NASA/TM-20260001044

Experimental Demonstration of a Supersonic Spike Ejector

Daniel R. Jones
National Aeronautics and Space Administration
Stennis Space Center, Mississippi

May 2026

NASA STI Program Report Series

NASA/TM-20260001044

Experimental Demonstration of a Supersonic Spike Ejector

Daniel R. Jones
National Aeronautics and Space Administration
Stennis Space Center, Mississippi

National Aeronautics and
Space Administration

NASA Stennis Space Center
Stennis Space Center, Mississippi 39529

May 2026

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Experimental Demonstration of a Supersonic Spike Ejector

Daniel R. Jones
NASA Stennis Space Center
May 2026

"…for the benefit of all mankind."
National Aeronautics and Space Act of 1958

Spike diffusers are presented as a means to improve supersonic ejector efficiency via reduction in shock losses. Design, fabrication, and testing of an articulated prototype is described. Experimental results are compared to empirical performance curves representing the loci of optimal one- and two-stage conventional ejectors driven by dry air and discharging to atmosphere. Operated at a compression ratio of ~10 with all inputs equal, the spike ejector is shown to have achieved up to 2.19X and 1.83X the secondary mass throughput of the one- and two-stage references, respectively. This suggests the potential of spike diffusers to reduce ejector operating costs by ~50%.

Introduction

Supersonic ejectors are a mechanically simple, durable, and reliable means of vacuum generation. With low initial, maintenance, and depreciation costs, raw energy consumption determines ejectors' economic viability in industrial practice [1,2]. Designs requiring lower motive temperature or pressure (or less of the fluid itself) will consume less energy and less money over time. This creates a strong financial incentive to understand and improve ejectors' internal flow characteristics. However, the fluid dynamics involved are complex.

For an ejector to function efficiently, a supersonic nozzle must be designed in balance with both an entrained secondary flow and a unified supersonic/subsonic diffuser. During operation, the nozzle's plume induces a combination of pressure, viscous, and impact forces on the secondary flow which drag, mix, compress, choke, and decelerate it through the diffuser. Depending on the application, the flow field may contain various molecular species, chemical reactions, phases of matter, shock/expansion cells, and shear layers propagating interdependently.

Immense collective effort has been expended to account for the breadth of physical phenomena in pursuit of optimal design, with 125 years of research overwhelmingly dedicated to ejectors with axial, central-flow diffusers [2-12][1]. Unfortunately, this geometric convention implicitly neglects several subtleties of supersonic flow which prove advantageous if applied with intent. The present work offers spike diffusers as a means to harness two of these - differential expansion and conical shock recompression - to reduce shock losses and surpass conventional ejector performance.

Background

Theoretical descriptions of normal, oblique, and conical shocks were published in 1870 [13], 1908 [14], and 1933 [15]. These relations show stagnation pressure lost through a shock generally increases with higher Mach number and decreases with higher dimensionality. Normalizing stagnation pressure lost by static compression ratio enables a simple cost/benefit comparison between shock types. Relative differences vary with deflection angle and fluid properties, but conical shocks typically offer the highest compression efficiency, as shown in figure 1. However, this remained unrecognized until World War II, when acute military interest in supersonics spurred the first applications of shock theory to diffuser design.

A particularly influential 1944 report [16] introduced jet engine inlet diffusers based on conical shocks. The concept was matured for flight over the following decade [17] and the resultant 'spike' inlets have now seen ~75 years of continuous deployment [18,19]. That enduring demand has cultivated a branch of diffuser design practice distinctive to aerospace which is occasionally adapted to suit other industry purposes. Propulsion test facilities periodically use spike diffusers to recompress jet and rocket engine exhausts [20-24]. While inlet diffusers operate on cold, quiescent atmosphere, exhaust diffusers must contend with turbulent, chemically reactive plumes. Design constraints are quite different between the two. Propulsive nozzles move during test due to a combination of thermal expansion, thrust vectoring, and load-induced structural deformation. The range of motion is mechanically accommodated by a radial offset between the nozzle and diffuser. That gap guarantees exhaust diffuser inflows are both actively expanding and divergent – an operating condition inlet diffusers never experience.

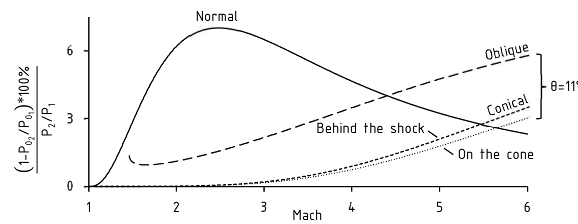

Figure 1 – Stagnation pressure lost normalized by static compression ratio through the elementary shock types, γ=1.4.

Upper stage rocket engines are commonly tested with truncated nozzles to ease facility vacuum generation requirements. Because the expansion and collimation processes are incomplete at the nozzle exit, the flow angle, Mach number, and thermodynamic properties vary in the radial dimension. The degree of nonuniformity presents a design challenge, but one that also carries an additional opportunity: differential expansion across the plume.

In the supersonic regime, disturbances can only travel downstream or radially across the flow, and they do so at a finite rate. Since any perturbation takes time and distance to propagate, a diffuser's spike can be placed to strategically obstruct the expansion of a divergent plume along its centerline while leaving the periphery unaffected through a given region of interest. This technique reduces the average Mach number leading into the diffuser's shock structure and the stagnation pressure lost through it. The result is a boost to the system's compression potential.

In rocket diffusers, the spike is designed to ensure the conical shock clears the nozzle wall and leaves thrust unaffected. The same principle can be applied to ejector diffusers with minor modification; conical nozzles also produce divergent flow. The shock just needs to clear the initial mixing region to leave entrainment unaffected.

Numerical simulation is a convenient tool for establishing appropriate spike diffuser geometries and illustrating their advantages. Figure 2 shows γ=1.4 critical flow through central and spike ejector inlets given identical axial area profiles and operating at the same motive pressure and entrainment ratio. In this case, the spike reduces the maximum Mach number from ~4.9 to ~3.25 without affecting the initial mixing region. Stagnation pressure lost through the first shock reflection varies radially from ~6-12% in the spike ejector vs. ~6-55% in the central design. The higher irreversible losses put the conventional ejector at a relative disadvantage; no matter how optimal the downstream contours, they cannot recover what is no longer there. The central design cannot match the spike design's compression ratio.

While modern analytical techniques are useful in ejector design, reliable performance predictions remain elusive. Little has changed since Flügel summarized the state of the practice in 1939:

> *The theory of jet pumps is still rather incomplete, and relatively little has been published so far. Successful designs have been developed by trial and error and information obtained in this way is naturally guarded by the various firms concerned.*
>
> – Gustav Flügel, 1939 [5]

[1] This is a small fraction of the available references; an exhaustive list would have been unwieldy.

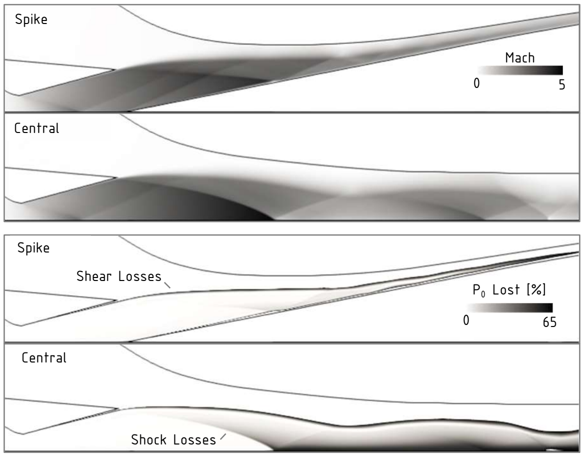

Figure 2 – Flow through central and spike ejectors given identical cross-sectional area profiles, computed by Loci-CHEM.

Theory remains limited, empiricism is still crucial to the design process, and manufacturers have ongoing incentive to guard their data. Hundreds of papers have been published, yet open literature contains insufficient information to confidently define the current state of the art. Despite an extensive review, the author found a singular disclosure of empirical performance envelopes, published in 1952 [25]. Its plots represent the loci of optimal one- and two-stage ejectors driven by dry air at 0.791 MPa and 366.5 K, discharging to atmosphere. The data is certainly old and possibly outdated but, given that commercial ejectors have remained topologically identical since its publication, it should still be representative of conventional performance. As such, these operating conditions were taken as the design point for a series of spike ejector prototypes to allow a 1:1 comparison with conventional baselines.

Apparatus

Preliminary nozzle and spike contours were specified using quasi-one-dimensional compressible flow relations and data from early spike diffuser experiments [20]. A shell contour was defined by skewing central-flow rules of thumb based on prior experience with spike diffusers. The Loci/CHEM computational fluid dynamics code [26,27] was used to assess ejector performance at a compression ratio of 10. Iterative refinements were made by manually adjusting geometry based on the computed flow fields.

Hardware development was also iterative, with later prototypes incorporating additional articulation and alignment features. The final test article, designated XE-2.2, is detailed in figures 3 and 4. Interchangeable spike and nozzle components were threaded onto cantilevered supports and attached to external stepper motors to allow axial translation through a static shell. Break-away shell extensions were included to allow truncation of the subsonic diffuser. All components were fabricated of 316 stainless steel with tolerances of ±0.025 mm. Pressure taps were bored via electron discharge machining and tubulations were sealed into place with RTV silicone.

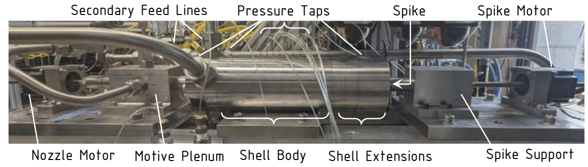

Figure 4 – The XE-2.2 prototype installed at Purdue University.

A small ejector testbed was installed at Purdue University's High Pressure Combustion Lab [28]. Motive and secondary mass flows were conditioned by the facility and metered by sonic nozzles per ASME MFC-7-2016 [29]. Motive temperature and pressure were measured in a plenum just upstream of the ejector. Secondary temperature was measured in the manifold just upstream of the suction chamber. Secondary pressure was measured through taps 1 and 2 in the suction chamber. Atmospheric discharge pressure was measured externally.

Pressure transducers were Druck Unik 5000s with errors of ±550 Pa in the motive plenum and ±55 Pa elsewhere. Thermocouples were Omega Type Ks, with errors of ±2.7 K in the motive plenum and ±2.2 K elsewhere. Positional feedback from the stepper motors was unreliable as the hardware would occasionally bind. Nozzle and spike positions were verified manually with calipers, with error estimated at ±0.5 mm. All sensors were factory calibrated and zeroed daily to account for offset drift. The sample rate was uniformly 100 Hz.

Experimental Procedure

Test days began with hardware installation and inspection. Once configuration and alignment were visually confirmed, facility heaters were brought online and motive flow established. While the facility was warming up, motive pressure was dialed in and spike/nozzle positions were adjusted using the stepper motors. Alignment was refined using flow uniformity as a guide. (The exhaust was comparable to a hair dryer's; a spread hand in the flow could easily detect circumferential bias.) After motive temperature reached its setpoint, a series of autosequenced test profiles were executed to characterize the configuration. The autosequences specified a time series of small adjustments to the facility pressures upstream of the sonic nozzles which corresponded to controlled, incremental changes in the mass flow rates delivered to the test article. This enabled the following test types:

Starting Envelope. With zero secondary flow and ejector unstarted, motive pressure was gradually increased through start then decreased through unstart to capture the operable range and any hysteresis.

Controlled Entrainment. With motive pressure fixed and the ejector started, secondary flow was gradually increased to evaluate secondary pressure vs. entrainment ratio.

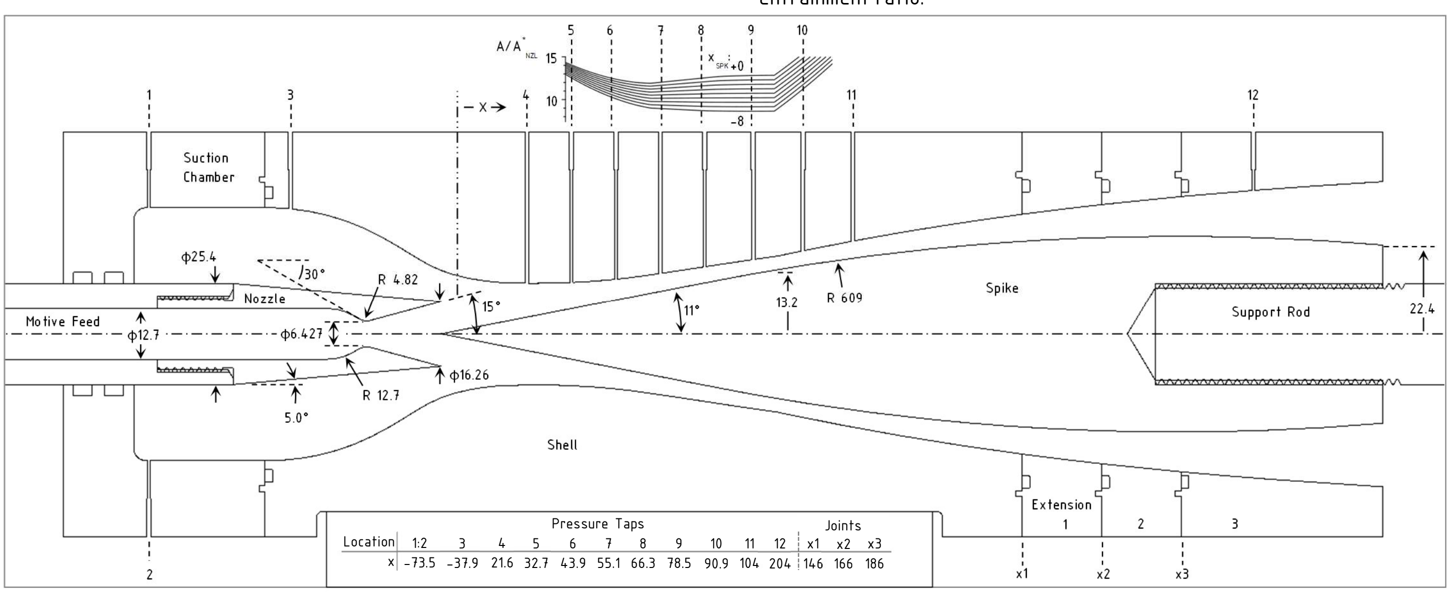

Figure 3 - Cross-section of the XE-2.2 spike ejector prototype, lengths in mm.

Evacuation. With the ejector started and operating at zero load, a valve was opened to allow evacuation of a 0.464 m^3 accumulator and capture its pressure trace down to ultimate vacuum.

Operating Envelope. With the ejector started and secondary flow held constant, motive pressure was gradually decreased through unstart.

Backpressure Envelope. With the ejector started and secondary mass flow rate fixed, a flat disk was placed just downstream of the ejector exit plane then translated axially through unstart/restart via obstruction-induced backpressure.

'Gradually', in the above context, indicates the commanded changes were slow enough to ensure the data was temporally converged. This was accomplished by stretching a given test profile over increasing duration until differences in the pressure traces between tests became negligible.

'Starting Envelope' tests checked whether the ejector was operable at the reference conditions. 'Controlled Entrainment' tests generated raw performance curves which were processed into dry-air equivalent (DAE) curves using the Heat Exchange Institute's corrections for load gas temperature [30]. Both test types were repeated for an array of nozzle and spike positions. High-performance articulations were revisited with multiple repetitions of all five test profiles. A total of 238 tests were conducted on the described aerodynamic contours: 101 with precursor hardware and 137 with the final test article.

Results

Optimum performance was observed with components articulated between x_{NXP} = -10 : -8.5 mm and x_{SPK} = -7.3 : -7.2 mm. At T_M = 366.5 K and ω = 0, the diffuser started at P_M = 762 kPa against P_B = 101 kPa and produced an ultimate vacuum pressure of 3.25 kPa. This can be seen in figure 5. Unstart hysteresis was negligible.

Ejection performance is shown in figure 6, contextualized by the empirical limits of central-flow designs given in [25]. Throughput surpassed conventional between compression ratios of 10.3 and 16.9. Peak performance was achieved at a compression ratio of 10.3 and an entrainment ratio of 0.081. All else equal, the spike ejector entrained 219% and 183% the mass flow of the one- and two-stage references at this point. Above this load condition, the adverse pressure gradient created by strengthening reflection of the nozzle lip shock caused the plume to separate from the shell wall and reattach downstream. Subsonic flow permitted the higher post-shock pressure to propagate upstream to the suction chamber, causing a sharp rise. Figure 7 illustrates the progression. The labels of α- and β- mode are introduced as shorthand for the low-pressure, pre-separation state and the higher-pressure, post-separation state, respectively.

Results from 'Backpressure Envelope' and 'Evacuation' tests are shown in figure 8. Critical backpressure varied between 103.6 : 108.9 kPa over the α-mode range of entrainment, with the minimum occurring at zero load. The evacuation trace has been normalized by accumulator volume. Operating at nominal conditions, the ejector would take ~3 minutes and ~9.5 kg of motive air to evacuate 1 m^3 of accumulation volume from 101 kPa to 7.0 kPa. Reaching 3.5 kPa would take double the time and motive mass. Figure 9 shows performance variation with motive pressure, obtained by running both 'Controlled Entrainment' and 'Operating Envelope' test profiles with off-design setpoints.

While the optimum articulation was revisited several times over the test campaign, the results described thus far were obtained during one particular pass. On this occasion, one member of the team tapped the spike support with a dead blow hammer to adjust its angular alignment relative to the shell. The other team members watched the data stream to see the effect of each tap on the zero-load suction pressure. A single fortuitous tap caused the ejector to cross an unknown threshold and slip into a lower-pressure operating mode than observed in prior tests. The prototype was left running without further hardware adjustment and the team took several steps to verify alignment as the cause of the new operating mode and rule out some unknown and unreproducible path dependency.

First, maintaining nominal motive pressure, the spike and nozzle were independently translated fore/aft to start/unstart the ejector multiple times, then returned to their optimum positions. The mode was reestablished each time. Second, keeping component positions fixed, motive pressure was

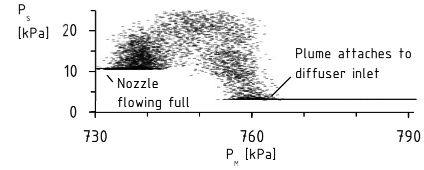

Figure 5 – Final phase of ejector pumpdown, ω=0.

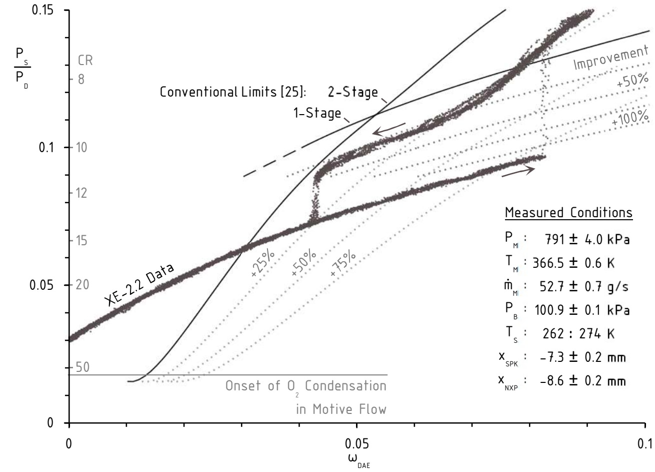

Figure 6 – Results from the best-performing XE-2.2 configuration.

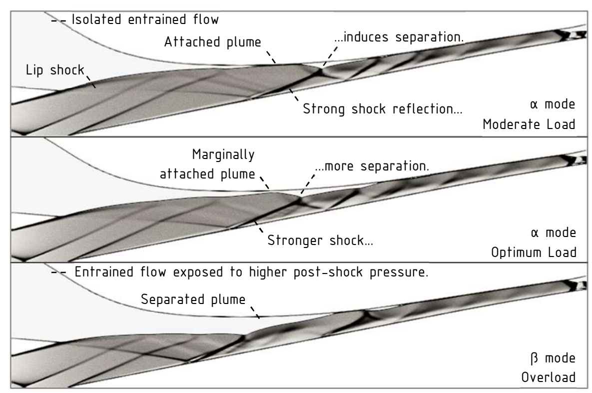

Figure 7 – Computational pseudo-Schlieren showing progression of the shock wave/boundary layer interactions limiting performance.

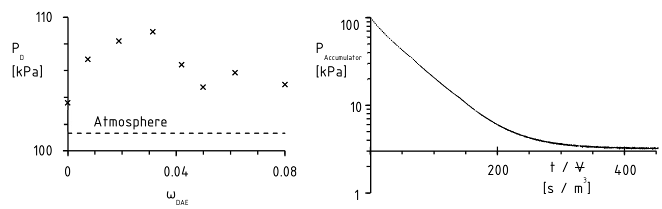

Figure 8 – Maximum backpressure vs. secondary loading (left) and normalized evacuation rate (right), both at nominal motive conditions.

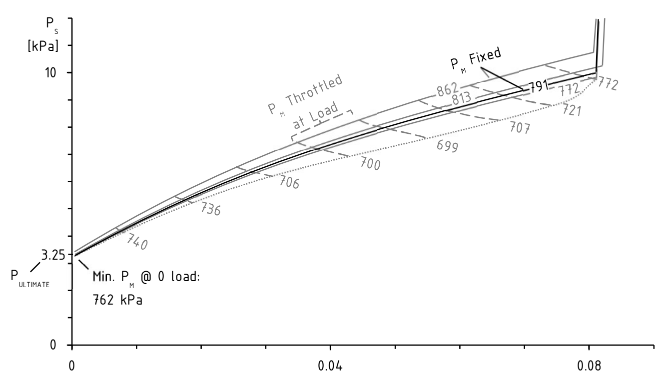

Figure 9 – Effect of motive pressure on entrainment performance.

raised and lowered through start/unstart several times with the same result. Convinced that the mode was replicable and a function of the hardware alignment, the team proceeded with the full suite of test profiles. 22 runs were performed before adjusting the hardware, each reproducing the lower-pressure operating mode. This was hypothesized to be the result of a beneficial misalignment, similar in effect to the slight performance boost from small gimbal angles in rocket diffuser testing [31].

Unfortunately, the author had not anticipated a need to measure misalignments in the design of the experiment and the team could not replicate that exact alignment on subsequent passes. Nevertheless, the other passes still reinforced spike ejectors' significant advantage over central designs. Figure 10 compares the two unquantified alignments. Even with 'typical' hardware alignment, the prototype entrained up to 176% and 159% the mass flow of the one- and two-stage references.

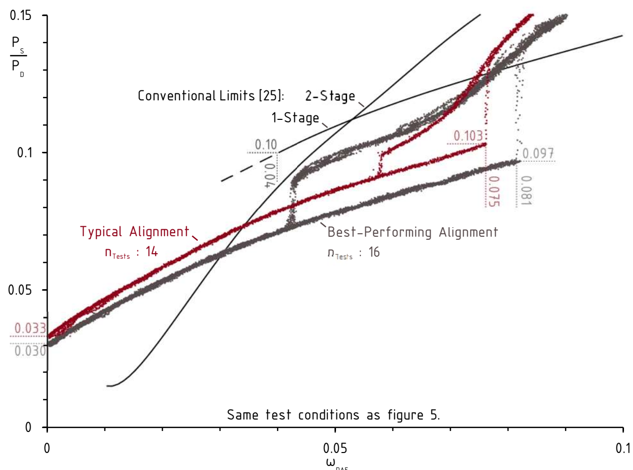

Figure 10 – Hardware alignment impacts performance.

Looking Forward

This project focused on the design and demonstration of ejectors leveraging a combination of differential expansion and conical shock recompression for aerodynamic advantage. Given the magnitude of its success and the multiplicity of potential industrial users, future development seems likely in the following areas:

Performance. Several prospective sources of additional performance were noted during the development of the XE-2.2 prototype but left untapped by it. The spike can be modified to weaken the nozzle lip shock's reflection and delay transition to β mode. This can be accomplished by contouring the spike to decrease the incidence angle, or possibly by carving out driven cavities to allow gentler reflection from a fluid boundary, similar in geometry to Multi-Row Disk inlet diffusers [32-34]. Adjustments to the shell could also be beneficial. Recontouring for a localized expansion might weaken or cancel the shock reflection, as in [35]. Decreasing the shell radius would constrain the plume, increase the pressure along its periphery, and possibly alleviate separation, but is also likely to diminish entrainment.

Adjustability. A simple spike translation mechanism can be used to control the diffuser throat area. Combined with conventional spindle-based nozzle throttling, this is likely a potent means for one set of hardware to maintain high performance across a variety of load conditions.

Practicality. Lab-scale prototypes are easily milled from steel, but economical fabrication at both larger and smaller physical scales will require simpler aerodynamic contours. Reworking the shell into a small number of conical frustra would be a good starting point. Substantial truncation of the subsonic diffuser contour is also possible. With only a minor nozzle translation, XE-2.2 maintained its optimal entrainment and compression performance without its shell extensions, though this left effectively zero operating margin.

Utility. Industrial rollout will require an array of spike ejector designs to cover the broad swath of motive fluids and operating conditions found in real-world applications. While the degree of single-stage performance augmentation is likely to motivate some level of uptake, returns on investment will be more pronounced in multi-stage systems; improvements to individual stages compound when they are installed in series.

Conclusion

Spike ejectors have been presented as a means to achieve robust, cost-effective vacuum generation. A lab-scale prototype was designed, fabricated, and extensively tested to experimentally support that claim. Results have been compared to the empirical limits of conventional design. Operating nominally, the spike ejector consumed 57-64% the motive mass of optimal one- and two- stage central flow equivalents for identical ejection. Operating with a beneficial but unquantified hardware misalignment, the prototype required 45-55% the motive mass flow of conventional designs. These results indicate spike designs can reduce the operating cost of ejector-based vacuum generation by at least 35-55%, with further reductions feasible in multi-stage systems.

Acknowledgements

Spike ejector development was supported by a combination of Rocket Propulsion Test (RPT) and Center Innovation Fund (CIF) technology projects sponsored by NASA/Stennis Space Center (SSC). Computational resources were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center. The author would also like to recognize the contributions of the following engineers:

Dr. Nicholas Nugent (SSC) handled test article mechanical design and served as a general enabler of the project. Dr. Carson Slabaugh (Purdue) navigated the paperwork of abundant contract modifications and kept the test team well-staffed. Dr. Rohan Gejji (Purdue) provided constant technical oversight that guaranteed the experiments were not just conducted, but conducted *well*. Brandon Reid, Robert Daigle, and Kevin Potthast (Purdue) built up the ejector testbed and manned the control room for hundreds of tests. But perhaps more crucially, they invested many hours at the lab deciphering strange ejector noises, troubleshooting alignment, and dialing in stringent setpoints to make the campaign maximally valuable.

Without the patience, dedication, and ingenuity of the above individuals, this effort would have remained unsatisfactorily in silico.

Nomenclature

A	Area	M	Mach number	¥	Volume
CR	Compression ratio (P_B / P_S)	P	Pressure	x	Axial distance
ṁ	Mass flow rate	t	Time	θ	Deflection angle
		T	Temperature	ω	Entrainment ratio ($\dot{m}_S$ / $\dot{m}_M$)

Subscripts/Superscripts:

0	Stagnation condition	D	Discharge	NXP	Nozzle exit plane
1	Pre-shock condition	DAE	Dry air equivalent	S	Secondary
2	Post-shock condition	M	Motive	SPK	Spike
*	Sonic condition	NZL	Nozzle		

Intellectual Property Notice

NASA has applied for a patent on the technology described in this report [36]. A license is required for non-U.S.-government use. Details are available at https://technology.nasa.gov.

Supplementary Material

A standalone datasheet [37] has been published with additional details pertaining to practical application of the ejector described in this paper. It is available online at http://www.ntrs.nasa.gov/

References

[1] Guelker, M., "Comparing the Real Costs of Vacuum Generators," Pneumatic Tips, 2016, http://www.pneumatictips.com/comparing-the-real-costs-of-vacuum-generators/
[2] Power, R., "Steam Jet Ejectors for the Process Industries," ASME Digital Collection, 2021, p. 309.
[3] Parsons, C., and Stoney, G., "Trials of Steam Turbines for Driving Dynamos," Proceedings of the Institution of Mechanical Engineers, No 61, p. 797-816, 1901.
[4] Watson, F., "The Production of a Vacuum in an Air Tank by Means of a Steam Jet," Institution of Mechanical Engineers, v. 124, no. 1, p. 231-300, 1933.
[5] Flügel, G., "Berechnung von Strahlapparaten," V.D.I. Forschungsheft no. 395, Berlin, 1939. (Translated as "The Design of Jet Pumps," NACA TM 982, 1941.)
[6] Keenan, J., Neumann, E., and Lustwerk, F., "An Investigation of Ejector Design by Analysis and Experiment," Journal of Applied Mechanics, v. 17, p. 299-309, 1950.

[7] Fabri, J., and Paulon, J., "Theorie et experimentation des ejecteurs supersoniques air-air." O.N.E.R.A. Note Technique No. 36, 1956. (Translated as "Theory and Experiments on Supersonic Air-To-Air Ejectors," NACA TM 1410, 1958.)

[8] Emmanuel, G., "Optimum Performance for a Single-Stage Gaseous Ejector," AIAA Journal, v. 14, no. 9, p. 1292-1296, 1976.

[9] Engineering Sciences Data Unit, "Ejectors and Jet Pumps, Design for Steam Driven Flow," ESDU 86030, 1986.

[10] Huang, B., Chang, J., Wang, C., and Petrenko, V., "A 1-D Analysis of Ejector Performance," International Journal of Refrigeration, no. 22, p. 254-364, 1999.

[11] Eames, I., "A New Prescription for the Design of Supersonic Jet-Pumps: The Constant Rate of Momentum Change Method," Applied Thermal Engineering, no. 22, p. 121-131, 2002.

[12] Dittman, F., "Study and Optimisation of Supersonic Ejectors for Heat Recovery Refrigeration Cycles," Université Paris sciences et lettres, 2024.

[13] Rankine, W., "On the thermodynamic theory of waves of finite longitudinal disturbances," Philosophical Transactions of the Royal Society of London, v. 160, p. 277–288, 1870.

[14] Meyer, T., Über zweidimensionale Bewegungsvorgänge in einem Gas, das mit Überschallgeschwindigkeit Strömt, Ph.D. Dissertation, Göttingen University, 1908.

[15] Taylor, G., and MacColl, J., "The Air Pressure on a Cone Moving at High Speeds. I," Proceedings of the Royal Society of London, ser. A, v. 139, no. 838, p. 278-297, 1933.

[16] Oswatitsch, K, "Der Druckrückgewinn bei Geschossen mit Rückstossantrieb bei hohen Überschallgeschwindigkeiten." Bericht Nr. 1005, Forschungen und Entwicklungcn des Heereswaffenamtes, 1944. (Translated as "Pressure Recovery for Missiles with Reaction Propulsion at High Supersonic Speeds (The Efficiency of Shock Diffusers)," NACA TM 1140, 1947)

[17] Garten, W., Jr., and Dean, F., "Evolution of the Talos Missile," Johns Hopkins APL Technical Digest. v. 3, no. 2, p. 117–122. 1982.

[18] Fry, R., "A Century of Ramjet Propulsion Technology Evolution," Journal of Propulsion and Power, vol. 20, no. 1, 2004.

[19] Smith, M. "Like Cars, Rockets Evolve: Navy's Ramjet Test Proves Game-Changing Potential", Naval Air Warfare Center Weapons Division, 2025, www.navy.mil/Press-Office/News-Stories/display-news/Article/4178471/like-cars-rockets-evolve-navys-ramjet-test-proves-game-changing-potential/

[20] Church, B., Jones, W. and Quentmeyer, R. : "Performance Evaluation of Fixed- and Variable-Area Rocket Exhaust Diffusers Using Single and Clustered Nozzles With And Without Gimbaling," NASA TN D-1306, 1962.

[21] Taylor, D., Duesterhaus, D. and Simmons, M. : "Diffuser Studies," AEDC-TR-73-198, 1973.

[22] Taylor, D., Duesterhaus, D., Lee, F. and Simmons, M. : "Variable-Area Ejector Development," AEDC-TR-76-97, 1976.

[23] Molloy, J. : "Design and Testing of Scaled Ejector-Diffusers for Jet Engine Test Facility Applications", AD-A136745, Naval Postgraduate School, 1983.

[24] Jones, D., "Passive Rocket Diffuser Testing: Reacting Flow Performance of Advanced Configurations," NASA TP-5635, 2023.

[25] Berkeley, F. D., "Air Ejectors Cheaper Than Steam", Chemical Engineering, v. 61, no. 11, 1954, p. 164-168.

[26] Luke, E., and George, T., "Loci: A Rule-Based Framework for Parallel Multidisciplinary Simulation Synthesis," Journal of Functional Programming, v. 15, no. 03, 2005.

[27] Luke, E., Tong, X-L., Wu, J., Tang, L., and Cinnella, P., "CHEM: A Chemically Reacting Flow Solver for Generalized Grids", AIAA, 2003.

[28] Meyer, S., Heister, S., Slabaugh, C. Lucht, R., Pratt, A., Gejji, R., Bedard, M., and Lemcherfi, A., "Design and Development of the High Pressure Combustion Laboratory at Purdue University," 53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017.

[29] Wright, J., and Johnson, A., "Measurement of Gas Flow by Means of Critical Flow Venturis and Critical Flow Nozzles", ASME Standard MFC-7-2016, 2016.

[30] Heat Exchange Institute. "Standards For Steam Jet Vacuum Systems", 7th ed., 2012.

[31] Roschke, E., Massier, P. and Gier, H., "Experimental Investigation of Exhaust Diffusers for Rocket Engines," JPL-TR-32-210, 1962.

[32] Kojima, T., Taguchi, H., Aoki, T., Okai, K., Sato, T., Tanatsugu, N., and Tomike, J., "Development of the Air-Intake of the ATREX Engine," AIAA 2003-7042, 2003.

[33] Kobayashi, H., Tanatsugu, N., Sato, T., Maru, Y., and Kojima, T., "Experimental Study of Multi-Row Disk Inlets for Hypersonic Air Breathing Propulsion," AIAA 2004-861, 2004.

[34] Maru, Y., Tanatsugu, N., Kobayashi, H., Kojima, T., and Okai, K., "Multi-Row Disk Arrangement Concept for Spike of Axisymmetric Air Inlet," AIAA 2004-3407, 2004.

[35] Neumann, E., and Lustwerk, F., "High-Efficiency Supersonic Diffusers," Journal of the Aeronautical Sciences, v. 18, no. 6, p. 369-374, 1951.

[36] Jones, D., "Systems for Diffusing Supersonic Fluid Flow," US Patent Application No. 19/003,234, 2024.

[37] Jones, D., "Supersonic Spike Ejector Testing: XE-2.2A Prototype Datasheet," NASA Stennis Space Center, 2025.