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Reusable Electron: Analysis of progress toward the world's first reusable commercial small rocket

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ABSTRACT

Leading end-to-end space company Rocket Lab has significantly advanced its rocket reusability program over the past 12 months, bringing the Electron launch vehicle closer to becoming the world's first reusable commercial orbital class small rocket. Applying the concept of a circular economy to rocketry, Rocket Lab's reusability of Electron is expected to produce benefits to the space industry including reduced environmental pressure, innovation in rocket reuse technology, better sustainability of material supply, and lower launch costs to the burgeoning small satellite market.

Rocket Lab's concept of operations for rocket recovery includes the capture of a returning Electron first stage mid-air by helicopter before the stage is brought back to the company's production facilities for refurbishment and relaunch. The survival of Electron's first stage through extreme atmosphere re-entry dynamics has been borne out across five missions since the reusability program began in mid-2019, including guided re-entries early in the program, stages returned from the ocean to the company's production complex for analysis, parachute testing, mid-air helicopter capture tests, and helicopter mission operations to prove concept of operations for rocket stage capture. Iterative developments to the launch vehicle and substantiated data gathered across these missions has progressed Rocket Lab to attempt the first aerial capture of a returning rocket stage during a mission scheduled to launch in 2022.
This paper will discuss the program's results to date and future planned development stages.

INTRODUCTION

Rocket Lab is a leading end-to-end space company delivering frequent, reliable, and affordable small satellite launch services, with 146+ small satellites deployed to space across 26 orbital launches of its small launch vehicle Electron (Figure 1) since 2017. To further increase launch cadence to meet the market demand, Rocket Lab is developing new systems, technology, and infrastructure (including its three launch pads) to make Electron the world's first orbital-class reusable small launch vehicle.

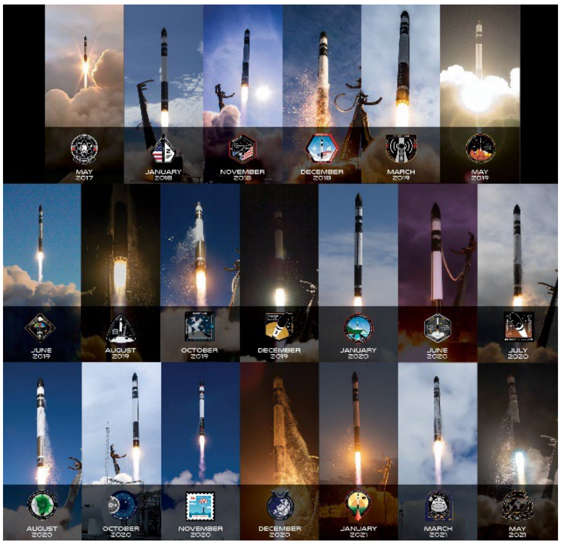

Figure 1: Electron launch vehicles in flight.

The plan to recover and reuse Electron's first stages involves eliminating the need to build a new first booster for every mission, thereby increasing launch frequency and enabling small satellites to access space more frequently and reliably. By recovering, refurbishing and re-flying Electron's first stage, Rocket Lab aims to reduce production timelines and drive the company closer to its ultimate goal of launching every week to meet market demand.

Rocket Lab’s reusability plans for Electron were announced in August 2019 and are being implemented in two phases. The first phase involved returning Electron’s first stage to Earth under a parachute for a soft water landing, to then be retrieved and returned to Rocket Lab’s Production Complex for analysis. This first phase was effectively completed in 2021 with the return of retrieved missions for analysis at the Production Complex. The current second phase builds on the progress made in the recovery program by returning Electron’s first stage to Earth under a parachute for mid-air capture by helicopter, before the stage is transported back to Rocket Lab’s Production Complex for analysis, refurbishment, and relaunch.

For the initial phases on the program – see SSC21-IV-02, the 2021 Paper, Return To Sender: Lessons Learned From Rocket Lab’s First Recovery Mission. That paper provides a highlight of what was achieved from the preliminary developments up to the dedicated recovery flights of Flight 16 – Return to Sender in November 2020, and prior to recovered stage analysis post Flight 20 – Running out of Toes in May 2021.

This paper summarizes Rocket Lab’s Electron reusability program and the innovative technology and systems developed and successful implemented the post Flight 20 up to the recent Flight 26 – There and Back Again recovery mission in May 2022.

ELECTRON LAUNCH VEHICLE

Electron is Rocket Lab’s small launch vehicle (Figure 2) designed for rapid manufacture and launch to meet the dedicated launch needs of the small satellite market. As of the date this paper was submitted in June 2022, Electron has delivered 146 small satellites to low Earth orbit for private, commercial, educational, and government enterprise.

Figure 2: Electron Launch Vehicle

With a lift capacity of up to 300 kg (661 lbs.), Electron nominally delivers up to 200 kg (441 lbs.) payloads to a 500 km sun-synchronous orbit. Orbital delivery across Electron’s 20 missions ranges from 430km to 1,200 km circular orbits. Rocket Lab primarily launches Electron from its privately-owned orbital launch site Launch Complex 1’s two launch pads in New Zealand (Figure 3) where it is licensed to launch up to 120 times a year, but the company also offers responsive launch capability on home soil from its second site Launch Complex 2 at the Mid-Atlantic Regional Spaceport at Wallops Flight Facility in Virginia, USA

Figure 3: Two Electron rockets on the pad at Rocket Lab Launch Complex 1, Mahia, New Zealand.

Electron's design incorporates Rocket Lab's in-house designed and manufactured Rutherford engine with the innovative use of electrical systems and carbon composite materials. The Electron launch vehicle dimensions and specifications are outlined in Table 1.

Table 1: Electron Launch Vehicle Dimensions and Specifications	
Length	18 m / 59 ft
Diameter	1.2m / 3.9 ft
Stages	2 + Kick Stage
Vehicle Mass (Lift-off)	13,000 kg / 28,660 lb
Nominal Payload Mass	200 kg / 441 lb(SSO) 300 kg / 661 lb (LEO)
Payload Diameter	1.07 m / 3.51 ft
Propulsion – Stage 1	9x Rutherford Engines (Lox/Kerosene)
Propulsion – Stage 2	1x Rutherford Engine (Lox/Kerosene)
Material/Structure	Carbon Composite
Launch Site Locations	LC1a/LC1b Mahia, New Zealand LC2 Wallops Island, Virginia

THE ARGUMENT FOR REUSABILITY

Rocket Lab's Electron reusability program was established on the foundational basis of eliminating the need to build a new first stage for every mission. Rocket Lab utilizes additive techniques like 3D-printing and carbon-composite structures to manufacture a complete Electron launch vehicle once every 30 days. However, manufacture of the launch vehicle's first stage consumes 40% of the company's labour hours and represents ~50% of the cost of Electron manufacture.

While Rocket Lab continues to scale its manufacturing capability, time, cost, resource availability, and material supply are all considerable constraints. Transitioning Electron from a fully expendable launch vehicle to a reusable one by recovering, refurbishing, and re-flying its first stage targets significant reductions in time and labour.

THE CHALLENGES OF REUSABILITY

Atmospheric re-entry

During launch, the first stage of Electron accelerates to a speed of approximately 8,400km/h and an altitude of 71km before Main Engine Cut Off (MECO) and separation. Electron encounters decreasing atmospheric density as it ascends and accelerates. The fairing at the top of the vehicle, encasing the payload during launch, is covered with a thick layer of thermally protective material, referred to as Thermal Protection System or TPS. The fairing TPS shields the payload from aerodynamic heating during ascent, while additional regions of TPS around critical areas of the vehicle provide protection to vulnerable components, including the powerpack that houses the engines and batteries.

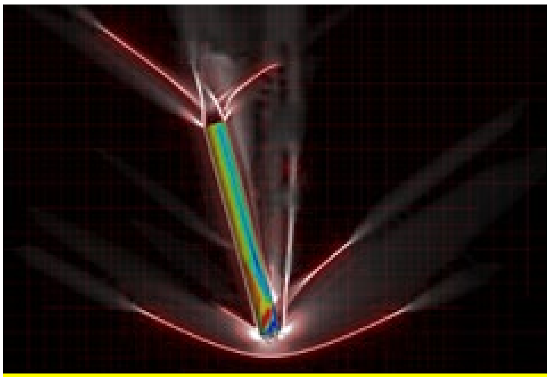

Figure 4: Visual depiction of thermal and shock loads on Electron first stage during atmospheric re-entry.

Following separation, stage one continues to coast in an upward trajectory before arcing over and accelerating under gravity back towards the ocean. As it descends and accelerates, stage one reaches speeds of around Mach 8 (eight times the speed of sound) and experiences a rapid growth in dynamic pressure and temperature as the air compresses and shocks down at the leading edge of the stage. At its maximum, the differential pressures and temperatures encountered can reach 120 kPa (1.2 atmospheres) and 2400 °C - nearly 1000 °C higher than the melting temperature of steel. At Rocket Lab, this environment is referred to as the Wall.

Limited mass margins

To make Electron recoverable and re-usable, the challenge is to turn a vehicle designed with tight margins and for a single, expendable use into one capable of withstanding the searing heat and crushing pressure during re-entry, then decelerate in a controlled manner to a velocity where it could splashdown intact or be captured during descent. These tight margins and single use design mean that mass and volume are at a premium, while the structure is designed for particular load cases and directions.

After careful analysis and evaluation of options, the approach selected was to turn the vehicle end-over-end after separation so that it enters engine first, and develop a recovery system to be housed in the interstage to provide communication, control, and deceleration of the stage to safe conditions for splashdown and retrieval.

Program Development

Subsequent to the flight success seen in Flight 16 – Return To Sender in November 2020, and the lessons learned from it that were incorporated into Flight 20 – Running Out of Toes in May 2021, there have been developments to improve on the path to development of a refurbishable and re-usable Electron booster stage.

FLIGHT 20 – Running Out Of Toes:

Based on the post launch and recovery of Flight 16 the key focus for development on the next mission was split into two main areas: Improving resilience of the power pack and engine area to the significant re-entry heat and pressure loading; and improving and expanding on the Sea Recovery Operations capabilities over different weather conditions and time of day.

For the initial area, there was some investigating and development of means to increase the ablative capability of the Thermal Protection System around the stage, especially around the engine and power pack areas. This took the form of additional re-enforcement to the existing flexible thermal blanket baffles, which are located around the lower heatshield bulkhead to protect the elements of the gimballing engines behind this bulkhead. In addition, the Thermal Protection Surface of the bulkhead heatshield were increased and extended to include localised protection to exposed elements of the engine outside the bulkhead interface, to offer additional ablative heat removal during this high energy re-entry.

The second area that was developed were improvements in the Sea Recovery operations from Flight 16. The two main areas were the development of the approach for securing and lifting the stage was completely revised, with the design, development, and deployment of the ORCA (Ocean Retrieval and Capture Apparatus) to improve and derisk the water retrieval aspect of recovery.

This apparatus is mounted to the back of the sea recovery vessel and is able to articulate in pitch to thereby assist the sea vessel crane operations in transferring the recovered stage from the water to the deck in a more controlled fashion.

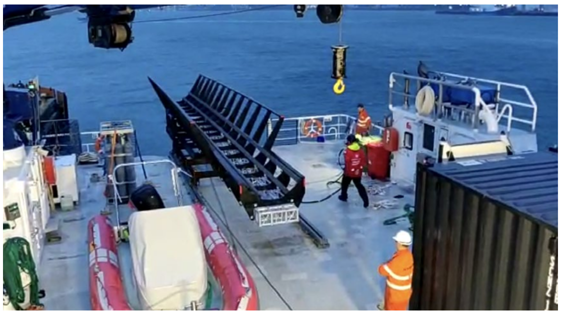

Figure 5: ORCA (Ocean Retrieval and Capture Apparatus).

The second aspect of the sea recovery that was new to Flight 20 – was that it would be a night time recovery (11:11 UTC, 15th May 2021). Due to the flexibility required for launch at any hour, this mission was a great exercise in preparation and evaluation of the additional challenges to the Sea Recovery. Key to this was verifying the methods and processes to be able to track the incoming stage and finding it post landing. Tracking was accomplished by utilising the onboard telemetry to monitor the re-entry and parachute descent to the sea from the bridge of the sea vessel. The methods, refined since Flight 16, for finding the stage once landed (where upon telemetry would not be detected easily) including fitting the Stage and Main Descent System with GPS trackers, RF tags and High Visibility Strobes.

Thanks to the above methods and technologies the stage was located post splash down within 90 mins of launch. This was despite the weather conditions at the splashdown location being at the higher end of the allowable sea recovery operations.

Figure 6: Flight 20 in the ocean.

Upon the successful on-boarding of the stage from the sea to the back of the sea vessel on its ORCA cradle it was transported back to the Auckland Production Facility for analysis and lessons learned.

This mission was very successful from a recovery equipment and operational refinement point of view and formed a completion of the first phase in the

FLIGHT 22 – Love At First Insight:

Following a detailed analysis of both the launch and recovery data, returned stage and sea operations debriefs the path was set for the next phase of reusability development of the Electron rocket. Apart from some minor feature refinement to the proven ORCA equipment, (focused mainly on increasing the independence from the sea vessel crane operation from the on-boarding of the stage), the main focus was set to developing the hardware and CONOPs for the first helicopter stage intercept during a recovery mission launch.

To this end, a preliminary intercept CONOPs was developed for the helicopter to be able to safely track and intercept with the predicted and then telemetry tracked stage as it descended under its Main Descent System. This was demonstrated on the Flight 22 Love At First Insight Mission in November 2021. To enable this practice mission the company helicopter was kitted out with extended range fuel tanks and appropriate safety and communications equipment for operations out at sea. For this mission, the helicopter was able to communicate and receive telemetry data on the descending stage from the Sea Vessel and to enhance the capability of the Sea Vessel to locate the position of the stage once on the surface of the sea. Key to the safety of this mission was significant effort by all parties involved in assessing the safest approach and clearance areas for both recovery vessels (helicopter and ship).

Additional preparation was made on the necessary forward operating base for refuelling the helicopter prior to and after the intercept demonstration flights.

A key enabler of the Mid-Air Recovery CONOPs planning included the requirement to increase the altitude at which the main parachute was deployed. For this mission the Main Descent System was set to ensure that the main parachute was at steady state descent from approximately 15,000ft. This is sufficient for the helicopter to be able to get eyes on the descending stage and vector for intercept and capture from approximately 10,000ft given its safe loiter position outside the possible descent track of the planned gliding parachute. This earlier deployment resulted in a need to increase very slightly the reefing time on the main parachute post deployment to manage inflation loads from the higher speed deployments without the nominal added deceleration from the Drogue parachute over a longer period.

Flight 22 launched from Rocket Lab Launch Complex 1 on New Zealand's Mahia Peninsula at 01:38 UTC on the 18th November 2021. It had a controlled ocean splashdown and recovery of the first stage. The helicopter was stationed in the recovery zone around 200 nautical miles offshore to successfully track the descending stage. The helicopter successfully tracked the returning rocket and completed communications tests in the recovery zone, bringing Rocket Lab a step closer to catching a rocket from the sky, bringing it back to the production complex for refurbishment, and then launching it to space again. The helicopter relayed the position of the stage back to the Sea Vessel prior to heading back to which arrived on seen for start of sea recovery withing 1.25 hours. The sea operations team then successfully and quickly retrieved the stage from the water and the stage was returned again to the Auckland Production Complex.

Figure 7: Recovery intercept trial helicopter flying back from observing the stage landing area

PRE-FLIGHT 26 DEVELOPMENTS:

After the successful demonstration in Flight 22 of the helicopter communications and tracking of a returning electron stage focus was set to developing and demonstrating the key elements that would allow the helicopter to transition from tracking to intercepting and capture of the parachute descending stage. These elements consisted of:

- Developing a Gliding Chute
- Developing the capture engagement features on the parachute
- Developing of the helicopter long-line fitted hook to enable the capture of the descending parachute.
- Obtaining a Dedicated capture helicopter capture attempt flight

- Preparation of logistics and operations teams prior to F26

Gliding & Engagement Parachute & Capture Hook Development

From evaluations and previous demonstrated experience of stage capture (ref March 2020 capture testing), the CONOPS for an intercept and capture attempt hinged on obtaining forward drive from the parachute suspending the stage underneath it.

Given the success of the existing round parachute and given the mass and volume constraints imposed by the size of the Electron interstage where it is housed prior to deployment, a development project was started to investigate the viability and characterise performance of the inclusion of drive features in the existing Ringsail design – termed a Glidesail parachute design.

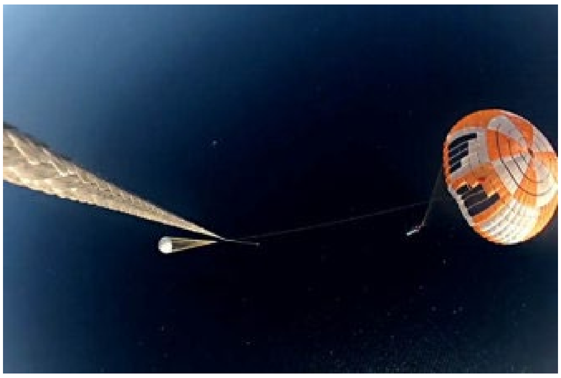

Figure 8: Modified Glidesail Parachute

In addition to the glide modifications to the parachute, features were added to enable the helicopter's long line suspended capture hook to positively retain it on intercept. This consists of a long tether line with a hook engagement feature placed ahead of a small parachute the guides this line engagement line to fly in a predictable position above and behind the crown of the parachute.

After a short number of modification iterations, coupled with helicopter drop tests to measure and tune performance, a preliminary configuration was selected for progression to Qualification of the modified design in January 2021 to verify no adverse impact to its' deployment and inflation would result during the high dynamic pressure conditions.

This Qualification testing was a resounding success, so the next step was to verify that its flying characteristics and the design and development of the capture hook would enable the successful Mid-Air Recovery of an Electron Stage. A completely in-house designed capture hook – based on some key features from initial capture hook developed and flown – designed and made and tested during helicopter drop testing prior to the Flight 26 mission. The testing was performed using two helicopters, a drop helicopter – which transitioned the packed parachute and its attached test article to the set drop point – and a catch helicopter. There were two catch helicopters used in this testing. It was start with light payload successful captures using the company B429 helicopter, and then subsequently using high payload mass (and more flight representative rates of descent and glide) with the newly acquired dedicated Electron Stage Mid-Air Recovery helicopter. This new helicopter has the higher lift and capture and range required to perform the Mid-Air Captures of the stage during a live launch recovery.

Figure 9: The S92 (HEV) helicopter flying with hook underneath on long line.

A minor modification to the Electron stage was the inclusion of a film thermal protection layer to the skin of the tank to increase resilience to the high thermal conditions during re-entry in order to significantly minimise the level of refurbishment upon return of a stage from recovery mission.

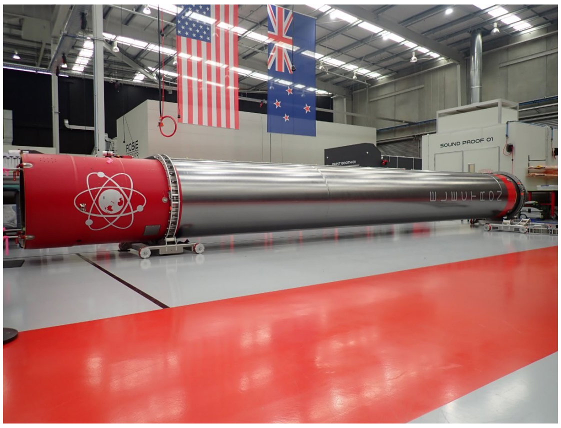

Figure 10: Silver Thermal Protection layer added to Electron firs stage.

In addition to the demonstration of successful capability to intercept and catch a fast-descending parachute the helicopter was fitted with required longline equipment and range extension fuel tanks as well as the necessary stage tracking and communications equipment as proven on Flight 22.

FLIGHT 26 There And Back Again:

For this mission, launched in May 2022, the key objectives were to demonstrate:

- A safe Mid-Air Recovery Helicopter capture attempt flight
- Function and behavior of the modified Glidesail parachute and engagement system with successful capture.
- Understand any further areas of development/refinement for next recovery missions.

Prior to the initiation of the Flight 26 Mid-Air recovery attempt mission significant transport logistics and operations planning and setup was performed – including devising means of offloading the recovered stage from helicopter to awaiting onward return transport to APC. This mission was being used to evaluate and practice and learn of any changes to the offload, transport and ground operations activities upon successful stage fly-back of following missions.

The mission was launched from Pad A at Rocket Lab Launch Complex 1 on New Zealand's Mahia Peninsula at 22:49 UTC on the 2nd May 2022. The launch was very successful, and the recovery objectives were met. "There And Back Again" was also a recovery mission where, for the first time, Rocket Lab caught Electron's first stage as it returned from space under parachutes using a helicopter. The successful catch brings Electron one step closer to being the first reusable orbital small sat launcher.

Figure 11: View from the S-92 helicopter moments before the catch.

After the catch, the helicopter pilot detected different load characteristics than previously experienced in testing and offloaded the stage for a successful splashdown. The stage was loaded onto Rocket Lab's recovery vessel for transport back to the Company's production complex for analysis.

At time of writing this paper, the recovered stage has been returned to Auckland Production Complex. Preliminary analysis of the returned stage has demonstrated that the newly added tank Thermal Protection System as well as the power pack TPS refinements have proven to have been very successful at isolating the heating experienced during re-entry.

The condition of the returned stage is the best seen to date and work ongoing on investigate and re-test significant sub-systems/elements to better understand what level of re-use can be achieved even from a wet booster.

NEXT STEPS:

Following on the success of this Flight 26 mission the key areas that will progressed, in addition to anything from the outcome of the ongoing analysis of data and hardware, will be:

- Further practice and refinement of the engagement and capture
- Improvements of the Main Descent System to make more repeatable and increase reliability
- Improvement of the CONOPS working towards fly-back and return of a dry booster for refurbish and re-use.
- Development & refinement of the logistics and operations methods and assets for the offload and Auckland Production Complex return activities.

Again, the approach of incremental development and improvement towards the goal of recovery and re-use has worked very well for the company to date. The development path so far has moved from controlling and characterising the re-entry through to the successful demonstration of capture of a descending Electron stage post launch.