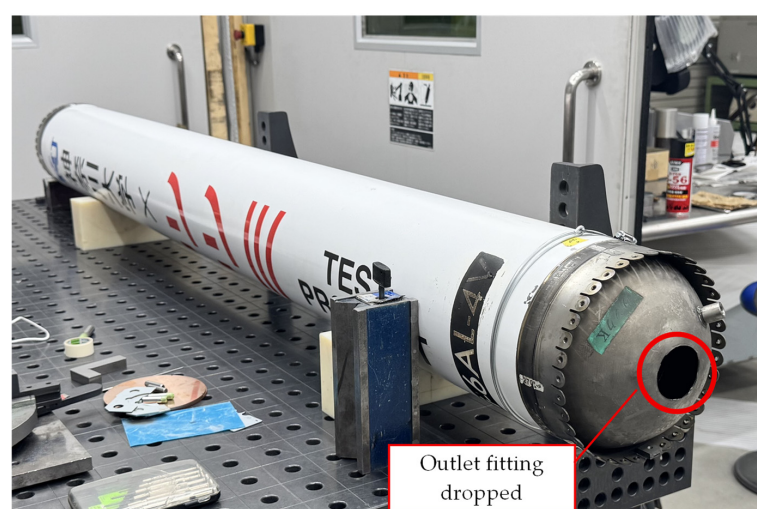


Figure 21. The recovered Ti-6Al-4V oxidizer tank.

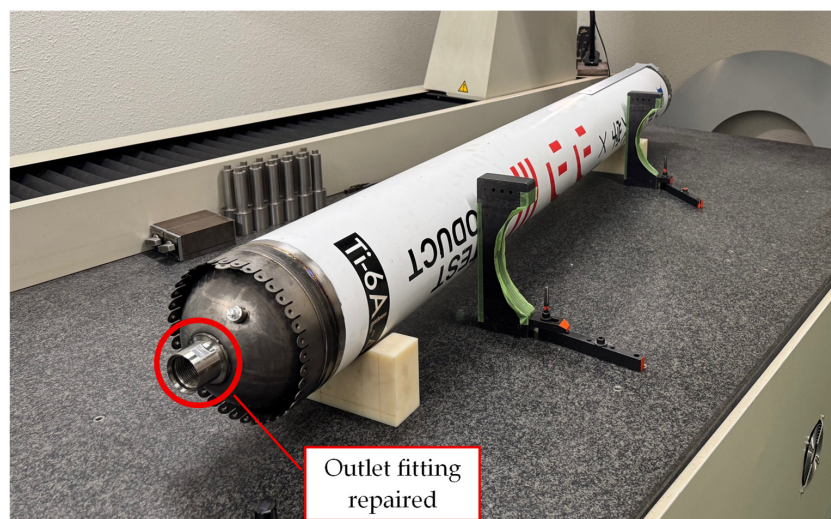


Figure 22. The repaired tank.

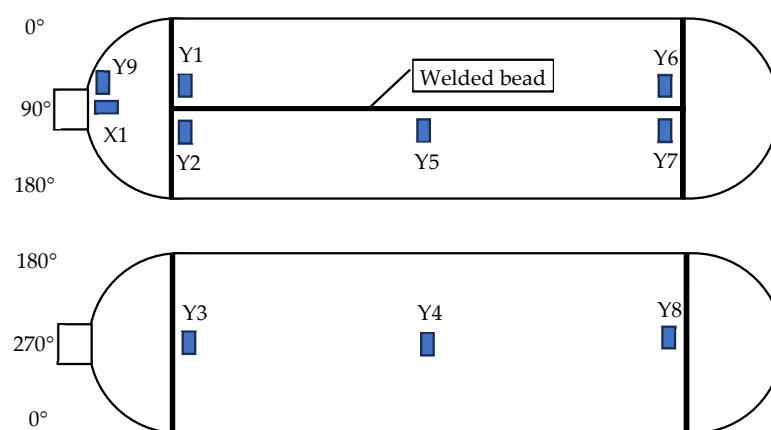


Figure 23. Strain gage layout.

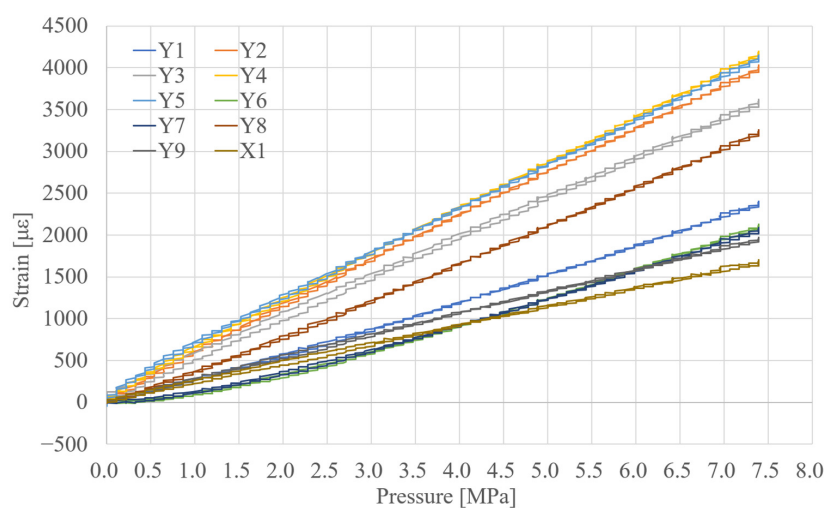


Figure 24. Pressure–strain curves.

6. Conclusions

This study focused on the development and improvement of the first and 1000 m altitude separation mechanisms, aiming to enhance the reliability of the separation operation

and conduct flight demonstrations. To evaluate the performance of the improved separation mechanism, a random vibration test was conducted to confirm its resistance to the vibration environment generated after engine combustion during launch. The results confirmed that the separation mechanism operated normally even under vibration conditions, ensuring reliable separation. Furthermore, to evaluate its operability in low-temperature environments, a low-temperature separation test was conducted with the device assembled in the rocket body and cooled to -20°C . The results showed that the separation mechanism operated properly under these conditions and that separation was successful.

In addition, a launch test was conducted using a hybrid rocket to verify the operation of the separation mechanism under flight conditions. The launch test successfully recovered most of the rocket body, and received telemetry confirmed that the 1000 m altitude separation mechanism operated according to the designed timing. Regarding the peak altitude separation mechanism, the altitude reached, condition of the recovered rocket body, and payload trajectory analysis suggest that separation occurred normally during flight. Additionally, the Ti-6Al-4V oxidizer tank, an important part that can be reused, was recovered with damage only to the outlet fitting. The tank was successfully repaired and passed a pressure test. This marks the first step in creating a reusable hybrid rocket.

These results demonstrate that the improved separation mechanism operate well in vibration environments, low-temperature environments, and actual flight environments, confirming its reliability for practical use.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because they are not open data.

Conflicts of Interest: Author Yoshihiko Kunihiro was employed by the company Toa Electric Industry Co., Ltd., and Makoto Miyake was employed by the company Fullheart Japan Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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