Proposed Flight Research of a Dual-Bell Rocket Nozzle Using the NASA F-15 Airplane

Daniel S. Jones and **Trong T. Bui**
NASA Dryden Flight Research Center
Joseph H. Ruf
NASA Marshall Space Flight Center

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Outline

- The Conventional-Bell (CB) Nozzle
- The Dual-Bell Nozzle
- Flight-Research Campaign, Objectives, and Captive-Carry Rationale
- The Flight-Testbed Capability
- Conclusion

The Conventional-Bell (CB) Nozzle
Development

- The Convergent-Divergent nozzle was developed by Carl G. P. de Laval
  - Utilized within his single-stage steam turbine, which was displayed at the 1893 World Columbian Exposition in Chicago, Illinois
- Robert H. Goddard was the first to utilize the de Laval nozzle with early rocket experiments, in 1915
  - Demonstrated a significant efficiency improvement in converting the fuel's chemical energy into the kinetic energy of the rocket
- The CB nozzle is still the gold standard of all rocket nozzles
  - Used within the architecture of virtually all rockets
- The CB nozzle is very efficient at converting the high pressure and temperature gases within a rocket's combustion chamber into thrust
  - Problem: The CB nozzle can only be optimized at one specific altitude within the rocket's entire trajectory

The Conventional-Bell (CB) Nozzle
Flow Physics

- During a rocket's trajectory, a CB nozzle has three distinct phases of nozzle flow:
  - At sea level / low altitude: Flow is over-expanded, and inefficient
  - At its design altitude: Flow is near-optimal
  - At high altitude: Flow is under-expanded, and inefficient
- With a CB nozzle, significant performance inefficiencies exist throughout most of the rocket's trajectory

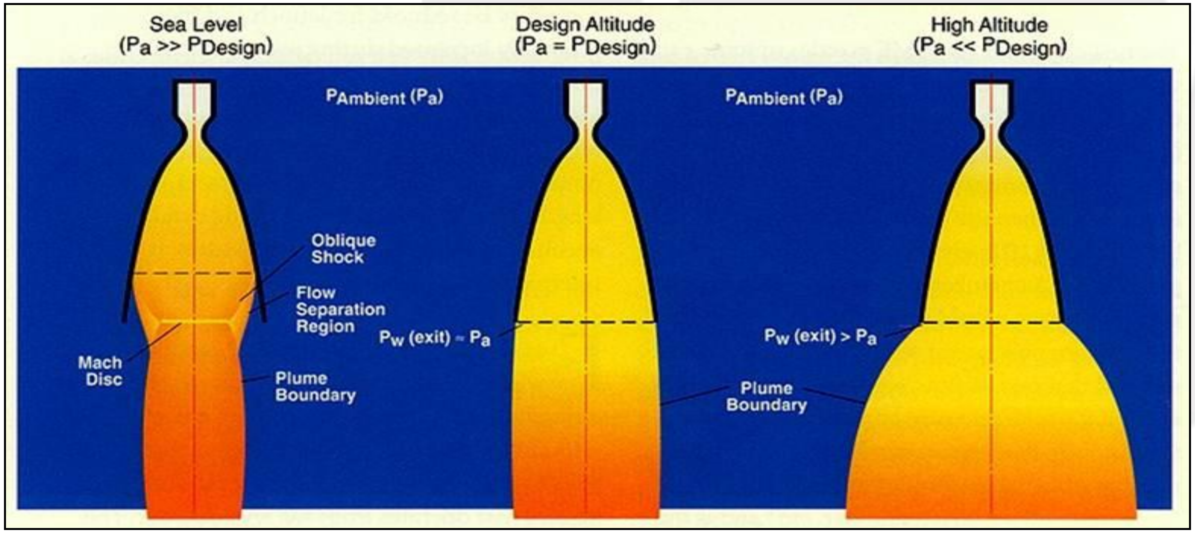

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Image courtesy: Aerojet Rocketdyne

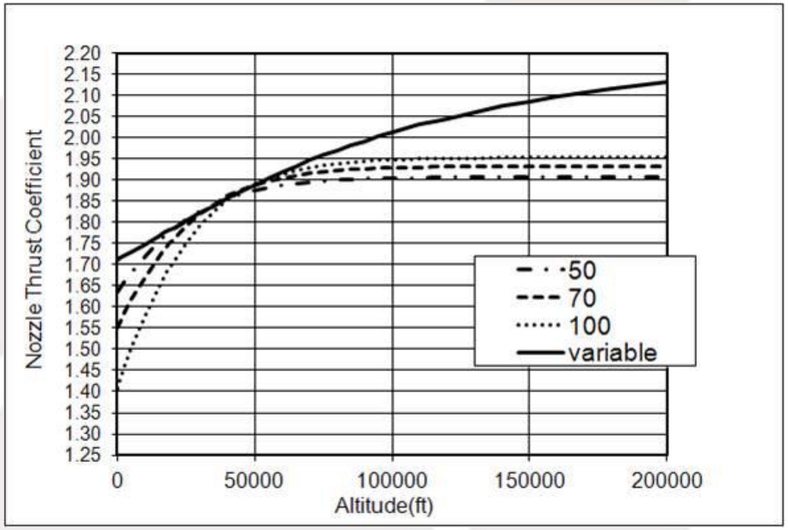
The Conventional-Bell (CB) Nozzle

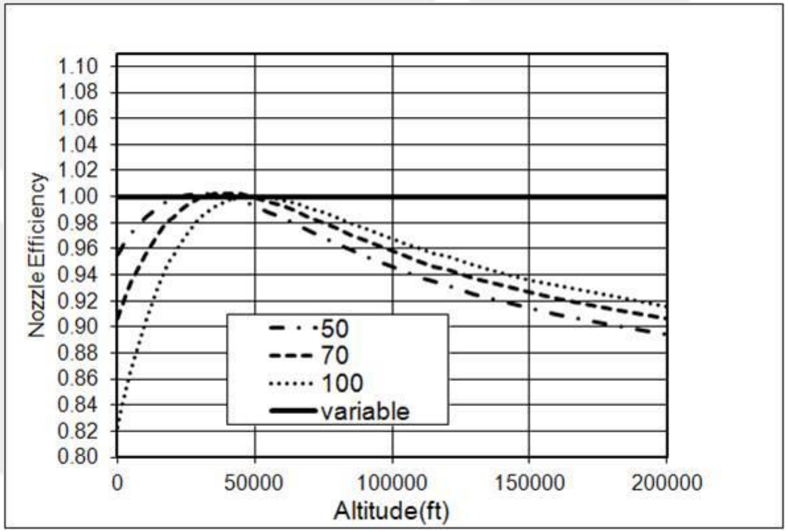
Performance

- The thrust coefficient (C_f) is used to evaluate nozzle performance
  - The thrust coefficient is related to the thrust (F), chamber pressure (P_C), and area at the throat of the nozzle (A^*):

$$C_f = \frac{F}{P_C A^*}$$

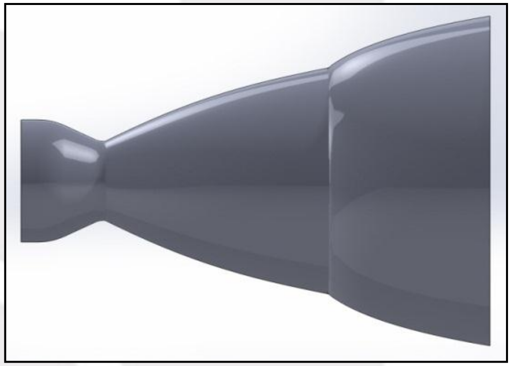
  - The performance of the nozzle is crucial to the performance of any rocket
- The figures show the performance of three different CB nozzles (with a fixed area ratio) during a rocket trajectory
- A CB nozzle experiences performance losses through most of its trajectory

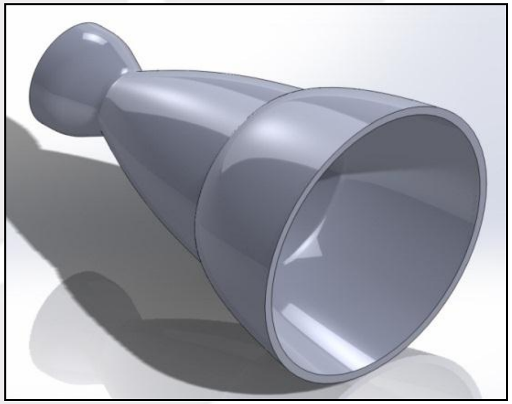




The Dual-Bell Nozzle
Development

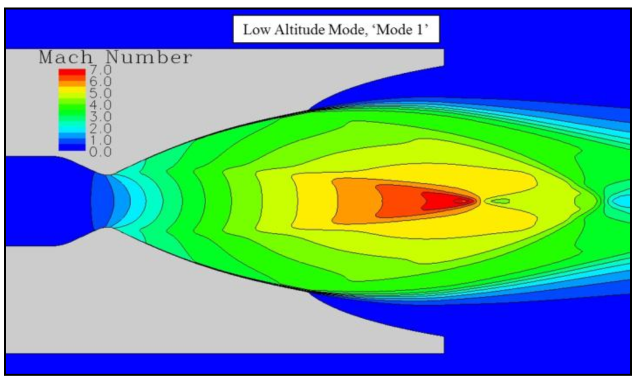
- Several Altitude-Compensating Nozzle (ACN) concepts have been proposed over the years
  - Goal: Reduce nozzle performance losses
  - The dual-bell rocket nozzle is one type of ACN
- Dual-bell nozzle development has been slow, despite the performance benefits that have been predicted
  - 1949: The concept first appeared in literature (JPL)
  - 1993: First publication on static testing (Rocketdyne)
  - 2013: Still requires testing in a relevant flight environment
- Performance predictions on the dual-bell nozzle continue to show advantages over the CB nozzle
  - The dual-bell nozzle has been analytically studied worldwide
  - Some organizations have complemented their analytical effort with static tests, to verify their performance predictions

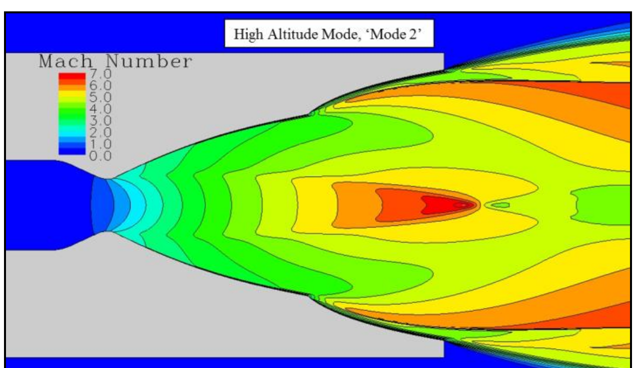




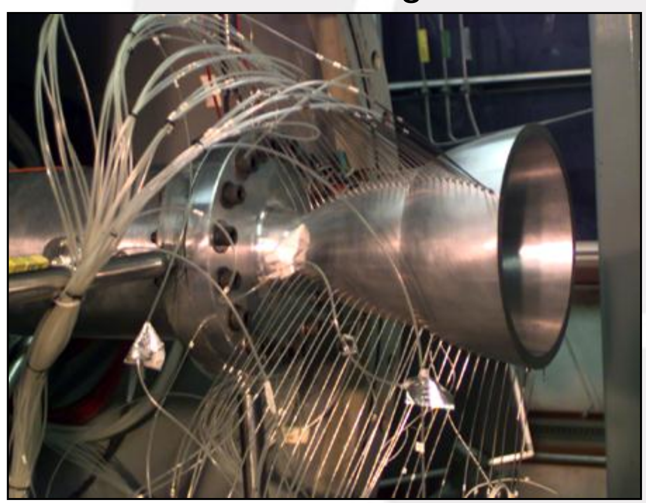
The Dual-Bell Nozzle
Research at NASA MSFC

- The NASA Marshall Space Flight Center (MSFC) has conducted research on several types of ACN concepts, including the dual-bell nozzle
  - Analytical predictions were complemented by and verified against static test data
  - The dual-bell nozzle was proven to offer a performance benefit over the CB nozzle

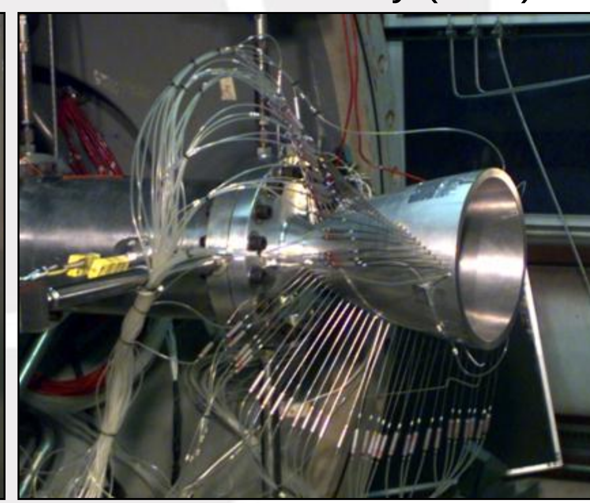




Nozzle testing in the MSFC Nozzle Test Facility (NTF)



Dual-bell nozzle testing



CB nozzle testing

Flight-Research Campaign, Objectives, and Captive-Carry Rationale

- Flight-research campaign, with NASA F-15:
  - Phase I: Flights to quantify the local flow-field conditions near the nozzle exit plane
  - Phase II: Flights while operating cold flow through various test articles
  - Phase III: Flights while operating reacting flow through various test articles
- Overarching Objective:
  - To advance the technology readiness level (TRL) of the dual-bell rocket nozzle
- Technical Objectives:
  - Develop methods to reliably control dual-bell internal flow behavior, and demonstrate those methods in a relevant environment
  - Develop and validate the design and analysis tools required for dual-bell nozzles
  - Develop the F-15 captive-carry flight testbed and the flight-test techniques required for advanced rocket nozzles
  - Develop dual-bell performance databases, and databases of flight research with advanced nozzles

Flight-Research Campaign, Objectives, and Captive-Carry Rationale

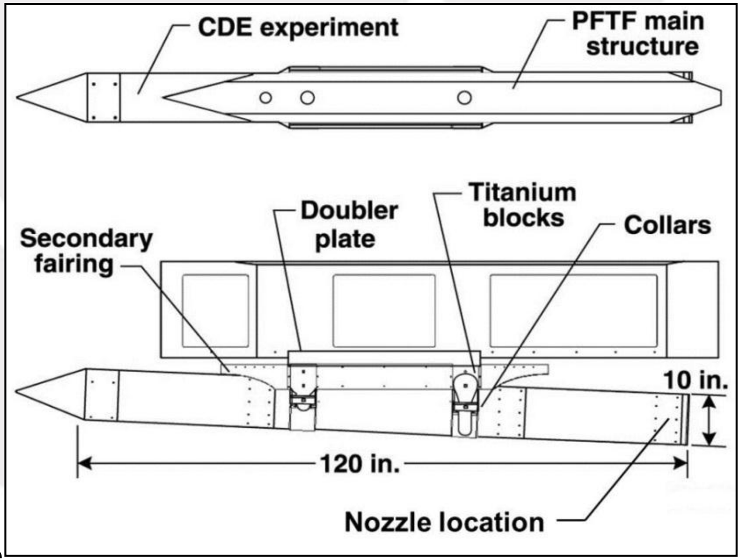
- Dual-bell nozzle flight research with a free-flying rocket should be conducted in the future, after captive-carry flight research
  - Flight research with a free-flying rocket is the most relevant flight environment
  - Captive-carry flight research will more accurately answer the fundamental questions
- Captive-Carry Flight Rationale:
  - Enables utilization of cold-flow propellant, allowing the existing MSFC NTF test data to be leveraged as much as possible
  - Permits a closer examination into the plume behavior and flow physics, with more control of the flight-test conditions
  - Enables an isolated performance assessment of the nozzle, as opposed to the combined performance assessment of the integrated rocket vehicle
  - Permits the propulsion assets to be better protected for future testing
  - Permits a rapid flight turn around, and assessment of nozzle performance with different nozzles at the same flight-test conditions

The Flight-Testbed Capability
The NASA DFRC F-15 Airplanes

- The NASA Dryden Flight Research Center (DFRC) has a long history of rocket propulsion flight research, and captive-carried flight research
- DFRC's fleet of airplanes includes an F-15B and three F-15D airplanes
    - Proposal: To utilize one of the NASA DFRC F-15 airplanes as a testbed to conduct captive-carry flight research with a dual-bell rocket nozzle

The Flight-Testbed Capability
The Propulsion Flight Test Fixture (PFTF)

- DFRC's background and expertise led to the creation of the PFTF
- DFRC led the design and development of the PFTF, and then integrated the PFTF with the centerline pylon of the F-15B airplane
  - F-15B/PFTF initial expansion flights were completed in 2001 and 2002
  - Flights included the Cone Drag Experiment (CDE), mated underneath the PFTF, and was utilized to spatially and inertially simulate a large propulsion test experiment
  - The F-15B/PFTF has been utilized to develop advanced technologies since 2002



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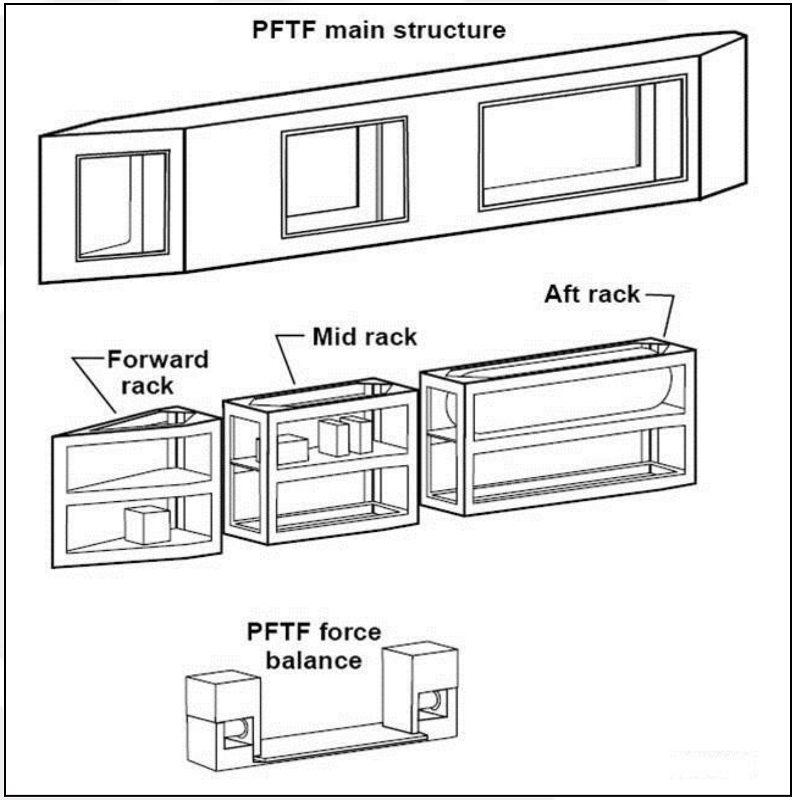
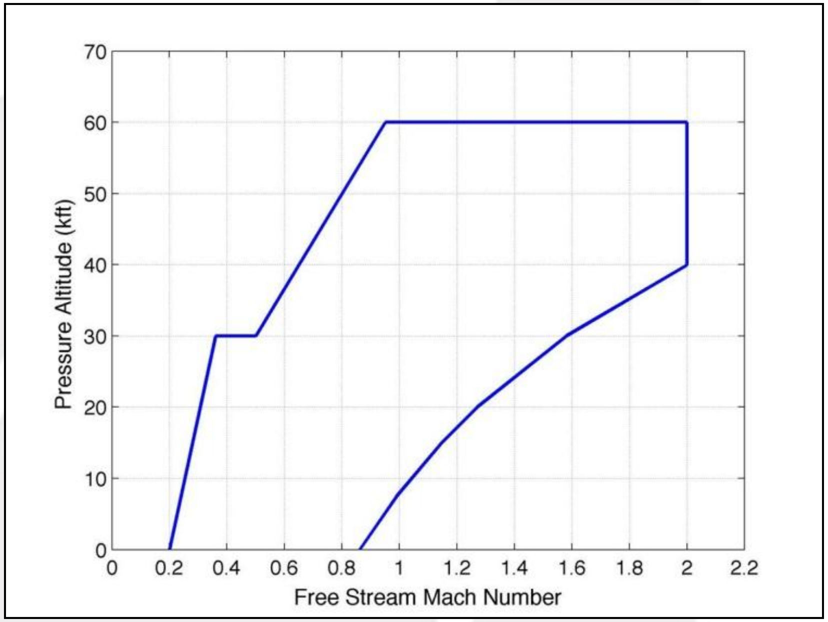
The Flight-Testbed Capability
The Propulsion Flight Test Fixture (PFTF)

- PFTF design and limitations
  - Fabricated from a solid billet of aluminum, 107 inches x 19 inches x 10 inches
  - Main structure is divided into three bays: forward-bay, mid-bay, and aft-bay
  - PFTF internal volume is intended to contain components such as propellant tanks, control valves, propellant feed system plumbing, and instrumentation
  - Includes a six-degree-of-freedom in-flight force measurement capability, with an axial force limitation of 2,000 lbf
- The design was flight-proven during F-15B/PFTF envelope expansion flights



The Flight-Testbed Capability
The Propulsion Flight Test Fixture (PFTF)

- PFTF flight envelope
  - Altitude limit: 60,000 ft
  - Mach limit: 2.0
  - Dynamic pressure limit: 1,100 psf
- Preliminary plans for dual-bell nozzle operation within flight envelope:
  - Phase I: All test points that encapsulate nozzle operation during Phase II & Phase III
  - Phase II: Low-altitude test points (perhaps ~25 kft) and high-altitude test points (perhaps ~50 kft) will be identified for nozzle operation that is optimized in each nozzle mode, as well as intermediate altitudes to research the mode transition
  - Phase III: In addition to the altitude test points (in Phase II), high dynamic pressure test points (perhaps ~1,000 psf) will be included to simulate a rocket trajectory



Conclusion

- The dual-bell nozzle is predicted to have greater performance than a CB nozzle over a rocket's integrated trajectory to low-Earth orbit
  - The performance benefit has been predicted analytically and through static test data
- This predicted performance benefit warrants investigation of dual-bell nozzle performance in a relevant flight environment
  - If the predictions are accurate, this performance advantage could result in delivering higher mass payloads to low-Earth orbit (thus, lowering the cost)
- The NASA DFRC F-15/PFTF has been proposed as the flight testbed
  - The F-15/PFTF was specifically developed and flight-proven for the purpose of advancing propulsion-focused technologies through captive-carry flight research
  - The F-15/PFTF has the potential to advance the TRL of the dual-bell rocket nozzle
- NASA DFRC and NASA MSFC have formed a collaborative effort to advance the TRL of the dual-bell nozzle, through flight research