2011-2012 Dryden Center Innovation Fund End of the Year Report: Altitude-Compensating Rocket Nozzles

Daniel S. Jones and Trong T. Bui
NASA Dryden Flight Research Center
Edwards, California

Introduction

This report highlights one of the many successful projects at the NASA Dryden Flight Research Center (Edwards, California) that was approved for FY12 funding under the Center Innovation Fund (CIF). The Center Chief Technologist (CCT) at NASA Dryden coordinated a competitive process for CIF projects, and the FY12 projects were carefully selected to support the formation of a balanced technology portfolio that could lead to significant technology developments for NASA and for the nation. This FY12 year-end report summarizes just one of the CIF projects that are focused on leveraging the expertise and capabilities of different NASA centers to advance the technological needs of the nation, an ideal that has been carried from the CIF program office at NASA Headquarters.

The Dryden Flight Research Center is NASA's primary center for atmospheric flight research and operations, with a vision "to fly what others only imagine." We believe that flight test and flight research is one of the crucial phases within the advancement of any technology, and is often the barrier to technology utilization by the private sector. We also believe that aerospace technology can be enhanced through flight early in the technology readiness level (TRL) lifecycle, and that some research can only be done in flight. This highlighted FY12 CIF project report is just one example of a technology that is theoretically advantageous, but has had little advancement in the TRL since it was first conceived over six decades ago. The report that follows provides some top-level details on how this TRL could be advanced for the nation, through flight test and flight research. This report also provides evidence of the excellent collaboration between NASA Dryden and the NASA Marshall Space Flight Center (MSFC) (Huntsville, Alabama), to utilize the expertise and capabilities of both Centers to conduct research and testing of this technology in a relevant flight-like environment.

Description

The conventional bell (CB) rocket nozzle is utilized on virtually all rockets today, for the launch of payloads and humans to low-Earth orbit (LEO) and beyond. Unfortunately, the CB nozzle can only be optimized for near-ideal flow at one altitude within a rocket's entire launch trajectory, because the ambient pressure decreases as a rocket ascends. Figure 1 illustrates this phenomenon, illustrating three distinct phases of a CB rocket nozzle plume throughout its trajectory: (left) at sea level (inefficient); (center) at its design altitude (optimal efficiency); and (right) at a high altitude (inefficient); (ref. 1).

To counter inefficiencies due to a rocket being at any altitude other than its design altitude, a type of altitude-compensating nozzle (ACN) is required, allowing the nozzle-flow pressure at the nozzle exit plane to be better matched with the ambient pressure. For more than a half-century, several types of ACN designs have been imagined, but minimal advances in the TRL of these designs have been achieved. In fact, to our knowledge, only the aerospike nozzle has been tested in a relevant flight-like environment - during the NASA Dryden aerospike nozzle flight research effort (ref. 2). The goal of the current effort is to explore the feasibility of advancing the TRL of one specific type of ACN through flight-testing: the dual-bell nozzle.

The dual-bell nozzle has a distinct dual-bell shape in the expansion region of the nozzle geometry, introducing an inflection point along the nozzle's inner contour. Figure 2 shows two views of a typical dual-bell nozzle. The dual-bell nozzle is expected to achieve a higher performance over the CB nozzle at lower altitudes, since the plume will not be significantly over-expanded, and it will be better matched to the atmospheric pressure. At higher altitudes, the dual-bell nozzle takes advantage of utilizing the second bell, expanding the plume further. Once again, the plume is allowed to be better matched to the atmospheric pressure, now at higher altitudes. Figures 3 and 4 show computational fluid dynamics (CFD) analysis conducted by NASA Marshall, with the dual-bell nozzle operating at different altitudes. When considering a rocket's performance over its entire integrated trajectory, the dual-bell nozzle has been predicted to achieve a higher total impulse, which is expected to result in a greater capability of payload mass to LEO.

In 1949, the dual-bell nozzle first appeared in literature within a study by the NASA Jet Propulsion Laboratory (JPL) (Pasadena, California) (ref. 3). At the time, this conceptual rocket nozzle shape was imagined to potentially offer performance advantages over the CB nozzle. Since that time, several organizations around the world have studied the dual-bell nozzle analytically, and echoed the belief that this nozzle promises greater performance. Considering the performance advantages suggested, the TRL of the dual-bell nozzle has not made the advancements expected. Although several organizations have studied the dual-bell nozzle analytically, only a few have complemented their analytical effort with static test data to verify their performance predictions. Of these few static tests, to date, most have been conducted with non-reacting flow exhausting through the nozzle into a quiescent environment. Very few organizations have conducted dual-bell nozzle testing with reacting flow, and no organization has tested the dual-bell nozzle in a relevant flight-like environment. It is the authors' opinion that dual-bell nozzle technology is approximately at a TRL of 3 (where a TRL of 9 corresponds to a flight-proven technology, through successful mission operations).

The current effort is focused on raising the TRL of the dual-bell nozzle to a level sufficient for the private sector to confidently incorporate this technology into their rocket designs. The strategy is to advance the TRL by three critical methods, which will be conducted in parallel: (1) continue the analytical effort of studying dual-bell nozzle flow behavior and performance; (2) expand on the limited ground-test data with dual-bell nozzles, both with cold flow and with reacting flow; and (3) operate a dual-bell nozzle in a relevant flight-like environment, first with cold flow and then with reacting flow. The near-term effort is focused on a feasibility study of flight-testing the dual-bell nozzle with cold flow in a flight-like environment.

Benefits and Values

As noted above, several organizations around the world have studied the dual-bell rocket nozzle analytically, and a few of these organizations have complemented their analytical efforts with actual test data. The studies and the test data published suggest that a considerable performance advantage is possible when utilizing a dual-bell nozzle over a CB nozzle. Figure 5 helps to illustrate this advantage, by plotting the thrust coefficient (C_f) of three different CB nozzles (each with one fixed area ratio) during operation at various altitudes, in comparison with the optimal thrust coefficient. From this figure, it is evident that each of the CB nozzles can achieve optimal flow conditions only at one altitude during the rocket's ascent. Careful observation of this figure reveals that each of the CB designs experience greater performance losses when operating farther from this design altitude, in either direction.

The thrust coefficient is used by nozzle designers to help evaluate nozzle performance. A simplified equation for the thrust coefficient (for optimal conditions) shows the connection to the rocket's thrust (F), chamber pressure (P_C), and area at the throat of the nozzle (A^*), as noted in equation 1.

$$C_f = \frac{F}{P_C A^*} \tag{1}$$

The combination of figure 5 and equation 1 help to illustrate that performance (thrust) is directly related to the thrust coefficient, and that a CB nozzle experiences considerable performance losses throughout most of a rocket's trajectory. Utilization of some type of ACN will enable the actual thrust coefficient to be closer to the optimized thrust coefficient, directly increasing the thrust over the rocket's integrated trajectory. This overall increase in thrust results in a rocket with greater performance, which can deliver higher mass payloads to LEO for a similar launch vehicle.

Decreasing the cost of delivering payloads to LEO has been a vision for NASA and the private sector for decades, and aligns well with national interests. Most recently, this national goal has been reiterated within NASA's integrated set of fourteen space technology roadmaps, each of which recommends the overall technology investment strategies and prioritization of NASA's space technology activities. The first of these fourteen technology areas is the Launch Propulsion Systems Roadmap, which emphasizes that "reliable and cost-effective access to space is a fundamental capability required for all of NASA's in-space missions." Repeatedly within this roadmap, the desire to reduce launch costs is highlighted as a figure of merit, and several technology investment areas are proposed to achieve this overarching goal, one of which is the development of advanced nozzle concepts. This roadmap recognizes and outlines that "design, modeling, and demonstration of advanced nozzle concepts" is necessary, and is the path required to advance this technology to a TRL of 6 (ref. 4).

Collaborations and Partnerships

NASA Dryden and NASA Marshall have been studying ACN technology for several years, often independently. In the summer of 2011, a small team of research engineers at Dryden and Marshall conceived of the ACN project, which would be a collaborative effort focused on combining the strengths and capabilities of both Centers to advance the TRL of several types of ACN designs. Team discussions were initiated in August of 2011 on the advancement strategy. One outcome of this strategy was the consensus to select and advance one type of ACN design first: the dual-bell rocket nozzle.

NASA Dryden has a long history of rocket propulsion flight-testing, including an equally significant background in captive-carry flight-testing. Under the current feasibility assessment, the NASA F-15B is being investigated as the flight testbed, which can utilize the Propulsion Flight Test Fixture (PFTF) (refs. 5 and 6). Figure 6 shows the F-15B/PFTF during the initial expansion flight phase which occurred in 2001 and 2002, including a simulated large propulsion test experiment that could be carried by the F-15B/PFTF (ref. 7). Ever since these initial expansion flights, the F-15B/PFTF has been utilized for a variety of propulsion-focused captive-carry flight tests. The flight-qualified F-15B/PFTF presents a unique capability to advance the TRL of the dual-bell rocket nozzle. Therefore, a feasibility assessment is currently being completed on operating the dual-bell nozzle in a relevant flight-like environment, while captive-carried by the F-15B/PFTF.

Impressive work has been completed by a small team of ACN researchers at NASA Marshall. The team has completed a significant number of tests with several types of ACN designs, one of which is the dual-bell nozzle. The dual-bell analytical effort at Marshall was complimented with static tests at Marshall's Nozzle Test Facility (NTF), and several tests have been completed while varying the nozzle pressure ratio (NPR). During these tests, the performance of the dual-bell nozzle was also quantitatively compared to a similar CB nozzle (with the same overall area ratio). These tests helped verify the prediction that the dual-bell nozzle has greater nozzle efficiency and thrust than the comparable CB nozzle at several NPR conditions, particularly at the lower NPR conditions. Figure 7 shows the test setup at the Marshall NTF with a dual-bell nozzle, and figure 8 shows the comparable CB nozzle. As can be seen in the figures, both tests included several pressure ports along the nozzle wall to measure how the plume responds to varying NPR.

The near-term goal of the flight test campaign is to leverage Marshall's dual-bell nozzle research and development (R&D) with Dryden's expertise in propulsion-focused flight-testing. In essence, this is the perfect collaboration to help advance the TRL of dual-bell nozzles, and finally, after over six decades, flight test this promising rocket nozzle technology in the appropriate environment.

Progress Achieved

The small ACN team has made significant progress in laying the foundation for TRL advancement of dual-bell nozzle technology. Accomplishments were initialized with an extensive literature search, exploring the history and more recent accomplishments made with the dual-bell nozzle. This search proved extremely valuable, not only for an estimate of the current TRL, but also to gain a greater understanding of the limitations in current ground-test research data. In many publications these limitations were often followed by the researcher's admission that the dual-bell nozzle flow field and performance should be investigated in a relevant flight-like environment to better understand the performance gains that are possible. Researchers note that the performance of the dual-bell nozzle is highly dependent on the mode transition (from the first bell to the second bell), which is greatly influenced by freestream flight effects, and these effects can only be investigated in flight. Focusing on advancing this technology through flight, this initial effort also encompassed an internal documentation search of the F-15B/PFTF capabilities, including the F-15B/PFTF flight envelope, as well as the limitations for captive-carrying a dual-bell nozzle experiment with the PFTF.

The collection of prior experimental data and analysis results led the ACN team to immediately establish our five-year plan for the project. This plan was created to provide a compass for how dual-bell nozzle technology could be advanced if given adequate resources. Continuation of this plan will also require that the technology continues to prove feasible and valuable for the nation. In condensed form, the five-year plan includes the following major phases: (1) design, analysis, planning, and publishing; (2) static ground testing, and flight planning; (3) static ground testing, and F-15/PFTF flight-testing; (4) F-15/PFTF flight-testing, and rocket free-flight testing; and (5) F-15 air-launch flight-testing. The five-year plan also included some top-level details of the preliminary test and research plans within each of the major technology advancement phases. The completion of the team's near-term research objectives and approach was also outlined, as well as the completion of the rationale behind these objectives. The current effort is focused on the first phase of this five-year plan, and is primarily focused on the feasibility of operating a dual-bell nozzle in a relevant flight-like environment.

The feasibility assessment of flight-testing the dual-bell nozzle in a relevant flight-like environment is well under way, with an initial focus on operating the dual-bell nozzle with non-reacting flow under the F-15B/PFTF. These initial operational flights will enable Marshall's laboratory test data on cold-flow nozzle operation to be leveraged for the flight test campaign, as well as to permit a build-up approach in complexity for risk mitigation purposes, prior to operating nozzles under the F-15B/PFTF with reacting flow. The current feasibility assessment is primarily focused on establishing the appropriate F-15B flight altitudes for full flow in the nozzle, defining the nozzle scale, and outlining the propellant feed system necessary for the required mass flowrate. Definition of the propellant feed system is currently being refined to help define individual components (for example: tanks, regulator, valves, and instrumentation), and these individual components are each being evaluated against sizing and placement requirements within the PFTF internal volume capacity. The preliminary assessment is revealing that the cold-flow flight test campaign is in fact feasible, and could provide valuable data and increased interest prior to dual-bell nozzle operation with reacting flow. Once completed, this feasibility assessment is planned for publication, and will be utilized to gain greater interest and collaboration for increasing the TRL of the dual-bell nozzle. The completed feasibility assessment will also enable the system requirements definition to be initialized, followed by the system design and a more refined definition of the required flight tests.

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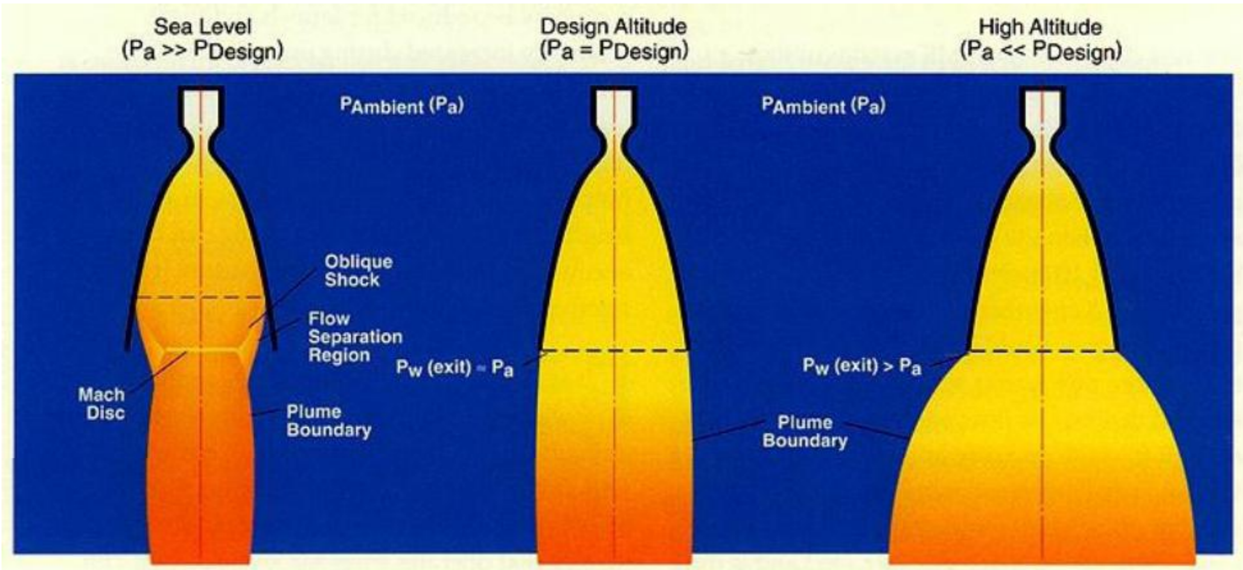

Image courtesy: Pratt & Whitney Rocketdyne (ref. 1).

Figure 1. Conventional bell (CB) nozzle exhaust plume conditions.

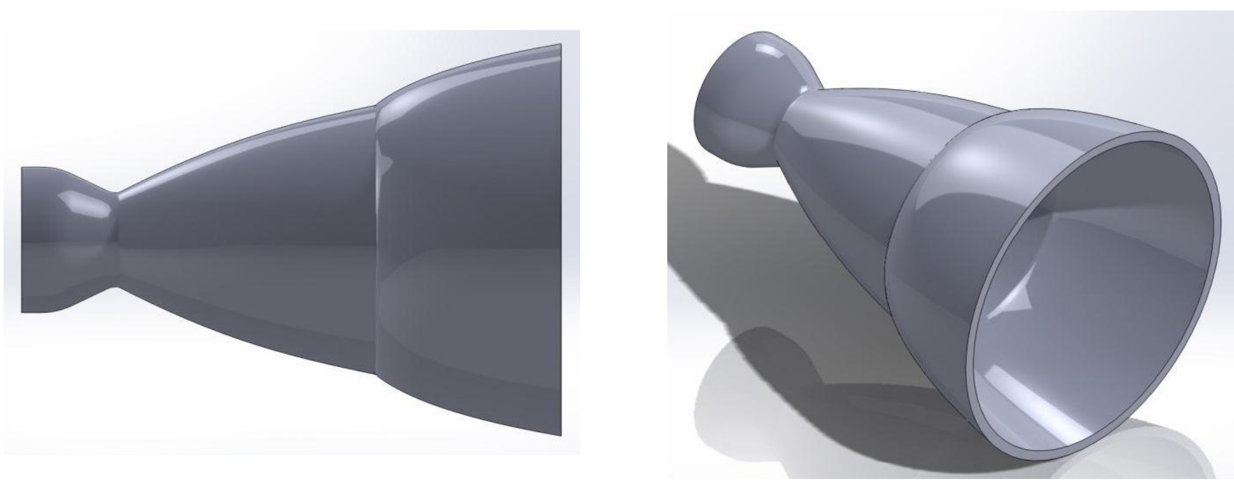

Figure 2. Front view and isometric view of a typical dual-bell nozzle.

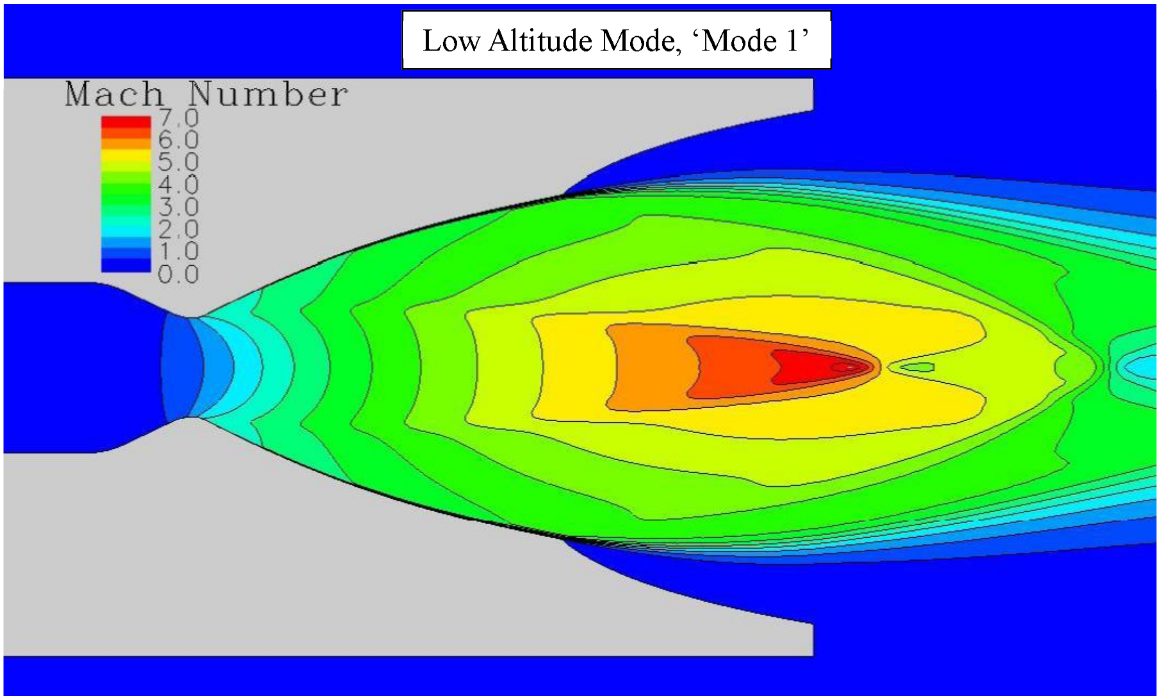

Image courtesy: NASA MSFC.

Figure 3. Mach contours from a CFD analysis for the dual-bell nozzle at low altitude.

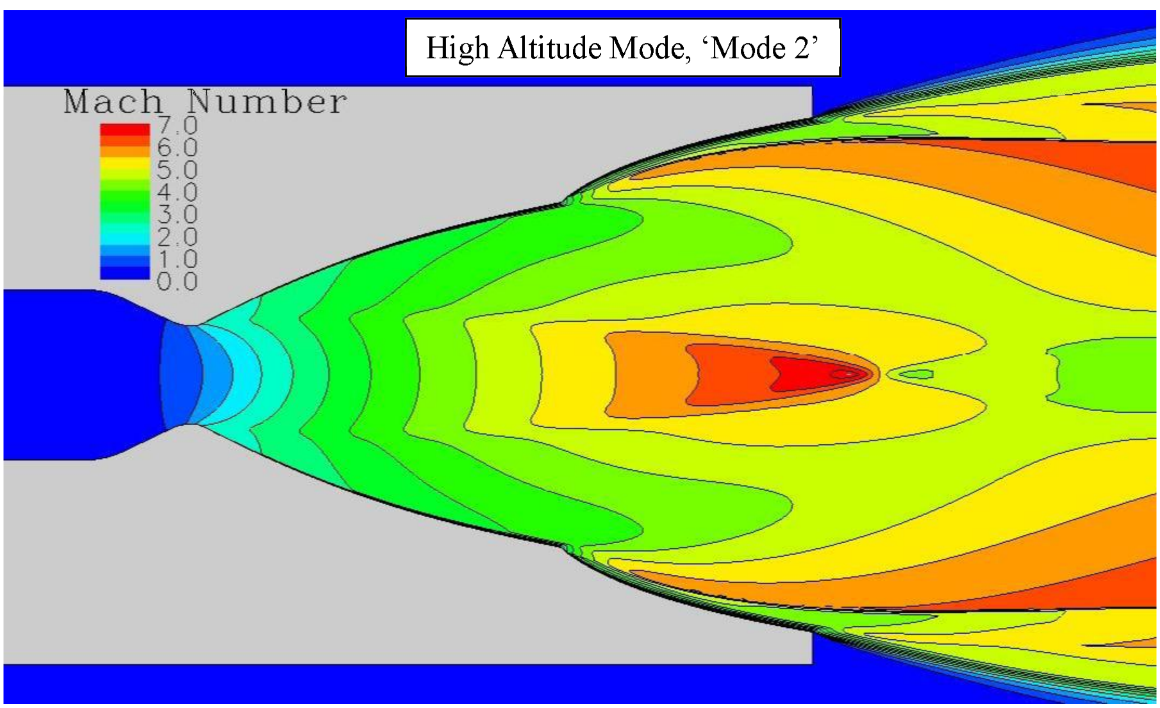

Image courtesy: NASA MSFC.

Figure 4. Mach contours from a CFD analysis for the dual-bell nozzle at high altitude.

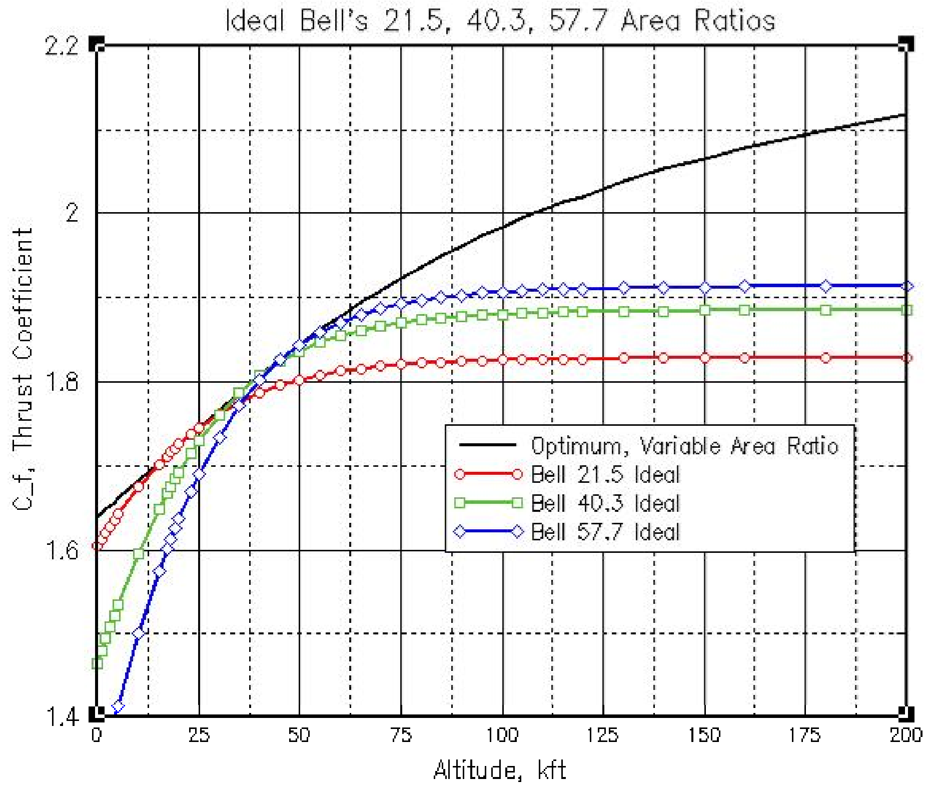

Image courtesy: NASA MSFC.

Figure 5. Plot of thrust coefficient versus altitude, with three different CB nozzles.

Photo courtesy: see ref. 7.

Figure 6. The NASA F15B/PFTF during flight.

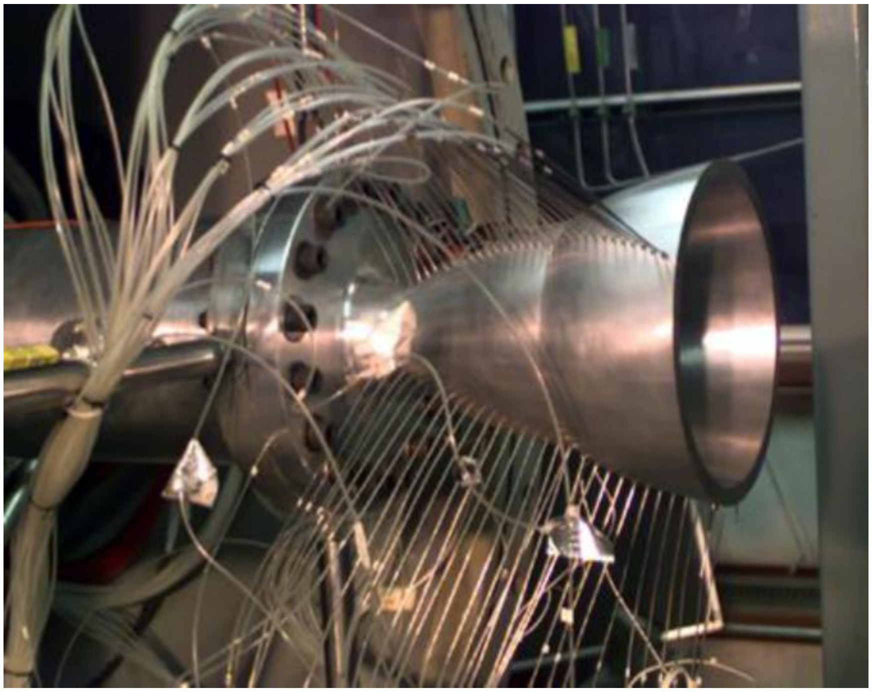

Photo courtesy: NASA MSFC.

Figure 7. Dual-bell nozzle during testing at the NASA MSFC Nozzle Test Facility (NTF).

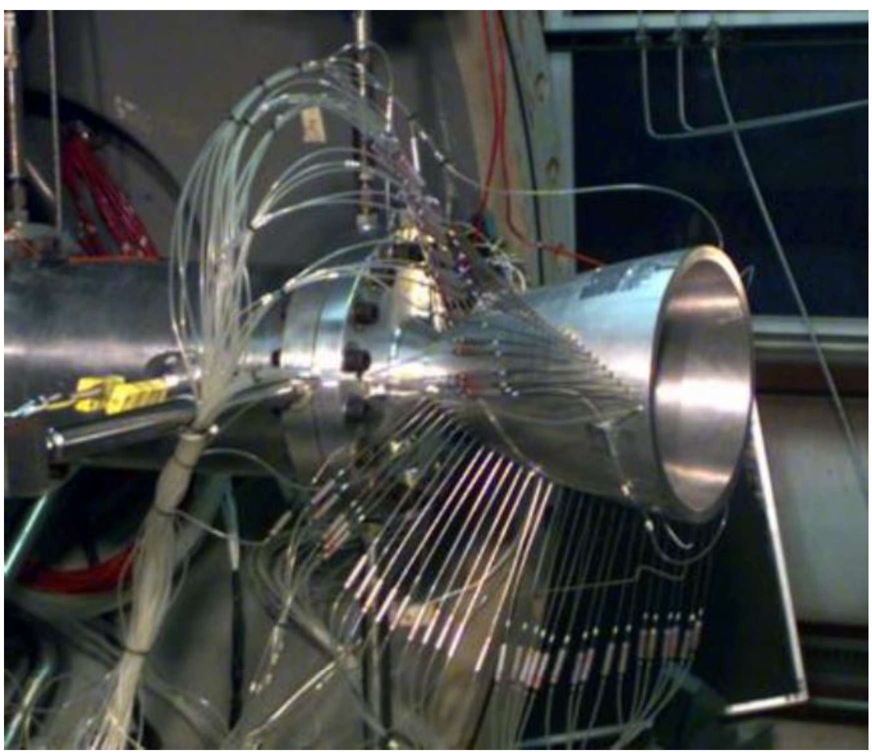

Photo courtesy: NASA MSFC.

Figure 8. CB nozzle during testing at the NASA MSFC NTF.