High-Reynolds-Number Laminar Flow in the Mach-6 Quiet-Flow Ludwieg Tube

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Abstract

The Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT) has been developed to provide laminar nozzle-wall boundary layers at high Reynolds numbers, and thus low noise levels comparable to flight. After four years of shakedown, quiet flow has now been achieved to moderately high unit Reynolds numbers of about 2.7×10^6/ft., and momentum-thickness Reynolds numbers of about 2700, although this performance is not yet reliable. Nevertheless, the BAM6QT is the only operational hypersonic quiet tunnel, anywhere. The freestream pitot-pressure fluctuations during high Reynolds number quiet flow are less than 0.02%, the lowest value ever reported.

Problems with early transition were apparently due to a small flaw in the leading edge of the bleed lip of the original electroformed-nickel throat. The bleed lip of the nickel throat was modified to eliminate separation bubbles that are still predicted by Rutgers-University computations. This process should further improve the quiet-flow performance of the tunnel. The modification is complete and the resulting bleed-lip shape is reported here, although the performance of the recut bleed-lip tip has not yet been determined. Additional measurements of the temperatures in the contraction entrance are also reported.

Introduction

Hypersonic Laminar-Turbulent Transition

Laminar-turbulent transition in hypersonic boundary layers is important for prediction and control of heat transfer, skin friction, and other boundary layer properties. Vehicles that spend extended periods at hypersonic speeds may be critically affected by the uncertainties in transition prediction, depending on their Reynolds numbers. Although slender vehicles are the primary concern, blunt vehicles are also affected by transition [1]. However, the mechanisms leading to transition are still poorly understood, even in low-noise environments.

Many transition experiments have been carried out in conventional ground-testing facilities over the past 50 years [2]. However, these experiments are contaminated by the high levels of noise that radiate from the turbulent boundary layers normally present on the wind tunnel walls [3]. These noise levels, typically 0.5-1% of the mean, are an order of magnitude larger than those observed in flight [4, 5]. These high noise levels can cause transition to occur an order of magnitude earlier than in flight [3, 5]. In addition, the mechanisms of transition operational in small-disturbance environments can be changed or bypassed altogether in high-noise environments; these changes in the mechanisms change the parametric trends in transition [4]. Mechanism-based prediction methods must be developed, supported in part with measurements of the mechanisms in quiet wind tunnels.

Development of Quiet-Flow Wind Tunnels

Only in the last two decades have low-noise supersonic wind tunnels been developed [3, 6]. This development has been difficult, since the test-section

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wall boundary-layers must be kept laminar in order to avoid high levels of eddy-Mach-wave acoustic radiation from the normally-present turbulent boundary layers. A Mach-3.5 tunnel was the first to be successfully developed at NASA Langley [7]. Langley then developed a Mach-6 quiet nozzle, which was used as a starting point for the new Purdue nozzle [8]. Unfortunately, this nozzle was removed from service due to a space conflict; it is now being reinstalled at Texas A&M. The Purdue Mach-6 tunnel is presently the only operational hypersonic quiet tunnel, anywhere in the world.

Background of the Boeing/AFOSR Mach-6 Quiet Tunnel

A Mach-4 Ludwieg tube was developed at Purdue in 1992-1994 [9]. Quiet flow was achieved at low Reynolds numbers, and the facility was used for development of instrumentation and for measurements of instability waves under quiet-flow conditions. However, the low quiet Reynolds number and the small 4-inch test section imposed severe limitations.

A hypersonic facility that remains quiet to higher Reynolds numbers was needed. Low operating costs had to be maintained, to make research affordable in the post-Cold-War environment. Beginning with Ref. [10], a series of AIAA papers have reported on the design, fabrication, and shakedown of this facility, on the development of instrumentation, and on progress towards achieving Mach-6 quiet flow at high Reynolds number. Refs. [11] and [12] summarize these earlier papers, including the initial quiet flow achieved at low Reynolds numbers (8 psia stagnation pressure) with the 6th bleed-slot design. Ref. [13] reported initial achievement of quiet flow at 20 psia stagnation pressure, using the unpolished surrogate throat. Ref. [14] reported hot-wire measurements of second-mode instabilities on sharp and blunt cones at conventional-noise conditions.

Ref. [15] reported the first high-Reynolds-number quiet flow, to a stagnation pressure of 95 psia, using the polished aluminum surrogate throat. This stagnation pressure corresponds to a freestream unit Reynolds number of 2.1×10^6/ft., using the stagnation temperature of about 433K, a freestream Mach number of about 6.0, and the Sutherland viscosity law. The high performance is thought to be due to the clean lip contour of the aluminum throat, while the poor performance of the original highly polished nickel throat is thought to be due to a kink in the contour near the bleed lip. Recent computations by Rutgers University show that a separation bubble is forming on the main-flow side of the bleed lip [16, 17]; at present, this appears to be the probable cause of transition in the nozzle-wall boundary layer. Since transition in all cases still appears at the same pressure both near the nozzle exit and halfway up the nozzle, it appears that transition on the nozzle wall is induced by this separation, bypassing the usual instabilities in the nozzle-wall boundary layer. In the case of the aluminum surrogate throat, this separation bubble is small enough to permit quiet flow to fairly high Reynolds numbers. In the case of the original electroformed nickel throat, the kink in the lip contour is thought to exacerbate the separation bubble, precluding quiet flow above 8 psia stagnation pressure.

Thus, the next step was to modify the shape of the bleed lip, to eliminate the separation bubble. Rutgers University provided a design for the new bleed lip shape [17]; this nearly semi-elliptical shape then had to be machined into the bleed lip tip, a nontrivial task, given the 0.015-in. radius of the original semicircular tip. The difficulty of machining such a small aerodynamic shape was part of the reason why it was not attempted when the nickel throat was originally built. It was difficult to find a machine shop that was even willing to attempt the task. Thus, in early Jan. 2006, the plan was to first machine the new contour into the lip of the surrogate aluminum throat, before risking the more expensive electroformed nickel throat.

However, in late Jan. 2006 quiet flow was achieved to stagnation pressures of more than 122 psia, as shown below, and this high performance of the aluminum throat made it also difficult to risk modification of the aluminum lip. ATK Microcraft was selected as a contractor to modify the lip, and it was decided that they would remachine the new contour directly into the lip of the nickel electroform, after first practicing on a piece of aluminum. The recut of the nickel throat was completed in the middle of May, so only the contour measurements are reported here, with the effects on the nozzle flow to be measured in June.

The Boeing/AFOSR Mach-6 Quiet Tunnel

Quiet facilities require low levels of noise in the inviscid flow entering the nozzle through the throat, and laminar boundary layers on the nozzle walls. To reach these low noise levels, conventional blow-down facilities must be extensively modified. Requirements include a 1 micron particle filter, a highly polished nozzle with bleed slots for the contraction-wall boundary layer, and a large settling chamber with screens and sintered-mesh plates for noise reduction [3]. To reach these low noise levels in an affordable way, the Purdue facility has been designed as a Ludwieg tube [9]. A Ludwieg tube is a long pipe with a converging-diverging nozzle on the end, from which flow exits into the nozzle, test section, and second throat (Figure 1).

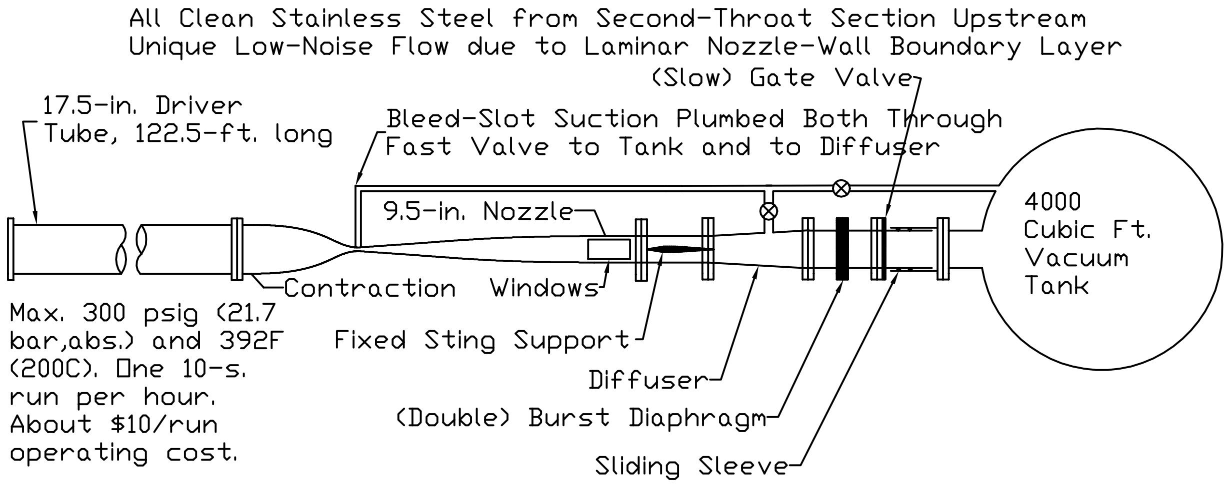

Figure 1: Schematic of Boeing/AFOSR Mach-6 Quiet Tunnel

A diaphragm is placed downstream of the test section. When the diaphragm bursts, an expansion wave travels upstream through the test section into the driver tube. Since the flow remains quiet after the wave reflects from the contraction, sufficient vacuum can extend the useful runtime to many cycles of expansion-wave reflection, during which the pressure drops quasi-statically.

The contraction-wall boundary layer is bled off just upstream of the throat, beginning a fresh undisturbed boundary layer for the nozzle wall. The nozzle-throat bleed air can be ducted to two alternate locations. A fast valve remains connected directly between the bleeds and the vacuum tank, allowing the bleed air to be dumped directly into the tank, with a small but significant delay of about 1/2 sec., which increases to perhaps 2 sec. at very low pressures, where the existing valve does not work well. In addition, the original plumbing connecting the bleed air to the diffuser enables a faster startup, if the jets of air into the diffuser are not a problem.

Figure 2 shows the nozzle. Here, z is an axial coordinate whose origin is at the nozzle throat. The region of useful quiet flow lies between the characteristics marking the onset of uniform flow, and the characteristics marking the upstream boundary of acoustic radiation from the onset of turbulence in the nozzle-wall boundary layer. A 7.5-deg. sharp cone is drawn on the figure. The rectangles are drawn on the nozzle at the location of window openings, all but one of which are presently filled with blank metal inserts. Images of the tunnel are available at `http://roger.ecn.purdue.edu/~aae519/BAM6QT-Mach-6-tunnel/`, along with earlier papers and other documentation.

Improvement in Quiet Flow Reynolds Number

During the first part of 2006, quiet flow was achieved to substantially higher unit Reynolds numbers, as described in the following section. Tunnel improvements remain a work in progress, but 86% of the design performance has already been achieved, although not yet reliably. At present, when the nozzle is quiet, it appears to be quiet all the way to the nozzle exit, so a quiet flow length Reynolds number cannot yet be determined, unlike in Ref. [3]. All the measurements were performed at a stagnation temperature of $160°C$, which appears to be sufficient to avoid liquefaction effects in the cold hypersonic flow.

Maximum Operating Pressure for Aluminum Surrogate Nozzle Throat

Pressure tests of the surrogate aluminum nozzle throat were conducted on three occasions, to set and then increase its maximum allowable working pressure (MAWP). The original MAWP for the surrogate, 88 psig, was calculated with the same (very conservative) temperature assumptions ($T < 300$ °F) as were used for the steel, but with the material properties of aluminum (29% the strength of steel at that temperature). The tunnel pressure was increased to 150% of the MAWP, 132 psig, and held there for 40 minutes. Leak tests were made with diluted liquid soap that would bubble at the location of a leak. None were detected.

Thermocouples were attached to the outer surface of the surrogate at several locations near the upstream end. The highest temperature detected was 63 °C (153 °F). For an operating temperature of 200 °F, the

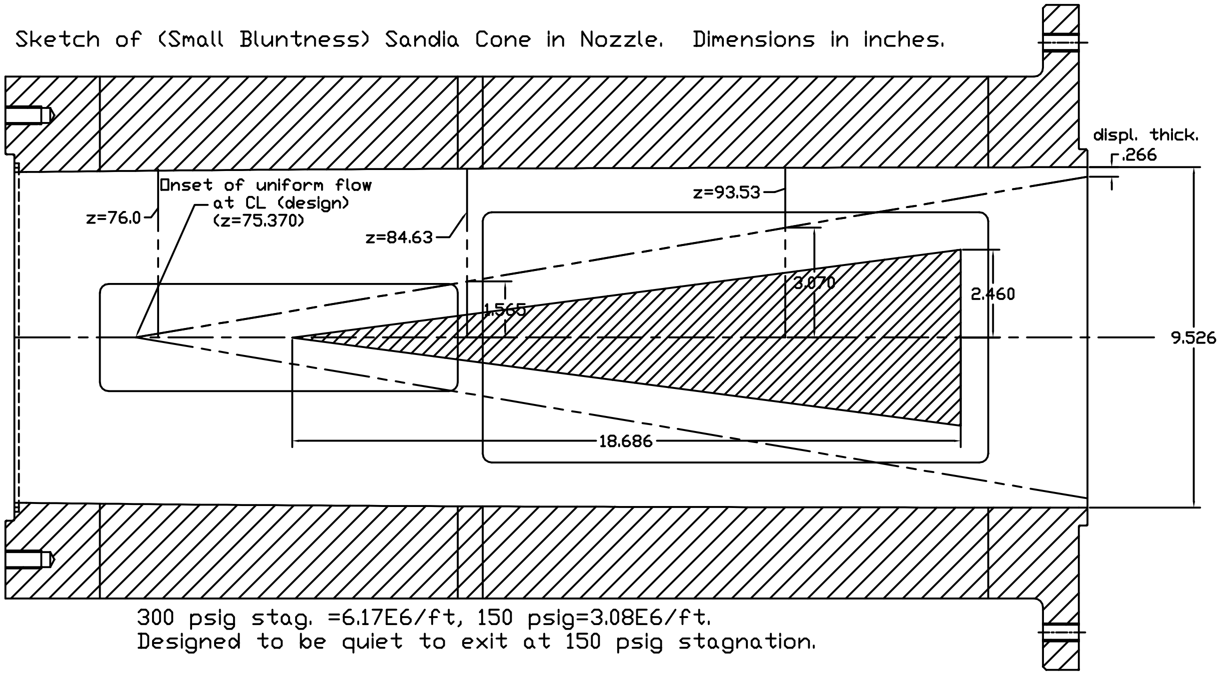

Figure 2: Schematic of Test Region of Mach-6 Quiet Nozzle with Model

MAWP is 107 psig (121.5 psia). Once again, the nozzle was pressurized to 150% of the MAWP. No leaks were detected after an hour at 161 psig.

In February 2006, the tunnel ran quietly above the 107-psig MAWP. The limiting component was the strength of the bolted joint between Sections 3 and 4; the threaded joint had a safety factor of 11.4 at 200 ˚F. Increasing the MAWP from 107 psig to 180 psig by a factor of 1.7 reduces the safety factor to 6.8, which is still above the minimum safety factor of 5. The nozzle's maximum temperature of 200 ˚F occurs near the throat, and the temperature decreases downstream, so the safety factor is actually greater than 6.8. Thus, operation to 195 psia and a pressure test to 270 psig were approved. The pressure regulator that allows air into the driver tube would not fill above 276 psia. The test was completed for $p > 270$ psia, increasing the MAWP to 185 psia.

Typical Oscilloscope Trace

Three pieces of data were collected from each tunnel run on the Tektronix TDS7104 oscilloscope at a rate of 2×10^5 samples per second: the pressure in the contraction, the pitot pressure in the nozzle, and the high-frequency (ac) component of the pitot pressure. High-frequency Kulite pressure transducers (model XCQ-062-15A) are used to measure the pitot pressure. The stopped version of these transducers allows the test area to be pressurized to the high stagnation pressure without damaging the sensitive transducers. The DC pitot pressure is amplified by a factor of 100 before digitization, and the AC pitot pressure is high-pass filtered at about 840 Hz and amplified by an additional factor of 100 before digitization, using custom-built electronics based on INA103 instrumentation-amplifier integrated circuits. Hi-Res mode was used to increase resolution and decrease noise, by averaging the sampled data on the fly before storing into memory. Using the pressure traces, the maximum quiet-flow pressure for the particular run can be calculated. Figure 3 is a typical calibrated oscilloscope trace. The blue line, referred to the right-hand axis, shows the stagnation pressure in the contraction entrance, p_c, while the black line, referred to the left-hand axis, shows the pitot pressure. The data was obtained with the Kulite on the nozzle centerline at $z = 93.4$ in. downstream of the throat.

The oscilloscope records data for ten seconds and is triggered by the sudden drop in pitot pressure when the diaphragms burst. The first second of data is from before the run and provides a baseline of electronic noise. Time $t = 0$ s corresponds to the diaphragm burst and the start of the run. During this run, the noise level is high until $t = 3.4$ s. The contraction pressure at which the noise level drops significantly (the quiet pressure) is 95.5 psia. With the exception of turbulent bursts at $t = 3.5$ and 4.8 s, the tunnel is quiet until the run ends at $t = 7$ s. The stagnation pressure

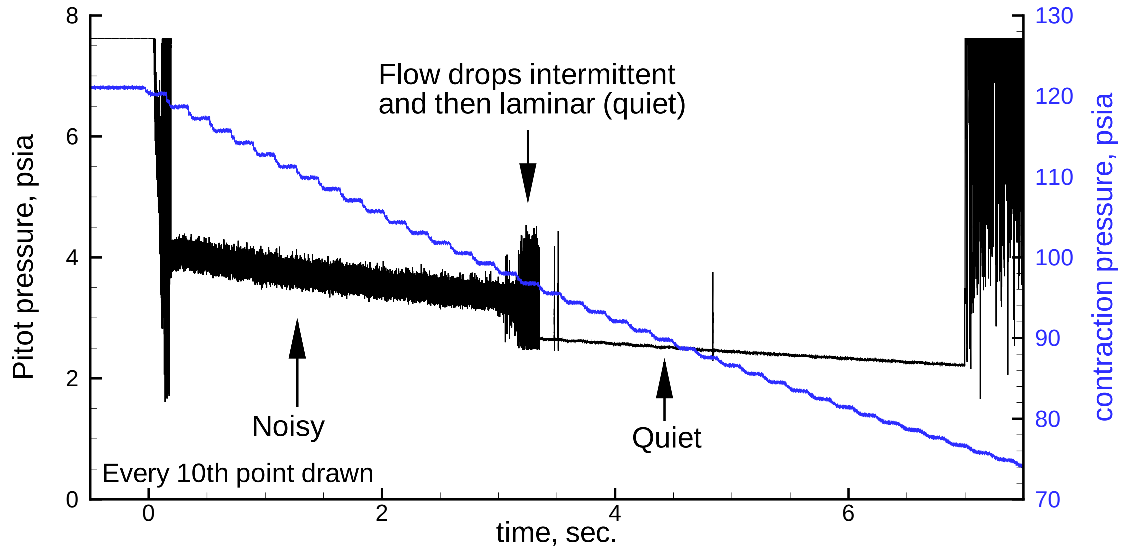

Figure 3: Typical Oscilloscope Output

drops in stair-step fashion, every time the expansion wave in the driver tube reflects from the entrance to the contraction.

Noise Levels

The pressure data is also used to calculate the tunnel noise level ($\tilde{p}/\bar{p}$). The noise level for the above run as a function of contraction pressure is shown in Figure 4. The noise is computed by breaking the run into 0.1-s intervals and calculating the root-mean-square ($\tilde{p}$) and mean ($\bar{p}$) pitot pressures over the segment. If the interval is quiet, the high-pass-filtered and amplified AC pitot pressure is used to find $\tilde{p}$; if not, the DC pitot pressure is used.

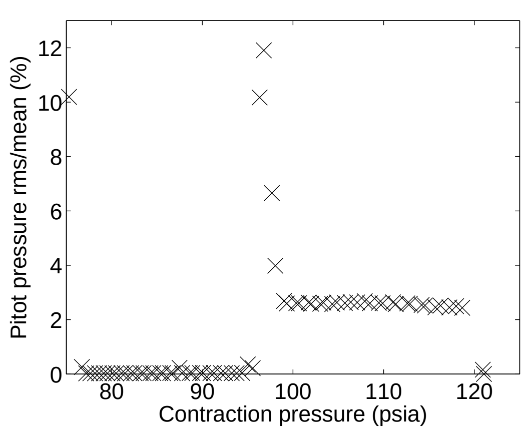

Figure 4: Typical Noise Level During a Run

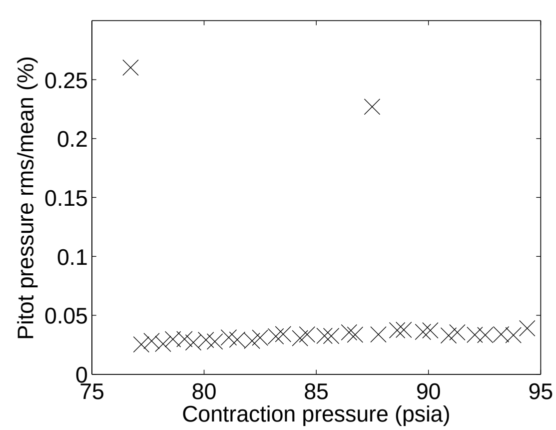

Figure 5: Typical Noise Level During Quiet Portion of Run

As expected, the pre-run ($p_c > 120$ psia) noise level is very small. The noise increases to 2.5% to 2.8% until $p_c = 98$ psia at which point the noise increases to above 12% during the series of turbulent bursts. When $p_c < 96$ psia the noise level decreases below 0.05%, except for the occasional turbulent spot (Figure 5). The noise level increases dramatically when the run ends ($p_c < 77$ psia).

The modifications made to the tunnel did not change the basic pattern of pitot pressure vs. time or of noise level vs. contraction pressure. Rather, the goal was to increase the contraction pressure at which the changeover from noisy to quiet flow occurred. Thus, after most runs data analysis consisted simply of applying the transducer calibrations to the oscilloscope data and identifying the maximum quiet pressure for that run. The reduction in noise level at the onset of quiet flow is quite pronounced and easily ascertained.

Chronological Account of Nozzle Performance

The original, electroformed nozzle never ran quietly for $p_c > 8$ psia. At the suggestion of Professor Garry Brown, a surrogate nozzle made of aluminum was made, using the same geometry, but with the intention of modifying it with additional sensor-access ports and a redesigned bleed lip. The surrogate nozzle was completed in January 2005 and first tested in February by Matt Borg. Initial runs indicated that flow through the surrogate nozzle was quiet for $p_c < 20$ psia. This improvement came as a surprise because the aluminum throat was much less highly polished than the electroformed-nickel throat, and was necessarily made in several sections with roughness-generating joints [15].

At this time, an aft-facing step was noticed between Sections 4 and 5, at the interface between the surrogate throat and the downstream portion of the nozzle. Jerry Hahn of the ASL shop increased the inner diameter at the end of Section 4 by 0.0044 inches and faired it smoothly to the rest of the section. This modification was tested in late June 2005 and yielded a quiet pressure of 37 psia.

The next change made to the surrogate was to have it polished by Optek, Inc. of Batavia, IL. The polish gave a dramatic improvement to the inside finish. Unfortunately, during the installation of the surrogate, the bleed lip was nicked. The next set of tests, during late August, 2005, assessed the effect of the nicks. The first tests after the damage gave quiet flow only below 12 psia. Mr. Hahn hand-polished the nozzle, improving its quiet limit to 34 psia, which was still lower than before the polish.

The surrogate was taken back to Optek for repair. They concentrated their work near the throat and extended the polished region around the bleed lip. The nozzle was returned and installed (uneventfully) for tests in late September 2005. These tests yielded quiet flow for $p_c < 94$ psia. The surrogate nozzle was swapped out for the electroform and reinstalled in early November, 2005. Initially, the quiet pressure was the same as before. However, *during* the fourth run of the week, the maximum quiet pressure dropped to 73 psia. There is no obvious explanation for this change.

Once again, the nozzle was removed and stored in its crate while the electroform was in use. In January 2006 the surrogate was reinstalled and at first ran quietly for $p_c < 73$ psia. However, starting with the week's fifth run, the quiet pressure was back up to 92 psia. It has been suggested that there was dust in the nozzle that finally blew out. Oily streaks were observed on the nozzle walls and a bit of a glint was present at the seam between Sections 1 and 2. They did not change much between the installation of the nozzle and its removal two weeks later. Acetone was used to wipe away the streaks that could be reached.

The tunnel was twice cooled and reheated to see if there was any effect upon the maximum quiet pressure. The temperature cycles had the unintended effect of distorting the o-ring between two contraction sections at $z = -23.73$ in., causing a leak. The temperature cycles, the leaky contraction, or some other cause reduced the quiet pressure to 54 psia.

The contraction o-ring and the leaky bleed-tube gaskets were replaced and the nozzles were swapped again before resuming testing on the surrogate in late January. Surprisingly, the maximum quiet pressure had jumped to above 122 psia, the maximum allowable working pressure for the aluminum nozzle at the time. Several leaks were made in the contraction by loosening the upper and lower access ports. Even with 0.183-inch-diameter holes in the upper and lower ports, the tunnel was still quiet for the entire run beginning at $p_c = 122$ psia. Loosening one of the bleed suction tube connections also had no effect. Note that these changes might have lowered the quiet pressure — just not below 122 psia. This robustness indicates that neither the leaky contraction o-ring nor old gaskets were the likely cause of the lower quiet pressure.

The tunnel continued to run quietly below 108 psia for two weeks while Shann Rufer performed low-noise boundary-layer-instability experiments on cones. A pressure test was done in February 2005 in order to approve the aluminum nozzle for higher allowable working pressures. After the test, the tunnel was quiet only for $p_c < 69$ psia. The pressure test was repeated with no further change to the maximum quiet pressure. The tunnel was not opened before or after the pressure test — making dust contamination or misalignment unlikely.

The nozzle was detached before Section 1 (at the throat) and after Section 4 (at the end of the surrogate portion). Streaks of oily residue were again present, emanating from the seam between Sections 2 and 3. Wiping with acetone removed them easily. The uneven glint between Sections 1 and 2 first noted in early January was visible from both upstream and downstream ends. To reach the joint, several Kimwipes were rubber banded to the end of a two-foot-long balsa stick. The step was merely accumulated gunk and it came off onto the acetone-wetted Kimwipes. The upstream face of nozzle Section 1 was fairly grimy, so acetone was again used to wipe the surface clean. The nozzle was realigned, reattached, reheated, and retested. The maximum quiet pressure decreased again, to 53 psia. The nozzle was detached and cleaned a second time. It was still very clean. After reattaching the nozzle and heating for < 24 hours it ran quietly below 58 psia.

Matt Borg was using the nozzle during the last week of February. Starting with his very first run, the quiet pressure increased to 130 psia, the current record. The nozzle was not detached in the interim. One possibility is that extra time was needed for the nozzle to heat up. After several equally-quiet runs, he opened and closed the top and bottom contraction access ports in order to change the location of his hot wires. The quiet pressure became just 31 psia. The nozzle was detached and cleaned as before. It was not particularly dirty and there were no scratches. Tests after reattachment (and heating for > 60 hours) showed quiet flow for $p_c < 50$ psia.

The electroform nozzle was reinstalled for two weeks in the middle of March 2006, then replaced again by the surrogate for Shann Rufer's second-mode-instability measurements. The surrogate appeared scratch-free and mostly clean but was wiped with acetone nonetheless. From her very first run, the tunnel exhibited a maximum quiet pressure of 108 psia.

Nozzle Modifications and Their Effect on Quiet Pressure

Thus, although it is clear that the tunnel is now capable of achieving quiet flow at high Reynolds numbers, it does not yet run reliably quiet at those Reynolds numbers, and some unknown factor is causing remarkably large variations in performance. Our experience to date is summarized as follows:

Aft-Facing Step When the aft-facing step between Sections 4 and 5 was removed, the quiet pressure increased from 20 to 37 psia. There are no other such large steps to be removed.

Polish Unfortunately, the direct effect of the first polish was overshadowed by the nick in the bleed lip. The maximum quiet pressure before the polish was 37 psia; afterward, 130 psia.

Nicked Bleed Lip The influence of the nick in the bleed lip cannot be precisely determined because it happened in conjunction with the polish. The maximum quiet pressure dropped from 37 psia to 12 psia with the nick. Subsequent repairs improved it to 34 psia, then 94 psia.

Misshapen Bleed Lip The electroformed throat has a better polish than the surrogate and no seams between sections, yet it is not quiet for $p_c > 8$ psia. The leading suspect is the 'kink' discovered in the electroform bleed lip (see Ref. [15] and Fig. 14).

Contraction Leaks Tests with leaks in the contraction only showed that the quiet pressure remained above 122 psia. Even fairly large leaks did not drop the quiet pressure far.

Oil Streaks Along Nozzle Wall Streaks were first noted on the nozzle wall in January 2006. They were cleaned whenever the nozzle was opened but they kept coming back. They seemed to originate from oil or grease between the joints of the aluminum throat. Removing them had no clear effect on quiet pressure.

Accumulated Gunk After Section1 In January 2006 an uneven step was noticed after Section 1. It turned out to be just some gunk and was removed in mid-February. After removal, the maximum quiet pressure actually decreased. The detrimental effect of the step must have been overshadowed by some other influence.

Temperature Equilibration Time During February 2006 the nozzle was opened for cleaning several times. After cleaning, it was reheated and tested within 24 hours. Though the contraction thermocouples showed that the temperature was up to nominal, there may have been nonuniformities. After another 60 hours of equilibration, the quiet pressure rose from 58 to 130 psia, possibly due to these temperature changes.

Seam at Joint between Sections 1 and 2 Even after the gunk was wiped away, a small step could be seen at the joint between Sections 1 and 2. It appeared to be nearly axisymmetric.

Dust Dust in the nozzle throat is the usual suspect for changes in performance that cannot be explained by observed changes in the tunnel configuration. High Reynolds number quiet tunnels are very sensitive to the throat finish, and it is not always easy to maintain a uniform high polish and uniform cleanliness. Sometimes opening, cleaning, and retesting the tunnel results in improved performance; sometimes performance degrades. Sometimes the tunnel will significantly change performance (for better or worse) in between runs when the tunnel was not opened. It is not yet known whether dust can account for these changes; it seems doubtful at present, since the sensitivity is more than has been experienced in previous quiet tunnels at Purdue or NASA Langley.

High Momentum-Thickness Reynolds Numbers in the Laminar Nozzle-Wall Boundary Layer

The nozzle-wall boundary layer is maintained laminar to high Reynolds number in order to achieve this quiet flow. Assuming the boundary layer is laminar all the way to the exit at 130 psia stagnation pressure and 160C stagnation temperature, the momentum thickness can be computed at the nozzle exit, using the Harris finite difference code [18, 19]. The nozzle wall temperature was assumed to decrease linearly from 160C at the throat to room temperature at the exit. This computational method gave good agreement with Skoch's measurements of the laminar boundary layer on the nozzle wall at lower pressures [20].

The computation predicts a laminar momentum thickness, θ, of 0.012 inches at the nozzle exit. The 99.99% thickness is 0.36 in. there, and the displacement thickness is 0.28 in. The freestream unit Reynolds number is 2.7×10^6/ft, using the Sutherland law for the viscosity, with Mack's linear assumption for temperatures below the Sutherland constant [21]. This yields a laminar momentum-thickness Reynolds number $Re_\theta \simeq 2700$. This is as high or higher than has been observed on polished models in flight [5]. However, it is not surprising, given the favorable pressure gradient in the expanding nozzle flow, and the great care that is taken to maintain laminar flow.

Axial Independence of Quiet Pressure and Noise Level

Though most data were collected from a pitot near the end of the nozzle (1.93 m $< z <$ 2.37 m), on two occasions a "far-forward" pitot was mounted in the forward-bottom access port in Section 8. This long pitot enabled centerline measurements farther upstream in the nozzle, to $z = 1.15$ m.

Noise level data is shown in Fig. 6 for two runs at the same starting conditions with different pitot locations. Transition to low noise levels occurs when $p_c \approx 95$ psia at both locations.

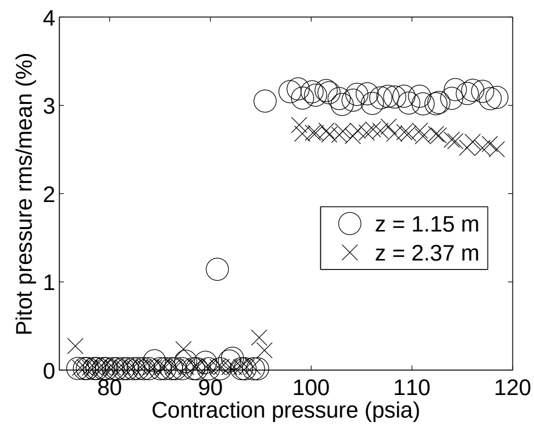

Figure 6: Axial Independence of Quiet Pressure

A similar axial independence was noted earlier, before the first polish, when the tunnel was only quiet for $p_c \leq 37$ psia. These results suggest a bypass mechanism remains responsible for the transition of the nozzle boundary layer, even at the higher quiet Reynolds number. The separation bubble predicted by the Rutgers computations seems to be a likely candidate for the cause of this bypass.

Settling-Time Dependence of Quiet Pressure and Noise Level

In January 2006, when the tunnel's maximum quiet pressure was greater than the maximum allowable working pressure of 122 psia, the settling time between filling and running the tunnel was varied. It was thought that a shorter settling time might reduce the quiet pressure enough that the switch from noisy to quiet flow could be observed during the run.

Another goal of these tests was to understand the unusual shape in the pitot AC pressure traces that was observed during this session in the tunnel, as shown in Fig. 7. The curious increase in noise at about 2.4 sec. had not been previously observed, and could not be readily explained. The noise-level data for three runs with different settling times are shown in Fig. 8. Though the entire runs were quiet (with the exception of turbulent spikes), the first two seconds of the run were quieter than the rest. The noise levels are extremely low during the first part of the runs, which begin at the highest contraction pressure. These low noise levels of less than 0.02% are lower than have been measured in any quiet tunnel to date, to the author's knowledge, perhaps due to the careful design of the settling chamber [22]. The increase in noise during the later part of the run may be due to increased noise from the thicker and more highly disturbed boundary layer in the driver tube. The initial noise level shown as 0% is not significant, as it is caused by clipping of the digitized signal during the startup process.

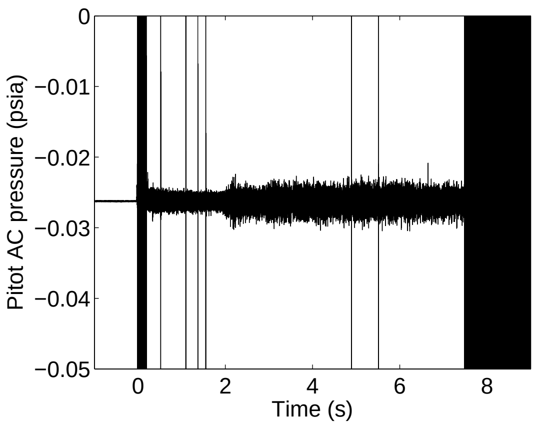

Figure 7: Pitot AC Pressure with Slight Increase in Noise at $t = 2.1$s. Ten-minute settling time

Figure 8 contains a comparison of tunnel noise levels during the course of runs with different settling times. The baseline case is 10 minutes. These three runs were conducted over two days and the tunnel configuration is the same. For each case the run start pressure was 122 ± 0.5 psia and the run was quiet throughout. The noise level does not depend strongly upon the settling time. The slight increase in noise level occurs at the same contraction pressure (or time into the run) and has the same magnitude. The only difference appears to be that the first two seconds of the one-minute-settling-time case were less quiet than the others. although noise level was still less than 0.025%.

Even a very short (one-minute) settling time did not leave the air in the driver tube so disturbed as to decrease the quiet pressure below 122 psia. Unfortunately, it is impossible to determine the precise effect from these data because the runs were always entirely quiet. It does indicate that data from runs in which the diaphragms burst early may still have significant value.

Effect of Jet into Upstream End of Driver Tube

Another attempt to lower the quiet pressure below the MAWP in January 2006 was made by running the tunnel without turning off the pressure regulator and

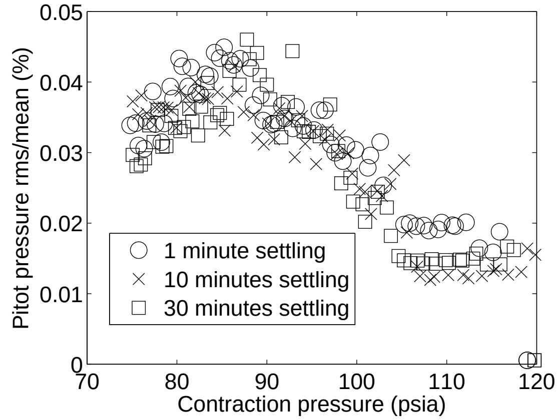

Figure 8: Noise Level Dependence on Settling Time

closing the solenoid valve. Basically, the tunnel was still filling when the run began, and continued to fill throughout the run duration. This test also simulates a disturbed driver-tube flow. The pressure regulator was set to 3.6 V, the typical final setting when filling to 120 psia. Once again, no change in the maximum quiet pressure was observed because it remained above the MAWP. The noise level versus contraction pressure exhibits the same behavior as other runs during this session in the tunnel — initially lower noise, then an increase peaking near $p_c = 90$ psia, then a decrease (Figure 9). Though the noise level was greater than the baseline case, it was still low.

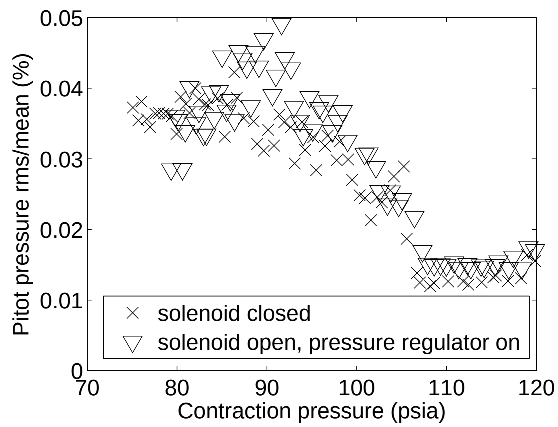

Figure 9: Effect of Jet into Upstream End of Driver Tube

Measurements of Free Convection in the Contraction Entrance

Free convection causes variations in the mean and fluctuating properties of the flow entering the contraction

[15]. These variations are larger than desirable, although they do not seem to cause major difficulties at present.

Variations in Settings for the Heater Controllers

In an effort to mitigate free convection and stratification in the contraction and driver tube prior to a tunnel run, the temperature settings for the driver tube and the three contraction band-heaters were modified. The two upstream contraction heaters are rated for 1500W at 240V, and the smaller downstream heater is rated for 3000W at 240V. For each setting of the heaters, a temperature profile in the contraction was measured for still air at local atmospheric pressure. Additionally, a series of measurements were made with a rubber-hemisphere throat plug inserted into the contraction, just upstream of the throat and bleed slot. This was done in order to see if the cooler air in the portion of the nozzle downstream of the throat was feeding upstream and promoting free convection in the contraction and driver tube, prior to a tunnel run.

The downstream end of the tunnel was left open to the room, so the pressure was always the ambient atmospheric pressure. After the temperature settings were changed, a minimum time of about 4 hours was allowed before new measurements were made.

For all measurements, an oven-calibrated hot wire was used in conjunction with a low-current constant current anemometer (CCA). The hot-wire probe was a TSI 1222-P12.5. It was a Platinum/10% Rhodium (Pt/Rh) wire with a diameter of 0.00015 inches and a length/diameter ratio of approximately 340. The wires were replaced by Purdue staff. The wire was precisely positioned at various locations in the contraction. The temperature was recorded over a ten-second period on a Tektronix TDS7104 digital oscilloscope operating in Hi-Res mode. The wire was moved to the next location, held there for approximately one minute, and then another measurement was made. Typically, temperature measurements were made near the contraction inlet, at vertical locations of $y = -3.00$ inches to 8.00 inches (with $y = 0.00$ being the tunnel centerline). A drawing of the measurement ports in the contraction entrance is shown in Fig. 10 of Ref. [15]. The measurements were made at one-inch vertical increments with an additional measurement made at 8.51 inches, which corresponds to 0.20 inches below the upper contraction wall.

The various contraction configurations that were used for the initial investigation can be seen in Table 1. The second column, labelled 'Insulation', lists whether the contraction was insulated or not. When insulated, the contraction was covered with fiberglass insulation about 2 inches thick. The third column of Table 1 lists the temperature to which the driver tube (DT) was heated. The fourth through sixth columns list the temperatures to which the contraction band heaters were set. The band heaters (BH) are numbered from the most upstream band heater (1) to the most downstream heater (3).

For all of these setups, the thermocouples that were used to control the band heaters were changed from the usual contraction setup. Typically, these control thermocouples are located on the surface of the contraction, about 1 inch from the band heater. For the current investigation, thermocouples directly underneath the band heaters were used instead. These thermocouples were provided with the commericial band heaters, and are clamped in direct contact with the contraction surface. When the controlling thermocouples were the ones located an inch from the band heaters, they typically read 138, 160, and 160°C , going from the most upstream heater to the most downstream heater (they were set to 138, 160, and 160°C). Immediately after changing the setup so that the controlling thermocouples were located under the band heaters, they read 238, 149, and 163°C . This shows that the most upstream heater was probably overheating the contraction, when the controlling thermocouple was located one inch away from the band heater. This helps to explain some earlier problems with heat-induced damage to the o-rings in the contraction.

As will be shown below, the tenth setup seemed to give a reasonably uniform temperature profile for y from -2.00 to 8.00 inches across the contraction for quiescent air at atmospheric pressure. This setup was thus maintained, and the probe was moved from the upper contraction access port to the lower access port in order to measure the temperature at locations from y=-8.51 to -3.00 inches.

Results from the measurements with no air flow can be seen in Figure 10. Each point is the average temperature over a ten-second time period. The red symbols correspond to the contraction not being insulated while the blue symbols are for when the contraction was insulated. As can be seen, most of the contraction setups give temperatures that typically vary by 10-15°C for locations between y=-2.00 to 8.00 inches. At y=8.51 inches, only 0.20 inches from the upper contraction wall, the temperatures are all significantly lower (by about 5-10% of absolute temperature).

The insulation made a significant difference only for setups 4 and 5. The addition of the insulation for these setups caused significant overheating across the contraction. Thus, the insulation successfully reduces

Setup Num.	Insulation	DT (°C)	BH 1 (°C)	BH 2 (°C)	BH 3 (°C)
1	No	160	138	160	160
2	No	160	160	160	160
3	Yes	160	160	180	160
4	Yes	160	180	160	160
5	Yes	160	160	160	160
6	No	160	180	160	160
7	No	160	160	180	160
8	No	160	160	160	180
9	Yes	160	120	120	120
10	Yes	150	120	120	120

Table 1: Contraction-Heating Setups without Throat Plug

the heat transferred to the room, but also requires reducing the set-point temperature for the heaters, to compensate for the change in temperature gradient.

For setup number 10, the only setup for which the cold wire was also used to measure locations below the centerline, it is clear that the temperature profile became significantly nonuniform below the tunnel centerline. The temperature variation for this setup was almost 70°C . This shows that substantial and complicated free convection effects still exist in the contraction, for the nominally still air before the run.

Measurements with the Throat Blocked by a Plug

Measurements similar to the previous cold-wire measurements were made with a soft rubber hemisphere placed slightly upstream of the contraction exit, to block any free convection through the throat. For these data, cold wires were placed in the contraction through the top and bottom access ports at the same time. Temperature data were collected for locations from y=-8.00 to 8.00 inches in 1 inch increments, with two additional locations near the upper and lower walls, at $y = \pm 8.71$ inches. Eight different contraction-heating setups were used and can be seen in Table 2. The first five setups are the same or are very similar to the first five setups listed in Table 1 for the case without the throat plug. Here, the 7th column denotes the location of the thermocouples that control each band heater. 'U' means that the thermocouples were located directly beneath the band heaters while 'NU' means that they were located about an inch away from each band heater.

Figure 11 shows the results of these measurements. Stratification in the quiescent air remains clearly evident. This is most likely due to free convection caused by nonuniform contraction heating.

Figure 12 shows temperatures with and without the rubber-hemisphere throat plug in place, for the five similar contraction setups. The black symbols show temperatures without the plug while the green symbols are for temperatures with the plug. It is clear that the inclusion of the plug had a profound effect on the temperature profiles for several contraction configurations.

The throat plug significantly reduced the mean temperatures for setups 4 and 5. All five contraction setups with the plug showed very similar temperature profiles. Between y =-3.00 and 7.00 inches, the temperatures are nearly constant. Near the upper contraction wall and below y =-3.00 inches, however, the temperatures drop markedly. This is also the general behavior of the temperatures without the hemisphere in place. Due to temporary equipment limitations, there are no data below y =-2.00 inches for the case without the hemisphere.

Thus the primary cause of the free convection and stratification observed in the contraction is most likely not cold air feeding upstream through the nozzle throat. The hemisphere did prove effective in mitigating the severe overheating that was observed for contraction configurations 4 and 5 without the hemisphere in place. It is unclear why the addition of the hemisphere would cause such behavior.

The free convection and stratification in the contraction must be due to uneven contraction heating. One future step to identify and isolate the problem would be to place thermocouples in multiple locations under each band heater to determine the uniformity of the actual band heater temperature. It may be possible also to modify the outer surface of the contraction to allow more than the three band heaters. The addition of one or more extra band heaters could possibly serve to create a more uniform heating and alleviate the observed free convection. Finally, it remains possible that additional modifications to the control scheme used for the heaters might improve the temperature uniformity.

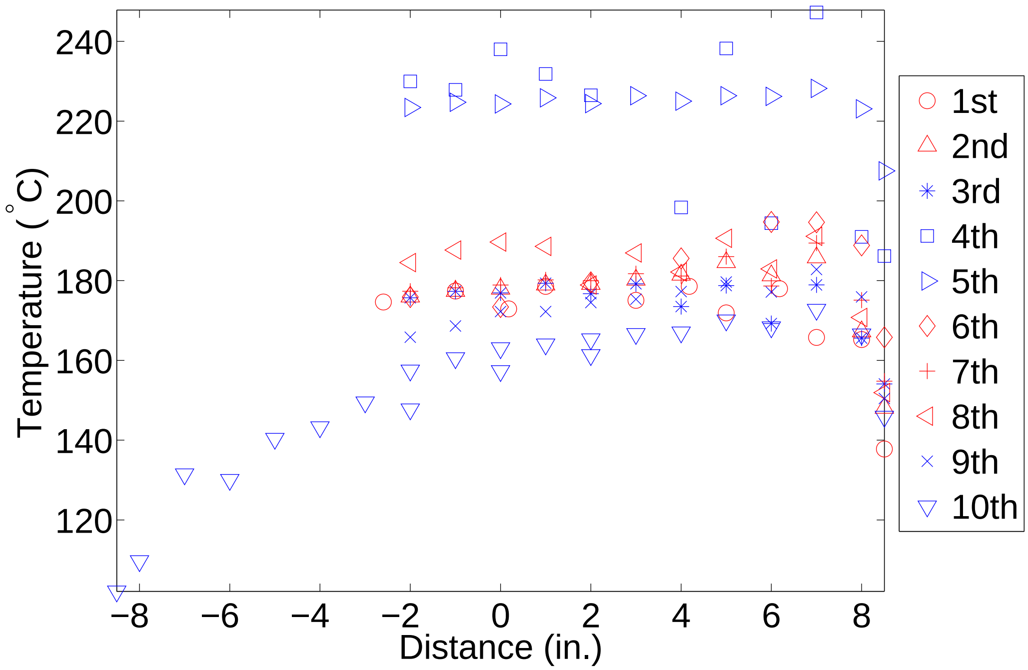

Figure 10: Temperature in Contraction for Still Air at Atmospheric Pressure

Setup Num.	Insulation	DT (°C)	BH 1 (°C)	BH 2 (°C)	BH 3 (°C)	TC Loc
1	No	160	145	160	160	U
2	No	160	160	160	160	U
3	Yes	160	160	175	160	U
4	Yes	160	175	160	160	U
5	Yes	160	160	160	160	U
6	No	160	138	160	160	NU
7	Yes	160	160	160	175	U
8	Yes	160	160	160	160	NU

Table 2: Different Contraction-Heating Setups with Throat Plug

Modification of Bleed-Lip Tip for Nickel Throat

The tip of the electroformed-nickel bleed lip was remachined from a half-circle shape to a nearly semi-elliptical shape, following the measurements, computations, and design reported in Refs. [16, 17, 15]. This was done in an attempt to eliminate the separation bubble that was thought to exist on the half-circle bleed lip, according to the computations. The remachining would also eliminate the kink in the as-built near-semicircular tip, which was shown in Fig. 4 of Ref. [15]. The kink was only about 0.001 inch high and was apparently caused by cutting the bleed lip using an axisymmetric lathe, on a nominally axisymmetric part that sprung about 0.001-0.002 inches out of round when removed from the mandrel. Thus, it was not going to be easy to remove the kink using an ordinary CNC lathe with a nominal accuracy of 0.001 inches.

Before cutting the part, ATK Microcraft in Tullahoma, Tennessee made precision measurements of the coordinates of the lip along 8 azimuthal rays. Station (or pass) 1 was on the left, looking downstream at the lip. The other stations were sequentially clockwise, at 45-deg. azimuthal intervals. Fig. 13 shows the measurements, which were only obtained near the tip. It is evident that the lip is about 0.005 inches out of round. Since the radius is about 0.7 inches, this is still less than 1%. The variation for passes 4 and 8 appears to be as much as 0.005 inches, considerably more than was shown in the Anderson Tool measurements reported in Fig. 4 of Ref. [15].

The source of the difference is not known, but

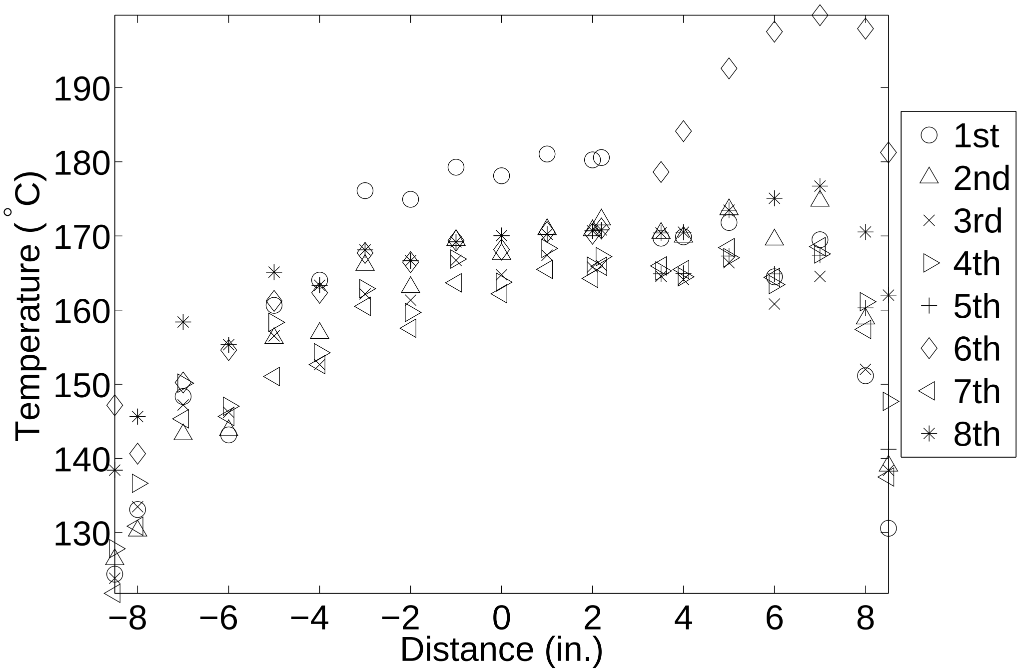

Figure 11: Temperature Profile in Contraction with Throat Plug

is possibly related to differences in the method with which the part was aligned in the coordinate measuring machine (CMM). For the Microcraft measurements, according to Noah Risner, the part was first aligned in the machine, to good approximation. *'At that point the machine is driven around the part to measure random points on the radius. In this case we took 8 points around the inside of the part at approximately the projected axial internal runout station (about .080 from the lip). These points did not necessarily correspond with the planned inspection stations. Using these measured points the machine software calculated an average center point that should be at worst within .0001" and this center point is what was used through the remaining measurements for inside and outside the part at the 8 stations. A similar process was used to locate the center of the part after the machining was completed for those measurements.'* This is doubtless not identical to the alignment method used by Anderson Tool, which might explain the difference in the measurements.

Figure 14 shows a detail of the lip coordinates, from the same set of measurements. Passes 4 and 8, shown in green and blue, have a substantially smaller inner radius. In addition, passes 3 and 7, shown in red and purple, display a kink near the inner shoulder of the semicircular tip. The kink is similar but not identical to that shown in Fig. 4 of Ref. [15]. It is thought that this kink exacerbates the separation bubble on the bleed lip and causes the dramatically reduced performance of the electroformed throat. However, a comparison of the various measurements also shows the difficulty of measuring, cutting, and controlling such small features on the lip of a fairly large part, using fairly ordinary and thus affordable machining processes.

Microcraft attempted to use a collar to remove the eccentricity of the bleed lip before machining it, but measurements of the bleed lip geometry with the collar installed and adjusted showed that it only improved the coordinates under the straightening screws. The overall uniformity of the lip was not improved, and there was no easy way to straighten the out-of-roundness. Thus, this collar was removed and the part was machined and hand-finished without it.

Fig. 15 shows the measured coordinates of the recut tip of the bleed lip, compared to the nominal contour design. The new contour was successfully cut, without introducing a noticeable flaw at the joint with the original contour. Variations of roughly 0.001 inches exist at various azimuthal and axial stations, as must be expected given the eccentricity of the original part and the limited accuracy of the affordable machine processes that were used.

Fig. 16 shows a comparison of the new contour with the old contour, for 4 of the 8 azimuthal stations. The new contour fairs into the original contour at about $z = -0.92$ inches. According to Noah Risner

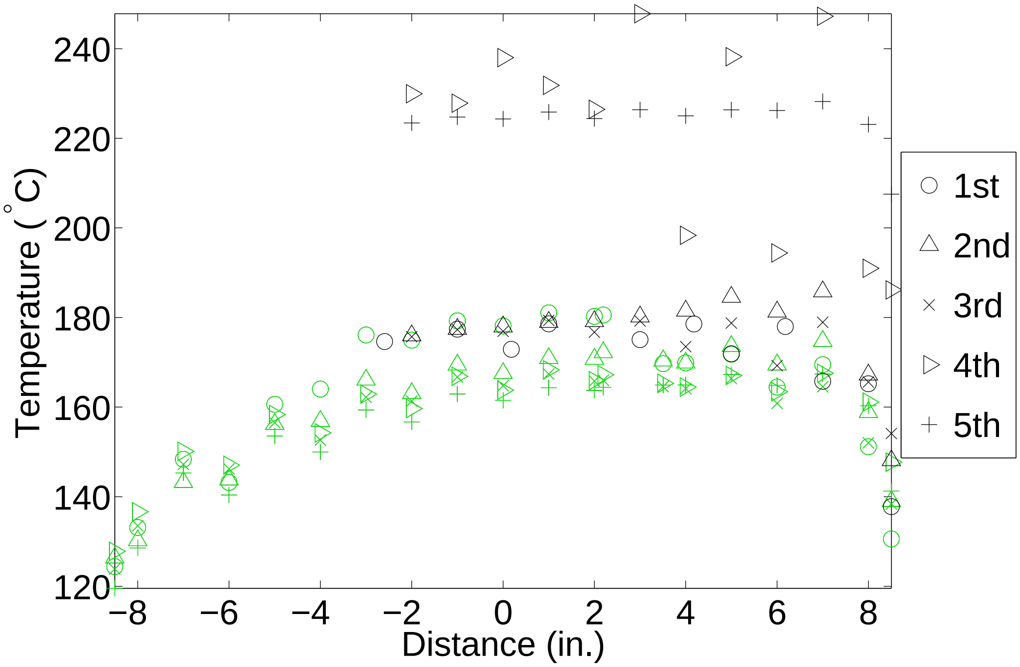

Figure 12: Contraction-Entrance Temperatures for Nominally Still Air with and without Throat Plug

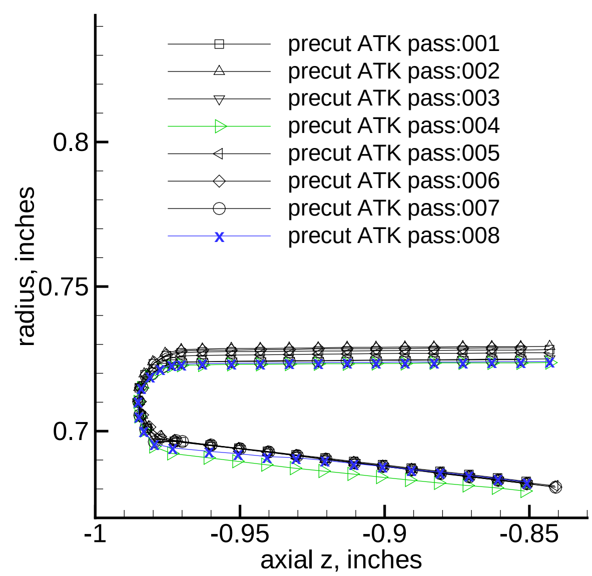

Figure 13: ATK Measurements of Original Geometry of Nickel Bleed Lip

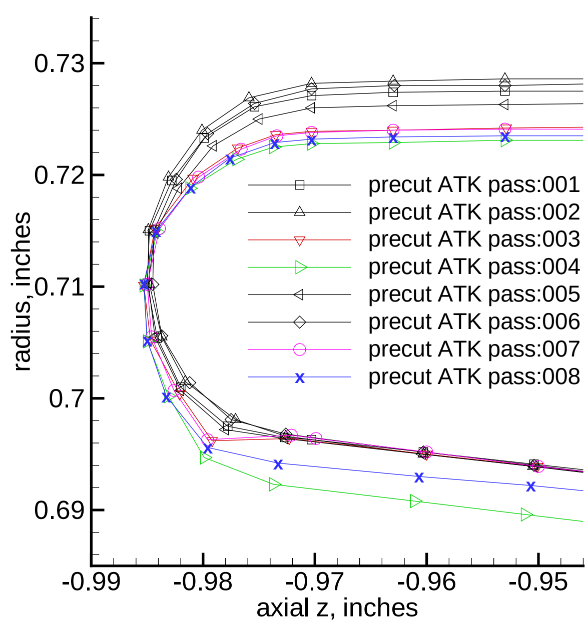

Figure 14: ATK Measurements of Original Geometry of Nickel Bleed Lip: Detail of Tip Showing Kink

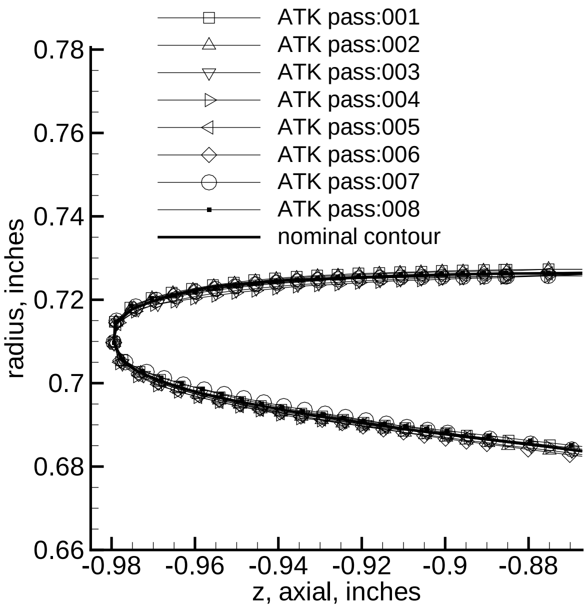

Figure 15: Measurements of Recut Geometry of Nickel Bleed Lip

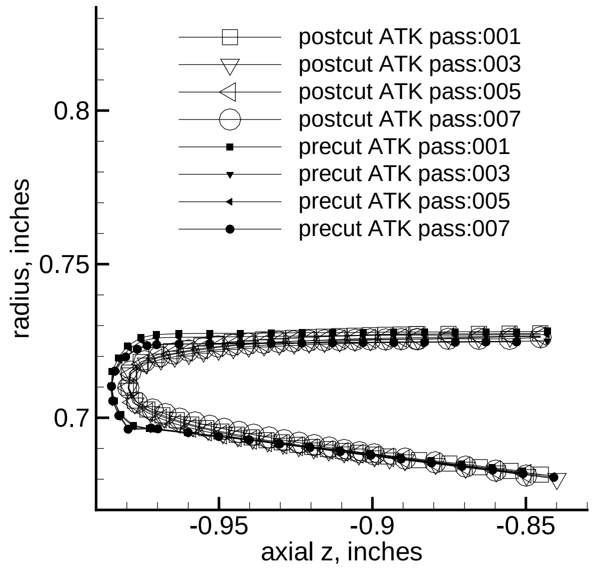

Figure 16: Measurements of Recut Geometry of Nickel Bleed Lip Compared to the Original Geometry

of Microcraft, the new contour ran out into the old contour at about 0.050 to 0.110 from the tip, on the inside, and at about 0.060-0.125 from the tip, on the outside. Since the new contour met the old contour on a slow taper, the joint should be smooth despite the large variation in the meet-up location (the ‘runout’). Bluing was used to detect the runout location, along with the change in surface finish of the newly cut surface as compared to the original surface. The measurements were thought to extend about 0.050 inches downstream of the runout point. If the new design is successful, it will be much less likely to separate, and so much less sensitive to small variations from the ideal contour.

Summary and Future Plans

The Mach-6 Ludwieg Tube at Purdue has now operated with laminar nozzle-wall boundary layers and quiet flow to freestream unit Reynolds numbers as high as 2.7×10^6/ft., some 86% of initial design performance. The nozzle-wall boundary layer has remained laminar to momentum-thickness Reynolds numbers of about 2700. However, this performance is not yet reliable. Shakedown continues, in order to achieve the highest feasible quiet Reynolds number in the most reliable way. Separation of the bleed-lip boundary layer remains the prime suspect for the cause of transition. This small separation bubble may be extremely sensitive to small variations in the bleed-lip finish and geometry, thus generating the lack of repeatability observed in the quiet-flow pressure. A newly modified bleed-lip tip has been machined and is now ready to be tested. During quiet flow at high Reynolds number, the pitot-pressure fluctuations in the nozzle are less than 0.02%, a value lower than has been reported in any previous tunnel, even previous quiet tunnels.

The bleed lip of the electroformed nozzle has been remachined to the coordinates provided by Professor Knight’s group at Rutgers. This new shape is expected to eliminate the separation bubble that calculations indicate exists there. The new maximum quiet pressure is to be determined. In addition, measurements will determine whether the axial independence of quiet pressure remains, suggesting bypass transition. The current plan is as follows:

1. Test the performance of the recently repolished surrogate nozzle.

2. Test the performance of the remachined electroformed-nickel nozzle with the elliptical bleed lip.

3. Polish the remachined nickel bleed lip.

4. Test the performance of the polished, remachined electroformed throat.

The free convection in the driver tube generates higher than desirable levels of contraction-entrance fluctuations. However, these evidently do not preclude quiet flow at high Reynolds numbers. Measurements of the flow uniformity near the nozzle exit are to continue, to determine if the stratified flow in the contraction has a significant effect on the test section flow, and to determine if there are any feasible methods of reducing nonuniformities in the driver-tube flow.

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