LeRC NATR FREE-JET DEVELOPMENT

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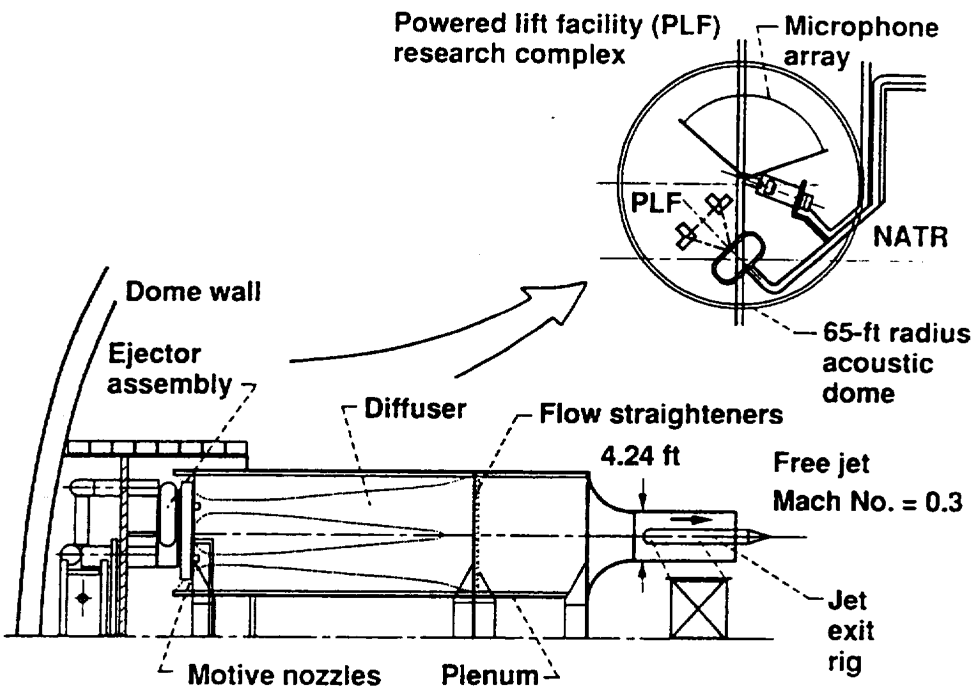
S36-09

AERODYNAMIC DESIGN OF THE NOZZLE ACOUSTIC TEST RIG



The Nozzle Acoustic Test Rig (NATR) was developed to provide additional test capabilities at Lewis needed to meet HSR program goals. The NATR is a large free-jet facility (free-jet diameter = 53 in.) with a design Mach number of 0.3. It is located inside a geodesic dome, adjacent to the existing Powered Lift Facility (PLF). The NATR allows nozzle concepts to be acoustically assessed for far-field (approximately 50 feet) noise characteristics under conditions simulating forward flight. An ejector concept was identified as a means of supplying the required airflow for this free-jet facility. The primary stream is supplied through a circular array of choked nozzles and the resulting low pressure in the constant, annular-area mixing section causes a "pumping" action that entrains the secondary stream. The mixed flow expands through an annular diffuser and into a plenum chamber. Once inside the plenum, the flow passes over a honeycomb/screen combination intended to remove large disturbances and provide uniform flow. The flow accelerates through an elliptical contraction section where it achieves a free-jet Mach number of up to 0.3.

OBJECTIVES OF 1/5-SCALE MODEL TEST PROGRAM

Determine ability of ejector system to overcome back pressure of configuration

Determine sensitivity of system to axial position, vertical alignment, and angular orientation of primary nozzle array

Determine velocity distortion levels at exit of the free-jet

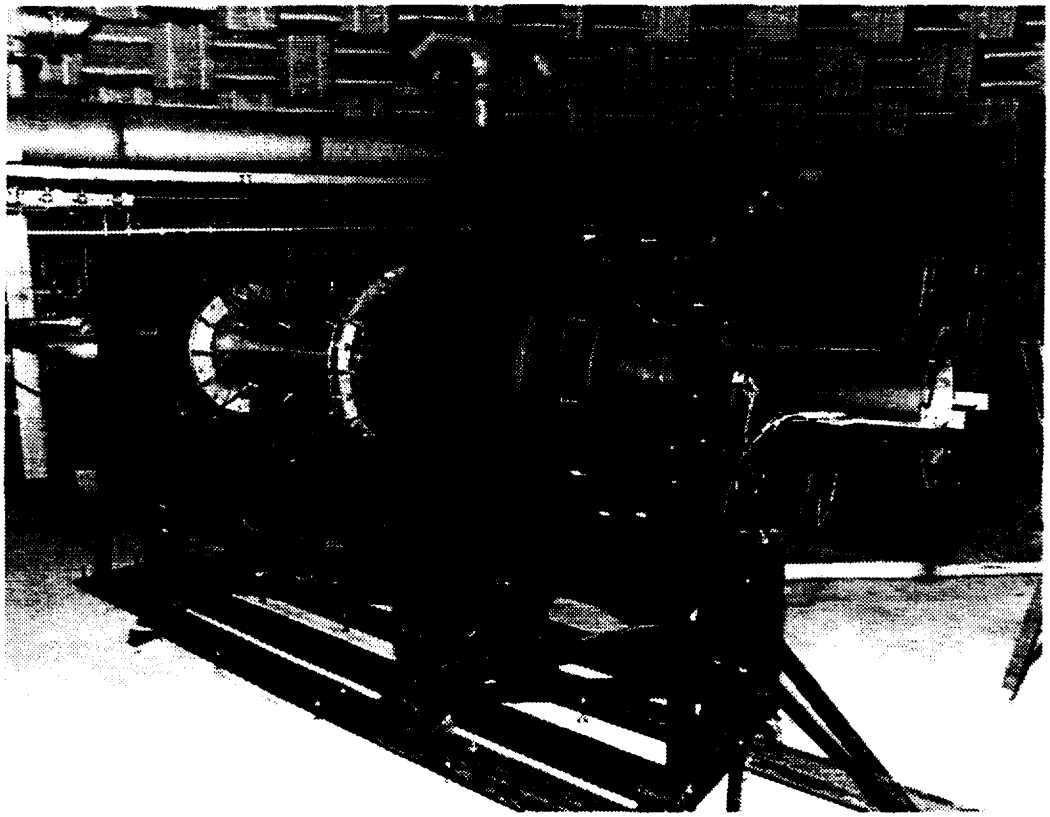
Determine effect of blockage due to inlet tunnel enclosing primary nozzle array

Several issues regarding the performance/operation of the NATR ejector system were identified:

1. The ability of the ejector system to successfully overcome the back pressure produced by the configuration.
2. The sensitivity of the system to the axial position, vertical alignment, and angular orientation of the primary nozzle array.
3. The quality of the flow at the exit of the free-jet as determined by the velocity distortion levels measured.
4. The effect of blockage due to an inlet tunnel enclosing the immediate area around the primary nozzle array.

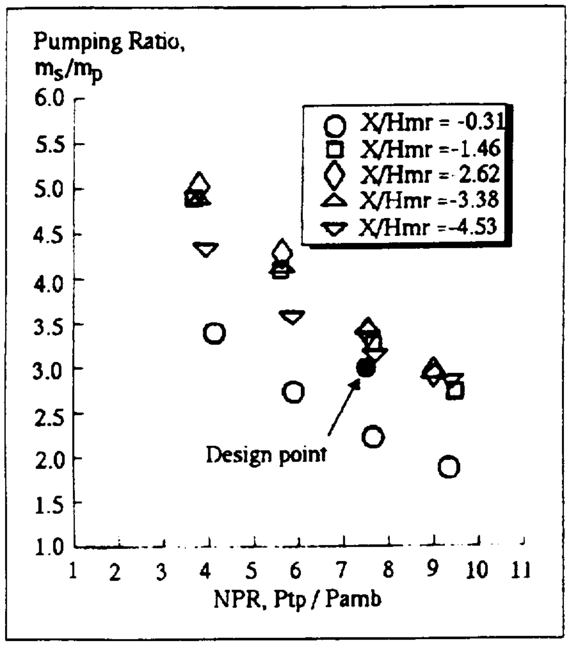
In order to address these issues, an experimental program was initiated, which involved building and testing a 1/5-scale model of the NATR.

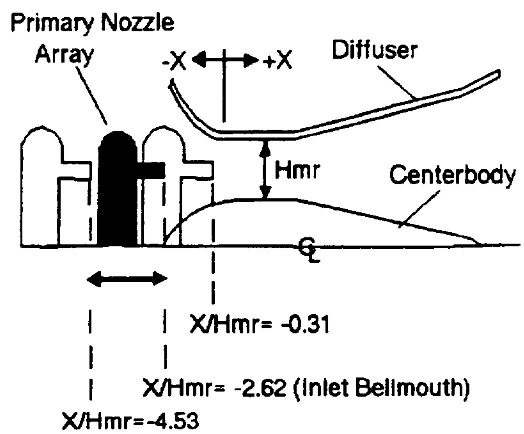
1/5-SCALE MODEL OF THE NATR



The 1/5-scale model of the NATR was designed by scaling (geometrically) the dimensions of the full-scale facility by 0.20. For ease of fabrication and cost considerations, the model was constructed from several different materials (i.e., wood, metal, plexiglass). In order to translate the model axially, it was mounted on v-groove rails. The large tolerances in the model supports and piping allowed the vertical and angular motion of the primary nozzle array. In order to investigate the effect of the honeycomb/screen position on the level of velocity distortion at the free-jet exit, the plenum was made of a series of 3-in. rings. One ring contained the honeycomb and another contained the screen. Their locations could be easily varied to determine if one configuration produced higher flow quality than another. Wall static pressures were measured longitudinally along the diffuser walls and the free-jet nozzle. A rake, extending completely across the diameter of the free-jet nozzle, measured total temperature and total pressure. A boundary layer rake was also located at the exit station of the free-jet nozzle in order to determine the boundary layer thickness.

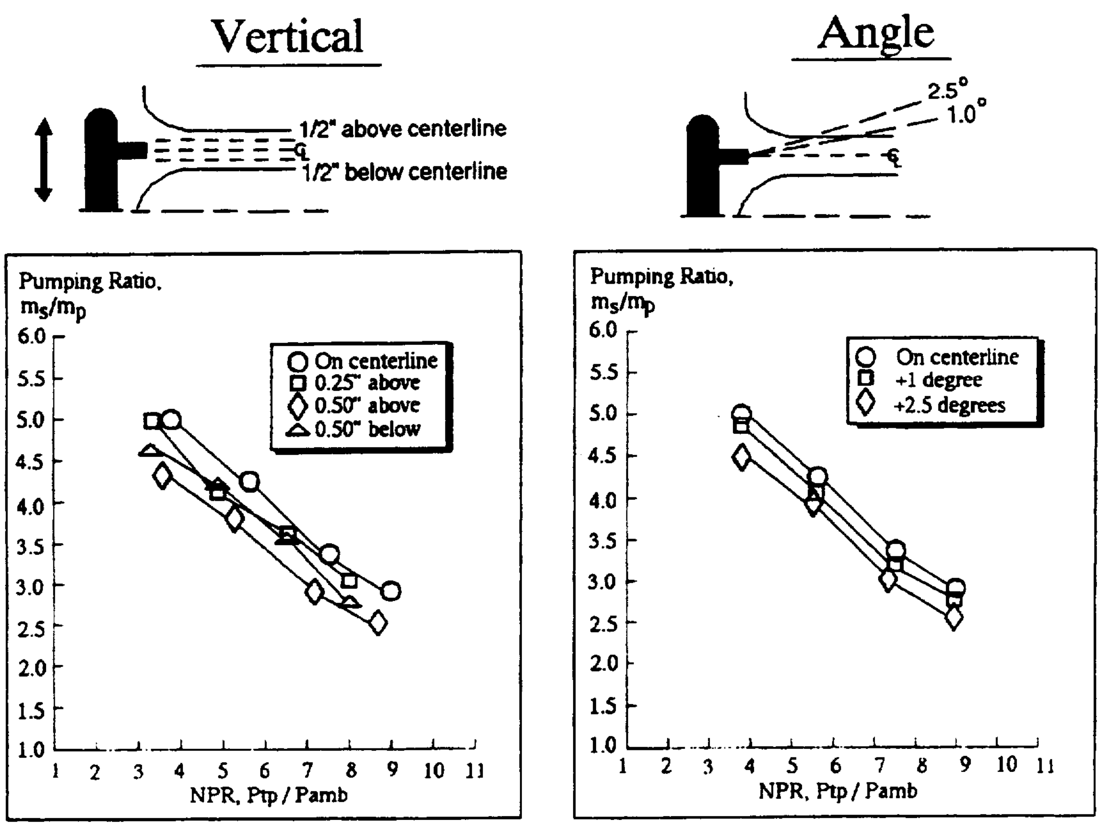
1/5-SCALE MODEL PUMPING PERFORMANCE





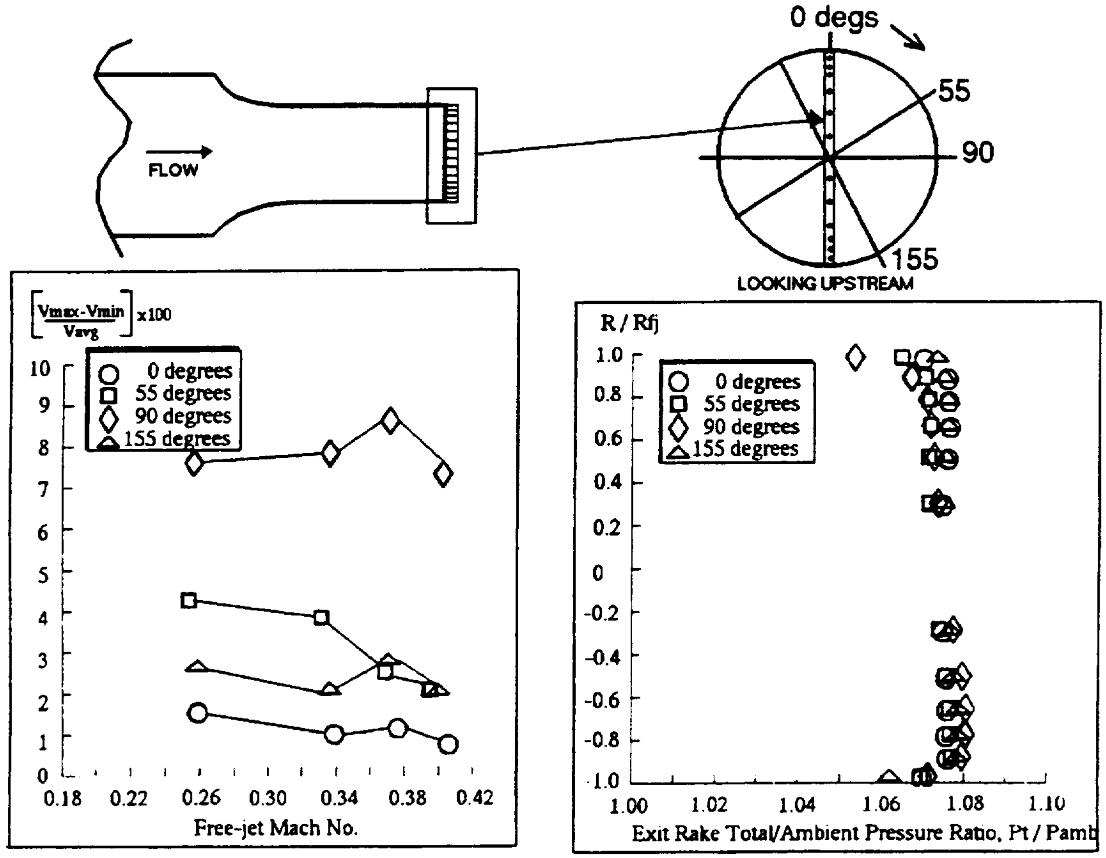
The figure above shows the pumping ratio, ms/mp, as a function of the primary nozzle pressure ratio for several primary nozzle axial positions. The axial position, X, is non-dimensionalized by the height of the mixing region annulus, H_{mr}. These performance results indicate the design pumping ratio of approximately 2.9 at primary nozzle pressure ratio of 7.5 was achieved for all the axial locations investigated, except $X/H_{mr} = -0.31$. The first objective of the 1/5-scale model program was accomplished-- the ejector system was able to overcome the back pressure produced by the system configuration and achieve the necessary levels of pumping. The results indicate that when the primary nozzle array was positioned with the primary nozzles flush with the entry plane of the inlet bellmouth (station $X/H_{mr} = -2.62$) the pumping performance was the highest. Slight changes in the axial position of the primary nozzles with respect to the inlet bellmouth did not affect the performance significantly. When the primary nozzles were placed extremely forward ($X/H_{mr} = 0.31$) or extremely aft ($X/H_{mr} = -4.53$) of the bellmouth, the pumping performance decreased. The inlet bellmouth station ($X/H_{mr} = -2.62$) was chosen as the optimum axial location for the primary nozzle array because of its convenient reference.

EFFECTS OF EJECTOR MISALIGNMENT



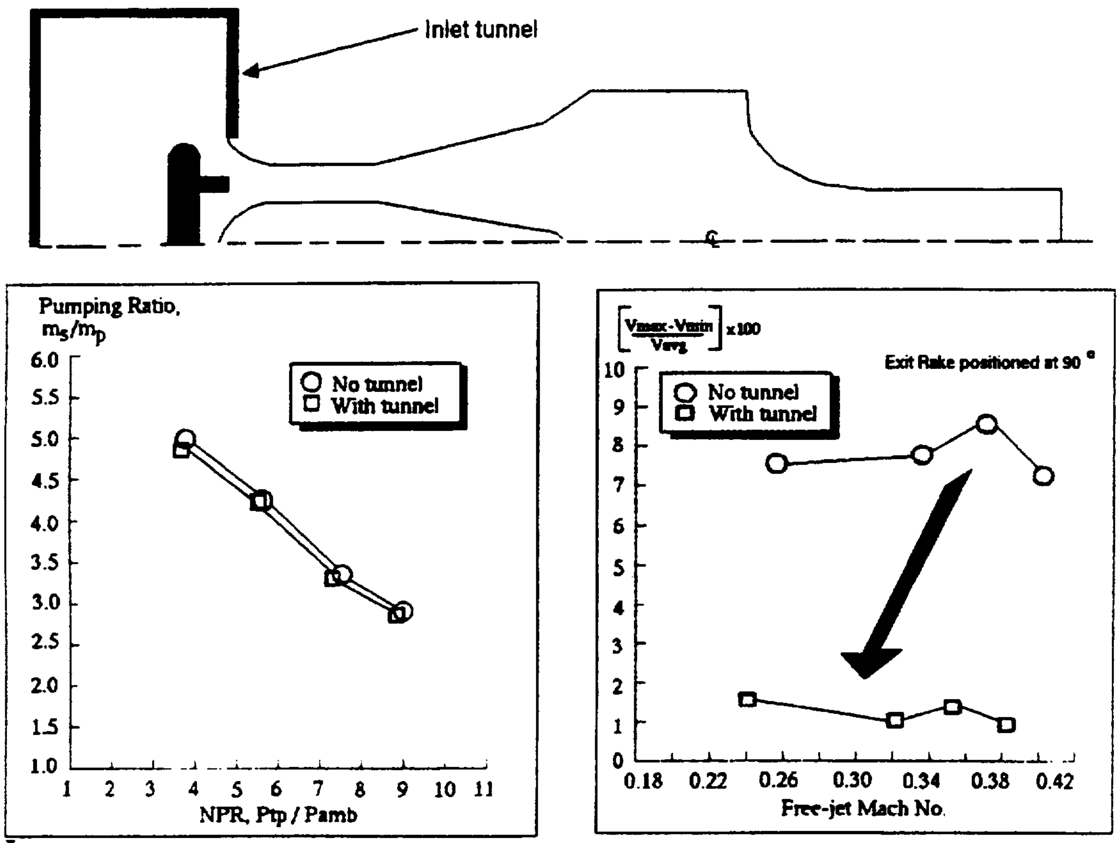
The results of shifting the centerline of the primary nozzle array up and down with respect to the annular mixing region centerline are shown in the figure. The data show that the ejector performance is very sensitive to vertical alignment of the primary nozzles. The array was shifted up and down 0.5 in. There was a decrease in the performance with any shift of the nozzle array. The greatest drop occurred with the nozzles positioned 0.5 in. above the centerline. Likewise, when the primary nozzle angle was changed, the pumping ratio suffered. The figure also presents the results of varying the nozzle angle. As evidenced, any angular misalignment of the primary nozzles caused a downward shift in the pumping performance curve. In general these results wee valuable when specifying the allowable tolerances of the full-scale NATR primary nozzle array installation.

FLOW QUALITY AT EXIT OF 1/5-SCALE MODEL FREE-JET NOZZLE



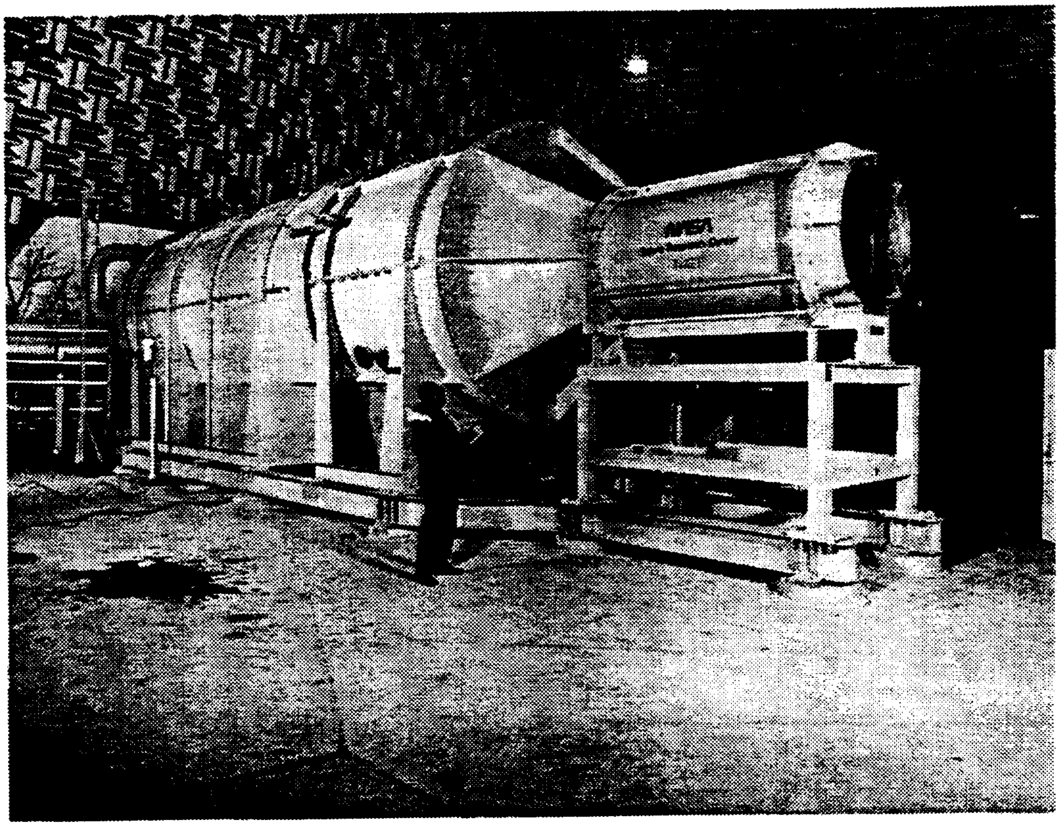
The second series of tests involved determining the flow quality at the exit of the free-jet exhaust. The figure shows the percent velocity distortion as a function of free-jet Mach number for each of the circumferential rake positions investigated. The results indicate that the velocity distortion levels were lower than 5% at three of the four circumferential positions. The distortion calculated at 90 degrees was approximately 3% higher than the others. The figure also shows the exit rake total pressure nondimensionalized by the ambient static pressure profiles for the 4 rake positions at a free-jet Mach number of approximately 0.34. It is clear that there is no single tube that appears to be causing the rake at 90 degrees to have an unusually high distortion level. As part of the flow visualization, smoke was used to study the inlet area of the ejector system. This investigation showed that the streamwise vortices, produced by the pumping action of the primary stream, had to turn sharply around the flanges of the primary nozzle array. The high distortion levels at the 90 degrees rake position are believed to have been caused by the interference of these flanges with the natural entrainment of the secondary stream.

EFFECT OF THE INLET TUNNEL



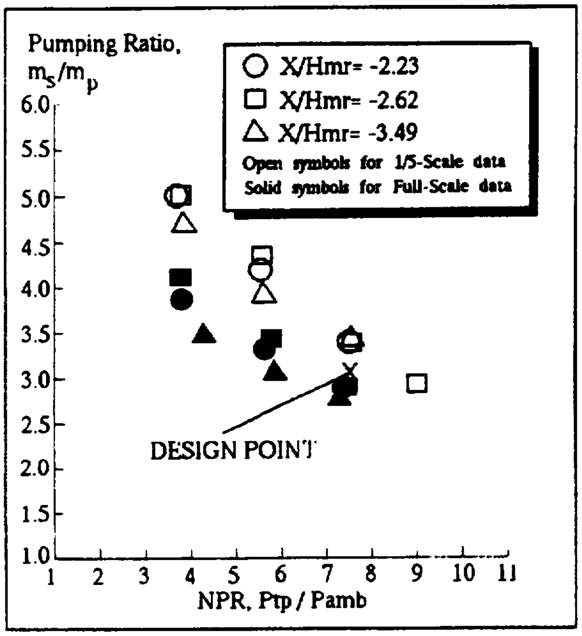
The figure above shows the results of adding the scaled inlet tunnel which enclosed the area around the primary nozzle array and inlet bellmouth. The effect of inlet blockage due to the tunnel was minimal on pumping performance. However, it is interesting to note that the inlet tunnel decreased the velocity distortion at the exit. The velocity distortion for the rake positioned at 90 degrees is plotted for both configurations (i.e., with and without the inlet tunnel added). As shown earlier, the distortion level without the tunnel is approximately 8%. With the tunnel installed, the distortion levels are lowered to approximately 1.5%. It is believed that the tunnel removed the interference effect of the flanges supporting the primary nozzle array and caused the secondary stream to be entrained more uniformly, from the frontal area only.

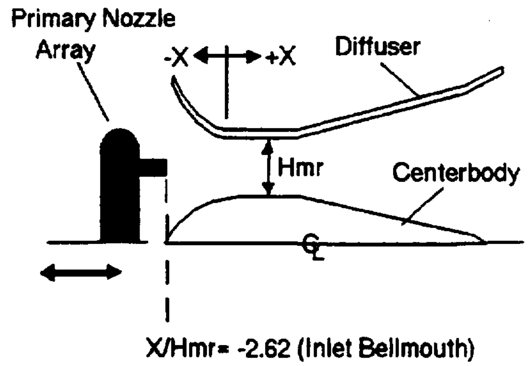
FULL-SCALE NATR FACILITY



The full-scale facility is shown in the photograph above. It is located inside a geodesic dome, adjacent to the Powered Lift Facility. In the full-scale facility, (unlike in the scale model), the annular mixing region, the diffuser, the 6 radial splitters and the plenum surfaces were treated with an acoustic absorber material to attenuate the noise radiating axially and circumferentially from the ejector system of the NATR. This acoustic absorber consisted of a three layer sandwich of bulk absorber material, held in place by a wire screen and covered by a perforated plate. The primary nozzle array was mounted on rails in order to change its axial position and determine the effect of its position on pumping performance. The instrumentation of the full-scale facility included wall static pressure taps along the walls of the annular mixing region and the diffuser. There were three total pressure rakes and wall static pressure taps equally spaced around the circumference of the plenum. A row of longitudinal static pressure taps was placed along the wall of the free-jet nozzle. Four total pressure/total temperature rakes and three boundary layer rakes were located around the circumference of the free-jet nozzle exit.

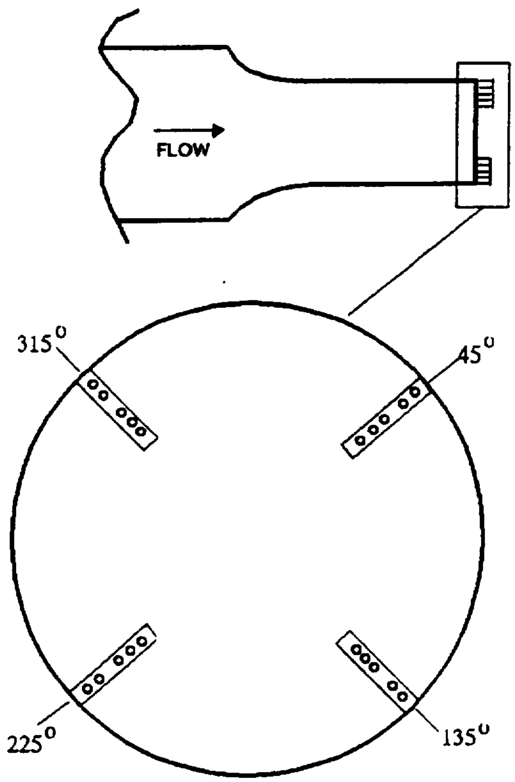
FULL-SCALE AND 1/5-SCALE MODEL NATR PUMPING PERFORMANCE



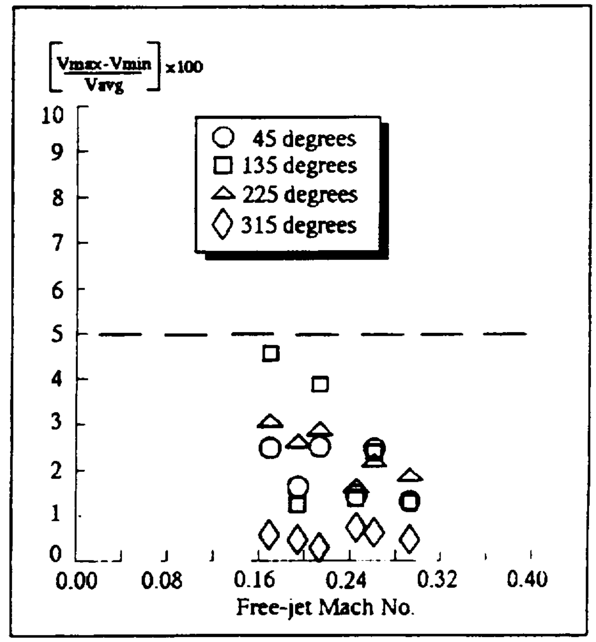


The figure above shows the pumping ratio versus the primary nozzle pressure ratio (NPR) for the 1/5-scale model and the full-scale NATR. The results show that the X/Hmr = -2.62 position (primary nozzles flush with the bellmouth) achieved the most favorable pumping ratio for both systems. The design point NPR of approximately 7.5 successfully produced the required pumping ratio of 2.9. The full-scale NATR, as expected, does not exhibit great sensitivity to the axial position of the primary nozzle array. The full-scale NATR pumping ratios are lower than those obtained for the 1/5-scale model. At the design NPR, the full-scale facility pumping ratio is 15% lower than the 1/5-scale model. Since, geometrically speaking, the scale model and the actual facility are the same, the cause of the different levels of pumping achieved may be attributed to the different fluid dynamics of the two systems. The net effects of the fluid dynamics of the flow (e.g., friction losses, boundary layer thickness, Reynolds number) are different for the full-scale facility because of the perforated plate in the mixing region. The perforated plate could produce a higher friction coefficient and a larger boundary layer thickness, and therefore a reduction in the secondary area available for flow entrainment.

FLOW QUALITY AT EXIT OF FULL-SCALE NATR FREE-JET NOZZLE



Looking Upstream



The figure above shows the velocity distortion levels measured by the four total pressure/temperature rakes at the exit of the full-scale free-jet nozzle. The plot shows all velocity distortion levels below 5% similar to 3 of the 4 scale model rake positions.

CONCLUSIONS

1/5 - Scale Model

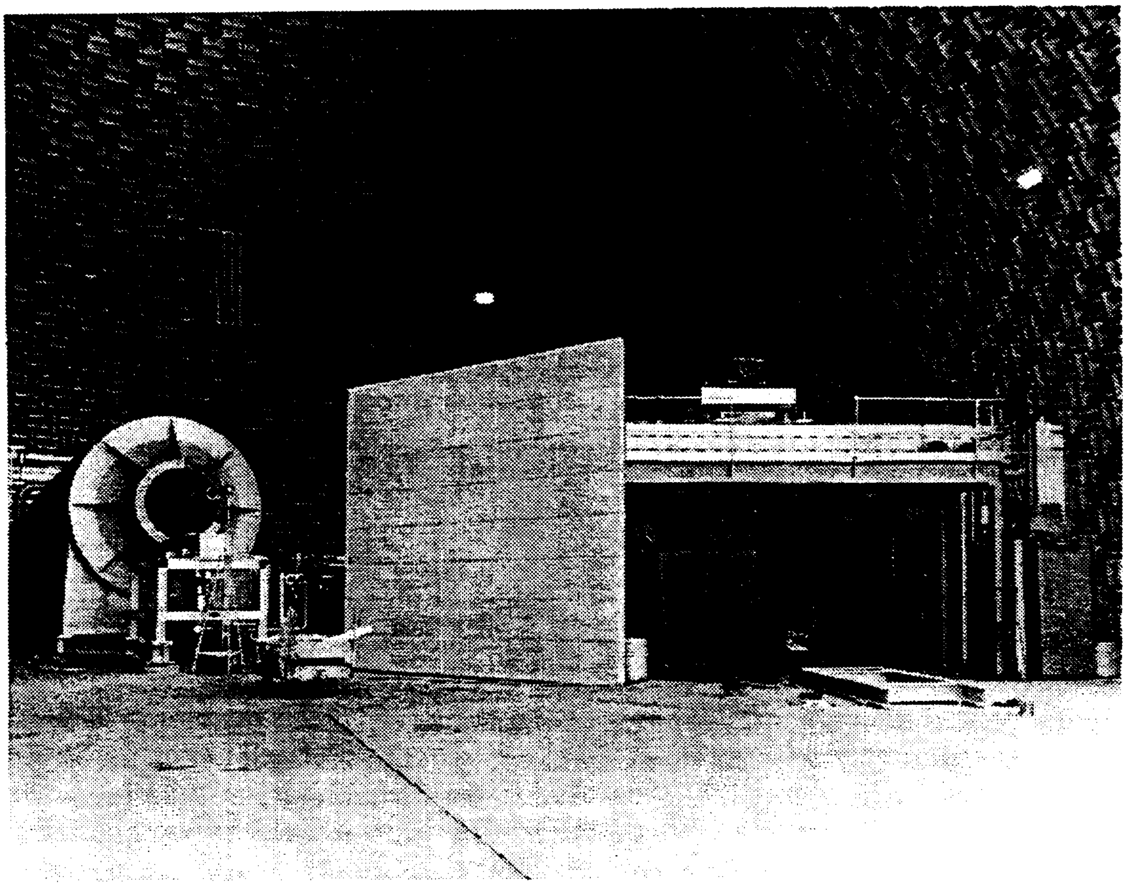
- Achieved significant pumping performance
- Flow quality at exit of free-jet nozzle determined to be acceptable
- Effect of inlet tunnel on pumping performance was minimal

Full-scale NATR

- Achieved required pumping ratio to attain M=0.3
- Velocity distortion levels lower than 5%
- Full-scale and 1/5-scale results show similar trends

The 1/5-scale model of the NATR provided valuable information for the installation and operation of the full-scale facility. The experimental program verified that the ejector system achieved the necessary pumping ratios at the design primary nozzle pressure ratio. The scale model results indicated little sensitivity of the system to the axial position of the primary nozzles; however, the ejector system is extremely sensitive to vertical and angular misalignment of the primary nozzle array. The flow quality at the exit of the free-jet nozzle was determined to be acceptable. The calculated percent velocity distortion at the free-jet nozzle exit was lower than 5% at tall circumferential stations investigated except 90 degrees where the level was approximately 8%. The effect of the inlet tunnel on the ejector pumping performance was minimal; however, it did act to reduce the velocity distortion at the 90 degrees position to 1.5%. The results from the 1/5-scale model experimental program greatly aided in the design and installation of the full-scale facility. The full-scale facility achieved the required pumping ratio to attain a free-jet Mach number of 0.3. Similar to the 1/5-scale model resuts, the full-scale NATR showed little sensitivity to the axial position of the primary nozzle array. The velocity distortion levels were less than 5%.

OVERVIEW OF AEROACOUSTIC PROPULSION LABORATORY (APL) ACOUSTIC DESIGN ISSUES



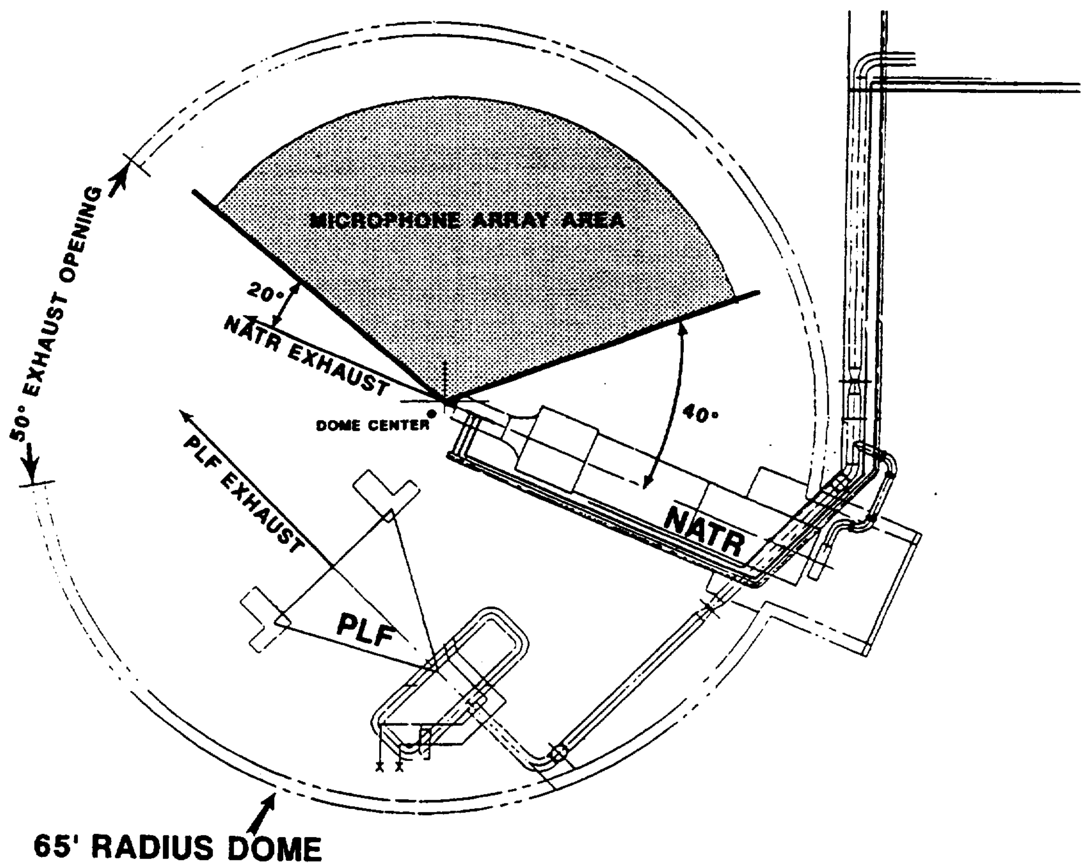
The Aeroacoustic Propulsion Laboratory (APL) Complex is a 130-ft diameter geodesic dome that provides a hemi-anechoic environment for aeroacoustic testing of aircraft propulsion systems while protecting Lewis Research Center's residential neighbors. The APL facility houses the new Nozzle Aeroacoustic Test Rig (NATR), an ejector-powered free jet for aeroacoustic testing of scale model supersonic aircraft exhaust nozzles, as well as the multi-axis force-measuring Powered Lift Facility (PLF) test stand for testing of Short Takeoff Vertical Landing (STOVL) vehicles.

FACILITY REQUIREMENTS AFFECTING APL AND NATR DESIGN PROCESSES

- REDUCE COMMUNITY NOISE LEVELS TO L_{DN} = 60 dBA
- PROVIDE ADDITIONAL CAPABILITY FOR AEROACOUSTIC NOZZLE TESTING (NATR)
- CO-LOCATE NATR AND PLF WITHIN ONE NOISE ABATEMENT STRUCTURE
- CONTAIN NATR AND PLF HARDWARE WITHIN CIRCULAR FOOTPRINT (GEODESIC DOME)
- PROVIDE HEMI-ANECHOIC INTERIOR ENVIRONMENT FOR ACOUSTIC TESTING

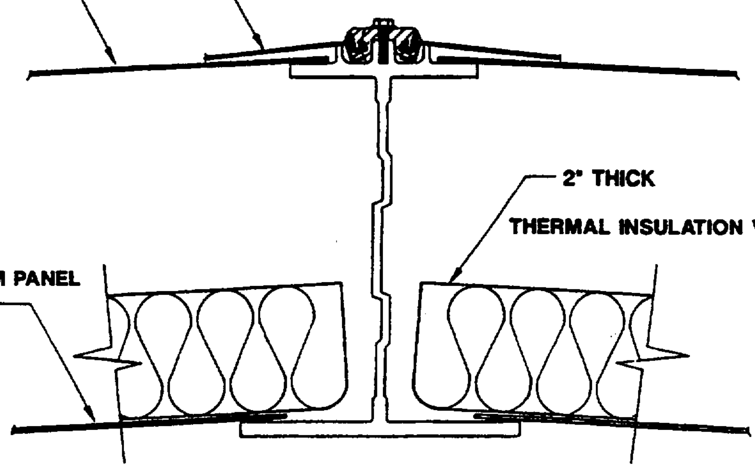
Originally conceived as a solution to a PLF community noise problem, APL was designed to reduce community noise levels to an acceptable level of L_{dn} = 60 dBA in residential areas (L_{dn} is a time-integrated noise metric that reflects a community's cumulative exposure to noise over a 24-hour period, with weighting applied for nighttime noise exposure). Midway through the APL design process, a need arose for an additional aeroacoustic nozzle test facility to supplement the capacity of the 9x15 Low Speed Wind Tunnel (LSWT). As a result of an extensive site selection study, the APL site was chosen for co-locating PLF with what is now NATR because of the availability of air services and existing control room as well as the expectation that NATR, as an outdoor free jet, would also require community noise control. The geodesic dome shape, which was proposed for its cost and structural advantages as well as for its all-weather and security features, gave rise to the requirement for a hemi-anechoic interior environment. These combined requirements: community noise reduction, NATR operations, PLF/NATR co-location, circular footprint, and hemi-anechoic interior; formed the basis of a tradeoff study to determine the size, orientation, and location of the dome structure as well as the geometry of the new NATR within that structure.

DESIGN CONSIDERATIONS INFLUENCING APL AND NATR GEOMETRY



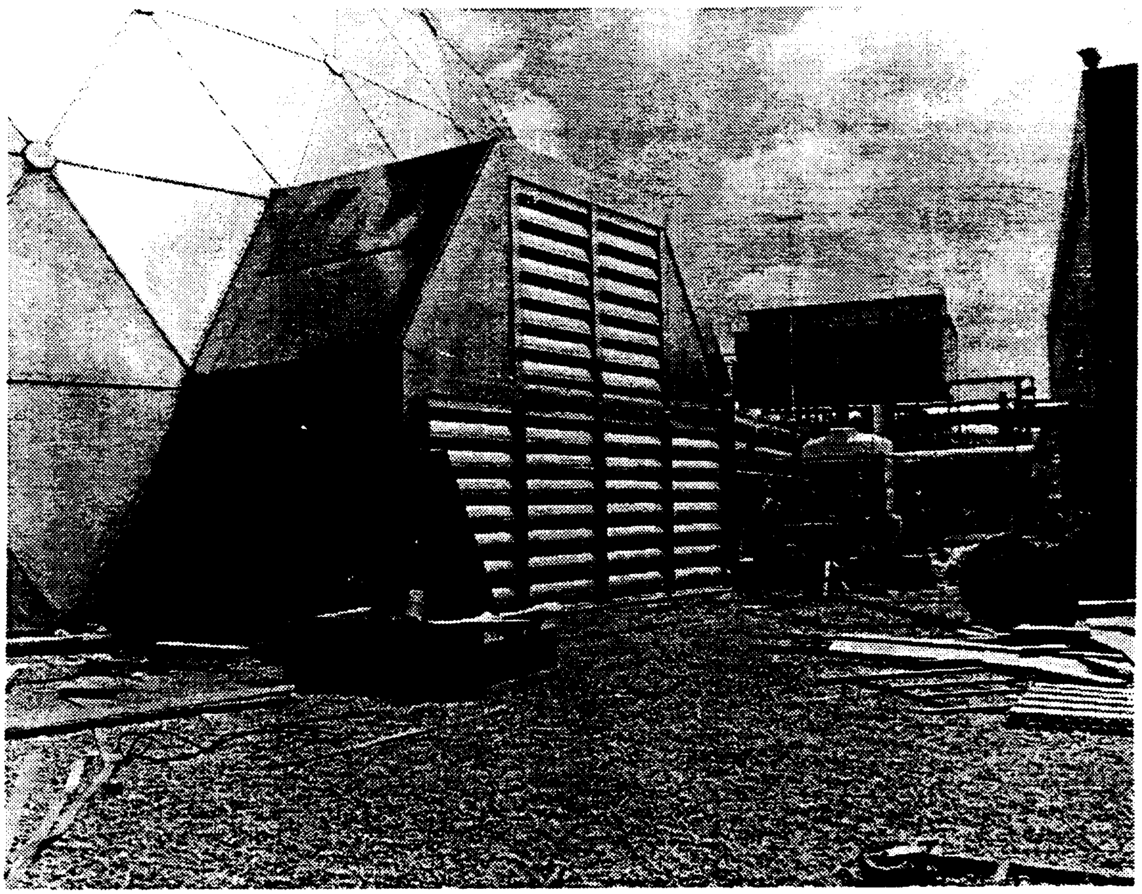
The geometry (size, location, orientation, and NATR geometry relative to the dome structure and PLF) were influenced by the following considerations: 1) overall dome size was minimized to control costs; 2) NATR and PLF were required to be able to run alternate day test schedules with minimal facility preparation; 3) NATR plume spread and temperature/velocity decay profiles dictated proximity of the rig to interior wall surfaces; 4) PLF aerodynamic concerns dictated proximity of PLF to interior walls; 5) the exhaust opening was tailored to be of the minimum size that would accommodate exhaust plumes of both rigs as well as operations vehicles, requiring the exhaust axis of NATR to be as coincident as possible with the PLF exhaust axis; 6) the planned 50' radial microphone array required a clear line of sight between the nozzle exit and the array area on one side of the jet axis; and 7) NATR was designed to accommodate 6-8" nozzles, which fixed the minimum free jet diameter, and, in turn, the minimum view angle to the upstream microphone array angles.

DESIGN OF DOME WALL PANELS FOR STC 55



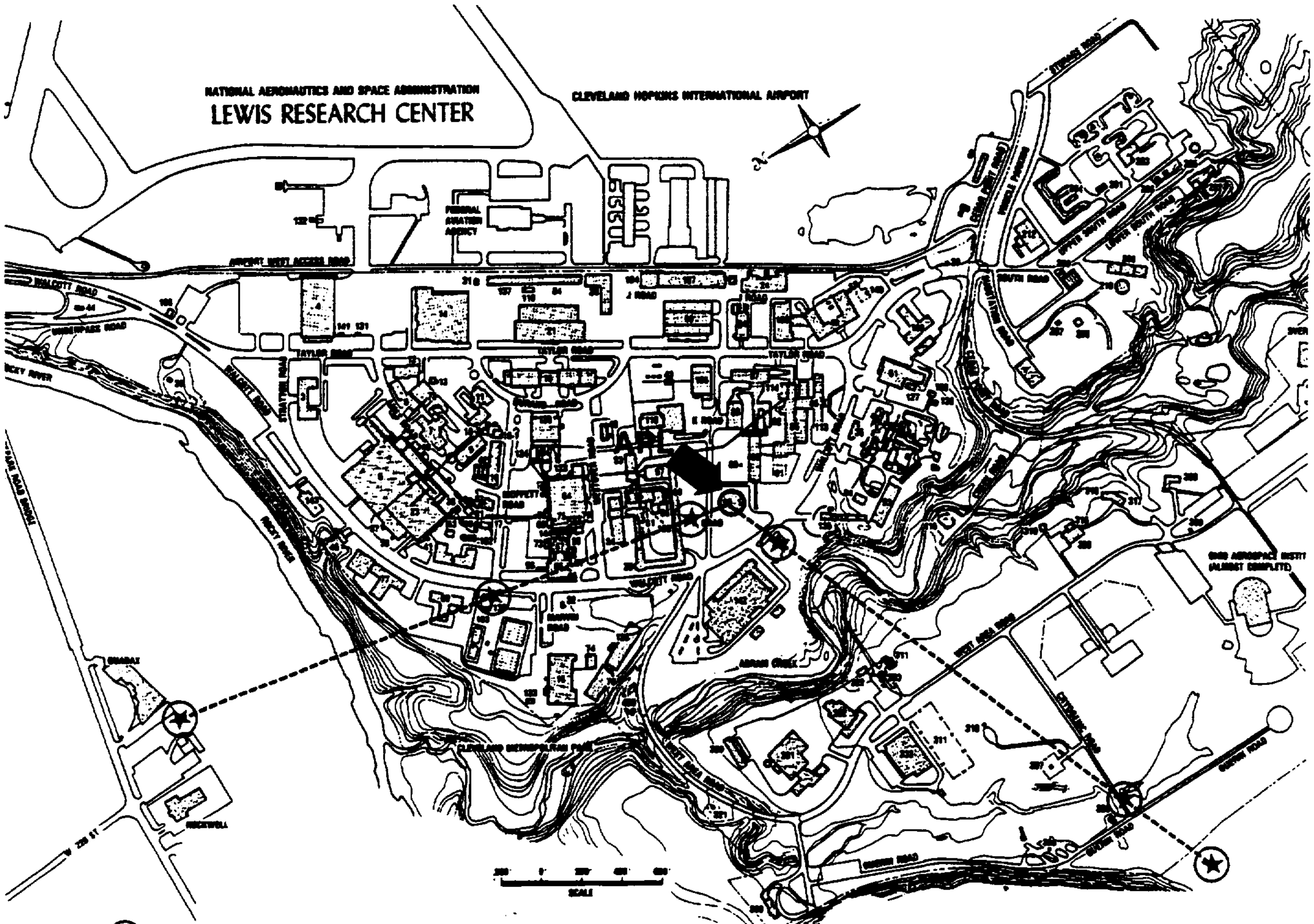
The dome wall panels were designed to provide a uniform level of noise reduction such that noise levels during APL test operations would be maintained at or below L_{dn} = 60 dBA in residential communities surrounding Lewis Research Center. A Sound Transmission Class (STC) requirement of 55 (a standard transmission loss vs. frequency contour named for its value at 500 Hz.) was identified to meet the noise reduction requirements at all 1/3 octave bands below 20 kHz. The custom-designed multi-layer "sandwich" panels, which were tested at Riverbank Acoustical Laboratories prior to dome construction, combine 2" of thermal insulating wool and a 6" airspace between two aluminum panels of differing thicknesses (.07" exterior; .19" interior). The custom-sized sandwich panels fit within the approximately 8" deep channels in the dome's structural beams and are enclosed on the interior side of a thin aluminum skin that covers the exterior surface of the dome.

DESIGN OF NOISE-ATTENUATING EJECTOR AIR INTAKE ENCLOSURE



Secondary air for the ejector-powered free jet is entrained through a noise-attenuating low-pressure air intake enclosure. The enclosure is designed to provide required airflow area as well as reduction of the predicted forward quadrant noise generated by the annulus of ejector nozzles. Outdoor air entrained by the ejector flows into the bellmouth through a wall of double-stacked noise-attenuating louvers, each of which consists of a cascade of parallel airfoil-shaped splitter blades filled with sound absorbing material. The remaining walls are designed to match the construction of the dome, acoustically and visually. Noise reduction requirements for the air intake enclosure were specified such that the ejector noise would be reduced to the same level in the community as test nozzle noise after attenuation by dome wall panels.

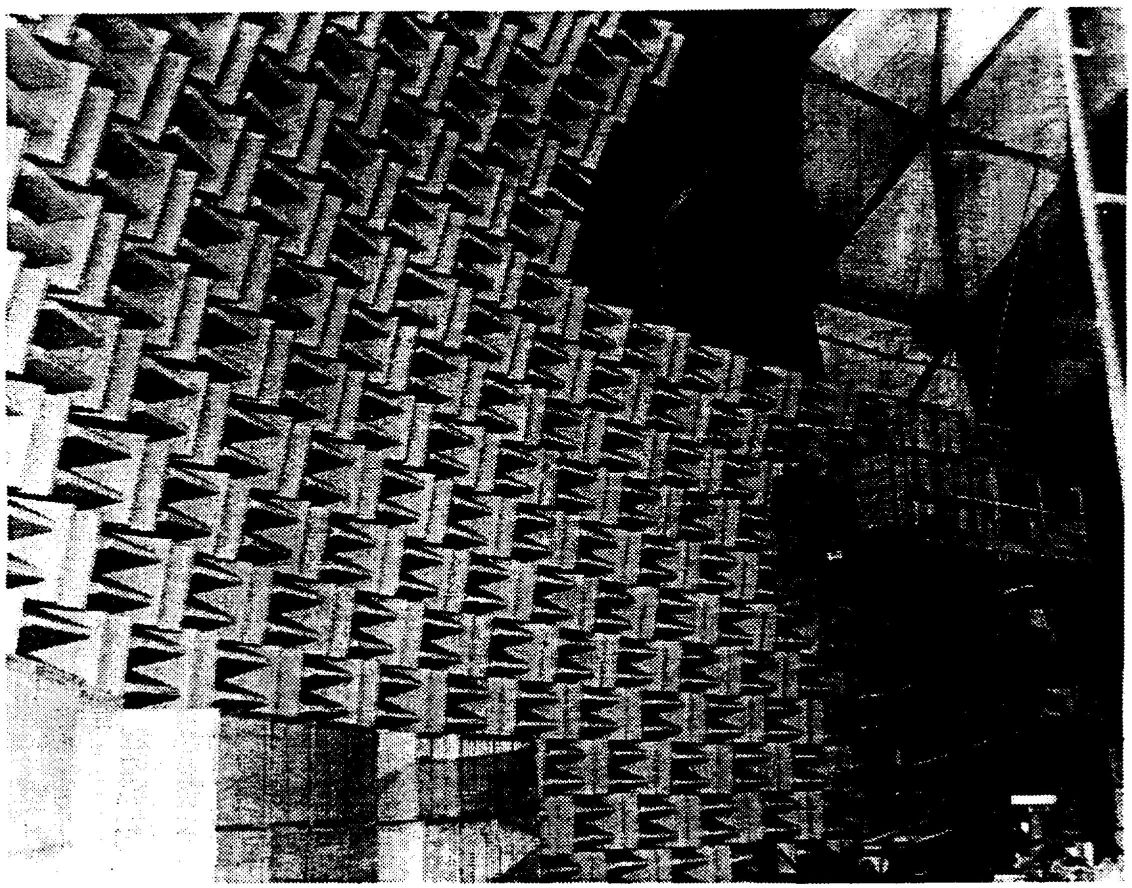
PROCEDURE FOR EVALUATING DOME NOISE REDUCTION PERFORMANCE



COMMUNITY NOISE TEST MEASUREMENT LOCATION

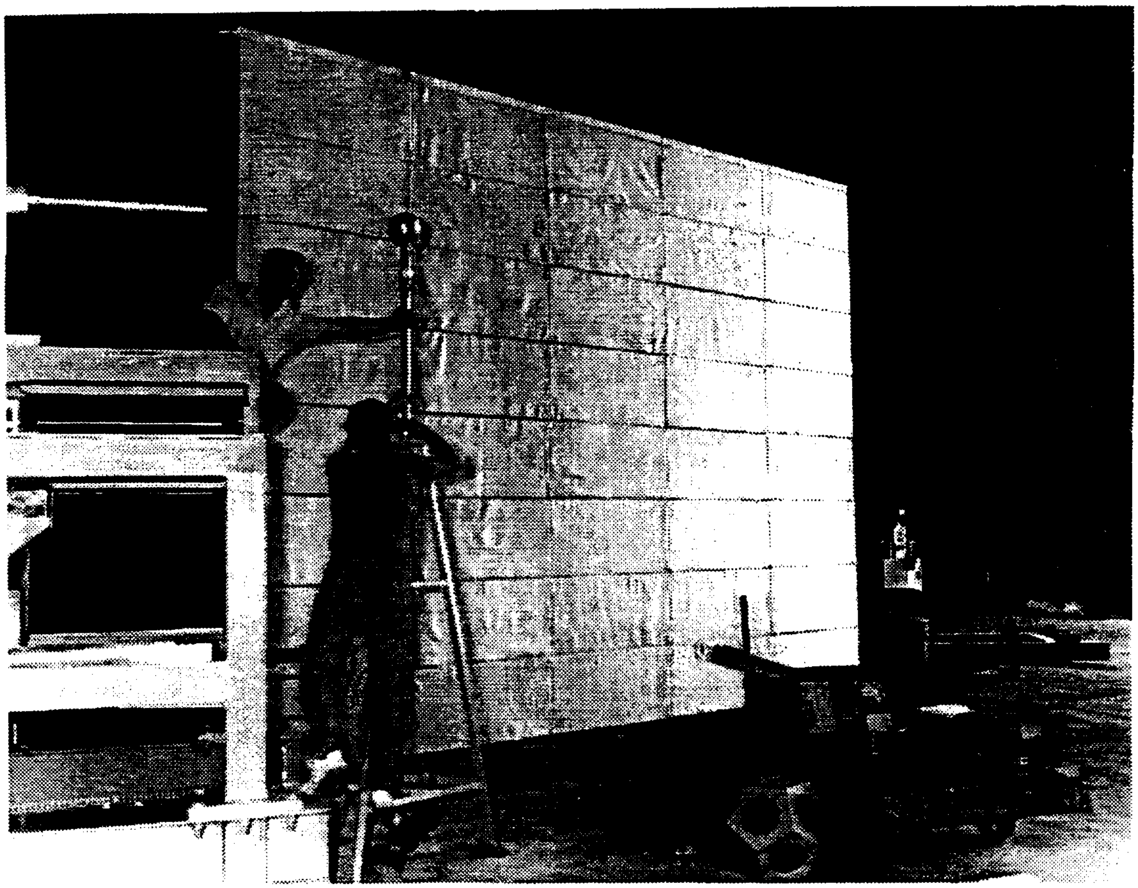
Preliminary results of initial noise reduction measurements conducted during NATR checkout tests in the Spring of 1992 indicate that the wall panels are performing as expected, and no noise complaints have been received since the completion of the dome construction. Detailed community noise tests are currently in progress, using a J85-21B (Lear Jet) engine as sound source. Noise levels will be measured along radial lines between the source and selected communities to identify locations, if any, where noise levels exceed acceptable L_{dn} limits or are grossly out of line with predicted community levels based on inverse square law (including atmospheric attenuation effects). If required, further noise abatement measures may be instituted.

HEMI-ANECHOIC INTERIOR ENVIRONMENT PROVIDED BY COMPREHENSIVE ABSORPTIVE TREATMENT



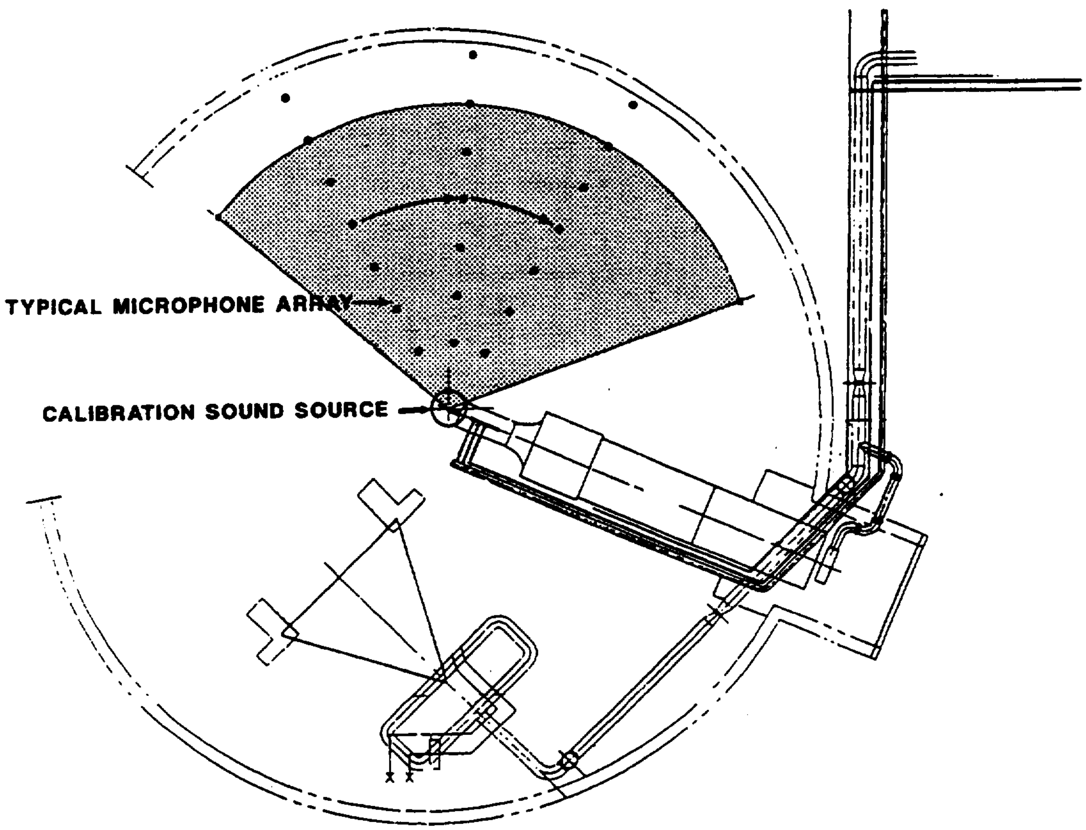
Fiberglass wedge treatment on the entire interior surface of the dome provides a hemi-anechoic interior environment for obtaining the accurate acoustic measurements required to meet research program goals. The 24" wedges are installed on a track system with a 2" airspace between the wedge base and the interior of the dome wall panel. The wedges are fully encased in fiberglass cloth and are held into the frames with 1/2" x 1" hardware cloth on all sloping edges of the wedge peaks. Results of impedance tube tests performed by the wedge manufacturer on the wedge material indicate an absorption coefficient of α = .99 above 125 Hz. Potentially reflective surfaces on internal dome structures such as test hardware, facility plumbing, instrumentation stands, etc., have been covered or shielded with a variety of absorptive materials to ensure the highest quality acoustic environment.

PERFORMANCE MEASURES FOR INTERIOR ACOUSTIC TREATMENT



Extensive checkout tests were conducted during the summer of 1992 to evaluate the interior of the dome structure with respect to a number of accepted performance measures, among them the absorption coefficient of the wedge treatment and the observed behavior of sound with respect to the inverse square law of sound propagation. It is common for a facility of this type to have an inverse square law error with $\sigma = 1$ dB. Three calibration sound sources (high-frequency airball, dodecahedron speaker ball, and starter's pistol) were used to generate broadband and pure tone signals over the frequency range of interest as well as an impulsive signal for time delay analysis.

PROCEDURE FOR PERFORMING ACOUSTIC CALIBRATION OF INTERIOR TREATMENT

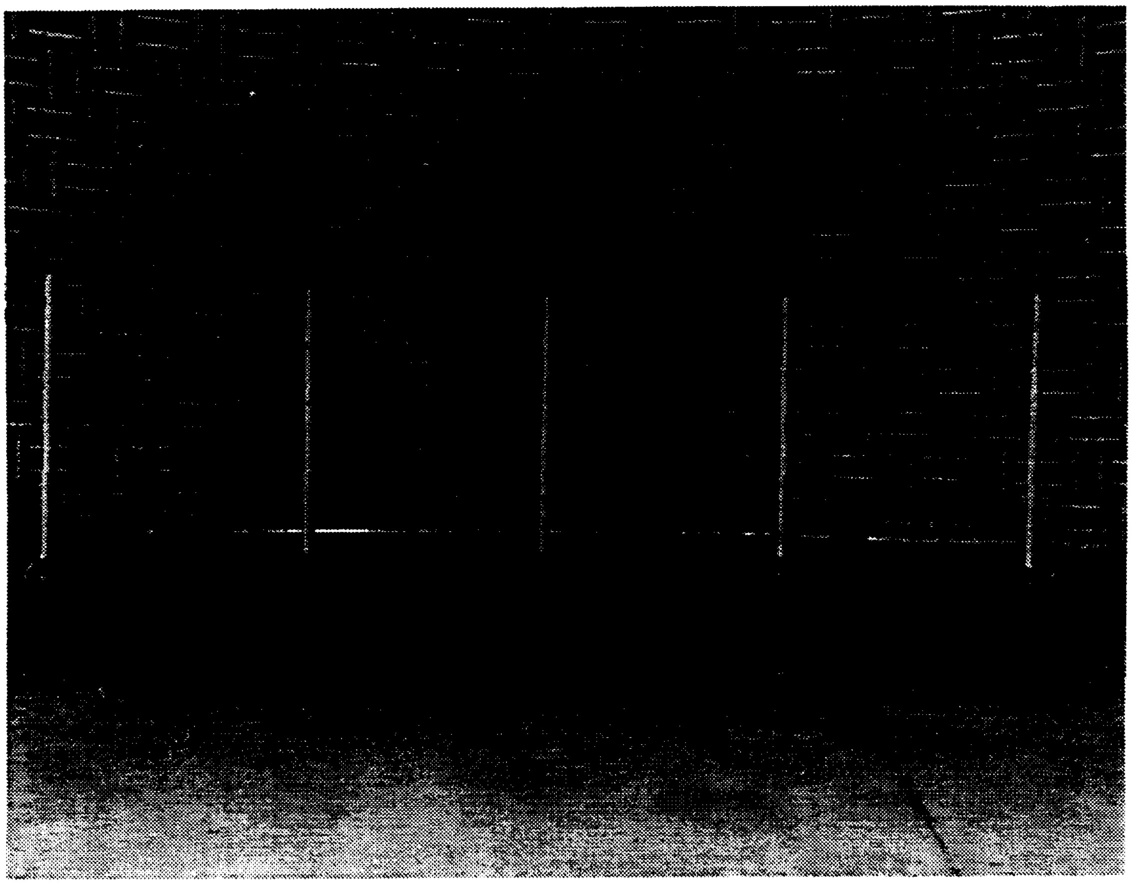


ANECHOIC CHECKOUT TEST

TYPICAL MICROPHONE ARRAYS

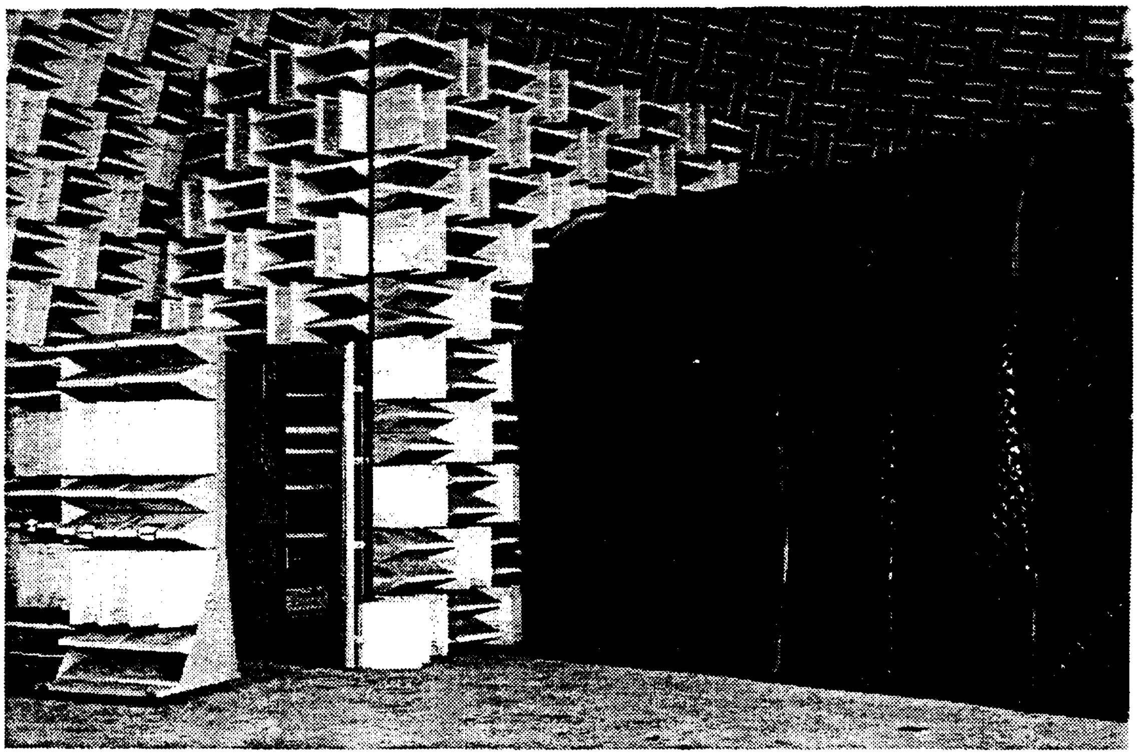
Radial arrays of pole and ground microphones at equivalent solid angles and distances were clocked through the microphone array region in 10° increments to measure direct and reflected sound in radial increments of 6'. Source directivity was also measured, and special tests were conducted to determine whether significant noise was being reflected from the fan opening at the top of the dome or from the wall of the 9x15 Low Speed Wind Tunnel, located about 250' from the center of the dome (through the exhaust opening). Analysis of this data using a variety of signal processing techniques will yield a frequency vs. spatial location map as well as a number of numerical indicators of the acoustic quality of the facility's intended microphone array region. Any sources of acoustically significant reflections will be identified and solutions implemented.

ACOUSTIC INSTRUMENTATION AND DATA ACQUISITION SYSTEMS FOR NATR



Typically, during HSR testing, acoustic measurements are taken with both ground and pole microphones at equivalent solid angles and radial distances. High frequency acoustic signals are measured with a farfield (50') array of pole microphones at centerline height and a nearfield sideline centerline array. Ground microphones are used to acquire low-frequency signals that are free of ground reflections. A 32-channel computerized data acquisition and processing system provides narrow-band and 1/3 octave band spectral analysis with compensation for microphone frequency response/directivity and correction of acoustic data to standard day conditions. This allows for next day turnaround of processed data, providing timely support for test program decision-making.

FACILITY SELF-NOISE LEVELS ALLOW ACCURATE ACOUSTIC MEASUREMENTS



Facility self-noise levels have been maintained at acceptable levels by requiring safety and operational systems to meet strict noise criteria for generated and reflected sound, specifically 20 dB below predicted 1/3 octave band levels for a typical quiet suppressor nozzle. The NATR itself is by design a low-noise system whereby ejector noise is attenuated as it travels downstream through the NATR by absorptive treatment in the walls of the diffuser and plenum sections. The microphone arrays are shielded from radiated aft-quadrant self-noise generated by the annulus of ejector nozzles by a sealed noise-attenuation (STC 54) structure that surrounds the ejector portion of the NATR. Furthermore, new tabbed nozzles are currently being designed and fabricated for the ejector to reduce the off-design screech experienced with the current nozzles. A 40,000 cfm fan at the top of the dome provides the continuous but quiet exhaust that is mandated for safety reasons while the NATR facility is burning gaseous hydrogen fuel during HSR testing.

ACOUSTIC INTEGRITY MAINTAINED DURING FACILITY DESIGN/UPGRADES

- BIRD-RESISTANT HARDWARE CLOTH SCREEN PROTECTS WEDGES WITH MINIMUM ACOUSTIC INTERFERENCE
- ELECTRICAL CONDUIT AND JUNCTION BOXES ARE INSTALLED BEHIND WEDGES
- CUSTOM WEDGED DOORS PROVIDE ACCESS TO ELECTRICAL JUNCTION BOXES
- FACILITY LIGHTING AND VIDEO CAMERA HARDWARE SELECTED FOR LOW FRONTAL AREA
- ACOUSTICALLY UNOBTRUSIVE LIGHTING AND CAMERA INSTALLATIONS ARE RECESSED INTO WEDGES

Acoustic integrity of the facility has been maintained during the ongoing process of new equipment installations and facility modifications by considering each action with regard to its impact on the research quality of the acoustic environment. A good example of this is the recent installation of a bird-resistant hardware cloth screen over the entire interior wedged surface. Facility lighting and video cameras have been selected for low frontal area and are recessed into the wedged interior walls to be acoustically unobtrusive. Electrical conduit and junction boxes were installed behind the wedges, with specially custom-wedged doors for electrical system access. Further facility upgrades and modifications to accommodate new test programs on both PLF and NATR will be accomplished in a similarly acoustically responsible manner.