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Development of a Telescoping Vaned Exhaust Nozzle for the ASTOVL LiftFan™ Application

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ABSTRACT

A discussion on the development of a Telescoping, Vaned, Exhaust Nozzle (TEVEN) is presented. This nozzle was challenged to meet the thrust vectoring requirements of an Advanced Short Takeoff and Vertical Landing (ASTOVL) aircraft. The nozzle underwent a development process from concepts to detail design using computational flow analyses and from subscale performance verification tests to full-scale hardware design. The LiftFan™ nozzle is capable of providing a pitch vector range of about 80 degrees from up to 20 degrees forward to 60 degrees aft. In addition, a set of post exit yaw doors provide ± 10 degrees yaw while maintaining a relatively high performance at all operating conditions. Further, the nozzle is axially compact, to be stowable in very short length (L/D < 0.3), while efficiently converging the upstream nozzle flow from an annular cross section to a "D" shape at the nozzle exit. The discussion includes a review of various nozzle concepts, viscous flow analyses, and results from 1/3 scale nozzle model tests conducted at NASA LeRC Powered Lift Facility (PLF) in 1994.

INTRODUCTION

Recently, there has been considerable discussion in the media about the cost reduction by the Pentagon in the purchase of military hardware by concentrating on the affordable aircraft that meet the requirements of all the military services. This led to JAST (Joint Advanced Strategic Technology) program efforts to evaluate the technology related to aircraft and weapon systems hardware, which can be developed jointly by the U.S. Air Force, Navy, and Marines. The studies have concluded that the development costs of a new generation aircraft can be significantly reduced if its various versions, suited for different mission objectives, can be designed with many common components. The Navy and the Marines have long been pushing for STOVL capability and have funded several technology efforts over the past decade and as a result, several STOVL aircraft systems have been pursued. This effort can be categorized into three types: lift plus cruise system, direct lift system, and the LiftFan™ cruise engine combinations. Power plant arrangements in such aircraft concepts have been varied as well, and include, for example, wing mounted lift fans, a multiplicity of separate lift engines, thrust vectoring lift/cruise engines, etc., and various combinations of these.

The development efforts on the vertical and/or short takeoff and landing aircraft have been going on since the 1950s. Many different aircraft concepts have been proposed and technology demonstrated and yet only a few aircraft have moved beyond the development/prototype stage: the well-known British Harrier and its derivatives, and the Bell/Boeing tiltrotor V-22. Nevertheless, there have been numerous reports written on various aspects of technology related to such aircraft and include study of lift engine, lift/cruise engine, tilt wing configurations, and developments of components. With respect to the development of nozzles, there has been exhaustive research on ground proximity effects, nozzle location and different conceptual designs for vectoring thrust. Kentfield* reviewed and discussed earlier work on the vectoring nozzles for different jet-Lift applications. Further discussion and test data** on several variations of hooded nozzles with and without venting is available.

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* Kentfield, J. A. C., "Nozzles for Jet-Lift V/STOL Aircraft," *Journal of Aircraft*, July-Aug 1967, Vol. 4, No. 4, pp 283-291.

** Esker, D. W., "Ground Tests of a 'D' Shaped Vented Thrust Vectoring Nozzle," NASA CR-13959, Oct. 1976.
Rolls, L. S., and Aoyagi, K., "Experimental Investigations of Thrust Vectoring Systems for VTOL Aircraft," AIAA Paper 77-805, July 1977.
Federspiel, J. F., "Static Test of a Large Scale Swivel Nozzle Thrust Deflector," AIAA Paper 79-1285, June 1979.
Rosenberg, E. W., and Esker, D.W., "Development of the 'D' Vented Thrust Deflecting Nozzle," AIAA Paper 80-1856, August 1980.

McCardle et al.* discuss several ventral nozzle configurations used for vectoring flow from the lower surface of the fan duct of an engine. The ventral nozzles also use the cascade vanes, but the reasonable vectoring performance is limited to 30 degrees. Further, the nozzle exit flow variation is unacceptable for typical cruise engine requirements. The LiftFan™ nozzle to be discussed below has a significantly different flow, thrust vectoring, and nozzle installation requirements.

The Shaft-Powered LiftFan™/Cruise Engine System concept was invented by Lockheed as an innovative way of increasing the thrust of the cruise engine without creating an unacceptable footprint or oversizing the engine. The LiftFan™, which operates only during STOVL operation, is connected to the cruise engine via a clutch engagement on a drive shaft. The Telescoping, Vaned, Exhaust Nozzle, designated as TEVEN, was originally developed for the STOVL version of the U.S. Strategic Supersonic Fighter (SSF), the predecessor to the current Joint Strike Fighter (JSF). Allison was awarded a contract to develop a complete LiftFan™ system concept along with a vectoring nozzle and then to build a Large Scale Propulsion Model (LSPM) LiftFan™ demonstrator. This successful, near full-scale ASTOVL propulsion unit was developed and tested in 1994-95.

NOZZLE DESIGN

The function of the exhaust nozzle for the LiftFan™ is to efficiently convert the energized airflow passing through the LiftFan™ into thrust, which may at pilot's control be vectored in a specified direction. The annular LiftFan™ flow entering the exhaust nozzle is accelerated and expanded to ambient exit conditions while being turned through a vector angle. In addition, the nozzle geometry hardware should be mechanically simple and feasible, and must be stowable in the aircraft fuselage as shown in Figure 1. On the left, a schematic of an Allison Shaft Driven Lift Fan with exhaust nozzle vectored 60 degrees aft from vertical is shown. This nozzle was designed to meet thrust vectoring requirements, which included a vectoring range of 80 degrees (pitch) from a 20 degree forward vectoring to 60 degree aft vectoring from vertical, and yaw vectoring range of 20 degrees (± 10 degrees). In addition, the nozzle must be axially compact to be stowable within the aircraft fuselage height (axial length to LiftFan™ diameter ratio of 0.3).

Figure 2 illustrates the basic elements of the nozzle, which consists of a rapidly convergent transition section, a set of stacking hoods covering a vectoring range of 40 degrees to 60 degrees, a set of exit guide vanes in a D-shaped vane box to have additional vectoring capability of ± 20 degrees. Thus, a combination of movable vanes and telescoping hoods allows a forward vectoring of 20 degrees plus an aft vectoring up to 20 degrees in addition to flow vectoring by the hoods. For yaw vectoring capability, a set of two post deflector doors attached to each flat side wall of the D-shaped vanebox is used. Another important element of the nozzle is a unique low-separation centerbody, which directs the flow efficiently through the cascade vanes.

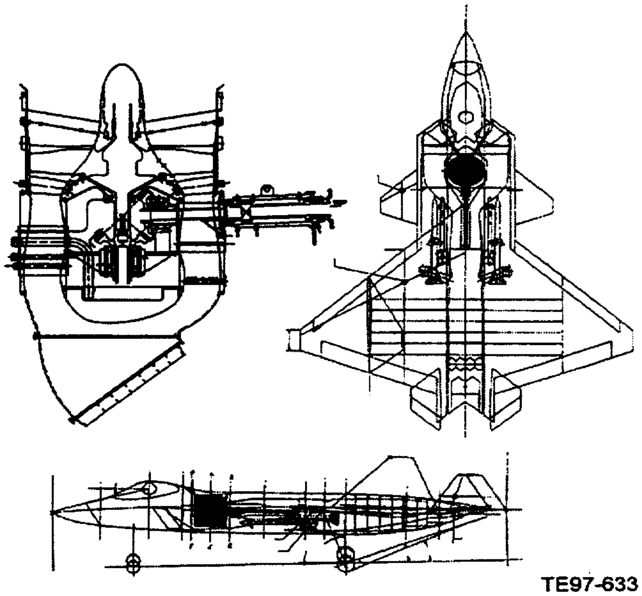

Figure 1: Shaft Driven LiftFan™ engine with Lockheed's version of SSF aircraft

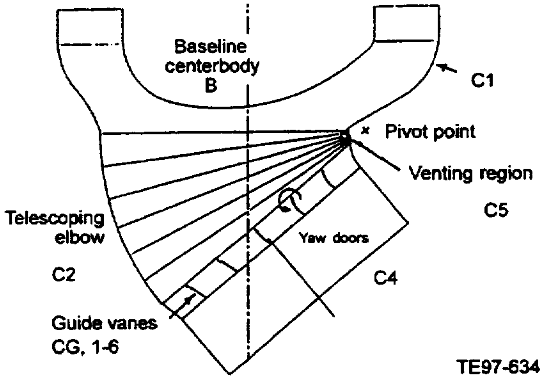

Figure 2: Schematic of TEVEN nozzle design

The preliminary design of the TEVEN nozzle was based on Allison's engineering experience data base on swivel nozzles with vanes, and the cascade vane designs used in commercial thrust reversers. Several concepts were developed to meet the STOVL nozzle requirements, and were evaluated based on aerodynamic performance, cost, mechanical design, and manufacturing complexity. Based on this trade study, the current TEVEN nozzle was selected.

CFD ANALYSIS

Due to the three-dimensional nature of the exhaust nozzle flow, a significant portion of the nozzle was designed using computational fluid dynamics (CFD) analysis. The design process consisted of analyzing a preliminary nozzle design and successively analyzing the

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* McCardle, J. G., and Esker, B.S., "Performance Characteristics of a Variable-Area Vane Nozzle for Vectoring an ASTOVL Exhaust Jet up to 45°," AIAA Paper 93-2437, June 1993.

modified nozzle designs, which provide improvements in flow field as well in predicted Cd and Ct values. The modifications included improved surface contours, high performance cascade vane designs, venting regions, and elimination of overexpanded exhaust plumes.

The ADPAC code developed by Allison for NASA Lewis Research Center was used to analyze TEVEN nozzle configurations. This code solves full three-dimensional Navier-Stokes equations with an algebraic turbulence model. The flow-field analysis grid is generated using GRIDGEN, as shown in Figure 3. Depending on the configuration, up to 1.2 million grid points were used in the solution. Figure 4 presents a midsection fore-aft cut of Mach number contours obtained on a preliminary nozzle design. Since a nozzle with thrust post pushed as far forward as possible was desired, a number of designs were developed to study the effect of nozzle exit offset on the aerodynamic performance as well as on the upstream distortion, The geometry in Figure 4 was found to have an unacceptable upstream flow distortion. As this parameter is critical to the LiftFan™ design, an optimum offset configuration was generated. The geometry was analyzed at different vector settings, the most important being the 90-degree unvectored configuration. Generally, a configuration was first selected based on a 90-degree flow-field analysis and then analyzed at other vector settings. Figure 5 presents Mach number contours about a final nozzle design set for 60 degrees of flow vectoring from vertical. The analysis of this "30-degree" vector position provided additional information on vane setting angles to get the flow in the desired direction. Figure 5 indicated that the flow in the vicinity of outermost cascade vane accelerated around the vane to supersonic speeds and resulted in a performance degradation. During the subsequent nozzle tests, a significant loss reduction was achieved by trimming each vane to an optimum setting angle. The flow analysis also indicated a separated flow region on the centerbody surface. Subsequently, a three-dimensional pointed centerbody design known as "Whale Tail" was developed and tested. It indicated that the flow separation accounted for at least 1 to 2% loss in nozzle performance.

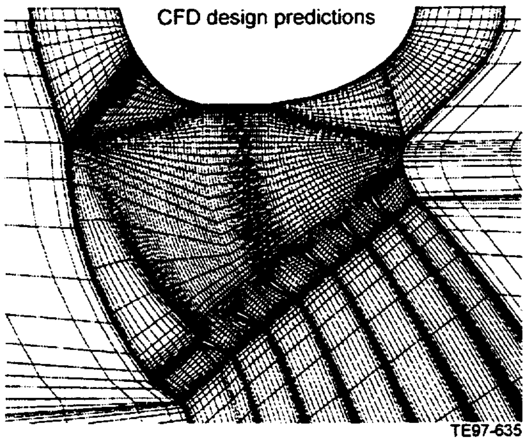

Figure 3: Typical LiftFan™ nozzle analysis grid: grid generation using GRIDGEN code

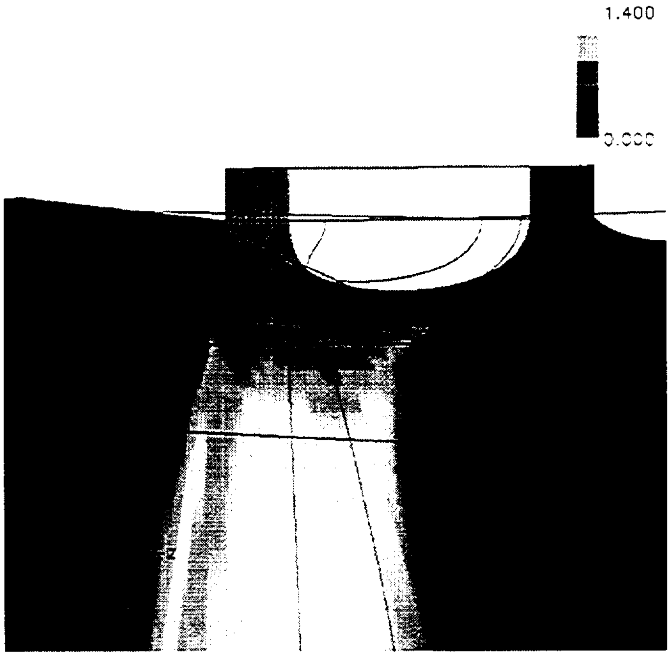

Figure 4: Mach number contours: initial configuration - NPR = 2.5, midsection fore-aft cut, 90-degree vector

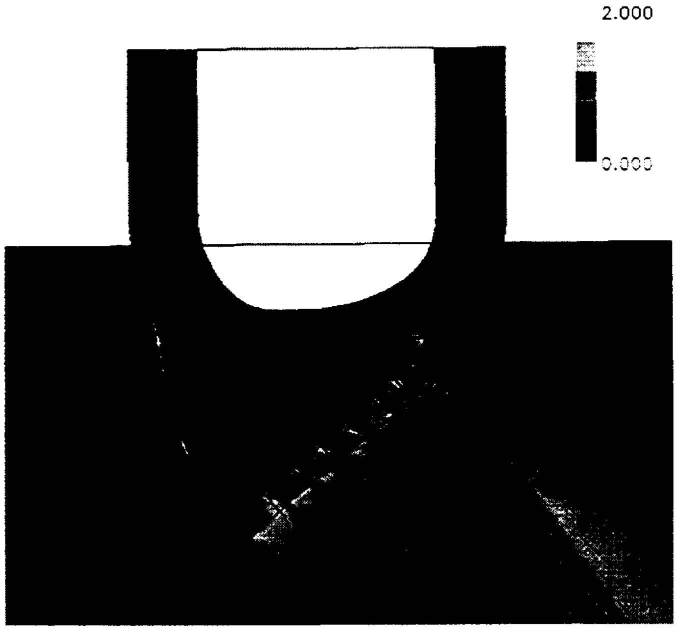

Figure 5: Mach number contours: final configuration - NPR = 2.5, midsection fore-aft cut, 30-degree vector

The ADPAC flow code was used to predict the nozzle performance of the nozzle at various vector settings and nozzle pressure ratios. This allowed the CFD-based design methodology to be calibrated with test data and thus improve the prediction capability of the analysis. The comparison of theoretical predictions and experimental data will be presented after the following discussion on the test program.

TEST DESCRIPTION

To verify CFD design and also obtain a valuable data base for the TEVEN nozzle, a 0.30 scale model test was conducted at NASA LeRC's Powered Lift Facility (PLF) in

January 1994. The facility was calibrated prior to the static nozzle test for flow and thrust measurements using a set of ASME nozzles installed respectively in the vertical and the horizontal directions. A typical TEVEN nozzle configuration was installed and fitted to the PLF annular air supply rig and tested to provide the exhaust thrust performance data. The nozzle performance as a function of nozzle pressure ratio (NPR) was obtained by measuring total nozzle flow, charging station total conditions, and various thrust components. The data was then reduced to provide nozzle discharge and thrust coefficients Cd and Cf, and exit flow vector angles, respectively. In addition, the diagnostic information on the nozzle flow field was obtained by measuring surface pressures, and in some cases, the fluorescent oil flow visualizations on the surface as needed.

DESCRIPTION OF TEST FACILITY

The Powered Lift Facility (PLF), located at NASA Lewis Research Center's Aeroacoustic Propulsion Laboratory, a geodesic-dome-shaped acoustic barrier (Figure 6) that also houses the nozzle Acoustic Test Rig, is a unique and valuable test facility designed to accommodate various test programs. Its main features are a triangular-shaped multiaxis thrust frame (30 ft on a side) and an air supply system capable of providing 150 lb/sec at 100 psia. Force levels up to 60,000 lbf can be measured for models weighing up to 40,000 lb. A J-58 combustor is available to provide inlet temperatures up to 1200°F. Since 1987, the PLF and its six component balance (Figure 7) has been used for various propulsion model concepts, including ventral nozzles, ejector-augmenters, and several offtake ducted tailpipes.*

The thrust balance system of the PLF stands 15 ft off the ground and is mounted on three concrete pedestals. The triangular frame is attached to the ground at its apex by a hinged ballows arrangement, which has an air supply. Six reaction load cells applied at the three corners of the triangular frame provide a simultaneous measurement of vertical, axial, and lateral thrust levels. Hydraulic calibration of the system is done periodically to provide accurate thrust measurement of ± 1.0% including both scatter and systematic errors.

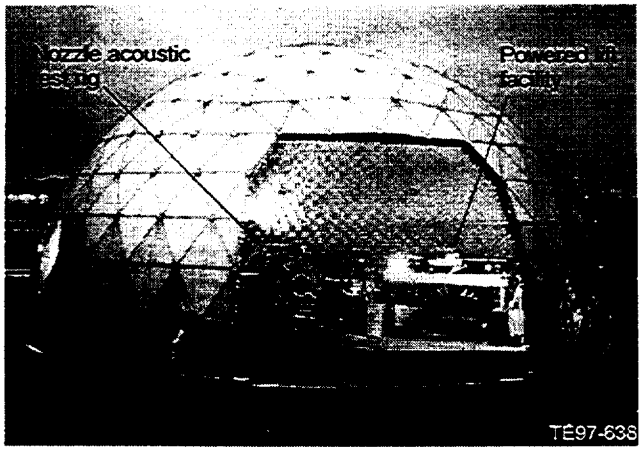

Figure 6: Aeroacoustic Propulsion Laboratory

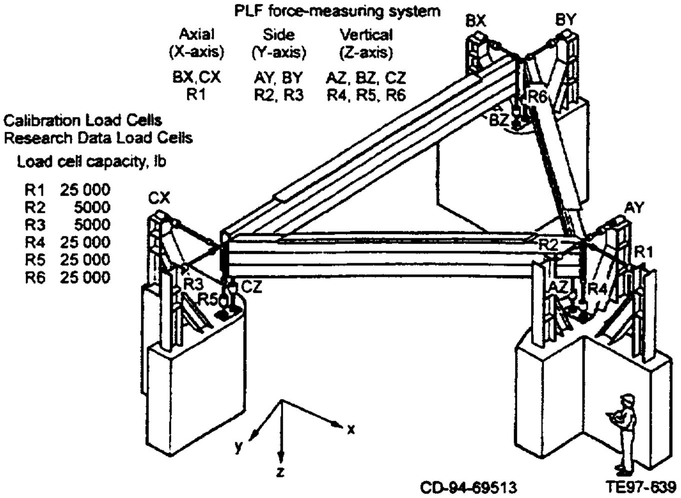

Figure 7: Powered Lift Facility (PLF) thrust balance showing position and orientation of load cells

The flow measuring system includes an ASME nozzle, 9.25-in. diameter, accurate to ± 0.5%. The nozzle is located upstream of the main airflow control valve. The PLF control room is remotely located in the adjacent building and has all the necessary monitoring equipment and video cameras.

TEST SETUP AND PROCEDURES

Prior to TEVEN nozzle testing, the test facility was calibrated using a set of three ASME nozzles (5.4-in. to 10.8-in. diameter) installed in vertical and horizontal positions respectively. This test procedure is performed prior to each test window and gives flow and thrust correlations applicable to the flow and the thrust ranges of interest. Calibration data is compared to the previous historical calibration data base and must fall within a predetermined data scatter band to be acceptable. For these tests, the nozzle calibrations were completed in December 1993. The TEVEN model setup and testing began in January 1994.

Typical test setup, shown in Figure 8, uses an existing three-strut annular "Spider" assembly and is installed upstream of the model to provide a uniform annular flow. New hardware included a 28-probe charging station rake flange, 8 static pressures on the inner and outer charging station radii. The model hardware was installed downstream of the charging station and consisted of a centerbody and vectoring nozzle assembly. Figure 9 shows the model configuration setup used for 90- and 50-degree vector positions. Several turning hoods were fabricated to provide the required vectoring range. The exit cascade vanes were designed to rotate ± 20 degrees to provide additional vectoring as required.

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* Perusek, G. P., "Powered Lift Facility at NASA Lewis Research Center's Aeroacoustic Propulsion Laboratory," AIAA Paper 94-2560, June 1994.

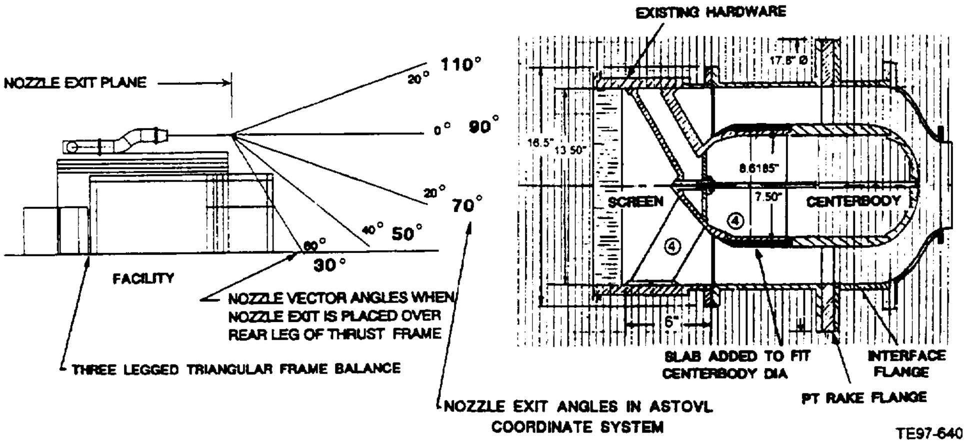

Figure 8: Test facility and setup for TEVEN at PLF

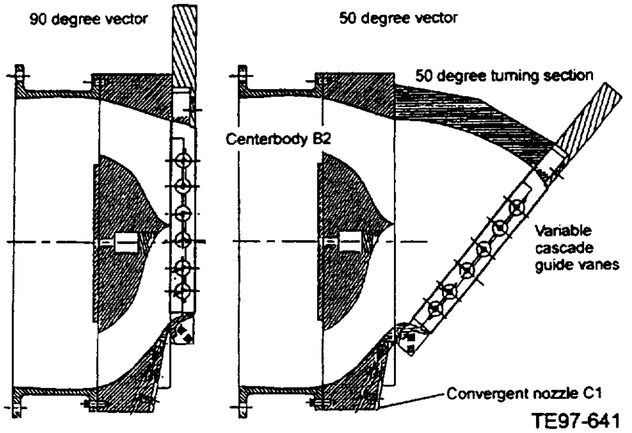

Figure 9: Model configuration assembly at 90 deg and 50 deg, respectively: "Whale Tail" centerbody B2

TEVEN test program matrix consisted of about 50 configurations and included numerous vaneless and vaned designs, seven vectoring positions (i.e., 110 degrees, 100 degrees, 90 degrees [unvectored], 70 degrees, 50 degrees, 40 degrees and 30 degrees), several unvented and vented vanebox designs, and six yaw configurations. Figure 10 presents five venting inserts used to either vent in or vent out the flow along the inner turning wall of the nozzle. The variable vanes were optimized for minimum total pressure loss measured using exit total pressure rakes. The exit total pressure rake was set up on a traversing mechanism to map the exit area of the nozzle.

Figures 11 and 12 show the model setup hardware for 30 degree and 90 degree vectoring positions. The exit vane box, which included 6 variable and twisted exit vanes, can be set at any setting using the circular scales provided. The yaw doors used as post exit deflector are shown in Figure 12.

The model testing commenced with highest nozzle pressure ratio of 2.6 and continued to lower nozzle pressure ratios per schedule. The test data is acquired using the ESCORT System, which was programmed to measure up to 200 pressures, required flow and thrust variables. Prior to and after each test run, zero thrust readings are taken to cancel any tear corrections.

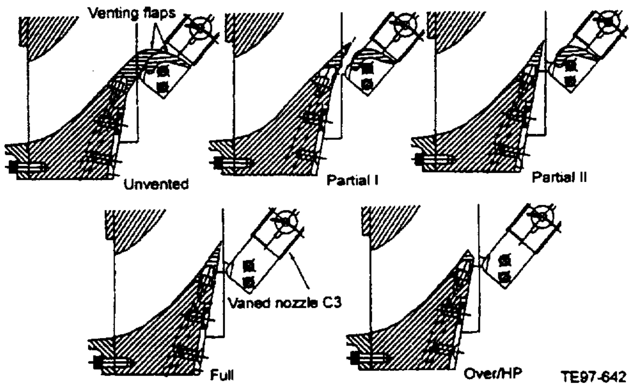

Figure 10: Various nozzle vent configurations tested: vent flaps are located near the nozzle pivot point

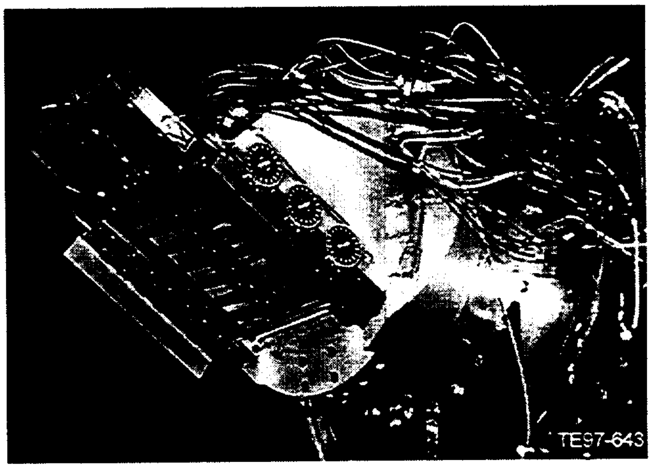

Figure 11: TEVEN nozzle model setup: 30-degree vectoring - 40-degree turning using hoods and 20-degree using guide vanes

TEST RESULTS

The following test results are presented in terms of nozzle performance characteristics (i.e., discharge coefficient Cd, thrust coefficient Ct, and measured pitch and yaw angles with respect to design values). Figure 13 shows the vectoring performance of a vaneless nozzle at various vector settings. At design nozzle pressure ratio (NPR) of 2.5, a total reduction in Cd of 7.0% occurs for

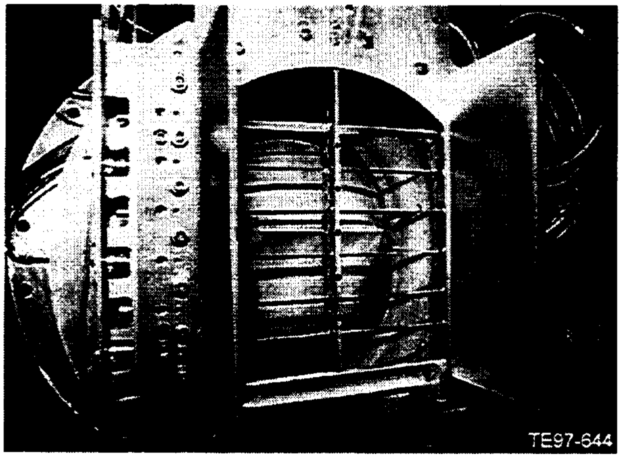

Figure 12: TEVEN nozzle setup for yaw vectoring: 90-degree vector, 10-degree yaw, yaw vectoring with post-exit doors

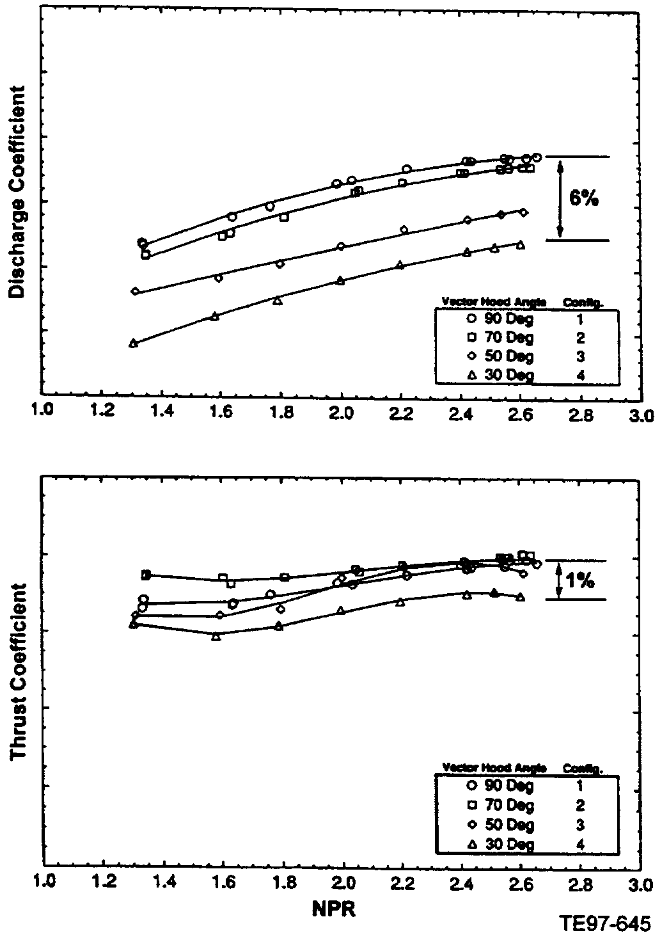

Figure 13: Vaneless unvented nozzle performance: vectoring using hoods, baseline centerbody

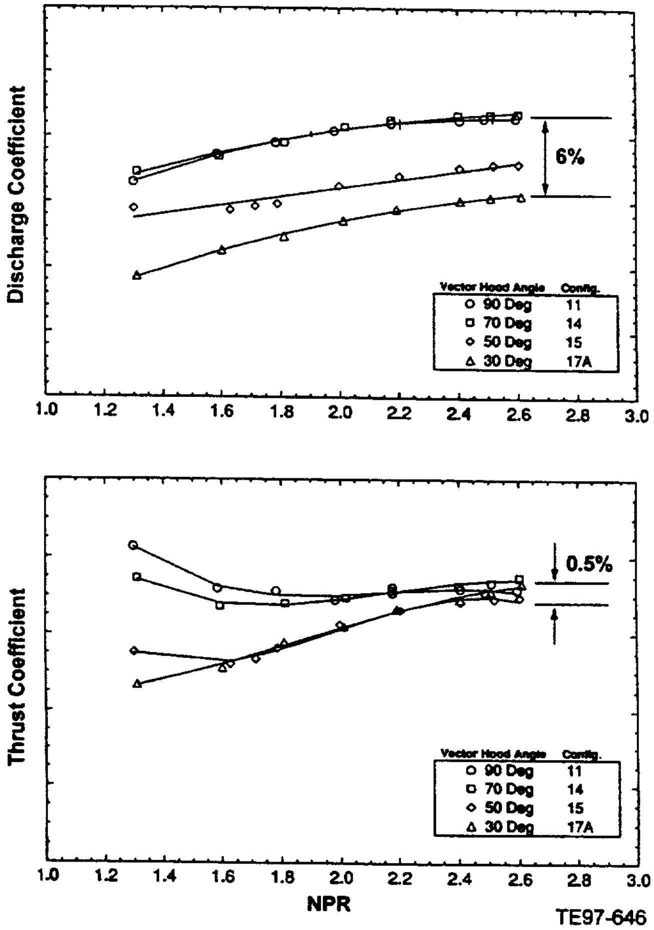

Figure 14: Vaned unvented nozzle performance: vectoring using hoods, "Whale Tail" centerbody

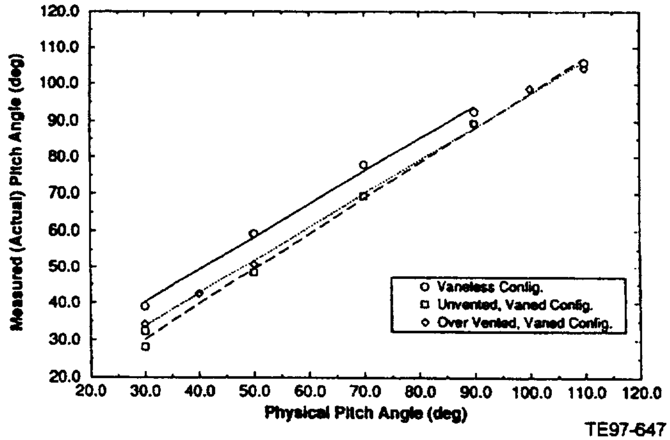

Figure 15: Nozzle turning effectiveness, physical versus measured pitch angles, NPR = 2.5

vectoring the nozzle from 90 degrees (unvectored) to 30 degrees aft. The corresponding reduction in Ct is 1.0%. Having cascade vanes, even if they are fixed in the exit plane at 0-degree setting, are significant, as Figure 14 illustrates. Overall, there is an increase in Cd of 2 to 3% at all vectoring angles, with only a 0.5% loss in Ct. The advantage of using exit cascade vanes is not clear from Figures 13 and 14; however, the vanes are necessary if the actual flow angles must closely follow metal exit angles. Figure 15 presents nozzle turning effectiveness represented by the physical versus measured vector angles. For a vaneless nozzle, the measured angle lags by as much as 10 degrees, as Figure 15 shows. This means that to achieve a vector angle of 30 degrees, the nozzle must be set at 20 degrees. This additional 10 degrees flow turning may require a larger, heavier hood section. In a vaned nozzle, on the other hand, the exit jet follows the nozzle metal angle closely, and therefore, no overturning is required. The nozzle venting has a small effect on the nozzle exit angles. At low NPR, the vaned nozzle shows an unexpected rise in Ct, as Figure 14 indicates. This may be due to error in measurement, better flow alignment through the vanes, or "Pointed" or "Whale Tail" centerbody, as Figure 16 shows. The effect of centerbody shape on nozzle performance was studied earlier during the nozzle design phase, where it was noted that nozzle flow separation occurs over a short stubby centerbody. The Pointed or Whale Tail design (Figures 9 and 12) of the centerbody was observed to reduce flow separation near its apex as flow visualization later confirmed. For a 90-degree vector, this centerbody design resulted in a 1.0 to 1.5 % increase in Ct while also reducing the dependence of Ct on NPR variation.

One of the reasons to use variable cascade vanes at the exit of the TEVEN nozzle is its ability to achieve forward vectoring up to 20 degrees. This effect is shown in Figure 17 for a 90-degree vector setting with vanes set at 20 degrees forward exit angle. As the vanes are vectored -10 degrees and -20 degrees, respectively, the effective vane exit area decreases significantly resulting in a large drop in Cd. At NPR = 2.5, a Cd loss of 12.0% and a Ct loss of 4% occur perhaps due to high vane incidence angles and also due to local flow accelerations followed by shock-induced losses. The inner wall region of the nozzle was vented to ambient flow conditions to reduce local flow turning/separation losses. The effect of NPR variation on both Cd and Ct is relatively small.

To achieve 30-degree vectoring, the first 40 degrees of aft vectoring (i.e., 90 degrees to 50 degrees) are obtained by a set of hoods while the additional 20 degrees (i.e., 50 degrees to 30 degrees) are obtained by turning the exit vanes in the positive aft direction. This aft vectoring due to vanes on performance is shown in Figure 18 for two vane turning angles, +10 degrees and +20 degrees. Comparing this to Figure 17, the aft vectoring is clearly more efficient, resulting in smaller reduction in Cd and Ct respectively. This is because these 6 exit vanes were designed with appropriate camber and incidence angle settings to keep the resultant thrust post as far forward as possible. The same trend was observed with hoods set at other vector settings. The effectiveness of flow vectoring between 90 degrees and 30 degrees using hoods alone was also investigated. In this case, the additional vectoring between 50 degrees and 30 degrees was obtained using an additional 20 degrees hood section, but keeping the vanes set at the nominal "0 degree" position. It should be noted from Figure 14 that forward vectoring using hoods alone is not possible for this configuration.

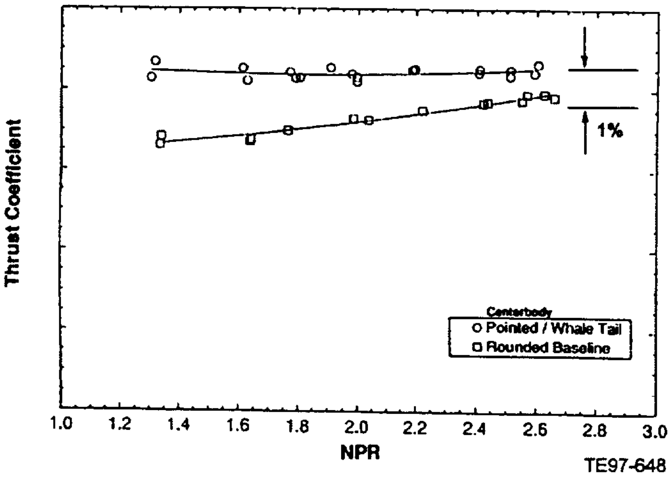

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Figure 16: Effect of centerbody shape on performance, vaneless and unvented configuration, 90-degree vector

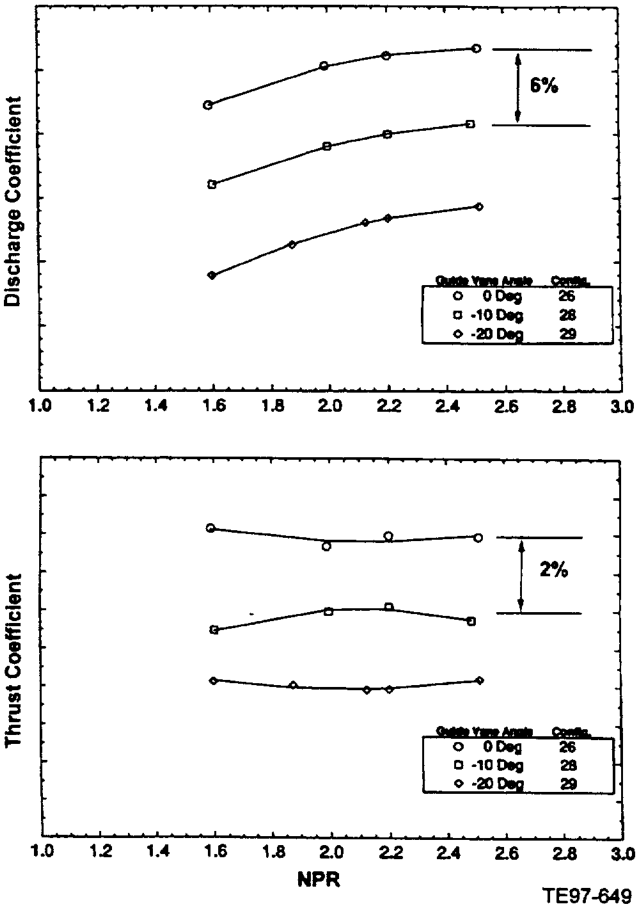

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Figure 17: Effect of forward vectoring of guide vanes on nozzle performance, over/HP venting, 90-degree vector

One of the early requirements of the TEVEN nozzle was to provide Yaw angle variation up to ± 8 degrees. This effect was studied by using post-deflector yaw doors downstream of the nozzle exit. This feature was most practical and compact for this design. As may be expected, the post-exit yaw doors result in a reduced performance since the exit flow is supersonic or near sonic. Figure 19 shows that by locating yaw doors on nozzle side walls and set at 10 degrees and 20 degrees respectively, there is a drop in Ct by 1 to 2% along with about 1% decrease in Cd. Note, that the yaw angle effectiveness of post-exit door depends on the nozzle vectoring angle as well as on the physical angle of the yaw doors. At 90-degree vector angle, it requires almost a 20-degree yaw door angle to get about 8 degrees of yaw. At 30-degree vector, the same yaw door results in actual yaw angle of about 17 degrees as Figure 20 shows.

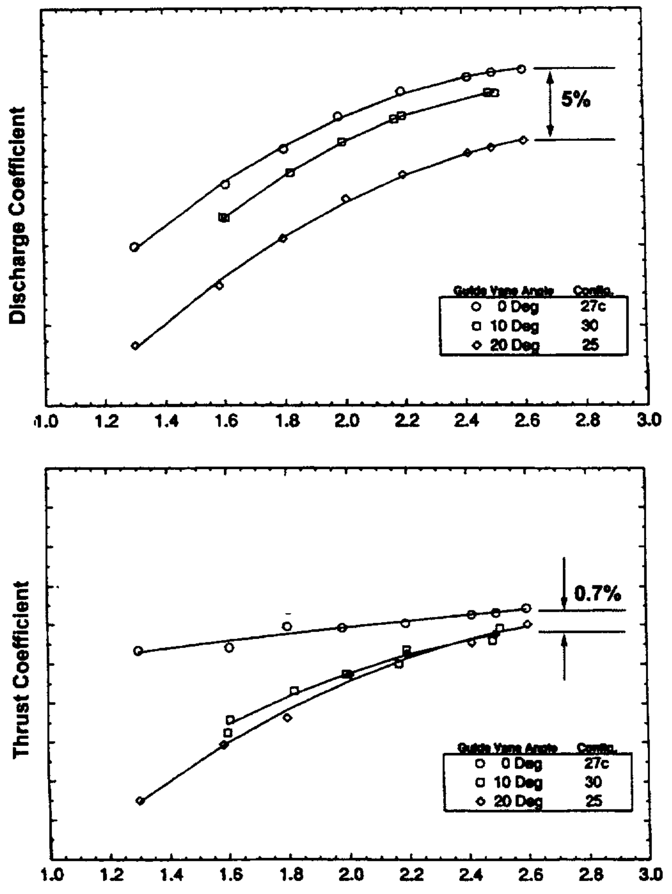

Figure 18: Effect of aft vectoring of guide vanes on nozzle performance, over/HP venting, 50-degree vector

The venting of TEVEN nozzle in the vicinity of the inside turning wall was studied in detail. Several venting designs were investigated. Some configurations resulted in overall performance degradation both in Cd and Ct while others showed improvements. Figure 21 compares the venting effectiveness at 90 degree vector for various configurations. In general, for the venting configurations where the flow is vented from the nozzle to the ambient, there was a considerable increase in Cd by as much as 5% with relatively small change in thrust coefficient. In one final design, referred to as high pressure (HP) or overventing, both Cd and Ct increase by 5% and 1% respectively. At other vectoring positions, this venting configuration also showed improvement, although it was smaller. Other venting configurations resulted in an increase in Cd but with a net loss performance loss. Based on this data, the overventing was selected and formed a part of final nozzle configuration.

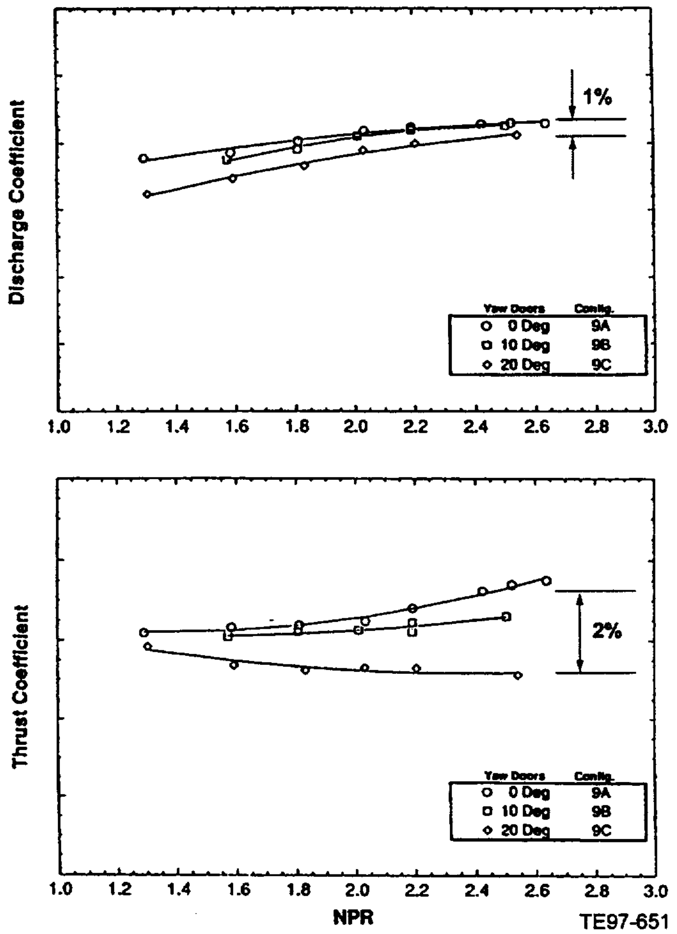

Figure 19: Effect of post-exit yaw doors on vaned nozzle performance, 70-degree vector

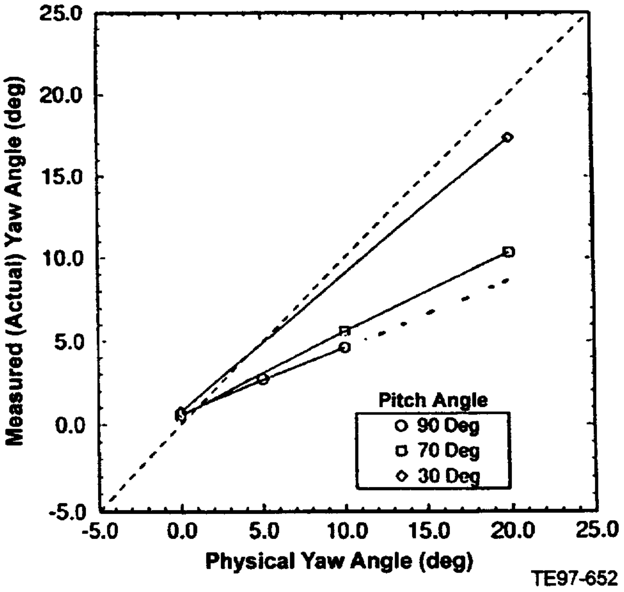

Figure 20: Yaw door flow turning effectiveness, physical versus measured yaw angles, NPR = 2.5

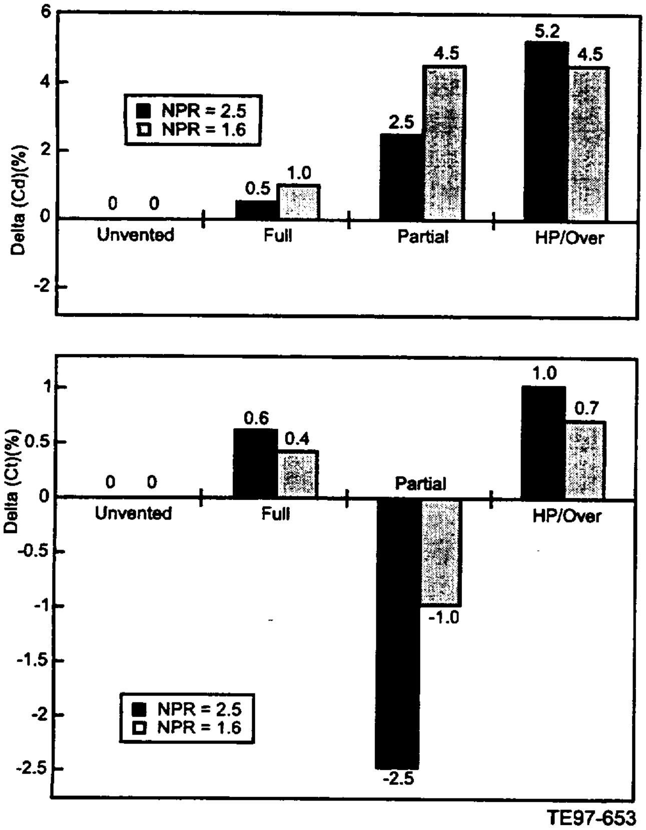

Figure 21: Effect of venting insert types, guide vane angle = 0-degree, 90-degree vector

ANALYSIS VERIFICATION AND CONCLUSIONS

An analytical discussion of test results as well as their comparison with the predicted CFD results is presented. Figure 22 presents a comparison of CFD predictions and the test data in terms of nozzle coefficients. The results show a good correlation between predictions and test data at selected flow conditions. It should be noted that as the nozzle is vectored below 40 degrees (aft) and above 90 degrees (forward), the thrust drops off rapidly. This is due to the turning vanes becoming less effective as vane turning angle is increased.

In general, these predictions were found to be optimistic in predicting nozzle performance coefficients by 1 to 2%. It should be noted that due to computer storage limitations, it was not possible to model any of the venting configurations accurately. However, the performance improvements as a result of flow venting are only a fraction of overall nozzle performance levels. Therefore, it is simple to develop correlations to account for small geometric variations. At AADC, the CFD methods are now used as a common design tool in analyzing nozzle flow fields prior to testing.

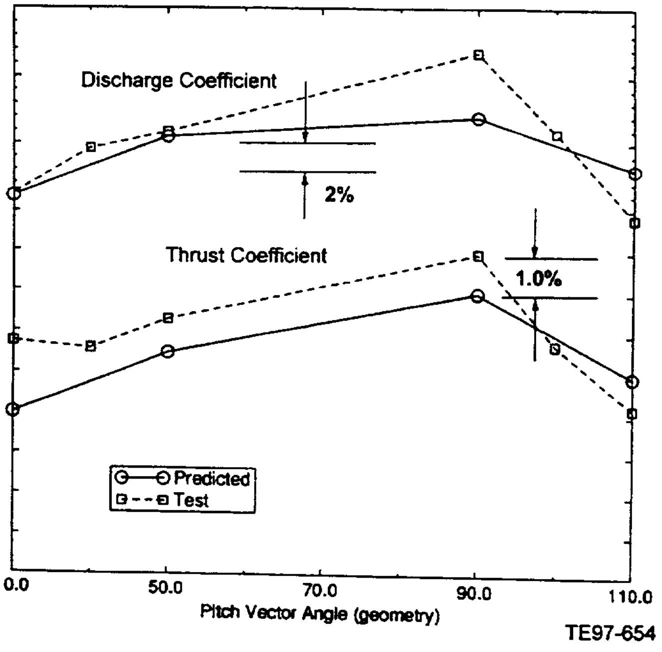

Figure 22: Comparison of test data with performance predictions, NPR = 2.5

CONCLUSION

In conclusion, the investigation carried out under this program provided a large data base on a very efficient LiftFan™ exhaust nozzle. The performance of the TEVEN nozzle indicated that the challenging vectoring requirements of a compact LiftFan™ exhaust can be achieved while maintaining high performance levels. The data corroborated the advantages of using CFD as a design tool for this nozzle. This CFD code has been successfully used in the current generation of LiftFan™ nozzle design for the JSF program.

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13. ABSTRACT ***(Maximum 200 words)***

A discussion on the development of a Telescoping, Vaned, Exhaust Nozzle (TEVEN) is presented. This nozzle was challenged to meet the thrust vectoring requirements of an Advanced Short Takeoff and Vertical Landing (ASTOVL) aircraft. The nozzle underwent a development process from concepts to detail design using computational flow analyses and from subscale performance verification tests to full-scale hardware design. The LiftFan™ nozzle is capable of providing a pitch vector range of about 80 degrees from up to 20 degrees forward to 60 degrees aft. In addition, a set of post exit yaw doors provide ± 10 degrees yaw while maintaining a relatively high performance at all operating conditions. Further, the nozzle is axially compact, to be stowable in very short length ($L/D < 0.3$), while efficiently converging the upstream nozzle flow from an annular cross section to a "D" shape at the nozzle exit. The discussion includes a review of various nozzle concepts, viscous flow analyses, and results from 1/3 scale nozzle model tests conducted at NASA LeRC Powered Lift Facility (PLF) in 1994.

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