

Article

Design, Kinematic Analysis, and Scaled Prototype Validation of a Pneumatic Ejection Mechanism for Supersonic Re-Entry Capsule Testing

Alfan Firmansyah Aditya^{1,2}, Bagus Wicaksono^{1,2}, Akhmad Mukhlisin^{1,2}, Nur Hadi Ardiyanto^{1,2}, Rajni Rizkia Sirat^{1,2}, Muhammad Rafi Akbar Salahudin¹, Afzalurrohman Abdullah¹, Alfin Mardiansyah¹, Muchammad Rifki Sistiawan^{1,2}, Rajib Alamsyah^{1,2}, Rahmat Dani Sulistyono^{1,2}, Ade Firmansyah^{1,2}, Luthfy Iqbal Musthofa^{1,2}, Yoga Aditiya Dwi Syah Putra^{1,2}, Ahmad Yusuf Maulana^{1,2}, Pandu Priyo Jatmiko^{1,2}, Muhammad Thoriq Akmal Aliansyah^{1,2}, Johnson Fernando^{1,2}, Prayogi Dwi Kuncoro¹, Diah Ayu Suci Kinasih¹, Fajrul Falah^{1,*}

¹Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, Salatiga 50711

²Department of Research and Development, DTECH Inovasi Indonesia Co. Ltd., Salatiga, Indonesia

* Corresponding: fajrul@inovasi.ac.id

ARTICLE INFO

Submitted 22 Dec 2025
Revised 30 Dec 2025
Accepted 31 Dec 2025
Published 31 Dec 2025



The work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License

Abstract.

High-altitude free-flight tests require release mechanisms capable of placing sub-scale re-entry capsules into a clean supersonic freestream while minimizing wake-induced attitude perturbations. This study presents AERO, a compact pneumatic ejection mechanism developed to support NASA SPEED-class capsule-release requirements as a scientific contribution to re-entry testing technology. The method combined wake-clearance interpretation, first-order kinematic sizing, pneumatic force analysis, CAD-based packaging, manufacturability assessment, and scaled prototype testing. A two-projectile-length clearance distance of 1.33 m was adopted, giving a required initial velocity of 5.11 m/s for a 0.5 s separation target. The full-scale analytical model predicted an ejection velocity of 5.2 m/s and a 0.44 s separation time at 0.5 MPa; increasing the operating pressure to 1.5 MPa increased the velocity to 9.7 m/s and reduced the separation time to 0.15 s. A 30% scale prototype using a 32 g Genesis Firefly capsule model showed a pressure-dependent height response, increasing from 63.0 cm at 0.2 MPa to 136.8 cm at 0.6 MPa. These findings provide analytical and scaled-prototype evidence that a pressure-tunable pneumatic architecture with a balancing hugger can support rapid, repeatable, and geometry-adaptable capsule ejection; flight-representative performance remains to be validated.

Keywords: pneumatic ejection mechanism; re-entry capsule; supersonic separation; scaled prototype

INTRODUCTION

Dynamic stability is a central concern for blunt-body and lifting re-entry capsules during transonic and low-supersonic flight because wake-induced pressure asymmetry, aftbody-flow hysteresis, and time-lagged aerodynamic moments can produce attitude oscillation before recovery-system deployment [1], [2], [3], [4], [5], [6], [7], [8], [9]. Free-flight architectures such as the Stratospheric Projectile Experiment of Entry Dynamics (SPEED) are therefore important because they can expose sub-scale capsules to representative dynamic pressure, Mach number, and disturbed-flow conditions that are difficult to reproduce with static ground testing alone [10].

A key requirement in SPEED-class experiments is that the capsule must be released from the carrier or first-stage projectile without remaining inside the first-stage wake. If the capsule lingers in the wake, the measured motion may reflect artificial release-system interference rather than the capsule aerodynamic response [11], [12], [13], [14], [15]. Prior store-separation and trajectory-prediction studies show that release kinematics, ejector force, initial attitude, and actuation repeatability strongly affect separation safety and data interpretation [16], [17], [18], [19]. Thus, the ejection device is not merely a packaging accessory but a subsystem that determines the initial conditions of the aerodynamic experiment.

The release of an internal or externally supported body into a high-speed stream is commonly treated as a coupled separation problem rather than a simple deployment event. Previous store-separation studies show that the early trajectory of the released body is governed by the interaction between the local shock system, base wake, pressure recovery region, and any small angular disturbance introduced at the moment of release [13], [14], [15], [16], [17], [18], [19], [20]. For a sub-scale re-entry capsule, this condition is especially important because the model is intended to represent free-flight aerodynamic behavior; therefore, the ejection mechanism must not only provide enough translational velocity but must also minimize off-axis impulse, side leakage, and contact-induced rotation. These requirements make clean separation a multidisciplinary design problem involving aerodynamics, actuation dynamics, structural packaging, manufacturing tolerance, and test repeatability.

From a mechanism-design perspective, compact projectile-based test platforms impose stricter constraints than conventional wind-tunnel rigs because the actuator, gas source, control valve, electronics, capsule interface, and retention system must fit within a limited internal volume while remaining reliable under low-pressure, low-temperature stratospheric conditions. Literature on pneumatic actuation indicates that actuator performance is strongly affected by pressure differential, valve response, seal friction, chamber volume, and flow-rate characteristics [21], [22], [23], [24], [25], [26], [27], [28], [29]. Consequently, an ejection system for SPEED-class testing should be

tunable, manufacturable, and experimentally verifiable before full-scale deployment. This motivates the development of AERO as a pressure-adjustable pneumatic mechanism that combines kinematic sizing, pneumatic force analysis, capsule-alignment support, and scaled prototype validation in a single design workflow.

Several actuation strategies are possible, including spring, pyrotechnic, electromagnetic, and pneumatic systems. Pneumatic actuation is attractive for this application because it offers high force density, simple construction, low parts count, and direct tuning of ejection force through operating pressure. However, pneumatic systems are nonlinear: gas compressibility, valve conductance, seal friction, leakage, dead volume, and temperature-dependent sealing behavior can influence transient response and repeatability [28], [29], [30]. These characteristics must be considered when designing a compact ejector for a cold, low-pressure stratospheric environment [3], [31].

Despite prior work on wake clearance, pneumatic actuation, and capsule dynamics, a compact SPEED-class ejector integrating pressure-tunable propulsion, capsule-alignment support, and prototype-level verification remains insufficiently documented. The novelty of AERO is the integration of a multi-exhaust pneumatic actuator, compact gas-storage layout, solenoid trigger, and geometry-adaptable balancing huffer in one configuration. This study aims to establish the wake-clearance velocity requirement, predict pressure-dependent performance, and evaluate the functional response of a 30% scaled prototype.

METHODS

Design requirements and analysis workflow

The design workflow consisted of six sequential activities: defining the release requirements, interpreting the wake-clearance criterion, estimating the required ejection velocity, sizing the pneumatic actuator, packaging the mechanism inside the projectile envelope, and validating the functional response through a scaled prototype. The mechanism was designed to accommodate capsule configurations with a maximum base radius of 12.5 cm and a maximum axial length of 15 cm while maintaining space for the actuator, gas tanks, valve, and electronics module.

Table 1. Baseline design requirements and assumptions for AERO

Parameter	Value or design decision
Target application	SPEED-class supersonic re-entry capsule release
Nominal release environment	High-altitude/stratospheric operation around 27 km
Representative Mach number	Mach 1.70–1.75
Wake-clearance target	Two projectile lengths, equivalent to 1.33 m

Parameter	Value or design decision
Baseline target time	0.5 s
Maximum capsule base radius	12.5 cm
Maximum capsule axial length	15 cm
Full-scale piston diameter	40 mm
Full-scale piston stroke	40 mm
Working fluid consideration	Dry compressed gas; dry nitrogen preferred for moisture mitigation

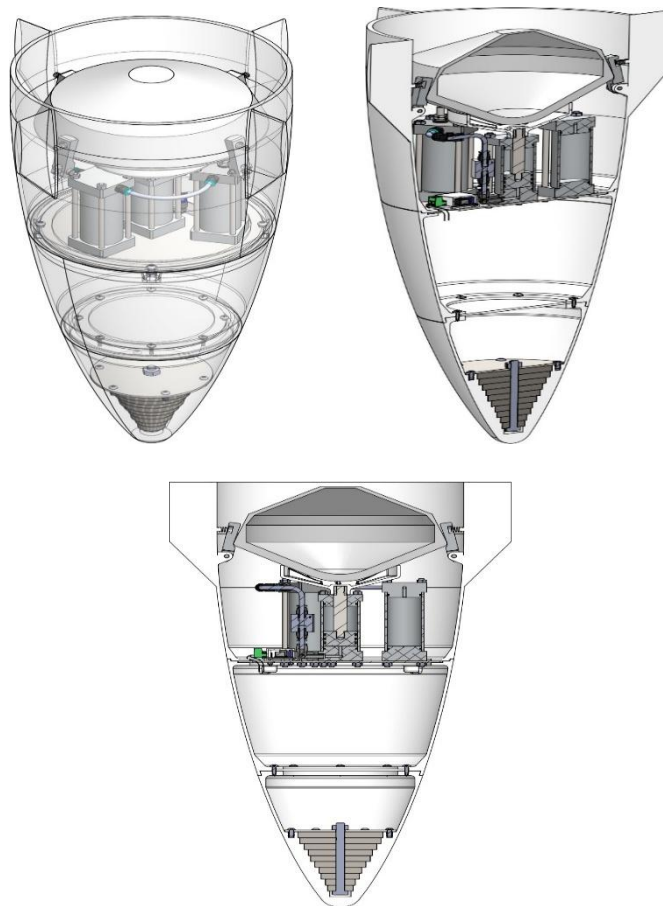


Figure 1. Full-scale AERO configuration integrated within the SPEED projectile envelope

Wake-clearance and kinematic formulation

The target separation distance was adopted from the SPEED design basis and checked against an independent compressible-flow visualization. The design objective was to move the capsule approximately two projectile lengths behind the first stage because this region provides a practical first-order criterion for reducing wake influence before interpreting capsule free-flight dynamics [1], [2], [10], [11], [12], [13].

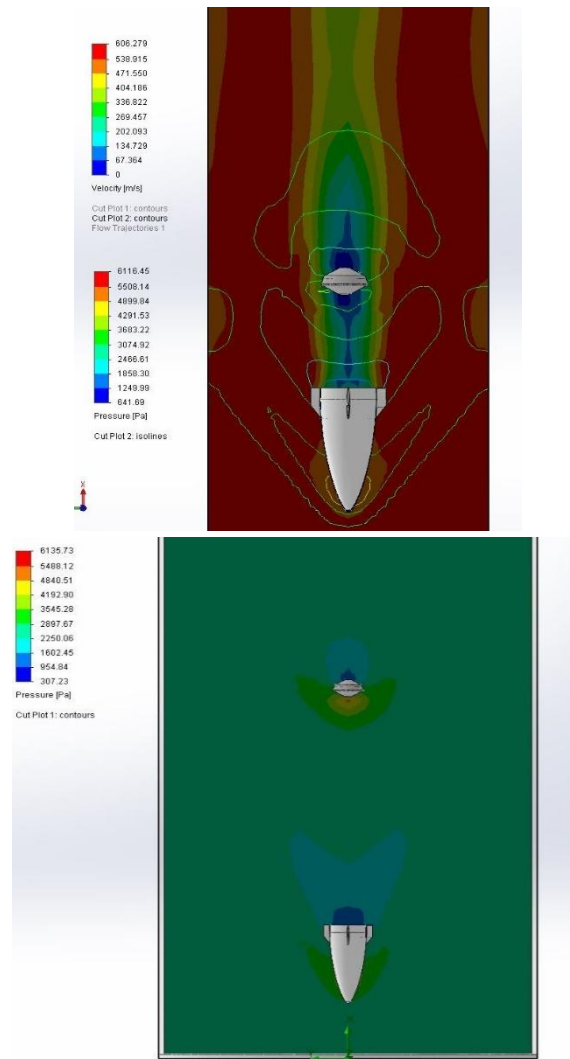


Figure 2. CFD verification of the wake-clearance criterion at Mach 1.75: velocity visualization near one projectile length and pressure visualization beyond two projectile lengths

To obtain a first-order mechanism-sizing envelope, separation was modelled as one-dimensional relative motion with drag neglected. Equations (1) and (2) relate the required clearance distance (s), initial ejection velocity (v_0), target time (t), and gravitational acceleration (a); Equation (2) is the rearranged form used for sizing.

$$s = v_0 t + \frac{1}{2} a t^2 \quad (1)$$

$$v_0 = (s - \frac{1}{2} a t^2) / t \quad (2)$$

For $s = 1.33$ m, $a = -9.81$ m/s², and $t = 0.5$ s, Equation (2) gives a required initial velocity of 5.11 m/s. This value was used as the minimum full-scale velocity target for preliminary pneumatic sizing.

Pneumatic force model

The pneumatic model estimated net actuator force from the pressure differential across the piston, piston face area, seal friction, and effective moving mass of the piston-capsule system. Equations (3)–(7) calculate the pressure differential, piston area, net force, acceleration, and idealised exit velocity based on the piston stroke. The model is a first-order calculation; transient gas-flow and friction effects are considered qualitatively when interpreting the results.

$$\Delta P = P_c - P_a \quad (3)$$

$$A = \pi D^2 / 4 \quad (4)$$

$$F_{\text{net}} = \Delta P \cdot A - F_{\text{friction}} \quad (5)$$

$$a = F_{\text{net}} / m_{\text{eff}} \quad (6)$$

$$v = \sqrt{(2aL_{\text{stroke}})} \quad (7)$$

Equation (8) estimates the post-stroke time required to reach the target clearance distance; the smaller positive root represents the first time at which the capsule reaches that distance. Equation (9) gives an idealised pressure-redistribution relation, in which gas initially stored in the tank expands into the piston chamber and reduces the useful working pressure.

$$t_c = [v - \sqrt{(v^2 - 2g(s - L_{\text{stroke}}))}] / g \quad (8)$$

$$P_{\text{useful}} = P_{\text{tank}} V_{\text{tank}} / (V_{\text{tank}} + V_{\text{chamber}}) \quad (9)$$

In Equations (3)–(9), P_c and P_a are chamber and ambient pressure, respectively; A is piston area; F_{friction} is seal friction; m_{eff} is effective moving mass; L_{stroke} is piston stroke; t_c is the post-stroke clearance time; and P_{tank} , V_{tank} , and V_{chamber} are the tank pressure, tank volume, and piston-chamber volume used in the pressure-redistribution estimate.

Mechanism architecture

The final AERO configuration contains five primary subsystems: a custom pneumatic actuator, a three-tank pressurized gas-storage system, a solenoid valve, a 5 V-to-24 V electronics interface, and a balancing hugger. The actuator transfers force through a cylindrical cup that supports the capsule base. The three-tank layout balances gas volume, dimensional constraints, manufacturing simplicity, and leak-point reduction. A commercial solenoid valve controls gas release, while the electronics module converts the 5 V avionics trigger to the 24 V signal required by the valve.

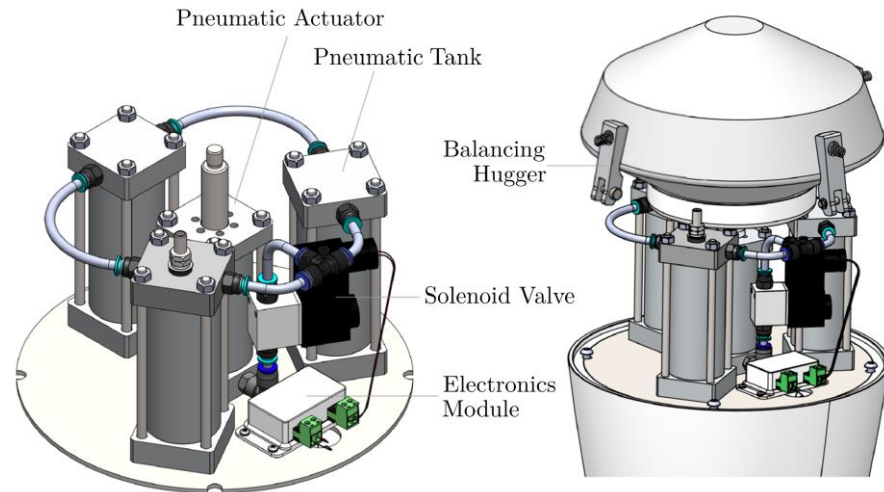


Figure 3. Functional configuration of the AERO mechanism and its major subsystems

A custom actuator was selected instead of a conventional single-exhaust commercial cylinder. The design incorporates six evenly distributed exhaust holes near the piston, intended to improve thrust distribution and reduce local jet disturbance near the capsule during release. Multiple seal configurations were also considered to manage leakage. A single seal minimizes friction, while redundant sealing improves leakage robustness at the cost of higher friction and lower effective thrust.



Figure 4. Pneumatic actuator piston and alternative seal configurations for leakage mitigation

The balancing hugger provides a passive stabilizing interface before ejection. It grips the capsule in four segments, maintains alignment during pre-release handling, and opens or disengages as the capsule gains sufficient upward velocity. The component was designed for additive manufacturing, allowing rapid customization for different capsule geometries and target ejection velocities.

Manufacturing and scaled prototype testing

Manufacturability was treated as a design constraint. The mechanism was arranged so that structural parts could be produced using 3D printing, CNC machining, and laser cutting, while the valve, fittings, and pneumatic hoses used commercially available components. This mixed strategy is appropriate for

rapid aerospace prototyping because it combines geometric flexibility with reduced procurement and machining lead time [35].

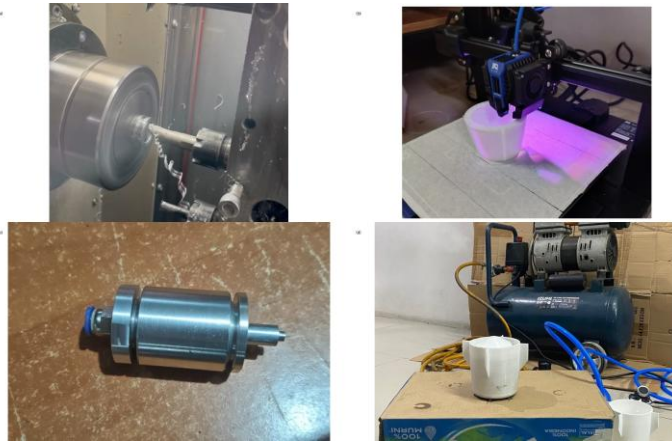


Figure 5. Scaled prototype fabrication and experimental setup used to verify ejection function

Because the team joined the challenge five days before submission, the functional demonstrator was manufactured at 30% scale rather than full scale. The prototype was intended for functional verification of pressure-dependent ejection only and was not designed as a dynamically scaled representation of the full-scale system. It used a 25 mm cylinder diameter and a 14 mm piston length. A compressor supplied controlled pressure directly to the actuator. The Genesis Firefly capsule model, with a mass of 32 g, was used as the test body. At each pressure level, 20 repeated measurements were collected to estimate average ejection height and observe motion stability.

RESULT AND DISCUSSION

Full-Scale Pneumatic Sizing Result

The full-scale analytical model indicates that the 0.5 s wake-clearance target is predicted to be achievable with the proposed pneumatic layout. At 0.5 MPa useful working pressure, the calculated pressure differential was 0.49806 MPa. With a 40 mm piston diameter, the model produced a piston force of 625.9 N. After subtracting 110 N for seal friction, the net force was 515.9 N. For a combined moving mass of 1.492 kg, the calculated acceleration was 335.96 m/s². Across a 40 mm stroke, the predicted ejection velocity was 5.2 m/s, corresponding to a calculated 0.44 s to reach the 1.33 m clearance target.

Increasing useful pressure to 1.5 MPa increased calculated net force to 1772.5 N and acceleration to 1178.21 m/s². The predicted ejection velocity increased to 9.7 m/s and the calculated clearance time decreased to 0.15 s. These results establish the pressure-performance relation within the analytical model; they do not experimentally demonstrate full-scale operation.

Table 2. Full-scale analytical ejection performance at two operating pressures

Parameter	0.5 MPa	1.5 MPa	Unit
Atmospheric pressure	0.00194	0.00194	MPa
Piston diameter	40	40	mm
Piston area	1256.6	1256.6	mm ²
Seal friction	110	110	N
Capsule mass	1.3	1.3	kg
Piston system mass	0.192	0.192	kg
Piston force	625.9	1882.5	N
Net force	515.9	1772.5	N
Acceleration	335.96	1178.21	m/s ²
Stroke	40	40	mm
Ejection velocity	5.2	9.7	m/s
Time to 1.33 m	0.44	0.15	s

Prototype ejection response

The 30% scaled prototype showed a monotonic increase in average ejection height as operating pressure increased, from 63.0 cm at 0.2 MPa to 136.8 cm at 0.6 MPa. This response confirms that, under the workshop test conditions, the demonstrator converted a higher pressure input into a larger ejection impulse. The measurements are functional evidence of pressure tunability and are not a direct dynamically scaled validation of the full-scale analytical velocities.

Table 3. Average ejection height obtained from 30% scaled prototype testing

No.	Pressure (MPa)	Average ejection height (cm)
1	0.2	63.0
2	0.3	86.4
3	0.4	95.2
4	0.5	128.8
5	0.6	136.8

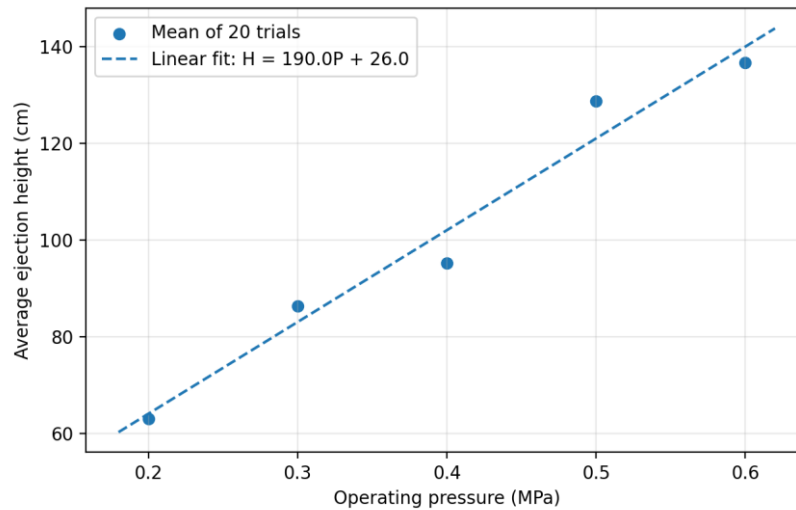


Figure 6. Pressure-dependent average ejection height from the scaled prototype experiment

The pressure-height response is directionally consistent with the full-scale analytical model: higher pressure increased the calculated launch velocity in the full-scale analysis and the measured peak height in the scaled prototype. The response was not perfectly linear because piston seal breakaway and running friction, valve and hose flow restrictions, gas expansion, dead volume, short stroke, and minor variation in capsule seating do not scale linearly with gauge pressure [28], [29], [30]. Therefore, the difference in the measured slope or magnitude should not be interpreted as a direct validation of the full-scale velocity values. Instead, the experiment supports the proposed pressure-tunable mechanism by demonstrating a repeatable, monotonic response to pressure adjustment under workshop conditions.

Design implications

The full-scale analytical sizing suggests that a compact pneumatic architecture could satisfy the SPEED-class separation requirement with adjustable pressure. In the baseline model, 0.5 MPa provided a small analytical margin above the minimum velocity required for the 0.5 s clearance target, whereas 1.5 MPa produced a substantially shorter predicted separation time. This pressure tunability could be useful for future experiments with different capsule masses, base radii, and axial lengths, but the operating envelope must be verified experimentally at full scale. The multi-exhaust actuator and balancing hugger address two different aspects of release quality. The actuator is responsible for generating the required impulse, whereas the balancing hugger is responsible for limiting pre-release misalignment and angular disturbance. In free-flight aerodynamic experiments, this distinction is important because translational clearance alone is insufficient if the capsule receives an excessive angular impulse during release [11], [12], [13], [14], [15], [16], [17], [18], [19], [20].

Environmental compatibility also supports the selection of dry compressed gas or dry nitrogen. The expected stratospheric temperature is low, but the ambient pressure is also very low. Dry gas reduces moisture-related risks, while nitrogen offers stable thermodynamic behavior and low moisture content when properly supplied [3], [31]. Practical implementation should still include cold-soak leakage tests, valve-response checks, and verification of seal behavior under reduced ambient pressure.

Limitations and future work

This work is an early-stage mechanism design and scaled functional validation, rather than a flight-qualified release system. The CFD visualization verified the separation-distance criterion but was not coupled to a six-degree-of-freedom trajectory model. The 30% prototype was tested vertically under workshop conditions and did not include cross-flow, wake unsteadiness, low-temperature soak, reduced ambient pressure, or high-speed optical tracking. Future work should include full-scale cold-temperature leak tests, valve-response characterization, high-speed video reconstruction of capsule attitude, six-degree-of-freedom separation simulation, and wind-tunnel or flight-representative release testing.

CONCLUSION

This study developed AERO, a compact pneumatic ejection mechanism for SPEED-class supersonic re-entry capsule testing. A first-order full-scale analytical model estimated that a two-projectile-length clearance of 1.33 m requires 5.11 m/s for a 0.5 s target and predicted 5.2 m/s with a 0.44 s clearance time at 0.5 MPa; at 1.5 MPa, the analytical prediction was 9.7 m/s and 0.15 s. The 30% scale workshop prototype showed a monotonic increase in average ejection height from 63.0 cm at 0.2 MPa to 136.8 cm at 0.6 MPa, demonstrating the basic pressure-tunable actuation principle. These observations support feasibility at the analytical and scaled-prototype level only; they do not validate full-scale dynamic performance, wake clearance, or reliability in stratospheric and supersonic operating conditions. Full-scale environmental, dynamic, and aerodynamic testing is required before flight-representative use.

ACKNOWLEDGEMENTS

The authors acknowledge the AERO team members whose design, CAD, manufacturing, prototyping, procurement, electronics, testing, physics analysis, and technical writing contributions supported the development of this mechanism.

REFERENCES

- [1] B. J. Libben, C. D. Kazemba, H. S. Alpert, and G. T. Swanson, "Design and Technology

- Maturation of the Stratospheric Projectile Experiment of Entry Dynamics ({SPEED}),” in *International Planetary Probe Workshop*, Marseille, France, Aug. 2023. [Online]. Available: <https://ntrs.nasa.gov/citations/20230011776>
- [2] C. D. Kazemba, B. J. Libben, H. S. Alpert, Q. E. McKown, M. Wilder, and G. T. Swanson, “Preliminary Results from First Flight of the Stratospheric Projectile Experiment of Entry Dynamics,” in *International Planetary Probe Workshop*, Williamsburg, Virginia, USA, Jun. 2024. [Online]. Available: <https://ntrs.nasa.gov/citations/20240001359>
- [3] National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and United States Air Force, “U.S. Standard Atmosphere, 1976,” Washington, DC, USA, 1976. [Online]. Available: <https://ntrs.nasa.gov/citations/19770009539>
- [4] C. D. Kazemba, R. D. Braun, I. G. Clark, and M. Schoenenberger, “Survey of Blunt-Body Supersonic Dynamic Stability,” *J. Spacecr. Rockets*, vol. 54, no. 1, pp. 109–127, 2017, doi: 10.2514/1.A33552.
- [5] C. D. Kazemba, R. D. Braun, I. G. Clark, and M. Schoenenberger, “Dynamic Stability Analysis of Blunt Body Entry Vehicles Through the Use of a Time-Lagged Aftbody Pitching Moment,” in *51st {AIAA} Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Grapevine, Texas, USA, Jan. 2013. doi: 10.2514/6.2013-226.
- [6] S. Teramoto, K. Hiraki, and K. Fujii, “Numerical Analysis of Dynamic Stability of a Reentry Capsule at Transonic Speeds,” *{AIAA} J.*, vol. 39, no. 4, pp. 646–653, 2001, doi: 10.2514/2.1357.
- [7] X. Yang and R. Radespiel, “Longitudinal Aerodynamic Performance of the Apollo Entry Capsule near Transonic Speeds,” *J. Spacecr. Rockets*, vol. 54, no. 5, pp. 1100–1109, 2017, doi: 10.2514/1.A33609.
- [8] Y. Okano, S. Sato, H. Nagai, and N. Ohnishi, “Dynamic Instability in Lift-Type Reentry Capsule at Supersonic Flow,” *Phys. Fluids*, vol. 36, no. 7, p. 76135, 2024, doi: 10.1063/5.0217605.
- [9] G. T. Chapman and L. A. Yates, “Dynamics of Planetary Probes: Design and Testing Issues,” in *36th {AIAA} Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, USA, Jan. 1998. doi: 10.2514/6.1998-797.
- [10] J. Anderson John D., *Modern Compressible Flow: With Historical Perspective*, 3rd ed. New York, NY, USA: McGraw-Hill, 2003.
- [11] J. J. Bertin and R. M. Cummings, *Aerodynamics for Engineers*, 6th ed. Boston, MA, USA: Pearson, 2014.
- [12] B. Etkin and L. D. Reid, *Dynamics of Flight: Stability and Control*, 3rd ed. New York, NY, USA: Wiley, 1996.
- [13] E. E. Panagiotopoulos and S. D. Kyparissis, “{CFD} Transonic Store Separation Trajectory Predictions with Comparison to Wind Tunnel Investigations,” *Int. J. Eng.*, vol. 3, no. 6, pp. 538–553, 2010.
- [14] E. N. Hallberg, A. Cenko, and S. Dodbelle, “Store Separation Trajectory Simulation for the High Speed Anti-Radiation Demonstrator ({HSAD}) from the {F-4} Aircraft,” in

- Proceedings of the 26th International Congress of the Aeronautical Sciences*, Anchorage, Alaska, USA, Sep. 2008.
- [15] A. Cenko, “Store Separation Lessons Learned During the Last 30 Years,” in *Proceedings of the 27th International Congress of the Aeronautical Sciences*, Nice, France, Sep. 2010.
- [16] H. Ö. Demir, N. Alemdaro\u glu, and B. T. gcan Selimhocao\u glu, “{CFD} Applications in Store Separation,” in *Store Separation and Trajectory Prediction*, no. STO-EN-SCI-277-2018, in {STO} Educational Notes. , {NATO} Science and Technology Organization, 2018. doi: 10.14339/STO-EN-SCI-277-2018-05-PDF.
- [17] K. Roughen, X. Wang, O. Bendiksen, and M. Baker, “A System for Simulation of Store Separation Including Unsteady Effects,” in *47th {AIAA} Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, USA, Jan. 2009. doi: 10.2514/6.2009-549.
- [18] D. MacLucas and I. M. A. Gledhill, “Time-Accurate Transonic {CFD} Simulation of a Generic Store Release Case,” *{R \& D} J. South African Inst. Mech. Eng.*, vol. 34, pp. 9–16, 2018, doi: 10.69694/2309-8988/v34a2.
- [19] W. Liu *et al.*, “An Experimental System for Release Simulation of Internal Stores in a Supersonic Wind Tunnel,” *Chinese J. Aeronaut.*, vol. 30, no. 1, pp. 186–195, 2017, doi: 10.1016/j.cja.2016.12.017.
- [20] A. Cenko, “Store Separation Overview,” in *Store Separation and Trajectory Prediction*, no. STO-EN-SCI-277-2018, in {STO} Educational Notes. , {NATO} Science and Technology Organization, 2018, pp. 4–16. doi: 10.14339/STO-EN-SCI-277-04-PDF.
- [21] E. Richer and Y. Hurmuzlu, “A High Performance Pneumatic Force Actuator System: Part {I}---Nonlinear Mathematical Model,” *J. Dyn. Syst. Meas. Control*, vol. 122, no. 3, pp. 416–425, 2000, doi: 10.1115/1.1286336.
- [22] J.-C. Maré, “An Improved Dynamic Model of Pneumatic Actuators,” *Int. J. Fluid Power*, vol. 1, no. 2, pp. 17–26, 2000, doi: 10.1080/14399776.2000.10781090.
- [23] P. L. Andrighetto, A. C. Valdiero, and L. Carlotto, “Study of the Friction Behavior in Industrial Pneumatic Actuators,” in *{ABCM} Symposium Series in Mechatronics*, 2006, pp. 369–376.
- [24] S. Jamian *et al.*, “Review on Controller Design in Pneumatic Actuator Drive System,” *TELKOMNIKA*, vol. 18, no. 1, pp. 332–342, 2020, doi: 10.12928/telkonnika.v18i1.12626.
- [25] F. Ning, Y. Shi, M. Cai, Y. Wang, and W. Xu, “Research Progress of Related Technologies of Electric-Pneumatic Pressure Proportional Valves,” *Appl. Sci.*, vol. 7, no. 10, p. 1074, 2017, doi: 10.3390/app7101074.
- [26] X. Xu, Y. Han, and J. Liu, “Modeling and Dynamic Analysis on the Direct Operating Solenoid Valve for Improving the Performance of Shifting Control System,” *Appl. Sci.*, vol. 7, no. 12, p. 1266, 2017, doi: 10.3390/app7121266.
- [27] E. E. Topçu, I. Yüksel, and Z. Kam\i\cs, “Development of Electro-Pneumatic Fast Switching Valve and Investigation of Its Characteristics,” *Mechatronics*, vol. 16, no. 6, pp. 365–378, 2006, doi: 10.1016/j.mechatronics.2006.01.005.
- [28] International Organization for Standardization, “{ISO} 6358-1:2013 --- Pneumatic Fluid Power --- Determination of Flow-Rate Characteristics of Components Using

- Compressible Fluids --- Part 1: General Rules and Test Methods for Steady-State Flow.” International Organization for Standardization, Geneva, Switzerland, 2013. [Online]. Available: <https://www.iso.org/standard/56612.html>
- [29] International Organization for Standardization, “ISO 4414:2010 Pneumatic fluid power - General rules and safety requirements for systems and their components.” ISO, Geneva, Switzerland, 2010.
- [30] International Organization for Standardization, “{ISO} 8573-1:2010 --- Compressed Air --- Part 1: Contaminants and Purity Classes.” International Organization for Standardization, Geneva, Switzerland, 2010. [Online]. Available: <https://www.iso.org/standard/52217.html>
- [31] S.-L. Zhu, Y. Li, R.-P. Zhang, Y. Tang, L.-M. Qiu, and X.-Q. Zhi, “Experimental Study on the Condensation Characteristics of Nitrogen with Non-Condensable Gas,” *Cryogenics (Guildf)*, vol. 98, pp. 29–38, 2019, doi: 10.1016/j.cryogenics.2018.12.007.