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A PERFORMANCE EVALUATION OF A THREE SPLITTER DIFFUSER AND VANELESS DIFFUSER INSTALLED ON THE POWER TURBINE EXHAUST OF A TF40B GAS TURBINE

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ABSTRACT

A field test was conducted on a three splitter diffuser and a vaneless diffuser (no splitters) to determine, the pressure recovery coefficient, effects on engine performance, exhaust collector temperature distribution, and exhaust gas noise.

This paper presents the cause of the mechanical failure of the three splitter diffuser, basic diffuser design, field test instrumentation, and the test results. The test results found the vaneless diffuser had a higher pressure recovery, created a lower back pressure, and did not raise the exhaust gas temperature (EGT) nor fuel consumption of the engine, as compared to the three splitter diffuser.

BACKGROUND

Four TF40B marine gas turbine engines, manufactured by AlliedSignal are installed on the US Navy Landing Craft Air Cushion (LCAC) amphibious craft. The TF40B engine is a two shaft engine rated at 3955 maximum continuous shaft horsepower at 80 °F inlet air temperature with standard inlet and exhaust pressure losses. As shown in Figures 1 and 2, the TF40B engine exhaust system consists of the short annular diffuser clamped directly to the engine, a collector duct which abruptly turns the exhaust 90° upward to vertical, and a short vertical stack mounted on top of the collector duct.

Due to the machinery space limitations on the LCAC, the TF40B gas turbine exhaust collector is only nineteen inches in depth. This compact exhaust collector forced the design of the diffuser to be very short in length. In an effort to reduce the amount of exhaust back presssure to the engine and to be within the space constraints of the exhaust collector, the diffuser was designed with three splitter vanes to produce a number of small-angle diffusers in parallel, and to help guide the exhaust gas flow out of the exhaust collector.

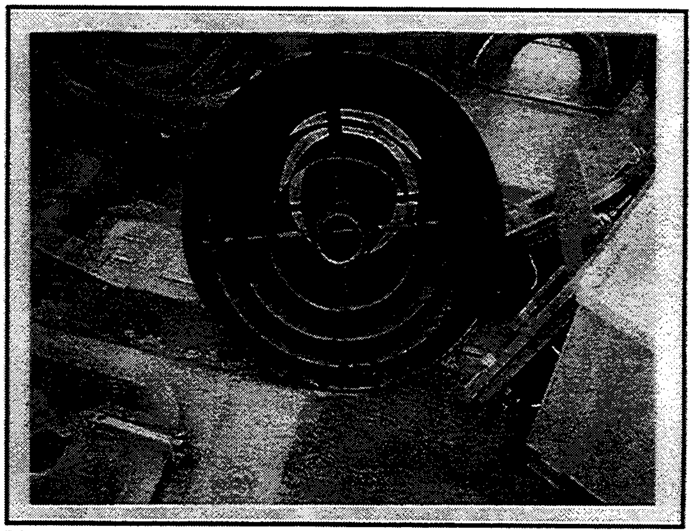

Figure 1. TF40B Exhaust Diffuser- Three Splitter Design

The three splitter diffuser had a sustained an unacceptable rate of cracking and failures of the vanes and support rods. Occasionally, pieces of vane material had broken off due to cracking and caused foreign object damage to the last stage power turbine wheel. Figure 3 identifies a common area where the cracks occurred.

This paper describes two design attempts to fix the failure mode of the three splitter diffuser. The first change to the three splitter diffuser was to modify the weld between the vanes and support rods. The second design alteration to this diffuser was to remove all the vanes.

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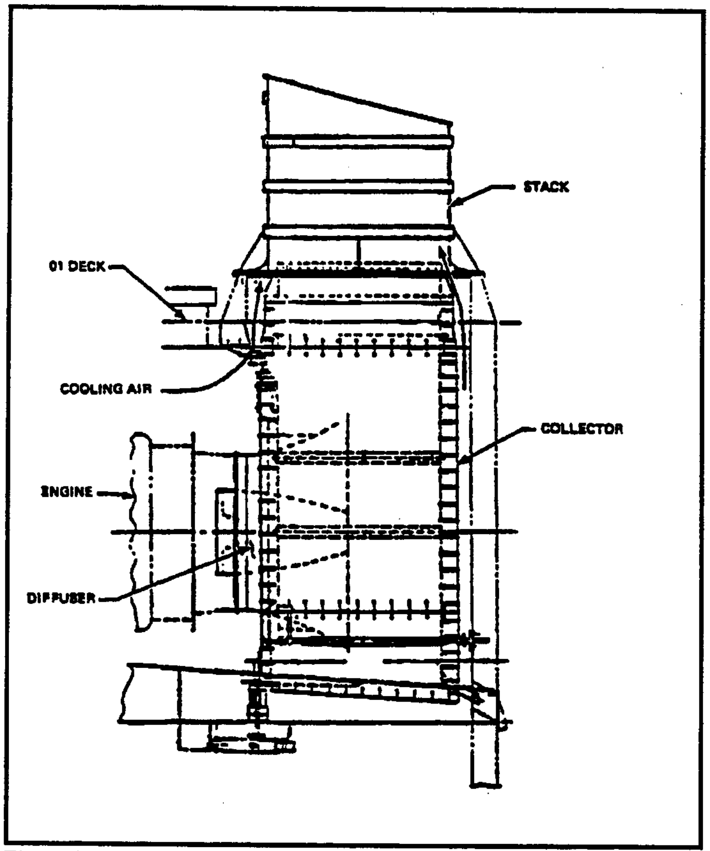

Figure 2. TF40B Gas Turbine Exhaust Assembly

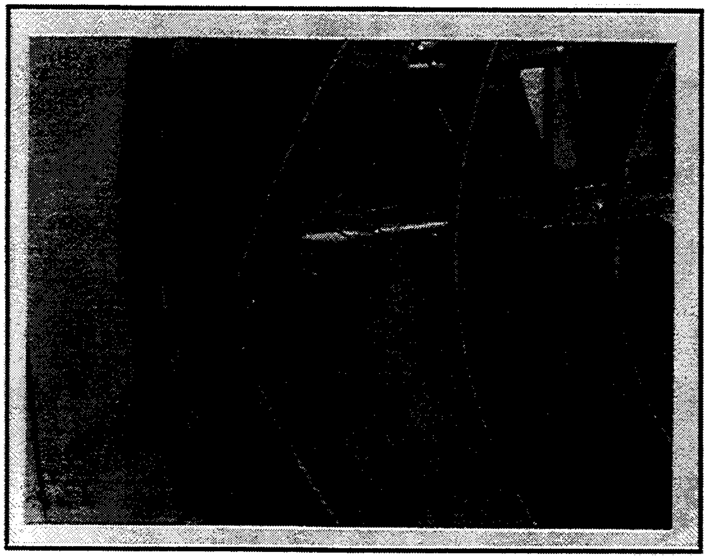

Figure 3. Cracked Outer Vane

Description of the Three Splitter Diffuser

The TF40B gas turbine exhaust diffuser includes a center body, forming an annular flow passage within which are three concentric vanes (splitters) supported by four 5/8-inch diameter rod struts. The inside diameter of the diffuser inlet shell is 18.6 inches; the outside diameter of the outlet rim is 29 inches (27.7 inches without the rim) and its length is 13.6 inches. The outer circumference of the flow passage is trumpet-shaped rather than conical. The center body is bullet-shaped, blunt at both ends, with outside diameters of 8.0 inches at the inlet and 5.0 inches at the outlet end.

Annular flow path areas are 583 and 189 square inches at the outlet and inlet, for an outlet-to-inlet area ratio of 3.09. The vane assemblies are made of Inconel alloy 625. The outer diffuser shell attaches to the exit plane of the TF40B gas turbine with a "V" clamp. The center body of the diffuser is sealed off to prevent recirculation of exhaust gases into the turbine shaft area. Half of the diffuser's length penetrates into the exhaust collector duct. A seal allows the engine and diffuser to expand thermally and move relative to the collector duct without exerting excessive force.

Weld Improvements

Martin Marietta Manned Spaced Systems conducted a laboratory investigation to determine the mode of exhaust diffuser cracking. The failure analysis concluded that the cracks are brittle cracks most likely due to thermal expansion. The mechanical restraint caused by the support tubes being welded to the vanes concentrates the stress at the fillet weld. As a result, the cracks initiate at the toe of the weld passing into the vane material. After the initial cracks have occurred, engine operation causes fatigue crack propagation at the ends of the longest crack. Fabrication quality was excellent and did not contribute to the failures of the welds.

This report also stated that a significant contribution to the stress is the bending moment caused by the eccentricity of the single-sided fillet weld at the outer surface of the vane and the support tube. During operation of the engine, the diffuser vanes experienced cyclic-straining which eventually results in low cycle fatigue and cracking of the vane around the toe of the fillet weld. It was recommended that the single-sided fillet welds be replaced with a double-sided fillet weld.

Based on this report, the Navy modified two diffusers by:
(a) changing the support tube to vane welds from single-sided to double-sided; (b) and by adding the double-sided welds, but limiting the welds to only one quadrant of each support tube, leaving the opposite quadrant un-welded.

The Navy then field tested both modified test diffusers on the LCAC. After fifty (50) hours of typical craft operation, the test diffusers were removed from the craft for inspection. Inspection revealed signs of wear at the support tubes and cracks, therefore the well-thought-out weld improvements alone were not considered to be a viable repair for the three splitter vane diffuser. Basic design changes were needed which could potentially affect engine performance.

DIFFUSER PERFORMANCE AND DESIGN

Performance

The purpose of any gas turbine exhaust diffuser is to draw the exhaust gases out of the power turbine with a minimum back pressure to the turbine. A well designed diffuser will convert dynamic pressure at the inlet to added static pressure at the outlet.

The divergent or expanding flow passage which enables an exchange of kinetic for potential flow energy purposefully creates a lower static (negative static pressure) at the diffuser inlet relative to its outlet. Thus, the reduced static pressure at the turbine enables the flow to do more work, increasing power and improving fuel consumption.

A useful measure of a diffuser's performance is the ratio of the increase in static pressure to the inlet dynamic pressure: the pressure-rise coefficient (C_{PR}). The C_{PR} is the amount of static pressure raise divided by the flow kinetic energy available at the diffuser inlet. The C_{PR} is a non dimensional parameter, with a range from zero to unity. Higher C_{PR} means better diffuser performance. Current accepted industry practice for short diffusers with a 90° bend at the large end is a C_{PR} of 0.4 to 0.65, depending on gas turbine application and limits on available space and weight.

$$C_{PR} = (p_{st,2} - p_{st,1})/(p_{T,1} - p_{st,1}) \qquad (1)$$

In this paper, C_{PR} test results are calculated from area-weighted averages of static and total pressure measured at 64 locations, 32 probes zero to one inch upstream of the inlet plane of the diffuser, and 32 probes located three inches upstream of the diffuser outlet.

Diffuser Design

To function efficiently and keep the C_{PR} as high as possible, air flow through a diffuser must be relatively uniform over a plane perpendicular to its axis and must have no flow separations or reversals of significant size. Diffuser performance is therefore sensitive to inlet flow non-uniformities, swirl, and the wakes of any obstructions, such as vanes or struts. Splitter vanes, such as those installed in the TF40B engine diffuser, would appear not to be an obstruction, but unless they are always perfectly aligned with a very uniform flow, vanes, all too frequently lead to slow-flow areas or eddies which significantly reduce diffuser performance.

Splitter vanes have large surface areas immersed in the air flow, which results in significant skin friction. If the flow shifts over slightly from the intended direction at the entry of the diffuser, then a local stall usually develops on the low pressure side of the splitter leading edge. These local stalls cause flow to concentrate in some passages thereby lowering pressure recovery.

A final difficulty with splitter vanes is the manufacturing, assembling, and welding the splitters to the diffuser. This was particularity true with the TF40B exhaust diffuser as proven by the high failure rate of the weld design.

Struts are often unavoidable, but they can sometimes be made small enough to avoid causing large wakes or flow instabilities. Scale model tests of other diffusers suggested that the 5/8-inch diameter round struts would produce significant wakes, though probably not significant enough to reverse diffuser flows. The authors of this paper hoped that even if highly disturbed flows were found with the three splitter diffuser, the flows would be acceptable efficient without the splitters, although there would be inevitable wall flow separations in a short, vaneless diffuser with an area ratio of 3.09.

TEST CONFIGURATION

Diffusers Tested

Both the vaneless diffuser and the three splitter diffuser were tested on engine position 1 on board LCAC 066, which was docked at the US Navy Coastal Systems Station (CSS) in Panama City, Florida. Tests were completed between 18 March and 26 March 1996. The vaneless diffuser was a modified three splitter diffuser, with just the three vanes removed. This vaneless diffuser is shown by Figure 4.

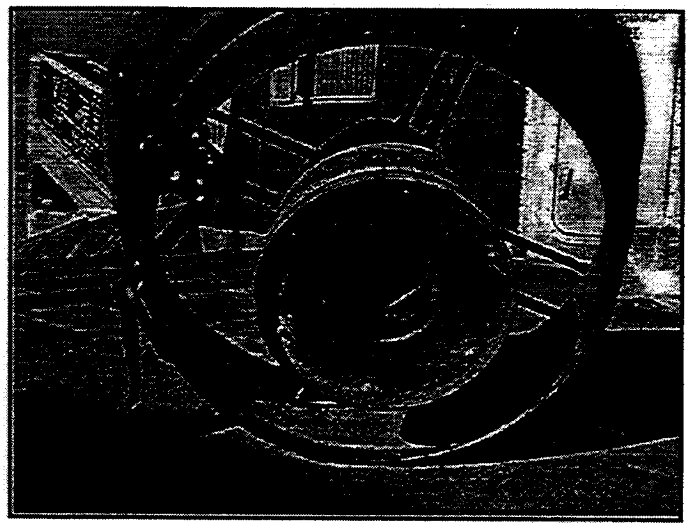

Figure 4. Vaneless Diffuser

TF40B Engine Exhaust Flow Conditions

The flow conditions at the exit of the TF40B engine during this test at 100% N1 and 95% N2 are summarized in Table 1.

Table 1. Engine Exhaust Flow Parameters

Exhaust Parameter	***Value***
Swirl Angle	+ 10°
Mass Flow (Air)	28 lb/sec
Air Velocity at Diffuser Inlet	~ 835 ft/sec
Area at Diffuser Inlet	1.31 ft^2
Exhaust Temperature at Diffuser Inlet	1100 °F

Test Measurements

Measurements obtained during this test were engine performance data, exhaust collector surface temperature, airborne noise, and diffuser pressure distribution.

Engine Performance: Engine data was obtained by LPAS (LCAC Performance Analysis System). Parameters included corrected N1, corrected N2, corrected EGT, fuel flow, compressor discharge pressure, lube oil temperature, inlet air temperature, ambient air temperature, and atmospheric pressure. For each diffuser, the TF40B gas turbine engine was operated at the same five different power levels.

Exhaust Collector Surface Temperatures: Four thermocouples (Chromel-Alumel) were installed inside the exhaust collector, to record metal surface temperatures. Two were placed directly on the outboard wall (the exhaust gas "impact wall"), one was placed on the forward wall, and one was placed on the aft wall. Figure 5 marks the location of the thermocouples within the exhaust collector.

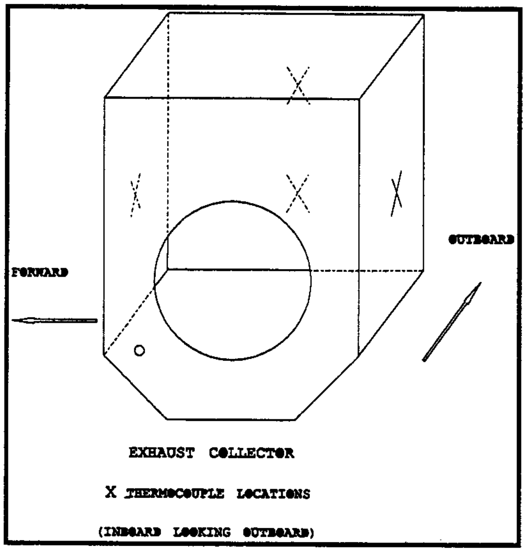

Figure 5. Exhaust Collector Thermocouples

Airborne Noise: Eight microphones were installed around the exhaust collector stack as shown in Figure 6. All microphones were calibrated prior to installation. Sound measurements were made in accordance with the current draft of ANSI/ISO standard for the "Measurement of Airborne Sound Emitted by Gas Turbines Sets-Engineering Survey Method" and MIL-STD 704-1, Airborne Sound Measurements and Acceptance Criteria of Shipboard equipment." The octave-band center frequencies (Hz) recorded were 4, 8, 16, 31.5, 63, 125, 250, 500, 1K, 2K, and 4K. All noise measurements were recorded on a tape deck for data storage.

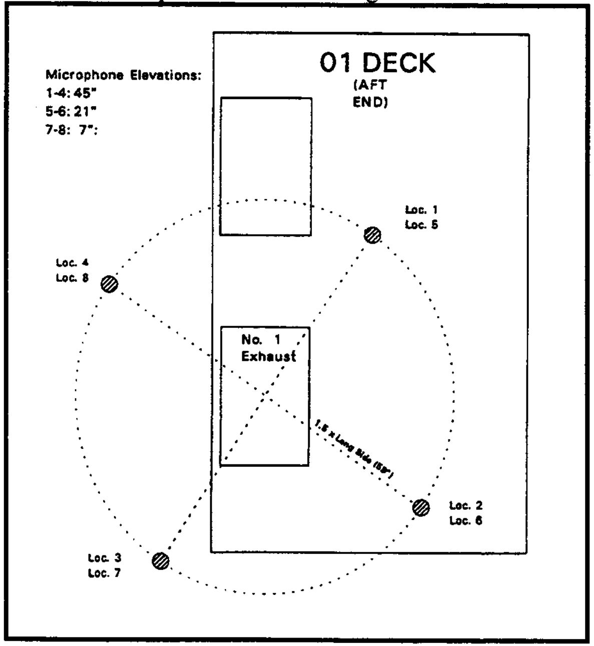

Figure 6. Microphone Locations

Diffuser Pressure Distribution: Total and static pressure readings were obtained upstream of the inlet and approximately at the exit of each diffuser. There were sixteen total pressure probes and sixteen static pressure probes at the inlet, and sixteen total pressure probes and sixteen static pressure probes at the exit of each diffuser, for a total of sixty-four pressure probes. The sixty-four pressure probes were stainless steel tubing, 1/8 inch in diameter. Open ended tubes were utilized to record total pressure. Standard 1/8 inch diameter stainless steel pitot tubes were not used for this test, because of their small orifices would respond too slowly to any transients. Larger, commercially available stainless steel pitot tubes were also not utilized during this test, because of the large diameter of the probes (5/16 inch) would disturb the exhaust flow. The static pressure tubes were TIG welded at the end, and four 1/16 inch diameter holes were drilled into the sides of the tube. A typical static pressure probe used during this test is shown on Figure 7. This type of static probe is sensitive to both angle of incidence and, with respect to the four holes, direction of flow. Calibration of static and total probes on a turn table near a wind tunnel outlet nozzle showed that up to ten degrees incidence, the total pressure probes have a maximum error of 4% of the velocity pressure and the static tubes have a maximum error of 6% of the velocity pressure. All are referenced to zero degrees incidence pressures measured with several ASME spherical tip pitot tubes, 1/8 inch in diameter, Dwyer Model number 166-12.

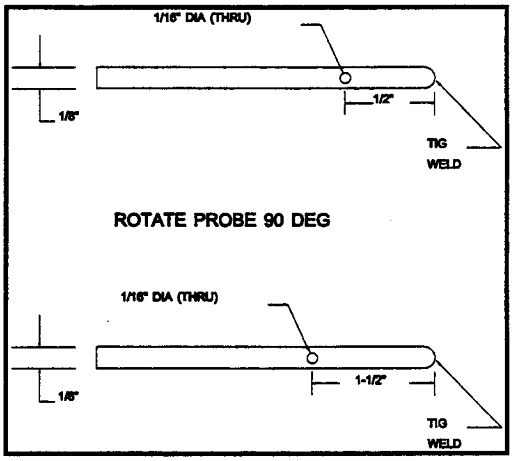

Figure 7. Typical Static Probe

Since the diffusers could not be modified (drilled) to install the pressure probes, the probes were installed through the back (exit) of the diffuser. The pressure probes were held in place by lock wiring the probes to the diffuser struts.

The pressure probe locations for the three splitter diffuser, are identified in Figure 8. The diffuser was divided into four radial positions: 10:30, 1:30, 4:30 and 7:30. The pressure probes were installed at each strut and between each vane to maximize accuracy of the pressure readings. The inlet static and total pressure probes were measured upstream from the diffuser inlet, where streamline curvature had not yet been induced by the diffuser.

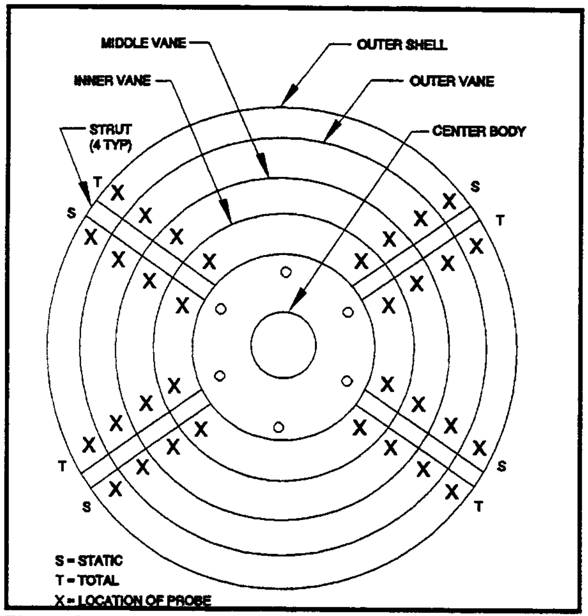

Figure 8. Pressure Probe Locations on Three Splitter Diffuser

For the vaneless diffuser, the same pattern and number of pressure probes were employed (64). Since there were no vanes to place the pressure probes between, the probes were spaced evenly between the center body and the diffuser outer shell. Figure 9 identifies the pressure probe locations for the vaneless diffuser.

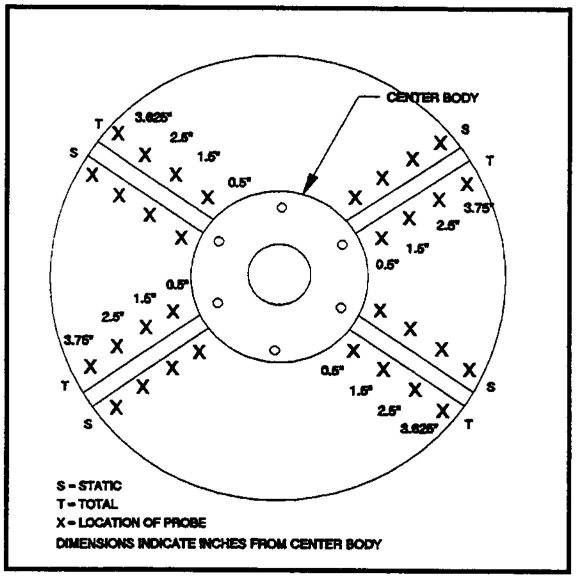

Figure 9. Pressure Probe Locations on Vaneless Diffuser

For each diffuser, the pressure probes were attached to a solenoid driven scanivalve, via ¼ inch stainless steel and plastic tubing. Four pressure transducers were located about one foot from the scanivalve to record the pressure measurement from each pressure probe. Once the pressure transducer had a value, a signal was sent to a computer where the software displayed the pressure in inches of water. The pressure transducers were calibrated and field tested prior to the start of this test.

To verify the accuracy of the pressure transducers and software, one pressure probe was connected to a U-type water manometer.

TEST RESULTS

Engine Performance

The corrected EGT and fuel flow of the TF40B gas turbine for both diffusers tested is shown in Figures 10, and 11.

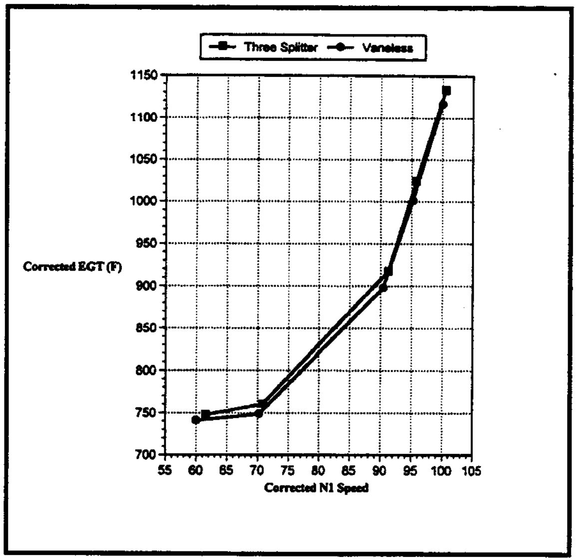

Figure 10. Engine Exhaust Gas Temperature

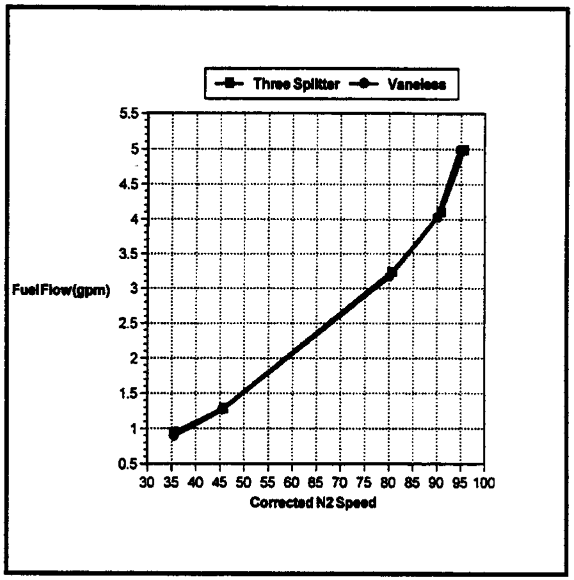

Figure 11. Engine Fuel Flow

Diffuser Performance

The calculated C_{PR} was obtained from the total and static pressures data. The total and static pressures were averaged over five separate runs. Calculated C_{PR} values for each diffuser at each TF40B engine speed is listed on Figure 12.

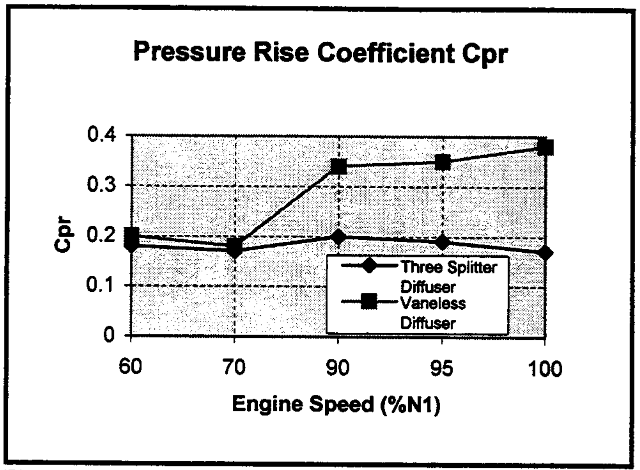

Figure 12. C_{PR} of the Diffusers Tested

Exhaust Collector Surface Temperature

The exhaust collector wall temperature for both diffusers and at the different engine speeds are shown in Figures 13 and 14.

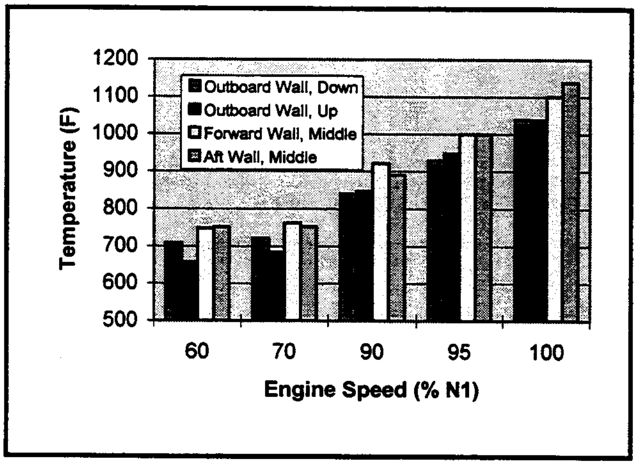

Figure 13. Exhaust Collector Surface Temperature for the Three Splitter Diffuser

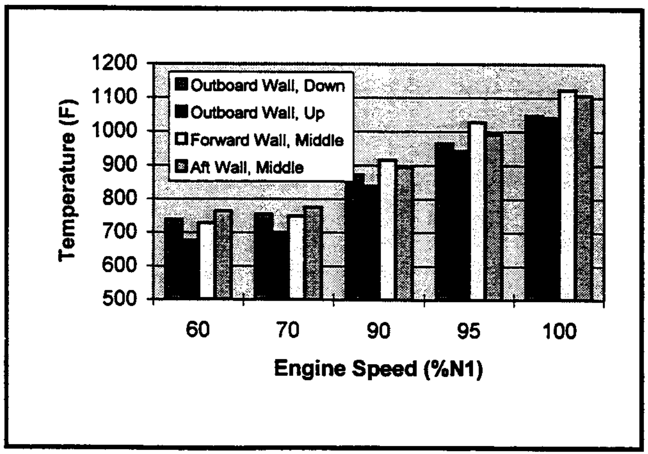

Figure 14. Exhaust Collector Surface Temperature for the Vaneless Diffuser

Exhaust Collector Airborne Noise

In an effort to eliminate background noise around the exhaust stack of engine position #1 (starboard side), a number of things were done. First, the port side APU was utilized, vice the starboard APU. Second, the starboard side bow thruster was positioned forward, or facing opposite to the exhaust stack. External noises that could not be controlled were the starboard propellers, lift fans, and weather conditions(wind speed).

The overall amplitude error for data acquisition and processing system is typically considered to be plus or minus two decibels, a three decibel change can safely be considered a real change in the noise characteristics of a machine. A six decibel gain equated to two times more noise.

The vaneless diffuser was eight times quieter than the three splitter diffuser, at frequencies below 16 Hz. At higher engine powers, the instrumentation was picking up craft propeller noise at the 63 Hz octave band, therefore no noise comparisons between the diffusers could be made at this specific band. At 125 Hz and 250 Hz and at engine full power, the vaneless diffuser was slightly quieter than the three splitter diffuser.

CONCLUSIONS

- The vaneless diffuser produced a higher C_{PR} at all engine speeds, reduced low frequency airborne noise, provided lower static back pressure to the engine, and did not increase the EGT nor fuel consumption, as compared to the three splitter diffuser.
- The vaneless diffuser did not create any "hot-spots" on the inner walls of the exhaust collector. The maximum inner wall temperature of the exhaust collector was within the craft specification of 1250°F.
- The vaneless diffuser will eliminate the repair cost to the three splitter diffuser, by the removal of the elements that fail (splitters) and eliminating the mode of failure (welding the support rods the splitters).

ACTION TAKEN

The vaneless diffuser has replaced the three splitter diffuser installed on the TF40B gas turbine on the LCAC.

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