NASA's Pursuit of Low-Noise Propulsion for Low-Boom Commercial Supersonic Vehicles

James Bridges[*], Clifford A Brown[†], Jonathan A Seidel[‡]
NASA Glenn Research Center, Cleveland, OH 44135

Since 2006, when the Fundamental Aeronautics Program was instituted within NASA's Aeronautics Mission Directorate, there has been a Project looking at the technical barriers to commercial supersonic flight. Among the barriers is the noise produced by aircraft during landing and takeoff. Over the years that followed, research was carried out at NASA aeronautics research centers, often in collaboration with academia and industry, addressing the problem. In 2013, a high-level milestone was established, described as a Technical Challenge, with the objective of demonstrating the feasibility of a low-boom supersonic airliner that could meet current airport noise regulations. The Technical Challenge was formally called "Low Noise Propulsion for Low Boom Aircraft", and was completed in late 2016. This paper reports the technical findings from this Technical Challenge, reaching back almost 10 years to review the technologies and tools that were developed along the way. It also discusses the final aircraft configuration and propulsion systems required for a supersonic civilian aircraft to meet noise regulations using the technologies available today. Finally, the paper documents the model-scale tests that validated the acoustic performance of the study aircraft.

I. Introduction

Looking back from the completion of a significant project milestone, it is hard to remember all the threads that were woven into the final product. The purpose of this paper is to capture the many disparate elements, document how they came about, why certain decisions were made, and tie together all the research that has been documented in focused papers. At its heart, this paper is a history lesson. It is hard to pick a particular starting point in history as there was always information being created (and relearned) that impact decisions. We could start in 2006 with the formulation of the Fundamental Aeronautics Program (FAP) and the Supersonics Project that focused on the airport noise problem with commercial supersonic airliners. This review could have started from 2013 with the reinvention of FAP and the morphing of the Supersonics Project into the High Speed Project (HSP), or from 2015 as the High Speed Project transitioned into the Commercial Supersonics Technology (CST) Project. The Technical Challenge which is the focus of this report was first formulated in 2013 under the High Speed Project, and changed little between 2013 and 2016 when it was completed. However, we choose to start roughly around 2010 because that was when the fundamental work, begun in 2006, was starting to give results concerning the various noise reduction concepts that were initially considered. In this timeframe initial industry-led system studies were giving form to conceptual vehicles and an engineering problem could begin to be formulated. At this point many efforts in theory, noise prediction methods, and advanced experimental techniques were bearing fruit and were ready to be directed toward a common problem. This paper will briefly review some of the earlier concepts explored and why they were or were not pursued, beginning in 2010.

The Technical Challenge was formally titled "Low Noise Propulsion for Low Boom Aircraft" with a milestone completion date of September 2016. Its exit criterion was given as

> *Deliver design tools and innovative concepts for integrated supersonic propulsion systems with noise levels of 10 EPNdB less than FAR 36 Stage 4 demonstrated in ground test.*

[*] Acoustics Branch, Associate Member
[†] Acoustics Branch, Senior Member [‡]
Propulsion Systems Analysis Branch

Note that the exit criterion could be broken down to include four main parts:

- "*Deliver design tools and innovative concepts*"—we were to deliver not only a quiet propulsion system, but also the analytical tools required to design them, to compute the trades between noise and performance and sonic boom.
- "*for integrated supersonic propulsion systems*"—we had to consider the impacts of installation on the propulsion noise, something that has rarely been done.
- "*noise levels of 10EPNdB less than FAR 36 Stage 4*"—we had to relate the noise predicted and measured in modelscale to the Effective Perceived Noise Level (EPNL) metric described in the Federal Aviation Regulations Part 36 for noise certification of aircraft.
- "*demonstrated in ground test*."—we had to create appropriate test articles and demonstrate their accuracy relative to real aircraft.

In the end, NASA used the Lockheed Martin N+2 concept vehicle[1], which has a cruise speed of Mach 1.6 and carries 70 passengers, as the basis for the propulsion study. This selection provided the estimates of range and sonic boom values, and prescribed the installation for the propulsion. We used propulsion systems analysis and noise models created during the program to explore propulsion cycle and nozzle options. System studies showed that the dominant noise source for the aircraft was the jet exhaust noise, and that the jet exhaust noise was most critical at the Lateral observer point in the certification process. We therefore focused on the installed jet exhaust noise, relating the goal metric of the FAR standard to the noise of the jet exhaust at the Lateral observer during the initial takeoff (actually at 1000-feet altitude where this noise peaked). The goal level at this certification point was established by starting with the Lateral noise level allowed by the Stage 3 rules for this weight of vehicle. Certification under Stage 4 requires at least another 1 EPNdB reduction at this certification point, and a further 3 EPNdB reduction (an even split of the 10EPNdB cumulative margin in our Goal statement) was subtracted from this, resulting in the established value of 93.3 EPNdB for the Lateral certification point to be equivalent to the Technical Challenge noise goal. Those engine cycles and installed nozzle concepts that maximized range while meeting the noise limit established by the exit criteria were tested in a high-fidelity, model-scale, simulated flight, anechoic facility to confirm that the design did meet the exit criteria. This was accomplished in a series of tests in the summer of 2016. However, a significant body of work went into this final demonstration test, and this document attempts to show how each contributed and to provide a common starting point for future reference.

This report is structured along the lines of the subproject, with accomplishments grouped into three main categories: Technologies, Tools, and Tests. As in the project, these categories overlap and cross-feed, but this construct helps give structure to the story. For many researchers, work focused mostly in one category, and their story can be seen from that one point of view. However, the purpose of this report is not to tell three stories, but to show how they cross-linked to meet the final project goal. So, the outline of the report is to briefly describe the Technologies (sometimes call low-noise concepts) that were considered, and the Tools (predictive and experimental) that were developed. Then the efforts will be cross-linked in a narrative of the Tests that were performed to develop the Technologies and Tools, hopefully showing how they culminated in a design process that met the project's Technical Challenge.

II. Noise Reduction Technologies Considered

From the beginning of the Supersonics Project in 2006 it was determined that jet noise was one of the primary barriers to a successful supersonic airliner. Fan noise was being worked by other NASA projects, and historical work had found that the high specific thrust propulsion (high speed jet plume) needed for efficient cruise was in direct conflict with the low specific thrust needed for acoustically acceptable landing and take-off operation. There was an effort to gather ideas regarding the reduction of jet noise and look at them afresh with new computational and experimental tools. An open-ended NASA Research Announcement (NRA) went out, seeking proposals for noise reduction ideas. Two large system studies, the N+2 Supersonic Concept Study[2,3] and N+3 Advanced Concept System Study[4,5], were done by industry with a specific requirement that they canvass the field for noise reduction concepts that might be applicable. By 2010 many of these ideas had been vetted and the remaining promising ones were being worked to determine if they could be made effective on an aircraft with cruise Mach number of 1.6, holding 50-100 passengers. Although a specific vehicle and propulsion cycle were not known, it was clear that the noise technologies would have to work on cycles at pressure ratios with the possibility of broadband shock noise. A few of the concepts that were investigated by NASA and its collaborators leading up to the selection of engine cycles and nozzle types are discussed below.

A. Plasma-excited jets

The promise of manipulating the instantaneous turbulent structures (eddies) through the instabilities that give rise to them has been the ultimate goal of jet noise for decades. The belief is that if the turbulent structures could be organized in proper phase there would be an evolution of the turbulent cascade which results in a minimal sound output. Or that at least the energy could be transferred from frequency ranges that are maximally annoying to humans into ones that would not be as objectionable. (See section III F on LES adjoint problems for a potentially definitive answer to this quest.)

This line of reasoning was guided by the model problem of noise generated by vortex rings[6]. If two coannular axisymmetric vortex rings interact they produce an axisymmetric quadrupole as they transfer energy from the vorticity to pressure field. When azimuthal variations are introduced into the vortex ring, the efficiency is reduced. If the azimuthal variations are analyzed by Fourier modes it is found that only the first two azimuthal modes, ±1 and ±2, can couple to the acoustic far-field solution for waves as a quadrupole. Higher order modes couple as inefficient octupoles and higher order sources. This leads to the idea that if turbulent energy in a jet shear layer could be directed into higher order azimuthal modes then the turbulence in the jet could be rendered less efficient as a sound source.

One problem experienced by researchers exploring this idea was how to introduce perturbations into the jet turbulence with enough energy to override the perturbations produced by the jet itself. In short, it was a problem of control authority. The only place where the jet turbulence is receptive to external perturbation is in the nozzle, especially the nozzle lip, or at a shock. In very low speed, nearly laminar jets, acoustic methods, such as local unsteady pressure sources at the nozzle lip, had been implemented. These jets had Reynolds numbers of $O(10^4)$ instead of the $O(10^7)$ typical of aircraft jets. When the Reynolds number increases in a jet, the energy required quickly exceeds that available by conventional acoustic methods. Many actuator methods have been investigated, but most methods were incapable of control over the frequency and azimuthal mode of the perturbation. Electronically controlled plasma arcs, sparks essentially, were capable of producing significant energy via thermal expansion waves, and an array of them around the nozzle lip could be phased to produce an arbitrary initial condition in time at the nozzle lip. The development of these plasma arc actuators and their control was carried out by Professor Mo Samimy and students at Ohio State University under an NRA grant NNX07AC86A which ran from 2007-2011, supervised by NASA's Cliff Brown. Most development was done in a smaller university rig[7–9]. The effort culminated in a series of tests at NASA Glenn's Aero-Acoustic Propulsion Laboratory (AAPL) on single-stream nozzles mounted on the Small Hot Jet Acoustic Rig (SHJAR) and the High Flow Jet Exhaust Rig.

In the final test a 15cm-diameter nozzle was fitted with a ceramic lip that contained 24 pairs of tungsten electrodes, allowing excitation up to mode ±12 (see Figure 1). Considerable technical difficulties were addressed, mostly arising from the powerful electromagnetic pulses produced that scrambled nearby electronics. Researchers eventually showed that the actuators achieved control authority over the turbulent structures in the potential core of the jet; however, the noise impact was very small and in overall terms was overshadowed by the noise of the actuators. The principle of controlling the jet structures, moving turbulent energy into higher order modes was demonstrated. Unfortunately, removing 10% or even 20% of energy from a source produces less than 1dB of noise reduction. One of the objectives of taking the concept from the small university nozzle (~25mm diameter) to the larger nozzle at NASA was to demonstrate the scalability of the concept. Recall that, historically, increases in Reynolds number had decreased the control authority of other actuator methods beyond the point of usefulness. While it was found that control authority was maintained over this large increase in scale by proportionally increasing the number of actuators, the electrical energy required, the inherent electromagnetic interference with nearby electronics, and the material difficulties in providing electrically isolated nozzles capable of withstanding the plasma temperatures seemed to be developmental barriers that precluded further investigation as the project downselected to more achievable technologies.

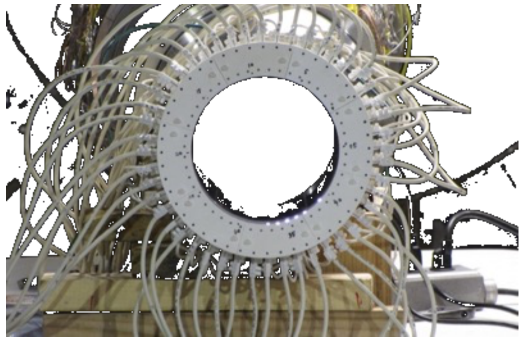
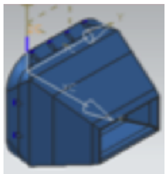
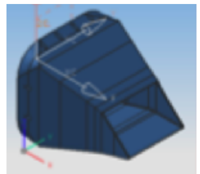


Figure 1 Plasma Arc Filament actuators on 15cm-diameter convergent nozzle as tested on Nozzle Acoustic Test Rig in NASA Aero-Acoustic Propulsion Lab in 2011.

B. High Aspect Ratio Nozzles (HARN)

High aspect ratio nozzles are appealing if a designer wants to embed the propulsion in the airframe. On the surface, they promise high rates of plume mixing, which is generally associated with reduction of jet noise by lowering the jet velocity downstream where the peak low frequency jet noise is produced. High aspect ratio nozzles also lend themselves to aggressive mixer-ejector concepts as the actuated surfaces can be rectilinear. (For an example of why the corner flows in axisymmetric ejectors are a problem, see Section II F.) A series of rectangular nozzles with varying aspect ratio, height:width (*h:w*), was developed to explore this technology. Experiments were conducted to provide data for the development of empirical noise models, to document the changes in the turbulence statistics required of acoustic analogies, and to validate the CFD, both Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES), needed to predict the noise of rectangular nozzle flows. A related effort was made to develop Green's function solutions required to make acoustic analogy based noise predictions for these nozzle flows (see Section III D 1). Three test nozzles with aspect ratios 2:1, 4:1, and 8:1 were built to fit on the Small Hot Jet Acoustic Rig (SHJAR) in AAPL, with the requirements that nozzle areas be the same, that the nozzles have a common exit point relative to the rig, and the exit velocity be constant over the nozzle opening with no axial vorticity. These latter two conditions produced a very challenging design problem as several ideas for transitioning from the round supply pipe of the rig to the rectangular nozzle proved to have significant secondary flow features. Reference [10] documents the final design. At this time RANS CFD still required weeks to grid and solve on NASA's supercomputer cluster for each nozzle geometry. An extension of one wide-side lip was added to each aspect-ratio nozzle to represent the aft deck of an aircraft. Two lengths of extensions *L* were created for each nozzle, each being the same for all aspect ratios. These nine total nozzles (three aspect ratios, three extensions including none; see Figure 2) were fabricated for use over the range of subsonic conditions at temperatures up to 1200°R without adverse deformations under load. Other papers documented the acoustic far-field trends[11], and the flow fields[12]. The exit flow requirements were met and the influence of aspect ratio and deck length was documented and modeled. A follow-on test[13] investigated the effect of larger surfaces without a bevel but with standoff distances to the nozzle lip. In short, the noise of the high aspect ratio jets is shifted in frequency from low to high, the peak frequency scaling more on the short dimension of the nozzle than on effective diameter (although initial empirical models used the latter), and the noise, especially at high frequencies, was loudest on the wide side of the nozzle. There was no net noise reduction; in fact, the nozzle would produce more annoyance to observers on the ground. Empirical models were created to predict the noise, with and without the lip extensions in Reference 11. That model was based on normalizing the spectra by the equivalent area of the nozzles; however, more recent work[14] at higher aspect ratios show that the noise is better scaled by minimum nozzle dimension rather than equivalent area.


NA2Z Basic nozzle, 2:1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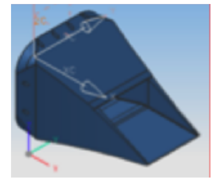
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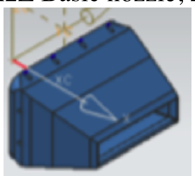
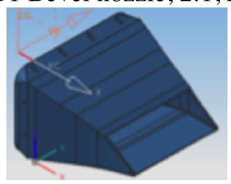

NA4Z Basic nozzle, 4:1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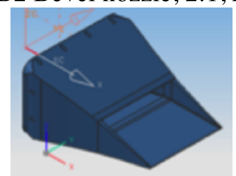
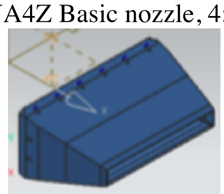
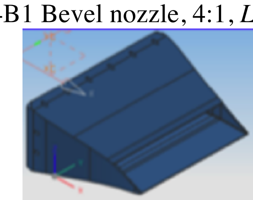

NA4B2 Bevel nozzle, 4:1, *L*/*h*=2.8


NA8Z Basic nozzle, 8:1


NA8B1 Bevel nozzle, 8:1, *L*/*h*=2

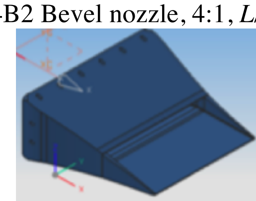

NA8B2 Bevel nozzle, 8:1, *L*/*h*=4

Figure 2 Gallery of Extensible Rectangular Nozzles.

C. Twin Jet

It has been known for some time, though apparently not well-documented, that noise from a jet appears to be somewhat 'shielded' when it passes through an adjacent jet on its way to an observer. Whether this is caused by actual propagation losses or by changes to the source from the induced flow of the second jet was unclear. Furthermore, given that installation impacts were thought to be a significant effect to be considered in supersonic aircraft design and no direct empirical model was available, a series of tests[15,16] were undertaken to explore this effect and to capture it in an empirical model. The changes in flow fields as the spacing of the jets was changed was carefully documented as well[17], both to aid in understanding the phenomenon and for validating computational tools.

Two test campaigns were mounted, looking at two single-stream jets in proximity in a simulated flight stream. A model was created to describe the change in noise of a jet in the presence of a second jet as a function of jet flow condition (single-stream only), flight speed, nozzle spacing, and observer angle. In the final analysis, the beneficial (e.g. noise reducing) effect was limited to a range of observer angles in the plane containing both jets, limiting the usefulness for most ground observers, and the effect was largely described by an SAE prediction method for ground-based attenuation. The SAE method specifies two different jet spacings, one for tail-mounted engines and one for wing-mounted ones. Our findings did not differ enough (more than 1dB) from the SAE methods to warrant further investigation.

Figure 3 Pictures of acoustic testing of twin, single-stream, round nozzles (left), and of PIV testing of twin rectangular nozzles (right).

D. Variable Cycle Engine (VCE)

From a system perspective propulsion systems need to produce low specific thrust when they operate around the airport where noise must be minimized. However, the propulsion system must shift to producing high specific thrust to provide efficient operation at supersonic cruise. The general idea of a variable cycle engine has, at a one-dimensional system level, many advantages for its ability to change its intrinsic specific thrust. One common architecture to achieve this variability is to tie a second, coannular fan to the core, with the ability to change the inlet and exhaust areas of the fan to shut it down during cruise operation, producing a variable bypass ratio engine. This tip fan flow must pass through a nozzle system, but it can be incorporated into the nozzle in several ways. Given that it is independent of the pressures of the core and inner fan, it usually needs to be exhausted independently, e.g. not internally mixed. One way is the Inverted Velocity Profile (IVP) nozzle discussed in Section II E. Another is to simply exhaust it on the outer annulus, either axisymmetrically or asymmetrically, as discussed in Sections II G and II H. An overview of the possible nozzle architectures enabled by the VCE was presented in Reference[18].

By the end of the Technical Challenge, enough cycles had been studied by the NASA Propulsion Systems group to determine that the benefits of the variable cycle engine over a conventional two-stream engine were not enough to overcome the deficits caused by the extra weight of the engine cycles that could meet the Technical Challenge noise goal. Or put another way, no propulsive nozzle variant using the three-streams produced enough noise reduction relative to the conventional two-stream nozzle to pay for the additional weight of the tip fan hardware. The system benefits of the variable cycle engine didn't show until the engines had engine pressure ratios over 3, at which point the noise was so much more than any of the noise reduction concepts could overcome that they were just too loud for commercial airport use. Section IV A discusses this in more detail. Add to this the fact that a three-stream engine only exists in advanced military development programs, it is clear that the future efforts should be directed at conventional engines.

E. Inverted Velocity Profile (IVP)

The IVP nozzle is usually achieved by ducting all or part of a fan stream to the inside of the hot core flow, producing a lower speed flow at the center of the jet plume. The IVP concept was first investigated many years ago[19]. At that time, the jet plumes of interest were supersonic and contained shocks. By putting a low speed flow at the center, the shocks on the core stream were reduced in strength, much like they are with a porous plug, and the enhanced mixing from having shear layers both inside and outside the core stream produced lower jet noise from the downstream region of the jet. If all the fan stream of conventional two-stream engine is directed to the inside of the plume, the high-speed shear on the outside can result in increased high frequency mixing noise near the nozzle.

The engines being considered for commercial service beyond 2025 could not have such high velocities that they are dominated by shock noise. But they could benefit from enhanced mixing. Furthermore, the high-speed shear created by ducting fan flow inside can be reduced if a portion of the fan flow is retained outside, possibly only on the side of the nozzle toward the observer. This was the rationale of engineers at General Electric Aviation (GEA) when they proposed the shielded inverted velocity profile nozzle for their variable cycle engine to be mounted on a study vehicle being designed by their partner, Lockheed Martin. The propulsion system was very complicated, having a second, tip, fan, making the engine have three streams. At the exit of the turbine, the inner fan and the core flow were mixed with an internal lobed mixer and directed out the nozzle's primary annulus. The tip fan flow was split 50/50, with one half being directed through strut ducts into the innermost annulus of the nozzle, while the other half was directed to an outer annulus that spanned 180° of the nozzle's perimeter. Although the nozzle had aspects that made it potentially have low noise, it's design was largely driven by the ability to vary the cycle of the engine, with the tip fan independent of the main fan pressure ratio, and with the nozzle convergence-divergence varied by axial translations of the nozzle elements. Because efficient supersonic cruise requires low boat-tail angle of the nacelle and nozzle, a sizeable plug was featured in the nozzle design, producing annular streams that were relatively thin, and hence mixed quickly. The overall objective for the nozzle system acoustically was to make no more noise than an equivalent fully mixed single-stream nozzle, but with the benefit of having the independence of the fan streams that comes with a separate flow nozzle.

An initial design, developed and tested in a Phase 1 contract[2], unsuccessfully attempted to maintain the divergent design of the cruise nozzle at takeoff. The divergent section of the nozzle developed a resonance over a substantial portion of its operating range, making it unacceptably loud. In a second design cycle, conducted during the Phase 2 contract with Lockheed Martin, the nozzle was redesigned to transition between a convergent profile during airport operations and a divergent profile during cruise. The design, in the convergent configuration, was built and tested acoustically during a Phase 2+ contract[1]. The second concept was found to meet, or even slight exceed, the design objective. Pictures of the two nozzle concepts are shown, as mounted at NASA's Aero-Acoustic Propulsion Lab, in Figure 4 and Figure 5. An additional benefit was that when the engine cycle was pushed to higher nozzle pressure ratios the onset of broadband shock noise was delayed compared to a conventional nozzle. The success of the concept, while modest, coupled with the potential system benefits from the enhanced flexibility of the third stream, caused NASA to pursue this architecture until the very end of the Technical Challenge, where most of the nozzles tested were variations on this design.

Because of the proprietary nature of this design effort, the open publications describing it are limited. Open literature is limited to NASA Contractor Reports on the Phase I effort[2] and a NASA Contractor Report covering the final Phase II effort, including the second generation IVP nozzle[1].

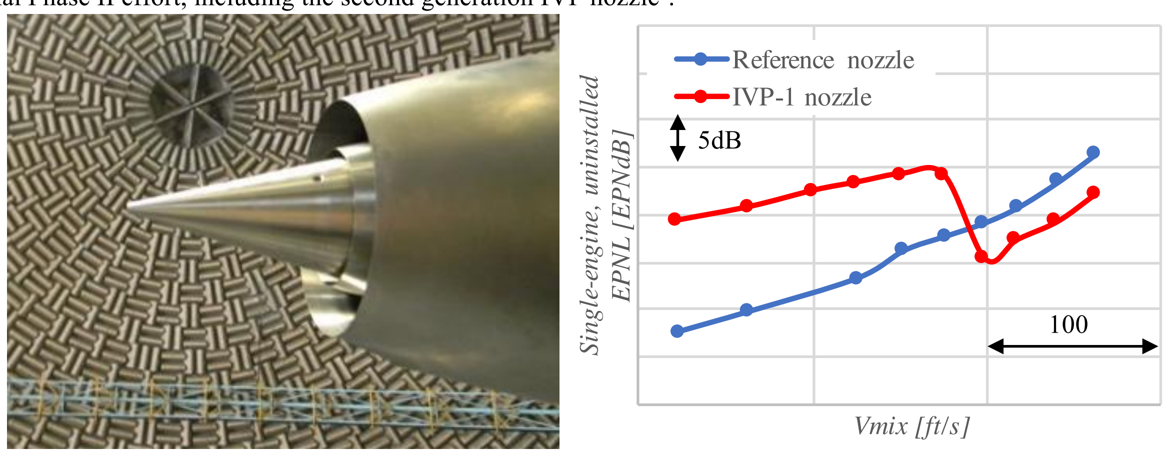
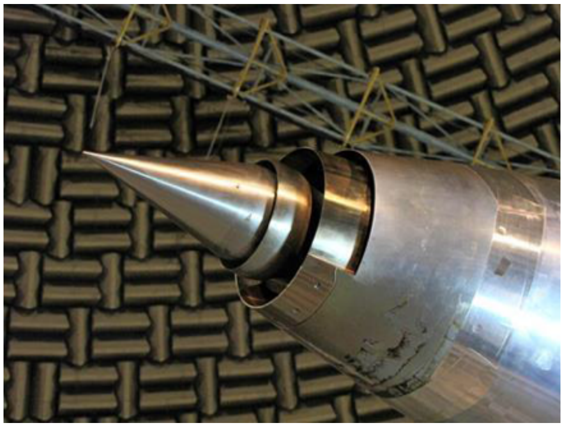


Figure 4 Left: NASA photo of GE's three-stream Inverted Velocity Profile nozzle, Phase 1, tested at NASA's Nozzle Acoustic Test Rig in 2011. Right: Computed EPNL over engine throttle line for reference fully mixed nozzle and Phase 1 IVP nozzle.



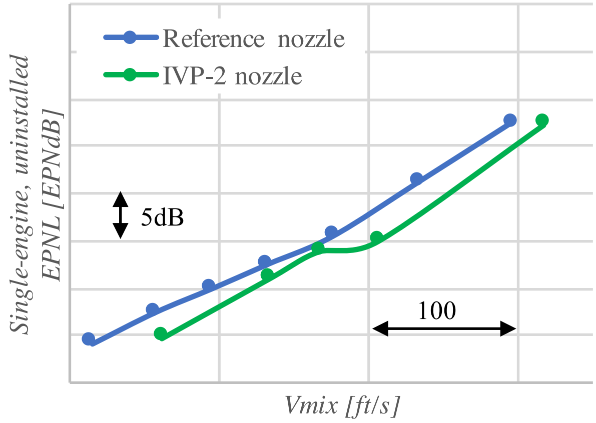


Figure 5 Left: NASA photo of GE's three-stream Inverted Velocity Profile nozzle, Phase 2, tested at NASA's Nozzle Acoustic Test Rig in 2014. Right: Computed EPNL over engine throttle line for reference fully mixed nozzle and Phase 2 IVP nozzle.

F. Clamshell mixer-ejector

The concept of using a clamshell thrust reverser mechanism, slightly deployed, as an ejector, has been attractive to many experts in the industry. NASA has hosted tests of concepts like this, often as completely externally funded activities, on several occasions. The common experience has been that the geometry has not entrained as much flow as expected, thus not achieving its noise reduction promise. It has also been a common experience that some aspect of the relatively complicated geometry caused by the actuation of the ejector walls causes a flow resonance, a whistle or howl, that completely overshadows any small benefit gained by the enhanced mixing. Still, the allure persists of gaining a few dB of suppression on an internally mixed turbofan nozzle with a bolt-on solution with known mechanical properties.

Two version of a clamshell mixer-ejector were considered in the NASA project. Both were designed by Rolls-Royce Liberty Works of Indianapolis, working with prime contractor Lockheed Martin under NASA contract NNC10CA02C. The results of this effort are documented in Reference 3. The first concept[20] was based on a conventional two-stream, internally mixed turbofan engine, while the second[21] was mounted on a three-stream variable cycle engine. Both were tested at NASA Glenn's Aero-Acoustic Propulsion Laboratory. This latter design attempted to drive the ejector by forcing the third stream to mix with the primary stream using a second, internal, ejector. Both concepts suffered from internal separations of the flow, the second version especially having a strong resonance that spoiled any benefits from enhanced mixing. Compared with a fully mixed, single stream baseline nozzle, the mixer-ejector produced more high frequency noise from the internal separations. Following the failure of the second version to produce noise reduction relative to the baseline nozzle, the clamshell ejector concept was abandoned. Some research was continued, attempting to use the nozzle as a test bed for physics-based noise prediction tools that could predict the resonant behavior, but the complicated geometry made such work very expensive and this effort was abandoned, also.

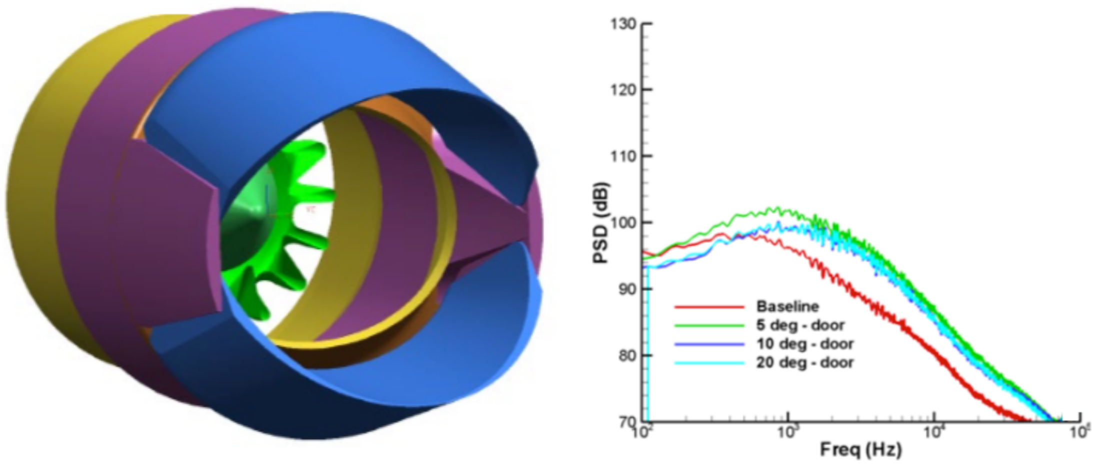


Figure 6 First generation (two-stream) clamshell ejector by Rolls-Royce LibertyWorks, tested at NASA's Aero-Acoustic Propulsion Lab in 2010. Left: nozzle geometry. Right: representative noise spectra of baseline fully mixed vs clamshell ejector nozzle at 120° to jet axis.

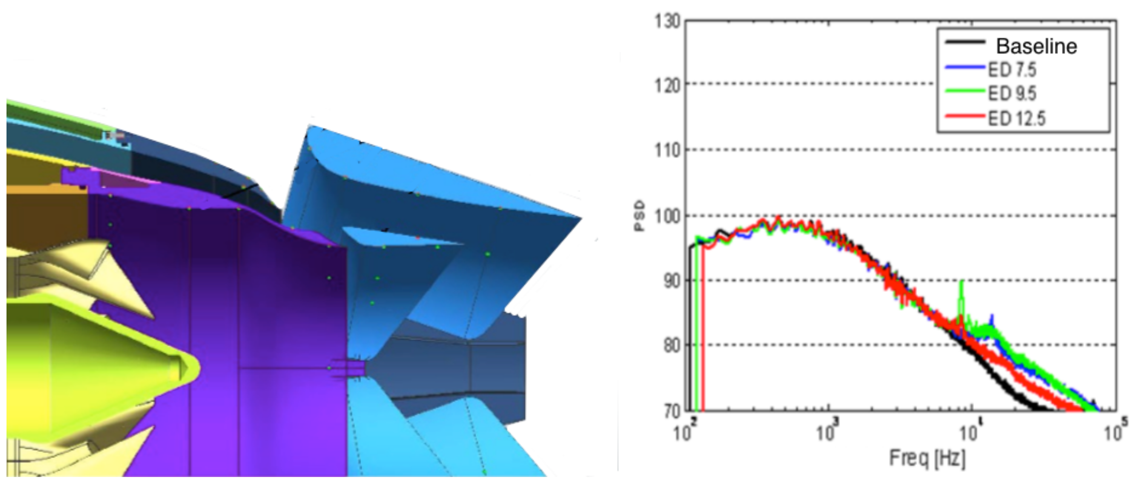
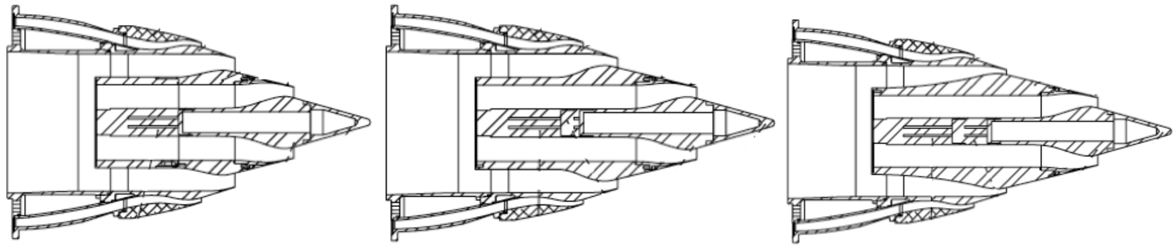


Figure 7 Second generation (three-stream) clamshell ejector by Rolls-Royce LibertyWorks, tested at NASA's Aero-Acoustic Propulsion Lab in 2011. Left: nozzle geometry. Right: representative noise spectra of baseline fully mixed vs ejector nozzle at 90° to jet axis.

G. Three-stream separate flow nozzles

Given a VCE with three streams of air, one hot, and two cold, the most flexible nozzle type is an externally mixed, or separate flow, nozzle, with coannular streams. With this configuration, the core and fan streams need not be matched in pressure. This type of nozzle usually has the least hardware, meaning the least weight and nacelle drag (at least until variable geometry is considered). It also usually has more noise than an internally mixed nozzle, meaning that a trade must be determined between weight, noise, and in the case of the supersonic aircraft, wave drag. Wave drag of the nacelle is minimized with fineness ratio, length vs equivalent diameter, of the propulsion system. A shorter nacelle, beneficial in subsonic applications because of reduced skin friction drag, can be detrimental to the supersonic aircraft both for cruise performance and sonic boom. However, the trade must be determined, and for that a method for predicting the noise of a three-stream externally mixed nozzle was required. No such method existed at the start of the Supersonics Project. NASA modified its high-fidelity dual-stream jet exhaust rig to add a third annular stream (also used in the GE IVP nozzles tests and the second Rolls-Royce LibertyWorks clamshell nozzle tests), and designed a series of nozzles with various area ratios[22] to build a noise database and ultimately an empirical model to predict the noise of a three-stream nozzle[23,24]. Drawings of three of the nozzle systems, showing various area ratios, are given in Figure 8. For the Technical Challenge study, system analysis never achieved the level of sophistication to definitely say whether the advantages of the separate flow nozzle (primarily lower weight) would outweigh the higher noise and wave drag for this application. However, the noise and flow fields of externally mixed, three-stream nozzles were definitely established[25].



(a) (b) (c)

Figure 8 Externally mixed, three-stream nozzles used in developing three-stream aeroacoustic database. Core-to-bypass area ratios (a) 2.5, (b) 1.75, (c) 1.0.

H. Offset stream

Current understanding of jet noise breaks the mixing noise sources into two categories, roughly omnidirectional 'fine-scale' sources, and aft-dominated 'large-scale' sources. The latter are associated with the locally supersonic phase speeds of large-scale eddies in the plume, usually located downstream of the potential core of the jet, that produce low frequency noise that dominates in the aft observer angles. The convection speed of these eddies, also referred to as instability waves, controls the efficiency to which they transfer energy from the turbulent flow to the acoustic field. One way to reduce their convection speed and lower their efficiency is to reduce the downstream jet velocity where these eddies, or instability waves, exist. Early work by Papamoschou[26] exploited this idea, diverting a portion of the fan stream to the observer side of the plume using vanes in the fan stream nozzle. By thus thickening the fan stream the convection speed was lowered on the observer side of the jet, reducing noise. This concept was explored further for two-stream engine cycles of interest to the NASA program, and the design space of fan stream vane characteristics mapped out in a design-of-experiments study[27].

While the three-stream separate flow nozzle explorations were attempting to explore how the arrangements of the velocities from the three streams affect the large-scale sources, an associated effort looked at enhancing the effect by putting more of a given annular fan stream to one side of the nozzle, producing a benefit that might be directed toward one side of the nozzle. Rather than employing vanes in the fan nozzles, which produced concerns for the nozzle operation over the flight envelope, the plume asymmetry in these three-stream configurations was achieved by modifying the nozzle profiles themselves. Researchers at University of California-Irvine[28] further explored the relationship between turbulent convection speed and aft-directed jet noise, and explored unique asymmetric nozzle designs for a three-stream, externally mixed nozzle. Internally, NASA explored[29] a number of offset configurations using small variations in the three-stream nozzle hardware, inserting an s-duct upstream of the outer nozzle to slightly change the annulus thickness around the nozzle (Figure 9), or by blocking off a portion of the outer annulus altogether. A few common configurations were tested at both UCI and NASA to establish commonalities between the rigs. The benefits were, as expected from the description above, limited to the aft angles, with at least some extra noise being generated at broadside angles relative to an axisymmetric separate flow nozzle. The principle of obtaining reduced large-scale noise by modifying the plume cross-section was proven, but a systematic method of predicting the noise using instability wave theory was still being finalized at the end of the Technical Challenge and was not used in the 2016 effort. Noise modifications by offsetting the third (outer) stream or by blocking portions of the outer stream nozzle were explored extensively, resulted in empirical noise prediction methods and projections of aircraft noise benefits[30].

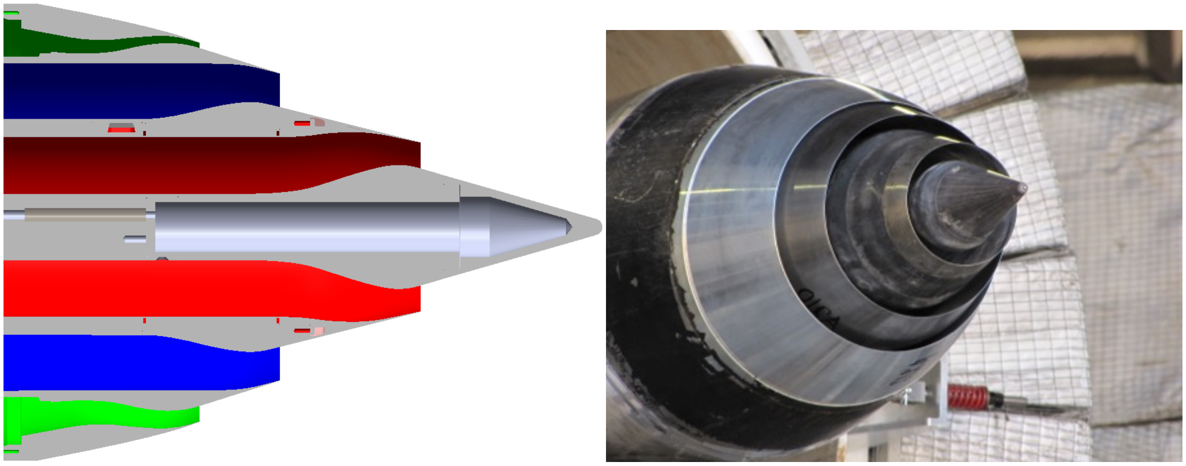


Figure 9 Offset tertiary stream produced by an s-duct on the outer stream nozzle. Cross-sections shows outer annulus to be thinner than bottom by 4mm offset of nozzle.

I. Shielding by Installation

In recent years, attention has shifted from looking for nozzle geometries that might produce significantly lower noise to aircraft configurations where propulsion noise, including jet noise, is reduced by putting the propulsion on top of the vehicle. Concept aircraft, such as the Hybrid Wing Body (HWB)[31], have shown that such an approach is very effective for fan noise, and can produce some reduction of jet noise as well. Conversely, it is becoming more apparent as propulsion units are installed closer to the airframe that when the propulsion is mounted under the aircraft there is a noise penalty associated with reflection off the aircraft and potentially new sources from interaction of the propulsive plume interacting with the aircraft surfaces. A series of fundamental studies of how jet noise is changed by the presence of a surface were undertaken, jointly supported by the NASA Supersonic and Subsonics Projects. The early tests used a simple single-stream nozzle and a very large (‘semi-infinite’) flat plate to explore and model the impact of the surface. Generally speaking, three effects are observed: a propagation effect being either shielding or reflection of the mixing noise sources relative to the observer, a source modification effect when the surface is near enough to the jet plume that the flow is modified by it, and a new noise source from turbulence in the jet plume convecting past the trailing edge of the surface. These have been modeled for simple-surface single-stream jets (round and rectangular), but as the Technical Challenge came close to conclusion it became important to account for the acoustic impact of installation with higher fidelity than could be reasonably expected from the simple empirical models; the concept aircraft being used for the Technical Challenge had a multi-stream propulsion system and the airframe was not semi-infinite in span. Furthermore, the effect of flight was not included in the simple models. However, it was not clear how to represent the aircraft body in the freejet rig as the entire vehicle could not be used, as it was in the 14x22 tests of the HWB, due to the size of the freejet and the scale required to simulated the complex propulsion systems being explored. A high-fidelity model-scale test was mounted to determine how to represent the airframe and to see how the simple models predicted the shielding and reflection of multi-stream plumes near complex surfaces[32]. The simple models worked surprisingly well, given their underlying simplifying assumptions, and the impact of engine installation one the airframe was found to be very significant on this concept vehicle. In fact, the acoustic benefits of locating the propulsion on the top of the vehicle are the basis for research going forward from the Technical Challenge.

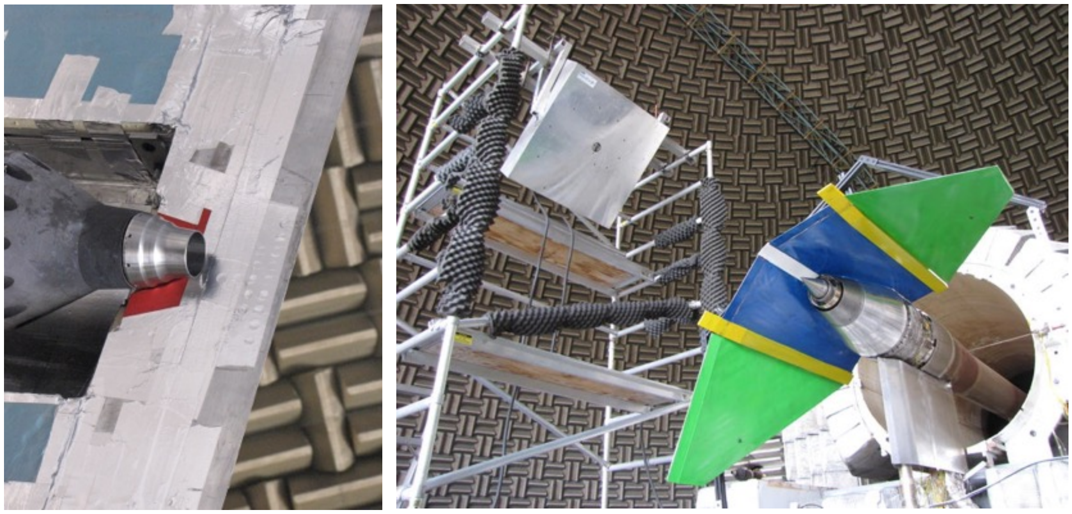


Figure 10 Early tests of jet-surface interaction, performed to establish and validate scaling laws for shielding and reflection of jet noise by the aft deck of an aircraft. Left: simple single-stream, semi-infinite plate configurations. Right: realistic multi-stream nozzle with geometrically accurate vehicle planform (shown with phased-array measurement system).

J. Advanced Takeoff Procedures

While not a classical noise reduction technology, the non-standard operation of the supersonic aircraft in take-off was found to allow it to better meet current noise regulations, both in level and in certification methodology. Given that the Lateral monitor used in aircraft certification testing is the one that most challenges the viability of the supersonic airplane, it helps to accelerate to a higher runway speed than conventionally done before reducing the throttle as the aircraft climbs away from the end of the runway. When done properly, the noise reduction caused by the side-by-side shielding of the jets and the attenuation of sound propagating along the ground would go away as the jet noise was reduced, causing a balanced minimum sound to the Lateral monitor. This operational procedure was considered in the final validation testing as engines that would not have met the noise goal under 100% throttle were tested to see that they could, if the throttle were reduced to projected lapse rate levels, such as 90% throttle. This was, not surprisingly, confirmed. Other operational modifications, such as accelerating during climbout, engine derating, and higher angles of descent during approach, while not currently allowed for certification, have also been found[33] to be very effective at mitigating noise for supersonic aircraft because of their inherently different operating capabilities.

K. Technologies Summary

Of all the noise reduction concepts studied, only installation effects (shielding) and advanced takeoff procedures had shown promise of significant noise reduction, meaning greater than 2 dB for a given engine cycle, and had been captured in a system-level model by late 2015 when the final concept had to be selected for validation. The research effort yielded important additions to the empirical toolbox so that system-level design work could be continued with the concepts explored. But there was no silver bullet in any of them for noise. Shielding, especially if combined with modifications to the nozzle to shift noise sources upstream for more effect, had the most promise for future development. The aeronautical challenges associated with mounting the propulsion on top of the planform, while formidable, should be weighed against the challenge of reducing specific thrust in conventional installations to meet noise requirements. Still, none of the noise reduction technologies considered here could significantly raise the specific thrust required in acoustically acceptable landing and take-off operations.

III. Noise Prediction Tool Development

While low noise propulsion concepts were being explored, significant effort went into improving capabilities for predicting jet noise and for creating tools that would allow engineering trades to be made between the noise benefits of the technologies and their inevitable aerodynamic performance disadvantages. These engineering tools generally fell into three categories: Empirical, RANS-based, and Time-Dependent. The primary example of an empirical prediction method is the Stone Jet model found in NASA's Aircraft Noise Prediction Program (ANOPP). For an axisymmetric jet of one or two coannular streams, a user inputs a minimal amount of geometric information (mostly inner and outer diameters of nozzles), and flow conditions (velocity and temperature), and Stone's model will predict the spectral directivity. The model has an amazing range of validity, but is limited in that it can't predict changes caused by geometry of the nozzle or its installation. Additional fixes can be applied to the basic Stone model, usually by creating a metamodel to fit some experimental database, which was done, but to predict the acoustic impact of geometric changes a model must start by knowing what changes are made to the flow by these changes. Hence the next level of codes, referred to as RANS-based, or sometimes as acoustic analogy based, since they use acoustic analogies to predict the sound given RANS solutions to model the noise sources and propagations. Development of RANS-based codes was tackled by breaking up the problem into validation of the RANS solutions, validation/creation of the turbulent source models, and extension of the propagation calculation, using Green's functions, to more arbitrary geometries. In some cases, nozzle flows exhibit resonant behavior, or other large-scale unsteadiness, that RANS representations cannot be expected to capture. For this reason, and to avoid modeling of the turbulent sources, time-dependent simulations of the flow are used. By the time one includes enough degrees of freedom to capture the broadband nature of the jet sources, the simulations have become Large-Eddy Simulations, stopping short of computing the flow down to the Kolmagorov scales, but still being very large computations. When the Project was beginning, this was pioneering territory and there was a great need for turbulence data beyond mean velocities to validate and guide the nascent codes. NASA's role in the early days was primarily to fund academic and research organizations in their work and to provide the validation data they needed to refine their work.

By the end of the Technical Challenge it was the empirical methods that were of most importance, as they were used to evaluate hundreds of designs with precision of ±1dB. The empirical codes 'TSS' and 'JSI', derived during the project for three-stream and jet-surface interaction effects respectively, were used in conjunction with the Stone prediction code to predict the noise of the various nozzle types at the many engine designs being considered, and to find the ones that met the Technical Challenge goal. The use of RANS-based codes was limited by real-world time restrictions, specifically in grid generation. Using structured grids, even overset structured grids, required days to weeks for a single configuration. Unstructured grids were not much faster for the complicated nozzle concepts being explored. And then the solutions would have to be interpolated onto a structured grid for the acoustic analogy codes to be applied. The acoustic analogy codes themselves had been developed to where they gave reasonable answers for non-axisymmetric and hot jet flows, but they were not entirely dependable, but mostly gave correct trends. The LES codes, while delivering amazing results, required months for a single answer, usually gave answers that were accurate only to within a few dB, and required operators with deep experience to produce reasonable results.

A. ANOPP/ANOPP2

As mentioned above, the Stone jet noise prediction method, coded as ST2JET in the ANOPP noise prediction system, is a mainstay for predicting jet noise. However, it couldn't predict the noise impact of having a third stream on the outside of the plume. Its prediction of the inverted velocity profile plume, created using a few datasets at supersonic conditions, was found to differ from tests done during the project when applied to lower speed plumes. Stone's method did not account for an asymmetric velocity profile either. And finally, there was no way to use the TSS or JSI tools to the jet noise source predicted by Stone's method directly within the ANOPP code. For these reasons, a set of parametric models were created to compute the corrections to Stone's result needed to reproduce the experimental database measured for nozzles with these features. The code 'TSS' has as input an integer specifying what type of three-stream nozzle is being predicted, and inputs regarding the third-stream feature in a manner similar to the original inputs for Stone's method. The code has options for single-stream and dual stream (essentially causing no correction), three-stream externally mixed nozzle, an inverted velocity profile nozzle, an inverted velocity profile nozzle with outer stream flow, and a three-stream externally mixed nozzle with offset outer stream. The TSS code creates a table of values to be multiplied by the Stone-computed spectral directivity, a process supported by the ANOPP code. Likewise, 'JSI' code computes corrections to the Stone model output, one attenuation table to describe either shielding or reflection of the Stone-predicted spectral directivity, and one describing the new source produced by the turbulence flowing over the trailing edge of the surface. The JSI code is based on single-stream jets and uses input for the Stone method to compute an equivalent single-stream jet. This method is necessarily limited in its accuracy by the relatively crude input, but it has proven surprisingly satisfactory when applied to axisymmetric multi-stream jets. These codes have been put together as modules within the new ANOPP2 code being developed at NASA Langley, and fed by input from standardized data that describes the engine and nozzle parameters created during systems optimization work.

B. Reynolds-Averaged Navier-Stokes (RANS) validations

Before acoustic analogy codes can be expected to successfully predict jet noise, the RANS solutions that feed the acoustic codes must be correct. As a distinguished acoustician was once heard to say, "I cannot guarantee that the acoustic predictions will be right given proper CFD input, but I can guarantee that they will be bad when given incorrect CFD." The improvements in particle image (PIV), including time-resolved PIV and large fields of view, have made measurements of turbulence a standard operating procedure for jets at NASA. Therefore, in almost all tests, measurements of flow were made to be used in validating CFD.

The standard RANS used in noise prediction work for many years at NASA Glenn was Wind and WindUS. There was some effort to validate the FUND3D code being developed at LaRC against the jet flow measurements, as FUN3D uses unstructured grids and promises to be faster going from geometry to solution. Most recently the flow solver that is sold with the SolidWorks CAD package, Solidworks Flow Simulation (SWFS) was also validated against measurements of jets. This code, which is actually produced by Mentor Graphics and marketed by Dassault Systems, has the advantage that it uses embedded boundaries and has flow-driven grid refinement to reach a solution very quickly without gridding.

Figure 11 shows an example comparison of two of these codes applied to a single-stream, unheated Mach 0.98 jet. The left plot shows turbulent kinetic energy, arguably the most important parameter for noise prediction, as predicted by the SolidWorks Flow Simulation and by the FUN3D RANS codes. Also shown in the plot is the measured turbulent kinetic energy (TKE) as documented in Reference [34]. Note that neither code predicted the TKE level correctly, but have the same level of error. This was seen repeatedly in applications of different RANS codes. However, for noise prediction, the absolute levels could be calibrated out, as long as the codes agreed with one another. Thus, when the same acoustic analogy noise prediction code was applied to both RANS solutions, the noise predictions were within 1dB of one another. More critical to the success of the noise prediction in more complicated nozzles was how robust the RANS code was in handling the complicated geometry and how efficiently the code could resolve the fine scales near the nozzle which contribute to the high frequencies of noise.

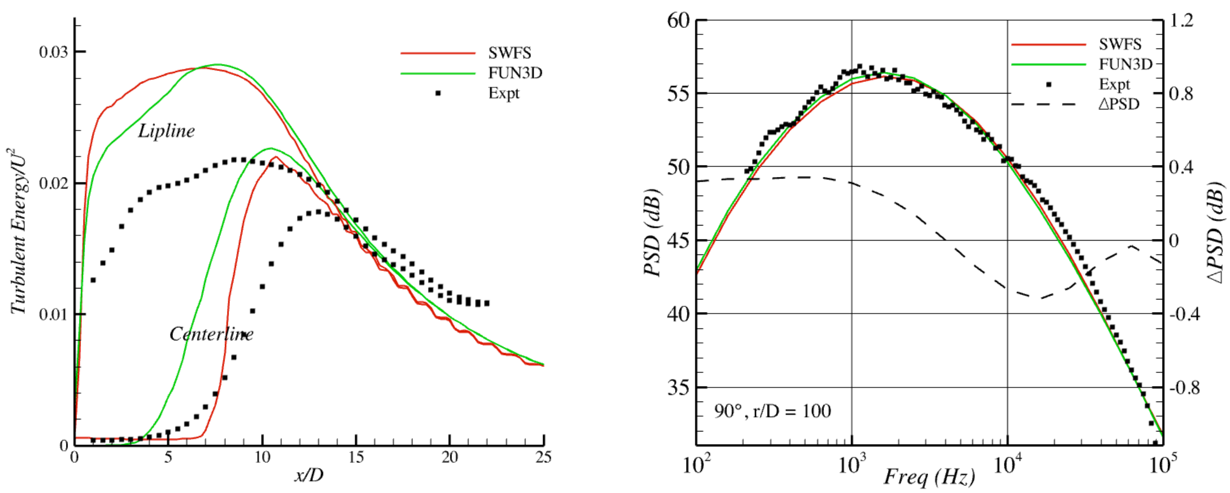


Figure 11 Example comparison of RANS solutions for jet turbulence and subsequent predictions of noise using acoustic analogy. Two very different RANS codes, SolidWorks Flow Simulation (SWFS) and FUN3D, compared with experimental data.

C. JeNo

The acoustic analogy code JeNo, first released in 2005[35], predicted spectral directivity of unheated axisymmetric jets. In 2012, an updated 'version 2' JeNo was released[36] which featured a model for the unsteady enthalpy terms in the acoustic analogy, based on the mean and turbulent velocities. This code was used in some explorations of two- and three-stream externally mixed nozzles and inverted velocity profile nozzles where it performed well. More importantly, several other codes have adopted this model for the 'hot jet source terms' since then, including the Goldstein-Leib code.

D. Goldstein-Leib code

1. Non-Axisymmetric Green's function

Starting in 2007, efforts had been underway to formally solve the Green's function problem for non-axisymmetric jets. The first attempts used a conformal mapping method for elliptic/rectangular jets. The Green's function was combined with the hybrid source model (below) into a code to make noise predictions for cold rectangular jets in 2012. Several other mappings were attempted for other geometries, some of whom are described in Reference [37]. Work on a more general approach, using Fourier series expansions, started around 2011. A version that uses RANS solutions as input, and included the hybrid source model was finished in 2013, and the enthalpy source terms were added in 2015. The method was documented in Reference [38]. Most recently, this code was validated against offset three-stream jets[24,39].

2. Source Modeling

At the heart of the acoustic analogy prediction method is the source terms which appear on the right side of a wave equation created by rearranging the Navier-Stokes equations. These source terms usually feature space-time correlations of turbulent Reynolds stresses and turbulent enthalpy. The models for these terms, based on quantities obtained from RANS solutions, is a key factor in whether the prediction method is successful, and has been the source of significant research in this project. The terms are often expressed as the product of a time-dependent function and a space-dependent function, but careful measurements show that the temporal and spatial aspects of these terms are not independent. Work on a hybrid source model with frequency-dependent length scales had been an ongoing effort for many years previous to the Technical Challenge, but was documented in 2011[40] and included in the working prediction code in 2013. The spatial aspects of the source term models were independent of the jet structure, being sensitive only to local gradients, while the cylindrical topology of the jet shear and its instabilities clearly indicated a preference for certain non-isotropic spatial features. A reformulation of the problem into circular cylindrical sources and azimuthal models was begun in 2012 and has been documented[41] but not yet formally implemented in the working code.

3. Weakly non-parallel mean flow

Another approximation often made in the development of an acoustic analogy is the assumption that the jet flow varies little in the axial direction compared to the radial, and that each slice of the flow can be treated as locally parallel for the purposes of computing how the turbulence there transfers its energy to the acoustic field. This assumption is difficult to avoid, but some work was done to work this as a small perturbation problem and solve for the first higher order approximation to this assumption, especially crucial at low frequencies where the wavelengths are large enough that the jet may change in the axial direction within the wavelength[42]. This effort has not been included in the working code but has been demonstrated[43].

E. Rapid Distortion Theory

Early in the experimental effort on the noise of jet-surface interactions it was recognized that a new source was produced by the turbulence of the jet interacting with the trailing edge of the surface. This is fundamentally the same type of source that has been studied in propeller and fan noise, but in those applications, it is of secondary importance and often not considered. Previous analytical approaches from decades ago, such as rapid distortion theory, were brought back and readdressed with modern tools and fresh data starting in 2011. Several early analytical results[44] explored the most profitable approaches before it was adapted to use flow input from RANS solutions[45]. This remains an active area of work, having served mostly to guide empirical models for this noise sources in the Technical Challenge.

F. Large Eddy Simulations (LES)

LES was not commonly used in industry or in NASA in 2010, but it was being actively developed in the academic and small-business world. NASA was a strong supporter of this work, both funding researchers through collaborative agreements, and providing validation data and expertise in flow and numerical methods. Some of the support NASA provided was in the form of assisting the Office of Naval Research with its efforts, including having a NASA researcher serve as a contract monitor for many of their research contracts.

Researchers at Stanford University had previously shown success predicting jet noise with high-order methods on structured grids using LES. The problem with this approach is the regular structured grid that the method requires, which is not easily created for more than the simplest nozzle geometry. The Stanford team tackled this problem by shifting to a low-order, unstructured grid code, called CharLES, which later became a commercial product. They demonstrated the accuracy of the code by first applying it to the problem of a single-stream, round jet[46] before taking on the case of a rectangular nozzle tested by NASA. The results were very favorable for both the basic rectangular nozzle[47] and ones with chevrons[48]. The rectangular nozzle was also used as a validation case by Combustion Research and Flow Technology, Inc (CRAFT) under SBIR contract NNX12CA17C. CRAFT used a structured grid method, focusing on minimizing the size of the grid required to obtain a good acoustic answer with their LES code[49]. CRAFT also looked at using LES data as input for a phased array algorithm, allowing researchers to identify the sources of different frequencies within the jet plume[50].

As mentioned above, LES was not commonly used within industry at this time. The lone exception was General Electric through their Global Research Center, which was developing the capability to run LES codes to support GE Aviation. When the first IVP nozzle was tested (Section II E), the nozzle created a very strong acoustic tone. GE-GRC was called upon to apply their LES expertise to understand the source of the parasitic noise. The LES was not used to compute far-field noise, but to show how the nozzle divergence of the original design was causing an unsteady separation and reattachment. This same case, which was unacceptable as a low-noise nozzle, was further used to test whether lower-cost unsteady flow prediction methods, such as unsteady RANS and detached eddy simulations, could be used to detect this flow behavior. Unfortunately, GE found that none of the methods short of LES was capable of finding this resonant behavior[1].

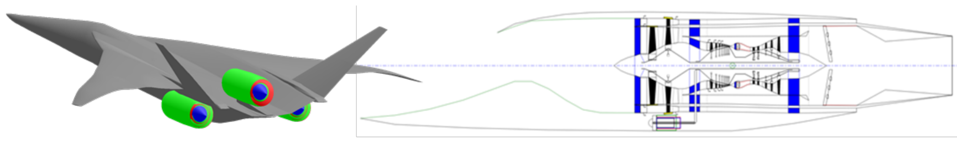
One of the most tantalizing findings that resulted from creative use of LES was the work by researchers at the University of Illinois. This work[51] was started in collaboration with OSU's work on plasma arc actuators. In an attempt to answer the question, "Can we silence a jet if we can control its turbulent structures?" they used a highly accurate LES code, both in the normal form and its adjoint form, to minimize the sound pressure around a M=1.3 jet[52]. They ran their time-accurate code forward in time, and then using adjoint optimization they created a forcing function, applied at the nozzle lip, which manipulated the flow structure to minimize the sound pressure near the jet plume. After several iterations, they were able to make what appear to be significant changes to the pressure signal during a very brief window during which their optimized control was applied. However, it was sobering to see that this change amounted to only about 3.5dB reduction in overall sound pressure level, primarily in the aft peak jet noise. So, even if one could magically stop time, turn back the clock and optimally perturb the flow by some control method, one would only achieve a relatively small decrease in jet noise produced.

IV. Validation

To ascertain whether the project goal of meeting noise certification levels was possible required applying the new predictive tools for the low-noise technologies to a vehicle design. The vehicle design started with a low-boom airframe design created under contract by Lockheed-Martin and General Electric Aviation which met the sonic boom requirements and provided aerodynamic characteristics. Then, variations in propulsion were considered using previously developed models of the propulsion system and the new noise prediction tools. Once designs were found that apparently met the noise goals, they were validated by experiments, first in isolation and then with representations of their installation to confirm the predictions. These steps are outlined below.

A. Propulsion system studies

In recent years, interest has renewed in a variable cycle engines (VCE) and specifically tip-fan engine architectures as a means to reconcile subsonic cruise fuel burn with installed supersonic cruise performance. A detailed engine cycle model with corresponding conceptual mechanical design was developed using the Numerical Propulsion System Simulation (NPSS) framework which enabled parametric exploration of this engine as well as the more conventional Mixed-Flow Turbo-Fan (MFTF) engine without a tip-fan or variable cycle features. This model, originally derived from initial military versions of a variable cycle engine, was employed to explore the impact of various engine parameters on the airport noise and mission range of a commercial supersonic aircraft. The principal engine parameters explored included fan pressure ratio, number of fan stages, tip-fan pressure ratio, tip-fan bypass ratio, combustor exit temperature, and nozzle type. A representative mechanical flowpath and complete set of engine parameters explored using the model are shown in Figure 12. A reference external-compression inlet designed for robust operation between Mach 1.6 and 1.8 was used for the propulsion system analysis. Curves of total pressure recovery as well as mass-fractions and corresponding inlet drags, along with nozzle aft-body drag, enabled full installation effects to be estimated. The engine installation shown is above the wing on the reference tri-jet vehicle, as seen by the inverted inlet ramp and cowl.



Cycle Parameters	NASA MFTF & VCE Parametrics
Fan Pressure Ratio	1.7 – 4.0
Overall Pressure Ratio	38 – 46
T4 design, sea level	3010 – 3410
VCE bypass ratio	0.0 – 0.5
VCE tip fan pressure ratio	1.8

Figure 12 LM1044 concept vehicle and key propulsion design parameters.

For each engine design, tabular propulsion performance data were generated for discrete Mach, altitude, and engine power setting throughout the flight envelope. These data were used as input to NASA's Flight Optimization System (FLOPS) code to perform flight simulation for a commercial supersonic airline mission, using the aerodynamic properties of the Lockheed Martin 1044 conceptual aircraft designed for low sonic boom. For the mission analysis, the aircraft geometry and maximum take-off weight was not scaled in order to retain the low-boom features. Only propulsion scaling was permitted (including inlet and nozzle) to establish the mission range as the figure of merit for each propulsion system. Those designs for which the mission could be completed were then evaluated for takeoff noise using NASA's ANOPP methods, augmented by the TSS and JSI codes, as described in Section III A. The noise predictions for each engine were made with different nozzle concepts installed on the LM1044 planform at the Lateral certification point as a relative measure of takeoff noise.

From this work, a trade space of takeoff noise vs mission range was developed, as shown in Figure 13, for conventional (two-stream) MFTF and Variable Cycle Engines (three-stream VCE) with different engine parameters. As indicated in the figure, takeoff noise, here given as a single-engine, uninstalled component EPNL, shows a direct correlation with design engine pressure ratio (driven by front fan pressure ratio) for these mixed-flow engines, as the acoustics track directly with jet exhaust velocity. Indeed, this was the most dominant engine parameter impacting takeoff noise. It was observed that the tip-fan VCE provided increased range at higher fan pressure ratios (or Engine Pressure Ratios - EPR) due to the ability to optimize installed inlet/engine airflow. In fact, the tip-fan exhibited a high degree of variability within performance and distortion limits. As design EPR was reduced to meet increased noise stringency, however, the additional weight of the tip-fan and variable cycle technologies debited the resulting mission range compared to the lighter and simpler MFTF. For EPRs consistent with single stage front fans, the tip-fan cycle thermodynamically resembles the MFTF but with less installed performance optimization potential.

As shown in Figure 13, the three-stream Variable Cycle Engine did not surpass the conventional two-stream MFTF engine in range until pressure ratios were high enough that the engine was not viable in the airport noise space, roughly denoted by having a Lateral EPNL below 90 EPNdB for a single, uninstalled engine. One significant caveat to this result is that while conceptual design weight and inlet + nozzle drag calculations were accounted for, the impact of the engine on wave drag and sonic boom strength was not considered. Furthermore, the coarseness of the aircraft model could only support gross propulsion trades and not absolute range sensitivities.

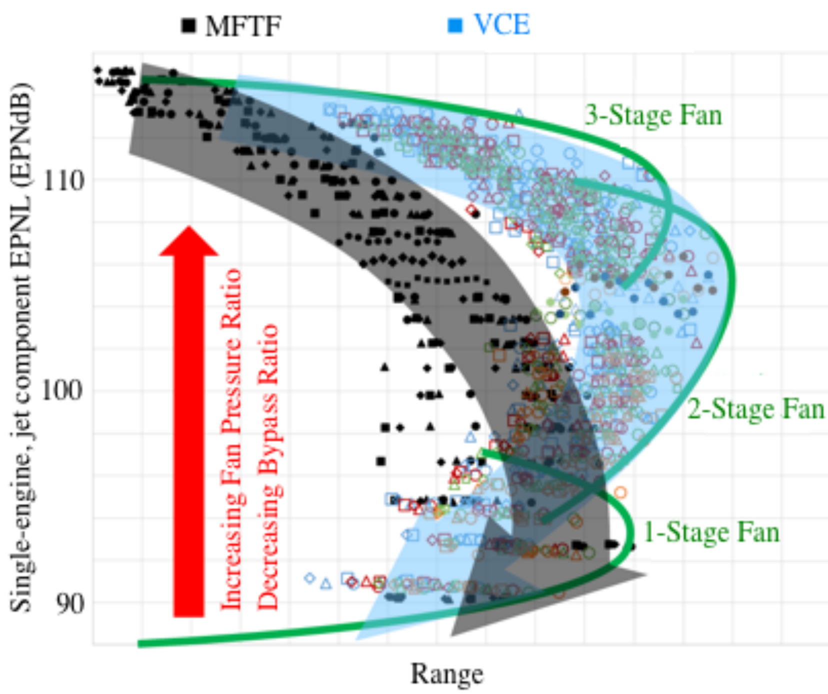


Figure 13 Results of noise vs range study for LM1044 concept vehicle with various engine designs. Trends highlighted: engine type (mixed-flow turbofan (MFTF) and variable cycle (VCE)), shown in broad arrows, engine designs grouped by number of fan stages, overall correlation of noise with fan pressure ratio shown by red arrow.

B. Model-Scale Validation Tests

Model-scale validation tests focused on two areas: noise impacts of variations in nozzle types, and noise impacts of installation, both shielding and reflection. The differences in noise from various nozzle types run in isolation (not installed on a vehicle) was assessed in a test internally called *Iso16*. Various types of nozzles (internally mixed, separate flow with and without offset, inverted velocity profile, split fan stream) were developed for the engine cycles described above. Whereas the experimental databases used to construct the empirical noise prediction tools covered a wide range of potential engine cycles, this test had all the nozzle types directly compared on the same engine cycle. The impacts of installation, both shielding and reflection, were evaluated for multi-stream nozzles in a test internally called *JSI-1044*. The empirical prediction methods used in the system design study were crude, having been developed for single stream jets near semi-infinite surfaces. The *JSI-1044* test was a higher fidelity representation of the LM1044 aircraft than previous tests, featuring multiple-stream nozzles on a realistic planform.

1. Isolated Nozzle Test (Iso16)

In the individual tests of various nozzle systems (described above), the nozzles were designed and operated for different candidate engines; comparison of nozzle types independent of engine cycle had only been done using the empirical noise models created from the individual test databases. In the *Iso16* test, model-scale nozzles of the various nozzle types were tested at the proper exit areas and flow conditions found to be near optimal in the propulsion system studies discussed above. Five nozzle systems were tested for six variable cycle engine (VCE) designs: conventional (tip fan stream outside the internally mixed primary stream), inverted (tip fan stream ducted inside the primary stream), a split (tip fan stream split equally between inside and outside the primary stream), and three-stream separate flow systems, axisymmetric and with the fan stream nozzle offset by a few percent. In addition, a common-flow nozzle with plug was tested for three mixed-flow turbofan (MFTF) cycles that met the same engine requirements as the VCE engines. To accommodate schedule, many of the nozzle systems reused components from previous tests with only a few modified parts, and the scale factor was not the same among the nozzle types. The scale factors were between 9 and 14. In all cases, including the separate stream nozzle systems, the NPR of the core and bypass were matched.

In preparation for the *Iso16* test a conventional velocity profile nozzle, having the tip fan stream on the outside of the primary stream, was designed and built. This nozzle was comparable to the inverted velocity profile nozzle system previously tested, having a similarly sized plug and area ratios. However, the conventional velocity profile nozzle was found to produce a loud resonant howl, later traced to the interaction of duct modes and vortex shedding from internal rig struts. Modification of nozzle lip geometry had no effect on the howling, and it was determined that the resonance was strictly internal and independent of the external flow. Consequently, the tone was removed digitally from the data in its analysis, a practice that casts some uncertainty on the evaluation of the conventional nozzle.

The different nozzles were measured over the same engine throttle line, then rescaled to full-scale thrust. The transformed spectral directivity was numerically flown past a lateral certification point observer, without ground attenuation, to compute a single-engine, jet-component EPNL. An example set of results is given Figure 14 for one engine. An internally mixed nozzle was run on the comparable MTFT engine. In the figure, there is very little difference between the different nozzle types, except for the externally mixed, three-stream nozzle. The nozzles with an internal mixing of the core and first fan stream were 1 – 2 EPNdB quieter than the separate flow nozzle. There is a hint of the trend that the conventional and inverted velocity profile nozzles are quieter than the mixed-flow turbofan at higher NPRs.

The second objective of this test was to determine the accuracy of the ANOPP and TSS empirical prediction models at engine conditions likely to meet the program noise goals. The empirical codes were exercised on all the tested configurations, and compared with measurements. Figure 15 presents a summary of this comparison in the form of errors in predicting the jet-noise component EPNL for a lateral certification observer. As seen in the figure, the prediction models were accurate to within 1EPNdB for isolated nozzles.

As a result of the *Iso16* test, four engine/nozzle types were selected for the final, installed, validation test of the technical challenge: for the VCE Conventional, Inverted, and Split nozzles, and on a MFTF engine a simple internally mixed nozzle.

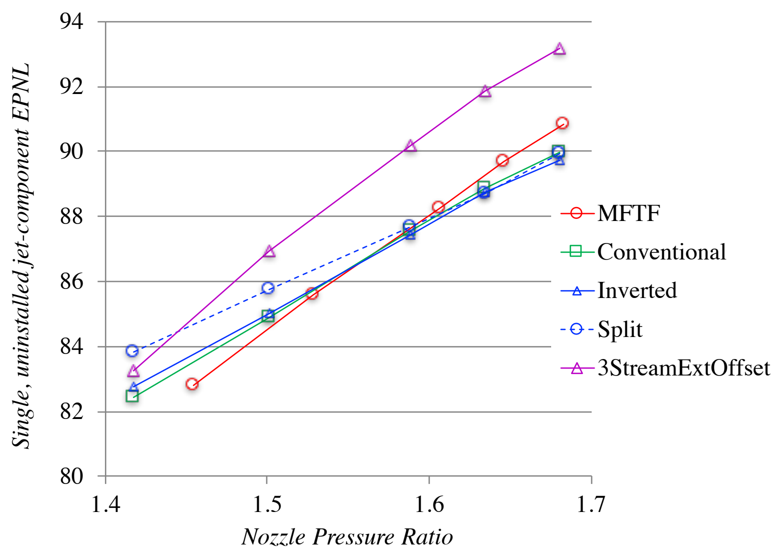


Figure 14 Head-to-head comparison of noise from isolated nozzles of various types on the same engine design.

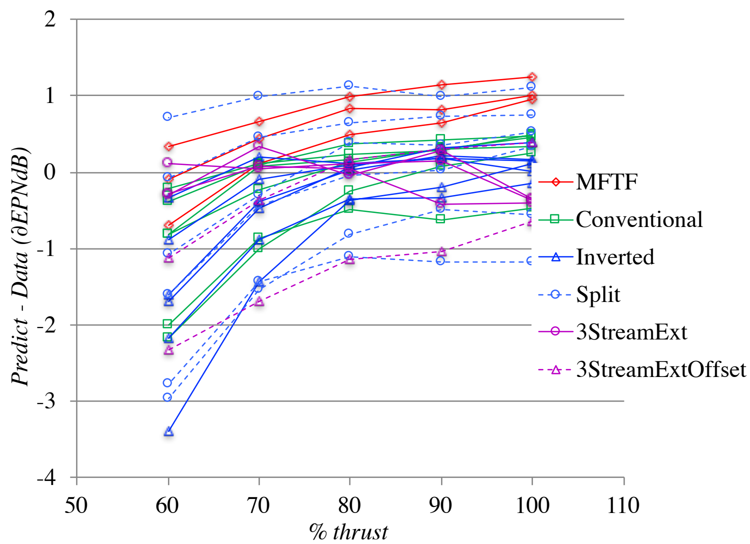


Figure 15 Summary of error in empirical noise predictions for various nozzle types and engine cycles.

2. Multi-stream installation test (JSI1044)

Also supporting the final validation test was a test campaign, internally called *JSI1044*. The purpose of this test was to evaluate test procedures for installed propulsion and to extend empirical models of jet-surface interaction from single-stream to multi-stream jet flows. This test was documented in Reference 33. The test determined that the planform representing the aircraft did not have to extend very far forward of the nozzle to block the jet noise, similar to the aircraft body, and established other design guidelines for the final test hardware, such as the method of mounting the planform in the freejet and the need to acquire data at several azimuthal locations. This test was very educational in preparing for the final integrated propulsion test.

3. Final Integrated Propulsion Test (JSI16)

A final acoustic test was conducted to validate that the engine and nozzle designed to meet the Technical Challenge acoustic goal did indeed meet the goal. The engine designs chosen for testing were ones that met the noise goal of 93 EPNdB for the lateral certification point, and maximized range. Four engine designs with each nozzle type were thus selected for testing, all of them having a nominal fan pressure ratio of 1.8 as they flew past the Lateral observer. In addition, four other engines were picked that would reach the noise goal level if they were throttled back during takeoff using an automated throttle lapse operation (see Section II J).These engines would have had fan pressure ratios of roughly 1.9 and 2.0 at the Lateral observer if they were not throttled back. Figure 16 shows the previous map of noise vs range, limited to designs that produce noise near the goal level. In the figure, the selected engine/nozzle combinations have been designated by large hollow symbols. The symbol style and color indicate the nozzle type. The noise goal is shown by the dash line. Three of the eight engine/nozzle combinations validated were internally mixed (two-stream) engines.

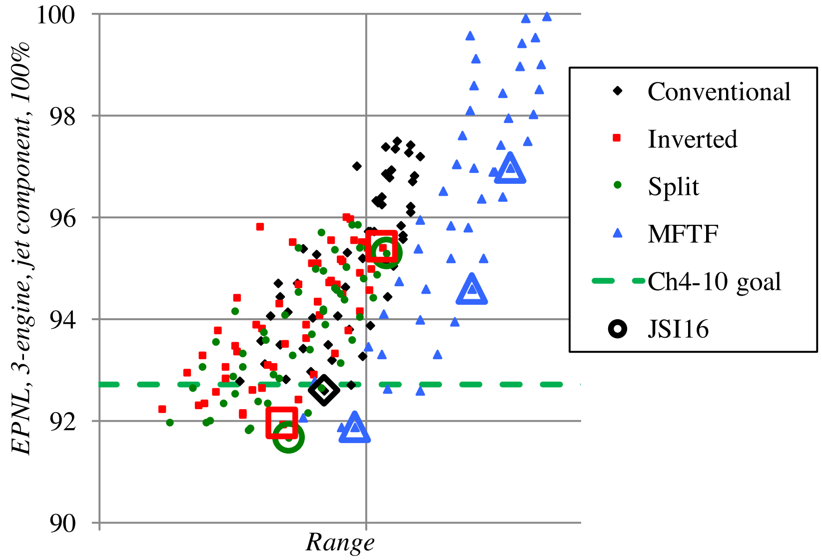


Figure 16 Chart showing predicted airport noise vs aircraft range for LM1044 aircraft with various propulsion systems. Different colors indicate different nozzles (description below) and open symbols highlight the propulsion designs validated in the JSI16 test.

The final validation test, referred to as *JSI16,* featured the four engine/nozzle concepts, configured on planforms representing the center and outboard engines of the LM1044 aircraft. Each engine/nozzle/planform configuration was tested at azimuthal orientations to the microphone array to allow the summation of noise from all three engines in their installed orientations to create a total exhaust noise record at the flyover and lateral observer locations.

The objectives of the *JSI16* test were primarily to validate that the system studies, and noise prediction models used in the system studies, were correct. Variations in design parameters, such as the nozzle types, engine placement on the aircraft, and flight speed were performed to confirm that noise prediction models could track these design parameters. If these were successful, an immediate fall out would be to confirm that the chosen cycles and nozzles met the Technical Challenge noise goal. A practical, precursor objective was to confirm that the model-scale designs of the planform were adequate representations of the LM1044 vehicle in flight, including that the planform was not allowing noise to diffract around edges where the full aircraft planform had been truncated for the test, and that the airflow around the nozzle, easily blocked by the bulky rig if not accounted for in the planform's aero design, matched that predicted by CFD for the full aircraft. Other objectives were to obtain data to extend the jet-surface interaction models to include flight, obtain noise source maps with phased arrays to determine how much of the 'shielding' was purely propagation effects, and provide flow field data to validate computational flow models used in detail design of installed propulsion systems. Figure 17 demonstrates the importance of the installation location on the noise produced by the engines by comparing the single-engine EPNL for the three engines of the LM1044 aircraft, all running identical nozzles and flow conditions.

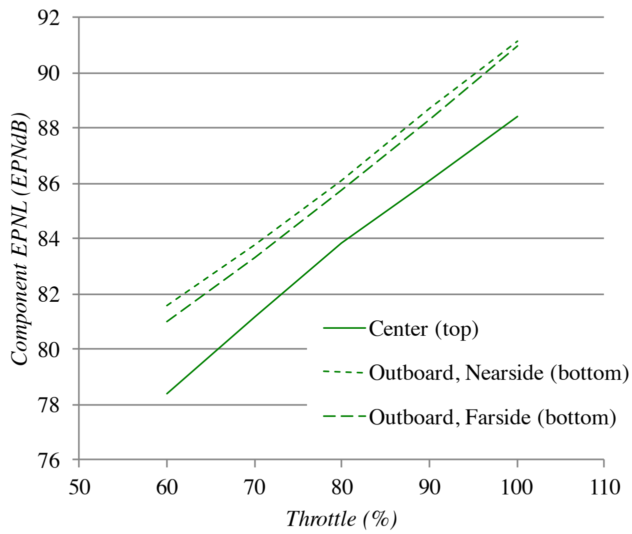


Figure 17 EPNL for inverted velocity profile nozzles mounted at the three locations on the LM1044 aircraft.

All objectives of the *JSI16* test were met. Details of the test and its findings are documented in Reference [53] along with a more detailed analysis of the jet-surface interaction in Reference [54]. Figure 18 summarizes the primary objective of validating the noise predictions for the chosen engine/nozzle designs. In all cases the validation data is within 1EPNdB of the predicted values, usually being a bit below the predictions. The range values were not validated and have been taken from the systems study on face value.

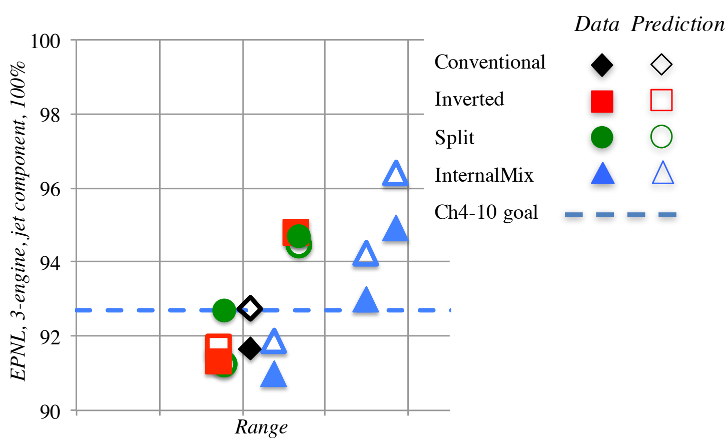


Figure 18 Result of validation test. Map of noise vs range of the LM1044 concept vehicle with various engine/nozzle combinations. Predicted noise values are given by open symbols and experimentally determined noise values are given by closed symbols.

V. Summary

The feasibility of commercial supersonic flight requires innovation to address noise during landing and takeoff. Proposed solutions to date have not simultaneously met the airport noise restrictions with viable sonic boom levels and economics. NASA has been conducting research to address these shortcomings, a part of which was to study the economic cost of meeting the airport noise restrictions with a low-boom configuration using low-noise propulsion technologies. Several of these technologies were studied, from exotic nozzles to variable cycle engines. This paper summarizes much of the work of the last ten years, which has culminated in the completion of a Technical Challenge, a design study of propulsion system options for a low-boom vehicle that would meet current airport noise regulations.

As jet exhaust noise is the dominant noise component for supersonic vehicles, work started looking at concepts to reduce jet noise. Among these, research into controlling jets with plasma actuators, high aspect ratio nozzles, jet-by-jet shielding, inverted velocity profile nozzles, actuated mixer-ejector nozzles, asymmetric velocity profile nozzles, three-stream nozzles, and shielding by installation were researched at various levels of fidelity. Empirical prediction models were created for the most promising concepts, and were used in system-level studies for the aircraft. Among the work done on low-noise exhaust concepts were vehicle studies done by industry teams to design low-boom vehicles carrying 70 passengers at a cruise Mach of 1.6. Recent development on low-noise propulsion focused on propulsion concepts that fit these aircraft, especially the LM1044 concept developed by Lockheed Martin and General Electric.

At the same time, significant effort went into developing physics-based prediction methods for exhaust noise. Such prediction methods would hopefully allow faster and cheaper evaluation of low-noise concepts, and ultimately optimal designs. Noise predictions based on RANS CFD, using acoustic analogies were pursued, both by validating the CFD and by improving the turbulence models used to convert RANS quantities into noise sources. There were significant improvements in the required Green function prediction methods for non-axisymmetric jets as well. NASA also invested heavily in the development of Large Eddy Simulation as a way to directly compute jet noise. These efforts, while not directly used in the designs of the final validation propulsion systems, provided many key insights, and will be well-positioned to aid in future noise work.

NASA internal system-level tools for mission trajectory analyses were used, along with the new noise prediction methods, to consider alternative propulsion designs than those considered in the industry studies. An overview of the study's results is shown in Figure 19. As shown in the figure, because the required noise levels (roughly 93EPNL on the chart) push the engine cycle down to where a single stage front fan (or lightly loaded two stage) is adequate, the tip-fan VCE cycle does not afford a substantial benefit over simpler and lighter MFTF counterpart. At higher fan pressure ratios (and much higher noise levels), the additional weight penalty of the tip-fan and variable technologies was overcome by the decreased nacelle diameter and greater design flexibility. Such high fan pressure ratios would be commensurate with cruise Mach numbers greater than the current design of M = 1.6, however. For cycles where single-stage fans (or lightly loaded two stage fans) were adequate, there was a clear disadvantage for the tip-fan VCE due the additional weight compared to the dual-stream MFTF engine.

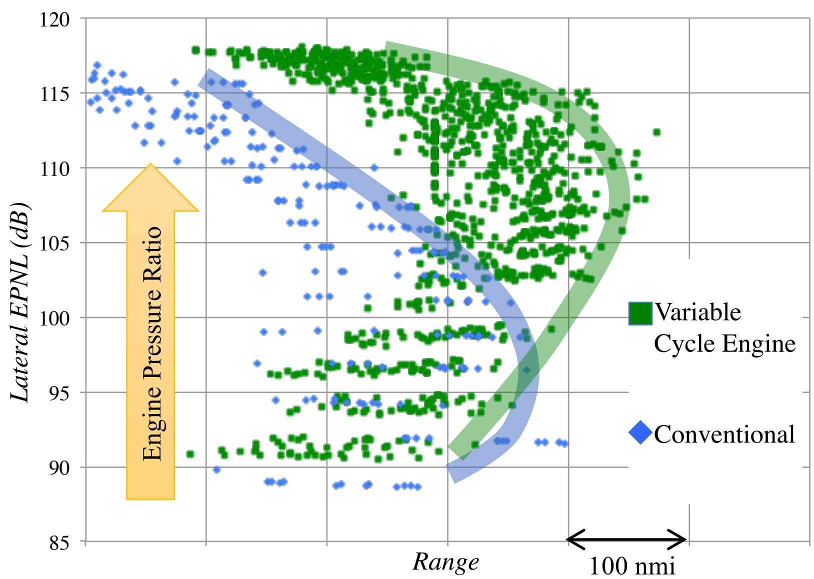


Figure 19 Summary of noise vs range as predicted by NPSS propulsion models, fixed aero characteristics of a low-boom aircraft, and the empirical noise prediction methods validated in the Technical Challenge.

Given NASA's modeling of the reference LM1044 aircraft design, there were several cycles that could meet the noise requirements, but the likely range enabled by the low-noise engine cycles is less than desired and with extreme sensitivity to further noise stringencies. Though impacts on sonic boom was not assessed, the large engine diameters necessitated by the low-noise engine cycles are not likely to be boom-friendly. While larger engines with lower noise may be possible, overall nacelle size and fineness ratio become critically challenged to maintain low sonic boom, due to the signal contribution from the vehicle aft-end expansion.

If one does not consider operational changes from conventional takeoff profiles, it appears that the engine cycles that meet the noise goal all have FPR <= 1.8. If the throttle is lapsed during the climbout phase an engine cycle with FPR > 2.0 might be considered and achieve greater mission range.

While there were differences in the lateral EPNL for different nozzle systems considered, the differences were less than 1EPNdB for a given engine FPR. As FPR increased, the different nozzle systems produced different noise results. At this low FPR, the internally mixed turbofan engine was the quietest of the nozzles for a given range, but it also had the largest diameter, making it least attractive when considering sonic boom.

The effects of installation were among the most significant to the propulsion noise. The top-mounted engine exhibited roughly 2EPNdB reduction over its uninstalled level, while the propulsion was 2EPNdB louder when it was installed in the outboard, underbody, position. This observation directs that future development should be in exploring new aircraft configurations featuring top-mounted propulsion, looking for technologies to overcome the aero performance impacts of this installation.

The Technical Challenge of demonstrating a low-boom commercial aircraft that meets airport noise regulations was formally met. Many low-noise concepts have been explored and their impacts on propulsion exhaust noise have been adequately modeled for system level design. The trades between nozzle and engine designs have been mapped out to guide future development. The cumulative observation of the study, however, is that until other noise reduction concepts are found, propulsion noise will prevent large commercial supersonic aircraft from being economically feasible because of the high risk to mission range.

Acknowledgements

The studies described in this paper encompass the creativity and hard work of many hundreds of individuals. We have tried to capture their contributions, as left in the public record. As with any NASA work involving industry partners, there were many technical contributions that were not put formal reports or publications. For this review, the authors acknowledge the NASA Aeronautics Research Directorate, and especially the management team that has supported the research on airport noise for supersonic commercial vehicles over the last decade: Peter Coen, Clayton Meyers, and Lou Povinelli. Finally, the editorial help of Maureen Kudlac and Jeff Berton is gratefully acknowledged.

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