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Experimental Investigation of an Ejector-Powered Free-Jet Facility

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EXPERIMENTAL INVESTIGATION OF AN EJECTOR-POWERED FREE-JET FACILITY

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SUMMARY

NASA Lewis Research Center's newly developed Nozzle Acoustic Test Rig (NATR) is a large free-jet test facility powered by an ejector system. In order to assess the pumping performance of this ejector concept and determine its sensitivity to various design parameters, a 1/5-scale model of the NATR was built and tested prior to the operation of the actual facility. This paper discusses the results of the 1/5-scale model tests and compares them with the findings from the full-scale tests.

INTRODUCTION

In view of the world market potential and international competition, the development of an updated technology base for high speed civil transports (HSCT) is an important national research objective, which is being addressed under NASA's High Speed Research (HSR) program. The goals for this second-generation supersonic transport include economic viability and environmental acceptabilty. One issue associated with the environmental acceptability of the HSCT is its ability to meet noise level standards, currently assumed to be Federal Air Regulation Part 36 Stage III levels now applied to newly designed subsonic transports. In response to this concern, NASA programs are investigating low speed performance and take-off noise characteristics of advanced low noise nozzle concepts for use on the proposed HSCT (ref. 1). Until recently, the 9- by 15-foot Low Speed Wind Tunnel (LSWT) was the only test facility at NASA Lewis Research Center with the capability for acoustic testing of these new low noise nozzles. Unfortunately, the 9- by 15-foot LSWT is limited to only near-field noise measurements and is also in heavy demand by other research programs.

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 = 4.25 ft) with a design Mach number of 0.30. Shown in figure 1, 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 ft) noise characteristics under conditions simulating forward flight.

Typically, a system of compressors or fans is used to provide the necessary air supply to power a wind tunnel or free-jet. However, there are several disadvantages associated with these systems:

1. High capital expenditure
2. High operating costs
3. Large building needed to house machinery
4. Substantial manpower effort involved in maintenance and operation of equipment

An ejector concept was identified as an alternate means of supplying the required airflow for this free-jet facility. An ejector system has several advantages:

1. Low capital expenditure
2. Low operating costs
3. Ability to use PLF's existing 125 psig combustion air line as the primary airflow supply

The purpose of the NATR ejector system is to augment mass flow. This ejector system provides the total flow necessary to allow testing over a range of free-jet Mach numbers from 0 to 0.30. The NATR is designed to operate at a free-jet Mach number of 0.30 given a maximum primary flow of 100 lb/s. This primary mass flow corresponds to a primary nozzle pressure ratio of 7.5. In order to achieve a free-jet Mach number of 0.30 with 100 lb/s primary flow, a pumping ratio of 2.9 is required. Although many ejector systems operate with the exit static pressure being equal to the ambient pressure, the NATR ejector system at design conditions must overcome a back pressure of approximately 1.25 psi due to the presence of the diffuser section. A failure to overcome this back pressure could result in a failure to augment mass flow.

For ease of discussion, the side-view schematic in figure 2 shows the NATR divided into six sections. The primary stream is supplied through a circular array of choked nozzles (A) and the resulting low pressure in the mixing section causes a "pumping" action that entrains the secondary stream. The constant, annular-area mixing section (B) employs a centerbody structure that also extends through the diffuser. As a result of the momentum exchange and the streamwise vortices in this region, the two streams mix into one subsonic stream. The mixed flow then expands through an annular diffuser (C) and into a settling chamber (D). Once inside the settling chamber, 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 (E) where it achieves a free-jet Mach number of up to 0.30 (F).

Ejectors have been studied extensively with control volume theory and a control volume analysis was considered appropriate for the NATR ejector system (refs. 2 to 5). In the control volume approach, ejector pumping can be calculated from conservation of mass, momentum, and energy using an internal control volume. The ejector pumping ratio can be developed in terms of ejector area ratios (A_s/A_p), flow parameters, and loss parameters (ref. 6). The loss mechanisms associated with ejectors include incomplete mixing and wall friction in the mixing region. The net effect of incomplete mixing in the developed equations can be accounted for in the skewness factor, β, where β is defined as

$$\beta = \frac{\int V^2 \, dA}{\bar{V}^2 A}$$

If ideal mixing has occurred and the velocity profile is uniform, the skewness factor is unity; in a nonuniform flow $\beta > 1$ (ref. 5). A constant-area control volume analysis was performed using a skewness factor of 1.25. As shown in figure 3, the control volume theory predicted that at the maximum primary flow rate (100 lb/s) the necessary pumping ratio is achieved.

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 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, which involved building and testing a 1/5-scale model of the NATR, was initiated. The lessons learned during the 1/5-scale model program were incorporated in the design of the full-scale NATR. The results from the 1/5-scale model program are presented in the following discussion. Comparisons between the performance of the 1/5-scale model and the full-scale facility are also made to address the issue of geometric scaling on ejector operation.

SYMBOLS

A	flow area
D	diameter, in.
H	annulus height, in.
L	length, in.
m	mass flow rate, lbm/s
m_s/m_p	pumping ratio
NPR	primary nozzle pressure ratio, P_{tp}/P_{amb}
P	pressure, psia
X	axial position of primary nozzle array, in.
β	skewness factor
Subscripts:	
amb	ambient conditions
fj	free-jet
h	hydraulic
mr	mixing region
p	primary
s	secondary
t	total

APPARATUS AND PROCEDURE

1/5-Scale Model NATR.—The 1/5-scale model of the NATR was installed and tested adjacent to the existing PLF (fig. 4) in order to take advantage of the 125 psig combustion air system to supply the primary nozzle array. The model of the NATR was designed by scaling (geometrically) the dimensions of the full-scale by 0.20 (fig. 5). The primary flow rate was measured using an unchoked American Society of Mechanical Engineers (ASME) flowmeter. Slightly upstream of the primary nozzle array, the total pressure (P_{tp}) was calculated based on the pipe wall static pressure measurement and Mach number. The primary flows for this test varied between 2 and 5 lb/s (corresponding to primary nozzle pressure ratios between 3.5 and 10.). The primary array consisted of 30 equally spaced nozzles supported by two side flanges. For ease of fabrication and cost considerations, the model was constructed from several different materials (i.e., wood, metal, plexiglass). The annular mixing region and diffuser incorporated an outer shell structure and a centerbody. This centerbody was connected to the outer shell structure by means of six radial splitters (fig. 5). Wall static pressures were measured along the outer shell and centerbody surfaces of the mixing region and the diffuser. The outer shell of the diffuser was made of plexiglass to allow for flow visualization studies. The plenum contained a honeycomb and screen combination intended to remove large scale disturbances and provide uniform flow at the exit of the free-jet nozzle. Four circumferential wall static pressures were measured in the plenum. The free-jet nozzle was instrumented with one row of longitudinal wall static pressure taps and three stations of four circumferential wall static pressure taps. A rake, extending completely across the diameter of the free-jet nozzle, measured total temperature and total pressure (fig. 6). A boundary layer rake was also located at the exit station of the free-jet nozzle in order to determine the boundary layer thickness.

In order to address the anticipated issues, the model was designed to allow configuration flexibility. The first objective of the program was to verify the pumping capability of the ejector system when subjected to a back pressure. The second objective was to determine the ejector system's sensitivity to the axial position, vertical alignment, and angular orientation of the primary nozzle array. 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. This series of tests involved varying the axial, vertical, or angular position of the primary nozzle array and varying the primary nozzle flow rate ($2\ \text{lb/s} < m_p < 5\ \text{lb/s}$). As mentioned previously, the primary flow rate, m_p, was measured using an ASME flow meter. The secondary mass flow, m_s, was determined by calculating the total mass flow through the free-jet nozzle (based on the P_t and T_t values measured by the exit rake) and subtracting m_p.

The third objective—determining the quality of the flow at the free-jet exit—involved varying the locations of the honeycomb and the screen. In order to accomplish this, the plenum was made of a series of 3-in. thick 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. This series of tests involved positioning the exit rake at four different circumferential locations (fig. 6) and varying the primary nozzle flow rate at each location ($2\ \text{lb/s} < m_p < 5\ \text{lb/s}$). The velocity profile across the exit of the free-jet nozzle was determined and the percent velocity distortion was computed to assess the flow quality.

The last objective was to determine the effect of inlet blockage caused by a tunnel that enclosed the immediate area around the primary nozzle array. In the full-scale facility, the purpose of this tunnel is to shield the microphone array from the noise that is generated by the ejector system of the NATR. A scaled version of this tunnel was added to the model. This tunnel caused all the secondary flow to be entrained from the front only. To determine the effect of the tunnel on the system performance, the primary nozzle flow rate was varied ($2\ \text{lb/s} < m_p < 5\ \text{lb/s}$). The pumping ratio was determined and the flow quality was assessed.

Full-Scale NATR.—Like the 1/5-scale model, the full-scale NATR took advantage of the existing 125 psig combustion air system to supply the primary flow. Similarly, the primary mass flow was measured using an unchoked ASME flow meter. A P_{tp} upstream of the primary nozzle array was determined using the same method as in the scale model program. The primary flows available for the facility were between 50 and 100 lb/s (corresponding to primary nozzle pressure ratios between 3.5 and 8).

In the full-scale facility, (unlike in the scale model), the annular mixing region, the diffuser, the six radial splitters and the plenum surfaces were treated with an acoustic absorber 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 Kevlar™ material, held in place by a wire screen and covered by a perforated plate.

The instrumentation of the full-scale facility included wall static pressure taps along the outer shell and centerbody of the annular mixing region and 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/temperature rakes and three boundary layer rakes were located around the circumference of the free-jet nozzle exit (fig. 7).

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 axial positions selected for study corresponded to those previously investigated by the 1/5-scale model program. The axial position was set and the primary flow rate was varied (50 lb/s < m_p < 100 lb/s). As with the 1/5-scale model, the secondary mass flow was determined by calculating the total flow at the free-jet nozzle exit (using the values measured by the four P_t/T_t rakes) and subtracting the primary flow. The four total pressure/temperature rakes at the free-jet nozzle exit were also used to determine the velocity distortion levels.

RESULTS AND DISCUSSION

1/5-Scale Model NATR.—Figure 8 shows the pumping ratio, m_s/m_p, as a function of primary nozzle pressure ratio (P_{tp}/P_{amb}) for several primary nozzle axial positions. The axial position, X, is nondimensionalized by the height of the mixing region annulus, H_{mr}. These performance results indicate the design pumping ratio of approximately 2.9 at a 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 1.25 psi back pressure and achieve the necessary levels of pumping.

All the curves demonstrate an asymptotic nature with respect to pumping ratio. As the primary mass flow is increased a point is reached at which the secondary area becomes choked and no additional flow can be entrained. 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. By cross-plotting the data at each axial station, the primary nozzle pressure ratio necessary to achieve a free-jet Mach number of 0.30 was determined and is shown in figure 9. Again, the optimum axial location is somewhere between $X/H_{mr} = -3.0$ and $X/H_{mr} = -2.0$. This result is the same at the other Mach numbers of interest (e.g., 0.15, 0.20, and 0.25). The inlet bellmouth station ($X/H_{mr} = -2.62$) was chosen as the optimum axial location for the primary nozzle array.

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 figure 10. The data show that the ejector performance is very sensitive to the 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. Figure 11 presents the results of varying the nozzle angle. As evidenced, any angular misalignment caused a downward shift in the pumping performance curve. In general these results were valuable when specifying the allowable tolerances of the primary nozzle array installation for the full-scale NATR.

The second series of tests involved determining the flow quality of the free-jet exhaust. Figure 12 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 percent at three of the four circumferential positions. The distortion calculated at 90° was approximately 3 percent higher than the others.

Figure 13 shows the exit rake total pressure nondimensionalized by the ambient static pressure profiles for the four 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° 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 (fig. 5). The high distortion levels at the 90° rake position are believed to have been caused by the interference of these flanges with the natural entrainment of the secondary stream.

Figure 14 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. In figure 15 the velocity distortion for the rake positioned at 90° 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 percent. With the tunnel installed, the distortion levels are lowered to approximately 1.5 percent. 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.

<u>1/5-Scale Model/Full-Scale NATR data comparison.</u>—Figure 16 shows the pumping ratio versus the NPR ratio for both the 1/5-scale model and the full-scale NATR. The results show that the $X/H_{mr} = -2.62$ 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 asymptotic nature of the curves with respect to the pumping ratio is evident in both sets of data. 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 percent lower than the 1/5-scale model.

As mentioned previously, a constant-area control volume analysis was performed on this ejector configuration. In figure 17, the open symbols represent the 1/5-scale model data and the solid symbols represent the full-scale facility data. The results of the control volume analysis, assuming different values of β are also shown. Note that the actual facility data agrees best with the control volume analysis which assumed $\beta = 1.25$. The 1/5-scale model data agrees best with the control volume analysis that assumed $\beta = 1.15$. To explain this, closer consideration of the skewness factor is necessary. The skewness factor is intended to account primarily for the skewness of the velocity profile at the exit of the mixing region because of incomplete mixing. The skewness factor is considered a function of the geometry of the ejector system. However, it is acceptable to assume that fluid dynamic characteristics of the ejector system (e.g., friction losses, boundary layer growth, Reynolds number) are also accounted for in the value of β used in the control volume equations. Reference 7 notes that mixing significantly affects pumping while wall friction losses tend to be negligible for mixing ducts with length-to-diameter ratios of 1 or less. In the case of the full scale NATR, the ratio of the length to the hydraulic diameter of the mixing region, L_{mr}/D_{hmr}, is 3.8. In addition to this large L_{mr}/D_{hmr}, the wetted surface area is a perforated plate—another source of losses due to wall friction. By design, the 1/5-scale model had the same L_{mr}/D_{hmr}, but the wetted surface area of its mixing region was smooth, resulting in lower friction losses and, therefore, higher pumping.

Figure 18 shows the velocity distortion levels measured by the four P_t/T_t rakes at the exit of the full-scale free-jet nozzle. These rakes were located at 45°, 135°, 225°, and 315°. The plot shows all velocity distortion levels below 5 percent similar to three of the four scale model rake positions.

CONCLUSIONS

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 NPR 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 percent at all circumferential stations investigated except 90° where the level was approximately 8 percent. 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° position to 1.5 percent.

The full scale facility achieved the required pumping ratio to attain a free-jet Mach number of 0.30. The pumping performance of the 1/5-scale model exceeded that of the full-scale facility by approximately 15 percent at the design NPR. The control volume analysis which assumed $\beta = 1.25$ agreed best with the actual facility data whereas the 1/5-scale model agreed best with $\beta = 1.15$. The lower value of β corresponding to the scale model data indicates that the scale model had better mixing and therefore higher pumping; the opposite is true for the actual facility. The β parameter is primarily a function of the ejector geometry and the mixing efficiency; but, it can also be considered a function of the fluid dynamics of the flow (e.g., friction losses, boundary layer thickness, Reynolds number). Since, geometrically speaking, the scale model and the actual facility are the same, the explanation for the different values of β associated with the experimental data is felt to lie in their different fluid dynamic characteristics. The net effects of the fluid dynamics of the flow 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. The higher β value associated with the full-scale facility indicates incomplete mixing and therefore lower levels of pumping.

ACKNOWLEDGMENTS

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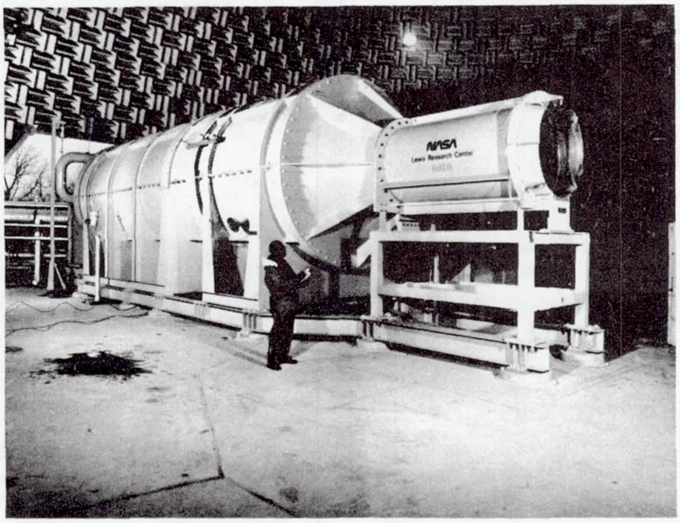

Figure 1.—Nozzle Acoustic Test Rig (NATR) located inside dome.

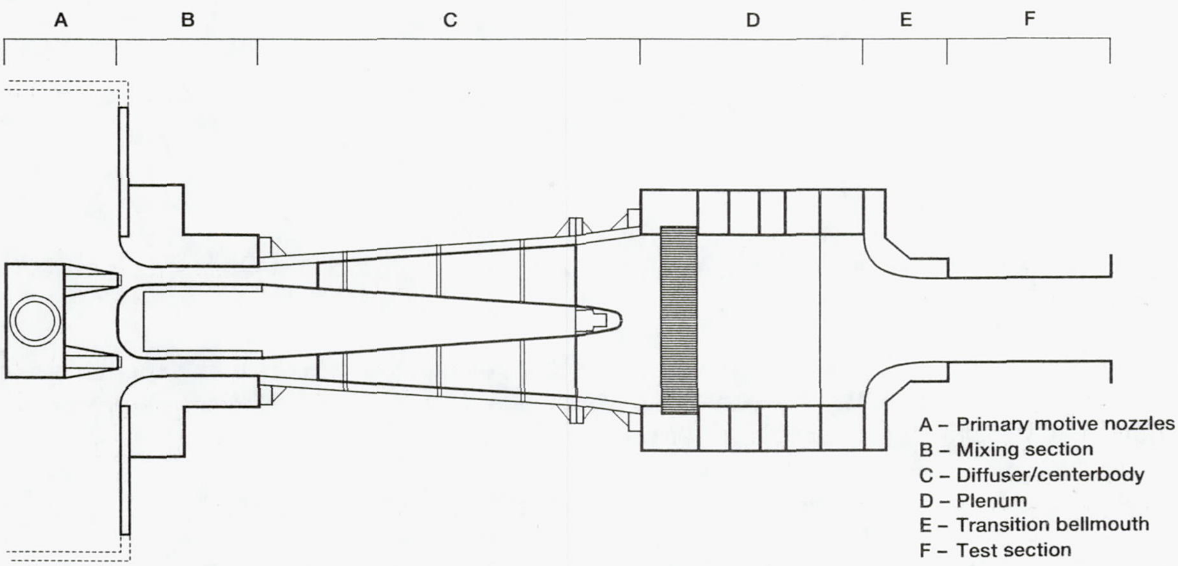

Figure 2.—Schematic of NATR.

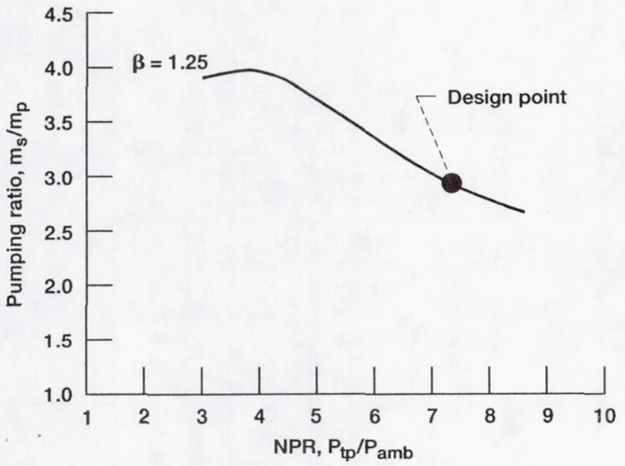

Figure 3.—Control volume theory results.

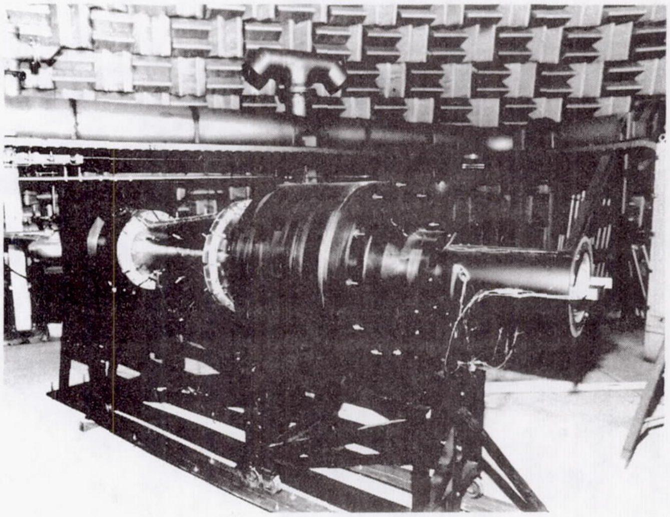

Figure 4.—1/5-Scale model installation.

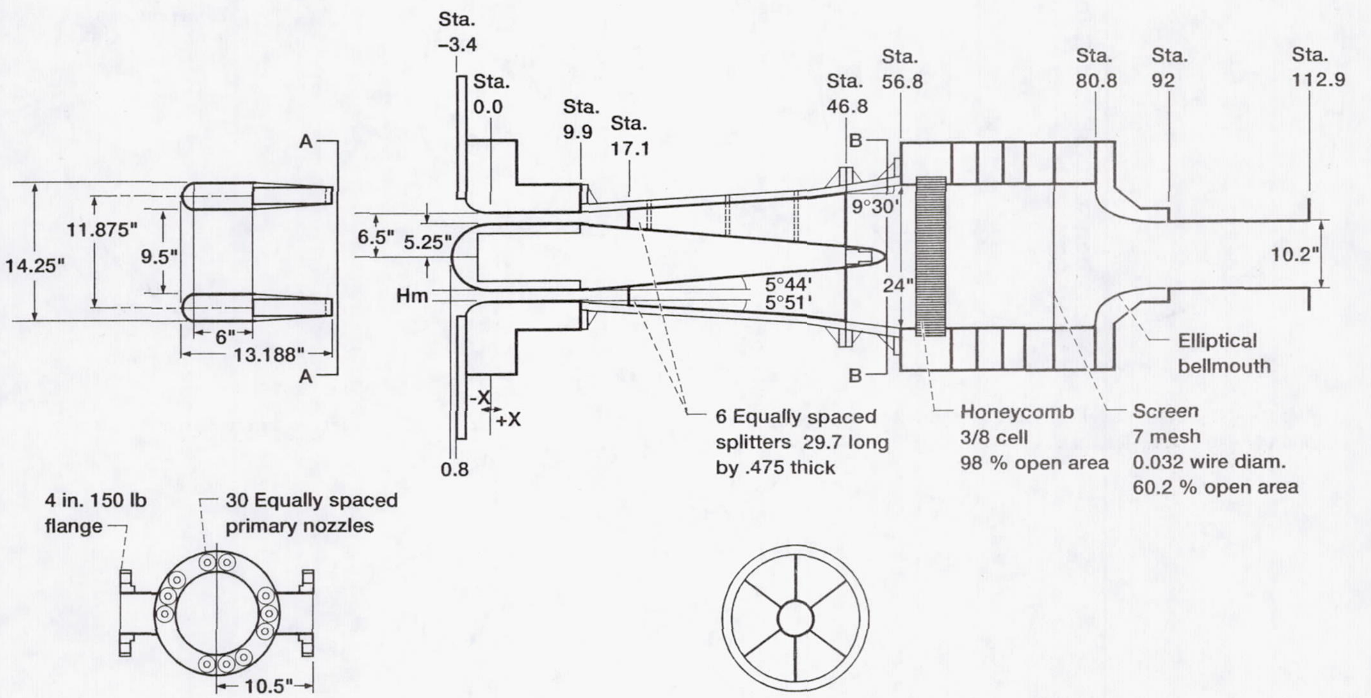

Figure 5.—Geometric details of 1/5-scale model.

Probe	R/R_{fj}
1	0.9575
2	.8661
3	.7637
4	.7071
5	.6455
6	.5000
7	.2886
8	0.0
9	−.2886
10	−.5
11	−.6455
12	−.7071
13	−.7637
14	−.8661
15	−.9575

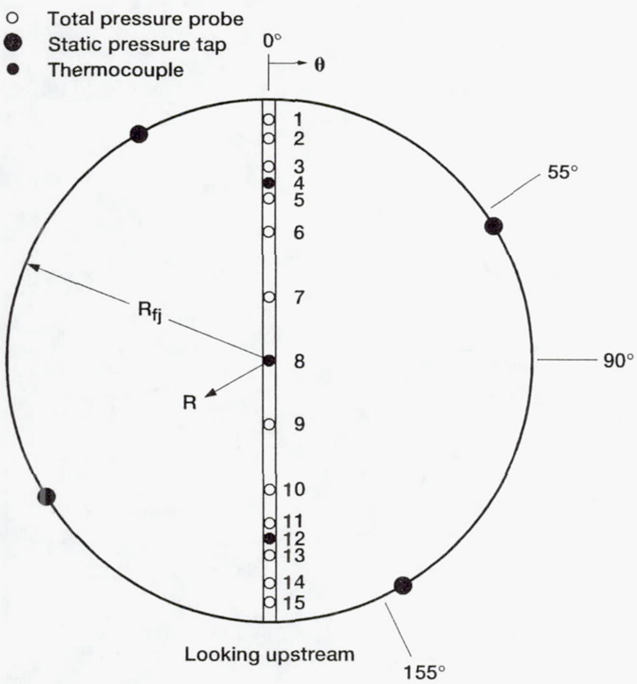

Figure 6.—1/5-Scale model pressure and temperature instrumentation at exit of free-jet nozzle.

Total Press/Temp Rake		Boundary Layer Rake	
Probe	R/R_{fj}	Probe	R/R_{fj}
1	0.9679	1	0.9965
2	.9004	2	.9894
3	.8540	3	.9788
4	.8272	4	.9646
5	.7464	5	.9469
6	.6551	6	.9256
7	.6366	7	.9008

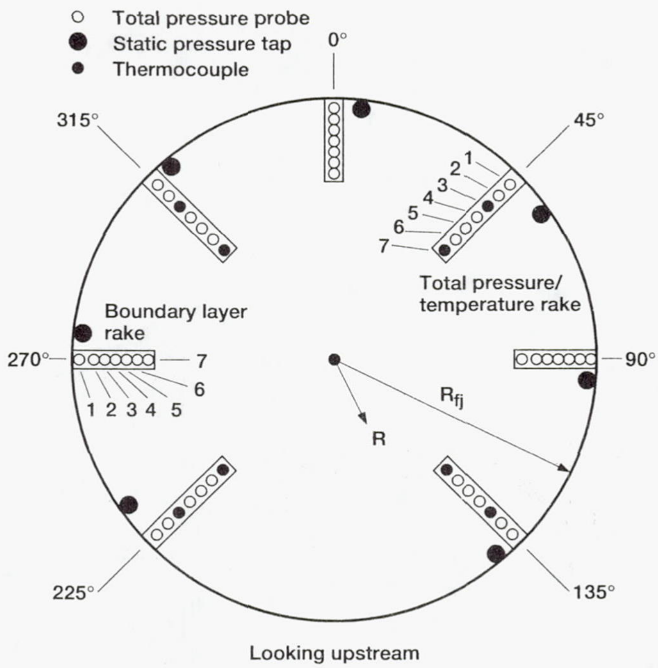

Figure 7.—Full scale NATR pressure and temperature rakes at exit of free-jet nozzle.

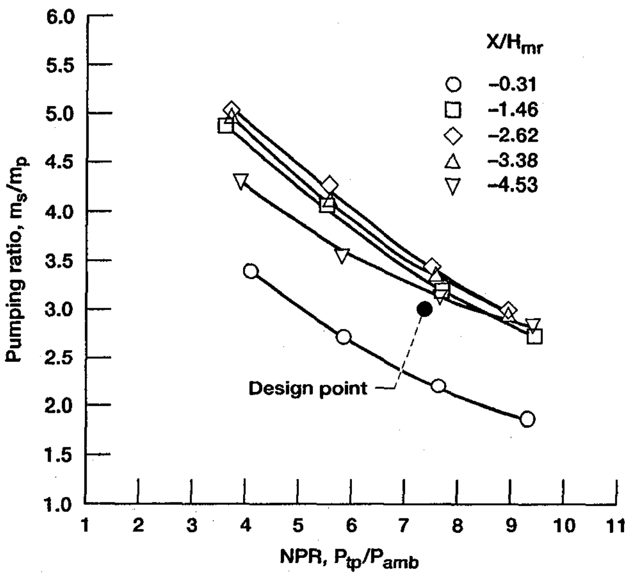

Figure 8.—Effect of primary nozzle axial position on pumping performance of the 1/5-scale model of NATR.

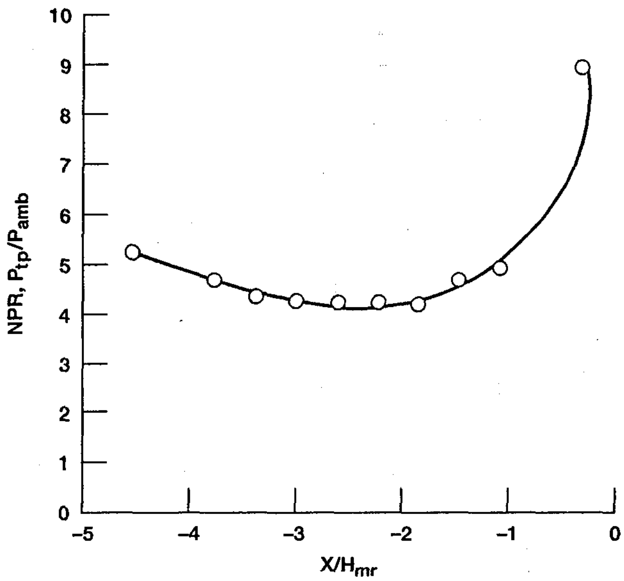

Figure 9.—Primary nozzle pressure ratio as a function of primary nozzle axial position (free-jet Mach No. = 0.3).

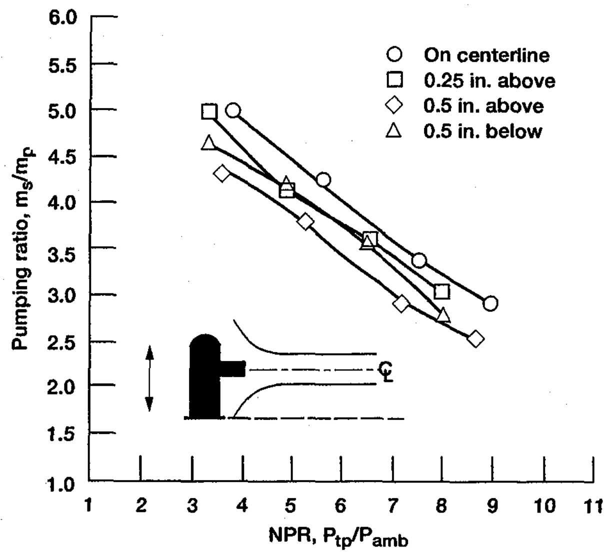

Figure 10.—Effect of primary nozzle vertical position on pumping performance of the 1/5-scale model NATR.

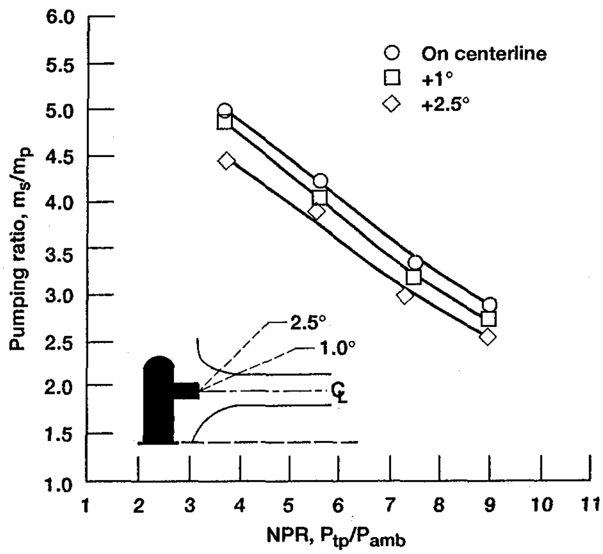

Figure 11.—Effect of primary nozzle angular orientation on pumping performance of the 1/5-scale model NATR.

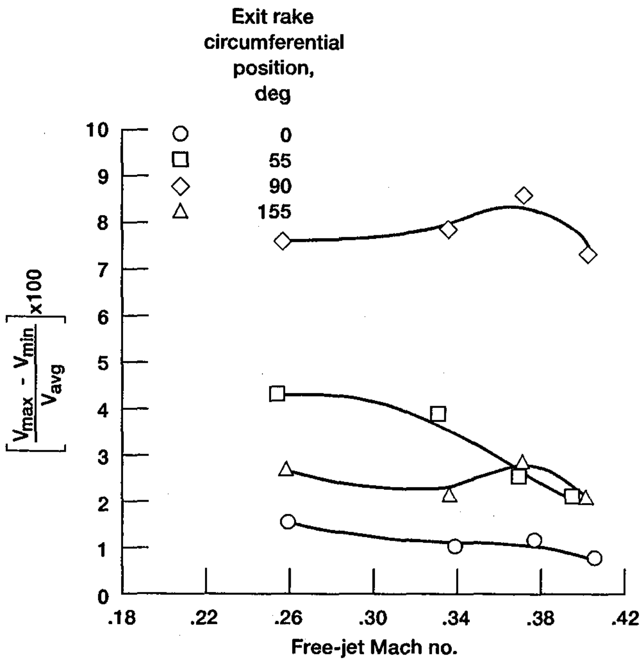

Figure 12.—Velocity distortion level vs. free-jet Mach number for the 1/5 scale model NATR.

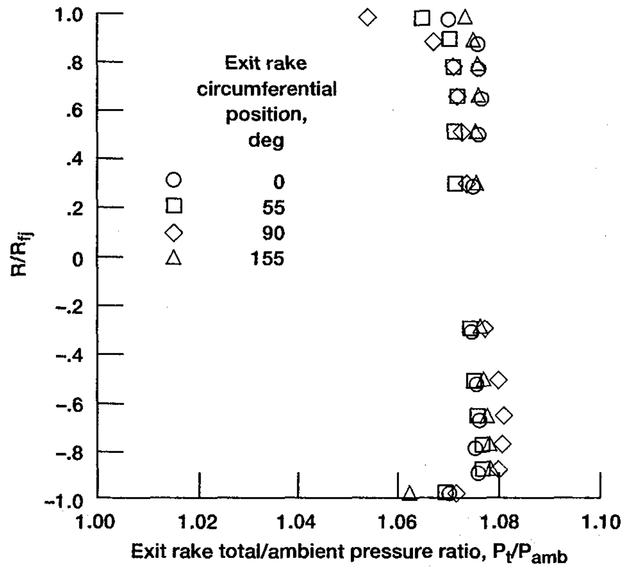

Figure 13.—1/5-scale model total pressure ratio profiles for various exit rake circumferential positions (free-jet Mach no. = 0.30).

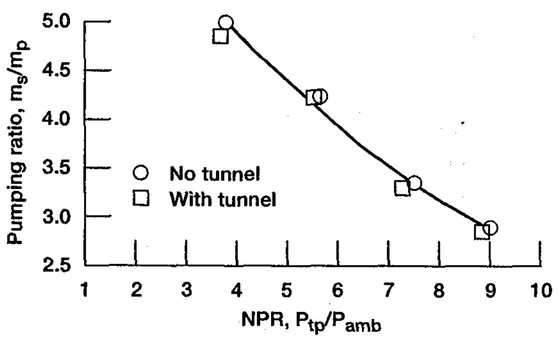

Figure 14.—Effect of inlet tunnel on pumping performance of the 1/5-scale model NATR.

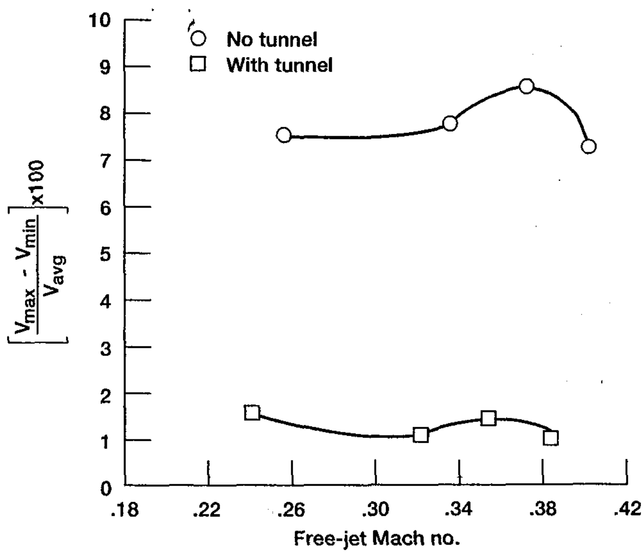

Figure 15.—Effect of inlet tunnel on velocity distortion level for 90° position of 1/5-scale model NATR.

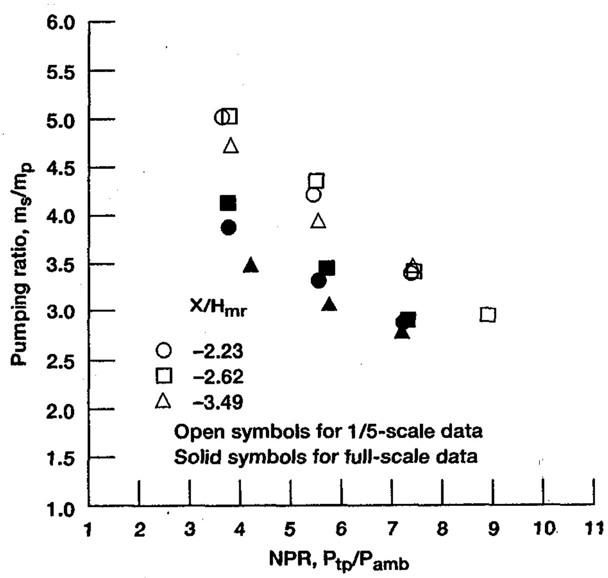

Figure 16.—Comparison of pumping performance for 1/5-scale model and full-scale NATR.

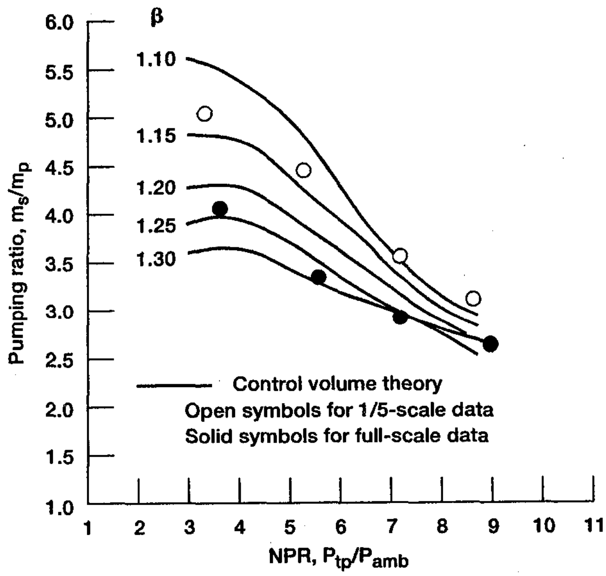

Figure 17.—Comparison of 1/5-scale model and full-scale facility data to control volume theory prediction.

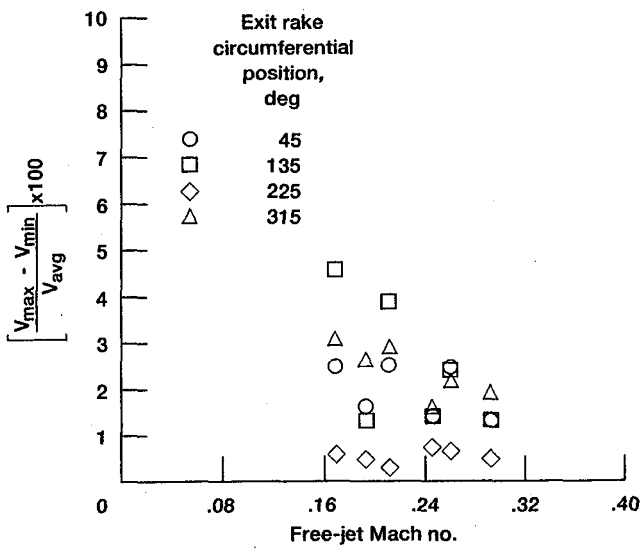

Figure 18.—Velocity distortion level vs. free-jet Mach number for the full-scale NATR.

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13. ABSTRACT ***(Maximum 200 words)***
NASA Lewis Research Center's (LeRC) newly developed Nozzle Acoustic Test Rig (NATR) is a large free-jet test facility powered by an ejector system. In order to assess the pumping performance of this ejector concept and determine its sensitivity to various design parameters, a 1/5-scale model of the NATR was built and tested prior to the operation of the actual facility. This paper discusses the results of the 1/5-scale model tests and compares them with the findings from the full-scale tests.

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