NASA CR-135219

ATTENUATION OF UPSTREAM-GENERATED LOW FREQUENCY NOISE BY GAS TURBINES

by

V.L. Doyle

R.K. Matta

GENERAL ELECTRIC COMPANY

Prepared For

National Aeronautics and Space Administration

NASA Lewis Research Center

Contract NAS3-19435

NASA CR-135219

ATTENUATION OF UPSTREAM-GENERATED LOW FREQUENCY NOISE BY GAS TURBINES

by

V.L. Doyle

R.K. Matta

GENERAL ELECTRIC COMPANY

(NASA-CR-135219) ATTENUATION OF UPSTREAM-GENERATED LOW FREQUENCY NOISE BY GAS TURBINES Final Report (General Electric Co.) 232 p HC A11/MF A01 CSCL 20A

N77-28122

Unclas

G3/07 40769

Prepared For

National Aeronautics and Space Administration

NASA Lewis Research Center

Contract NAS3-19435

1. Report No. NASA CR - 135219	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ATTENUATION OF UPSTREAM-GENERATED LOW FREQUENCY NOISE BY GAS TURBINES		5. Report Date August, 1977
		6. Performing Organization Code
7. Author(s) V.L. Doyle, R.K. Matta		8. Performing Organization Report No. R77AEG482
		10. Work Unit No.
9. Performing Organization Name and Address General Electric Company Aircraft Engine Group Evendale, Ohio 45215		11. Contract or Grant No. NAS3-19435
		13. Type of Report and Period Covered Final Contract Report
12. Sponsoring Agency Name and Address NASA-Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135		14. Sponsoring Agency Code

15. Supplementary Notes

NASA Project Manager: Ronald G. Huff
Lewis Research Center

16. Abstract

An experimental investigation was conducted to determine the acoustic transfer functions of low frequency (below 3500 Hz) noise through aircraft turbines. Comparisons of the model test results were made with theoretical predictions in order to assess the validity of the theory.

Component tests were conducted on both high pressure and low pressure model turbines. The influence of inlet temperature and turbine speed attenuation was evaluated, while the effects of turbine pressure ratio, blade-row choking, and additional downstream stages were determined. Preliminary identification of pertinent aeroacoustic correlating parameters was made.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Combustor Noise Attenuation Turbine Transfer Function Blade-row Attenuation Core Noise Source	UNCLASSIFIED, UNLIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	223	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

SECTION 1.0

SUMMARY

The study of the attenuation of low frequency noise by turbines was the purpose of this NASA Lewis Research Center Program (NAS3-19435). The program objectives were to experimentally determine the acoustic transmission loss through aircraft-engine-type turbines as a function of the acoustic wave frequency; and to compare the results with an existing theory in order to assess the validity of the theory.

The blade-row attenuation data were obtained from acoustic tests on typical high pressure and low pressure turbines run over a full range of turbine speeds and pressure ratios. A siren was used to simulate combustor noise.

The transmission loss spectrum determined from the turbine tests fell into three well-defined regions from 0 to 3500 Hz. A mid-frequency region extends from 200 to 1200 Hz, where the attenuation remains relatively constant. The attenuation on either side increases rapidly, suggesting a bathtub shape. The very low frequency region, below 100 Hz, could be controlled by the effect of propagation through the varying-area blade passages which carry an accelerating flow. The increase in attenuation for frequencies above 1500 Hz is attributed to the physical blockage presented by the turbine blades as the wavelength approaches the blade size. The bathtub floor region apparently is controlled by the mechanism used in the actuator disk theory. This region spans the frequencies of primary interest for combustor noise.

Salient results from this investigation on both high and low pressure turbines showed that for the bathtub floor:

- The blade-row attenuation increases with pressure ratio until choking occurs. After choking, the attenuation remains virtually constant for that given stage.
- The effect of turbine speed on attenuation is insignificant for any given turbine.
- The inlet temperature effect is not discernible if flow triangles are maintained constant.
- The addition of downstream stages increases the attenuation, but by a smaller amount than predicted by isolated blade-row theory.

A clearer understanding of source-noise components will be achieved from the information gained on this program, which will enable better prediction of the combustor noise transmitted through the turbines to the farfield.

SECTION 2.0

INTRODUCTION

The acoustic characteristics of combustion noise for advanced, low polluting combustors are now being determined. Other researchers are conducting source-noise investigations as evident in References 1 through 5. In order to apply this acoustic information to real engine noise estimates, it is necessary to know how much of the combustion noise is transmitted through the turbine. External engine measurements include a combination of source and transmission effects. The need for understanding what happens to combustor noise as it passes through the turbine is an essential part of source-noise research. This program fills that need and the results are added to the growing data bank of information available for updating core noise prediction theories and improving engine noise estimates.

This final report documents the work performed by the General Electric Company for the NASA-Lewis Research Center on Contract NAS3-19435, "A Program for Measuring the Noise Transfer Functions Through Aircraft Engine Turbines".

The objectives of this experimental program were to obtain data on the acoustic transmission loss through aircraft-engine-type turbines as a function of the acoustic wave frequency, and to compare these data with theory in order to assess the validity of the theory.

The theoretical prediction routine (Reference 6) for low frequency noise attenuation through blade rows was employed to conduct a parametric evaluation of the aero-acoustic parameters which showed the largest influence on the attenuation, and to obtain levels for comparison with data generated by two turbine test series.

Acoustic tests were conducted on a high pressure turbine (single-stage) to investigate effects of different inlet temperatures and of blade-row choking on the attenuation.

A second series of tests was conducted on a low pressure turbine, tested as a three-stage machine and then as a single-stage alone to investigate the effects of additional stages and of blade-row choking on the attenuation.

Comparison of the test results with the predicted attenuations served to determine the accuracy of the existing theory and its limitations.

SECTION 3.0

DESCRIPTION OF TESTS

3.1 DEFINITION/SELECTION OF CONFIGURATIONS

The acoustic tests performed under this contract to meet the program objectives were defined as shown in the flow chart of Figure 1. Selection of representative turbines was made based on the availability and applicability of existing vehicle hardware to fulfill the program objectives.

3.1.1 High Pressure Turbine

The NASA core high pressure turbine was selected for this program based on its capability of being operated at different inlet temperatures. This single-stage core turbine is typical of the present-day high pressure turbine (HPT) technology. A cross section of the NASA core turbine is illustrated in Figure 2. The hardware used was model-size with a 50.8 cm rotor-tip diameter.

3.1.2 Low Pressure Turbine

The selection of the Highly Loaded Fan Turbine (HLFT-IVA) was based on the turbine's capability of being operated as both a single- and three-stage machine. This low pressure turbine (LPT) is a highly loaded design with a large number of blades in all three stages. It is part of an ongoing research and development program at General Electric and, as such, represents advanced technology in fan turbine design. Figure 3 shows a cross section of the three-stage build. Removal of the last two stages and replacement of the exhaust inner and outer casings yield the single-stage build illustrated in Figure 4.

3.2 TEST FACILITY

3.2.1 Warm Air Turbine Facility

Testing of the high and low pressure turbine vehicles was conducted in the General Electric Company's warm air turbine facility (see Figure 5) located at the Aircraft Engine Group's plant in Evendale, Ohio. This facility can accommodate turbine configurations ranging from a minimum hub diameter of 35.6 cm up to a maximum tip diameter of 81.3 cm with operational capabilities up to 11,185 kW at 15,000 rpm.

Air can be supplied to the turbine at conditions up to 36.29 kg/sec, 866 K and 1034.1 kN/m^2 absolute. This air is delivered from the Central Air

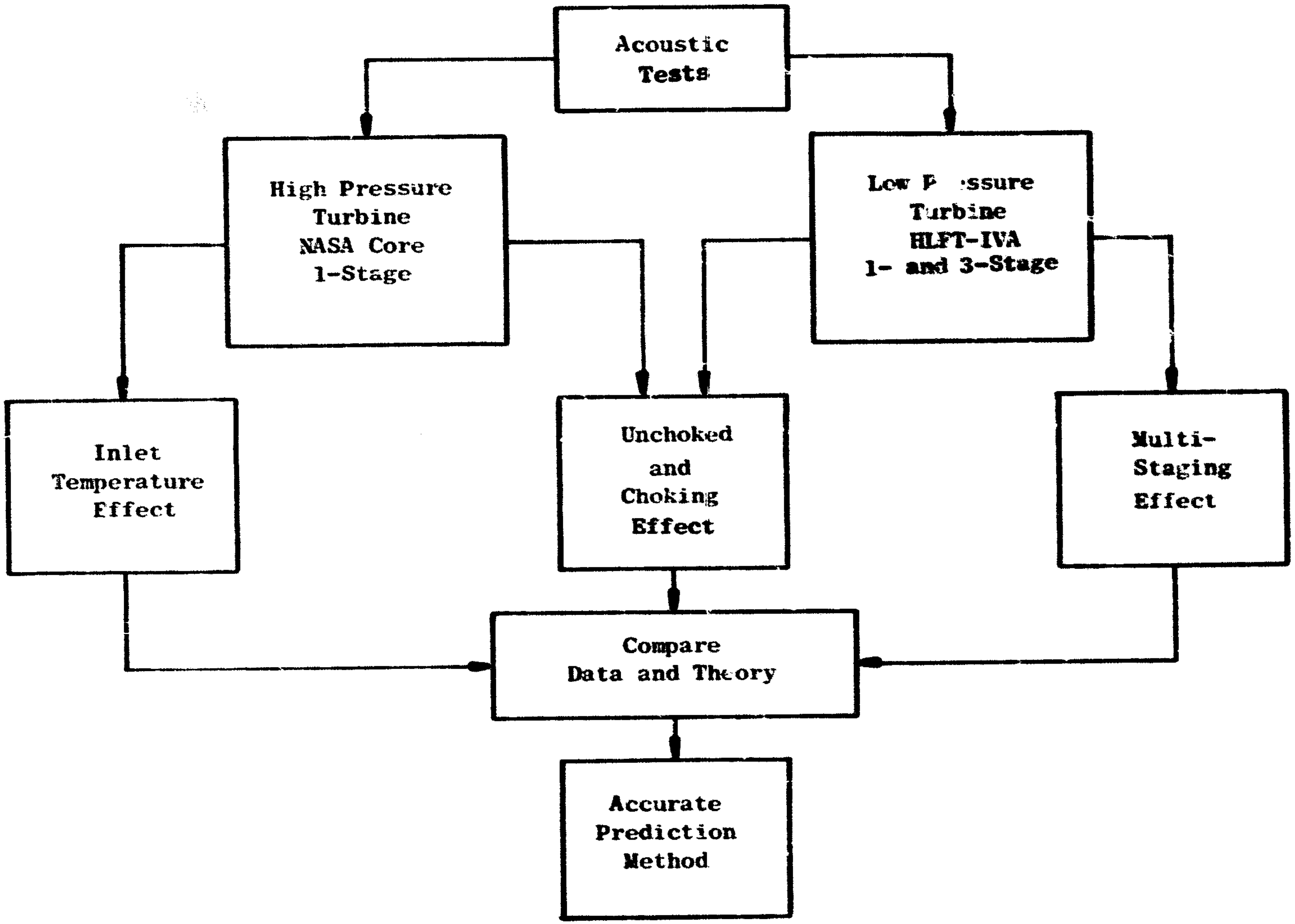


Figure 1. Structure of Acoustic Tests for Determining Low Frequency Noise Objectives.

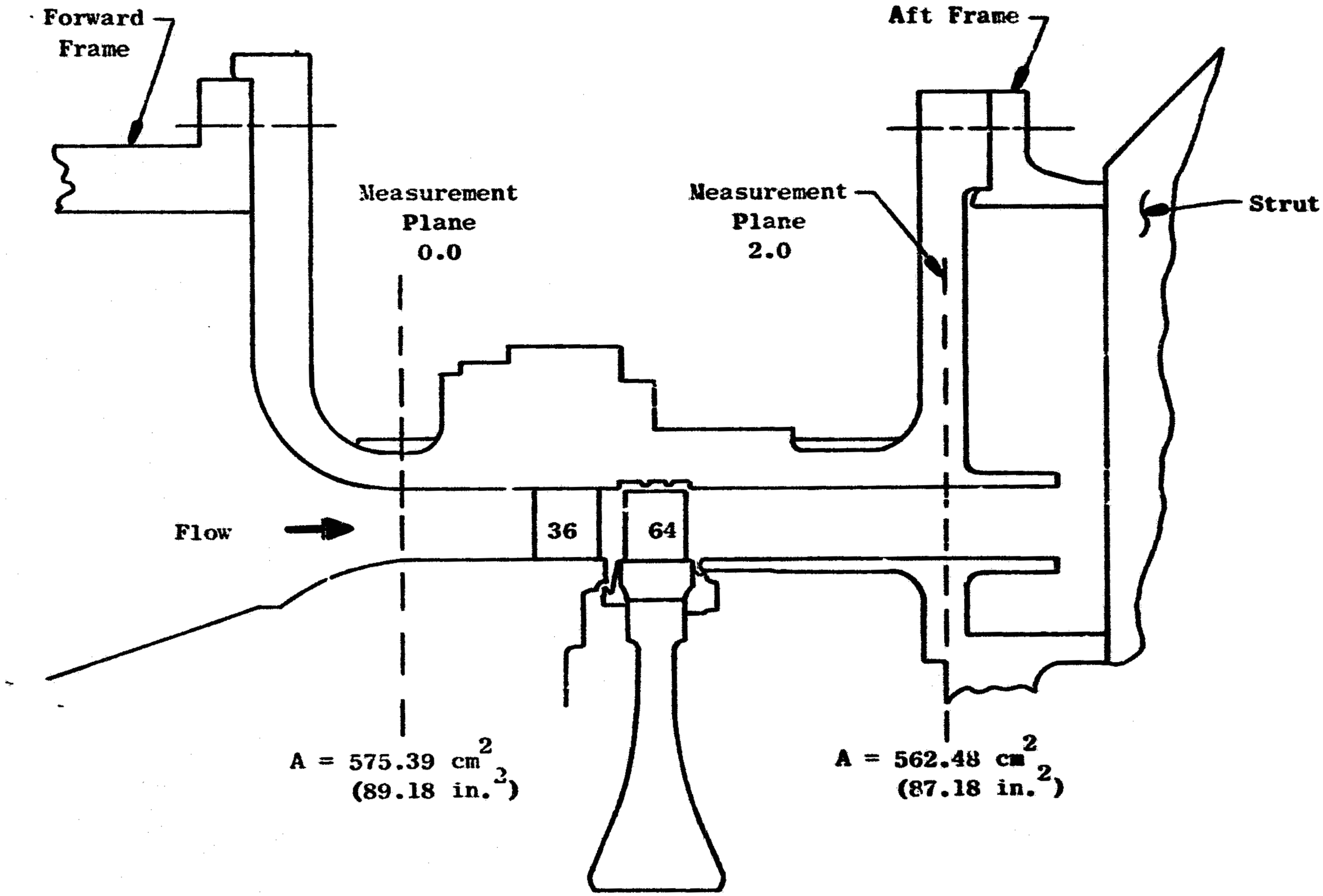


Figure 2. Schematic of NASA Core High Pressure Turbine.

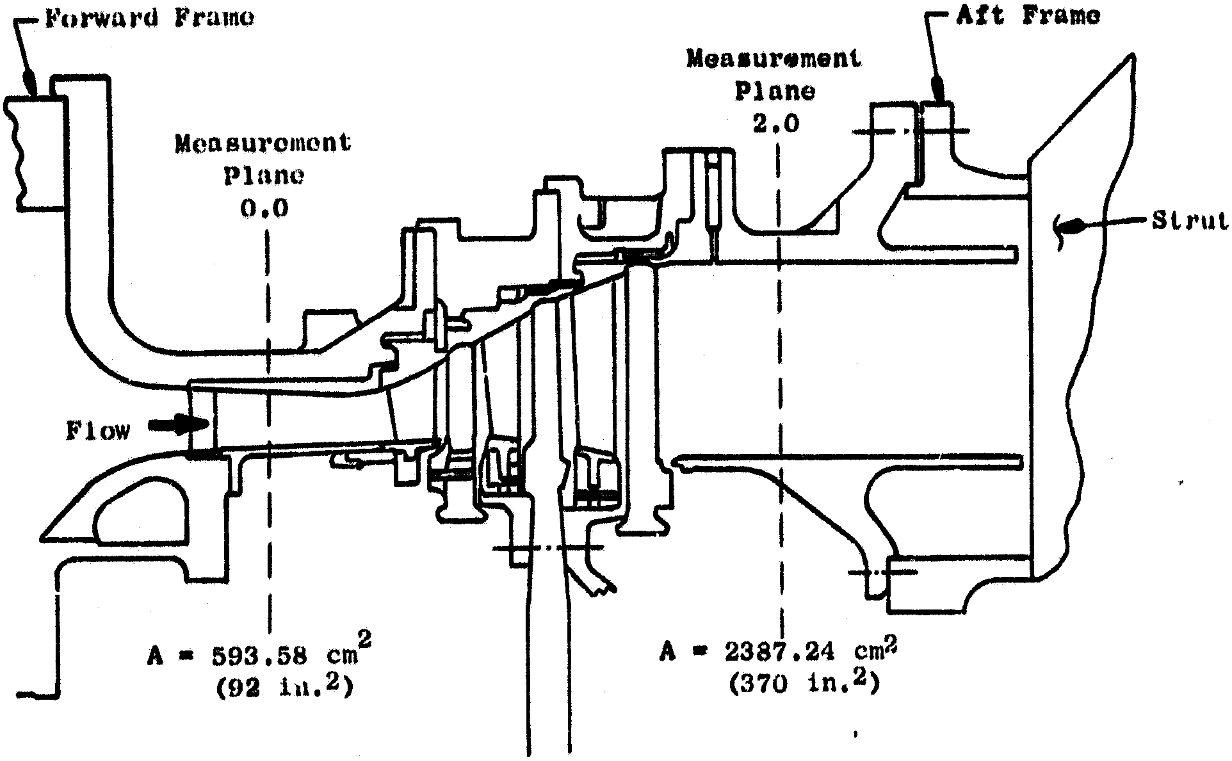


Figure 3. HLFT-IVA Low Pressure Turbine, 3-Stage Build.

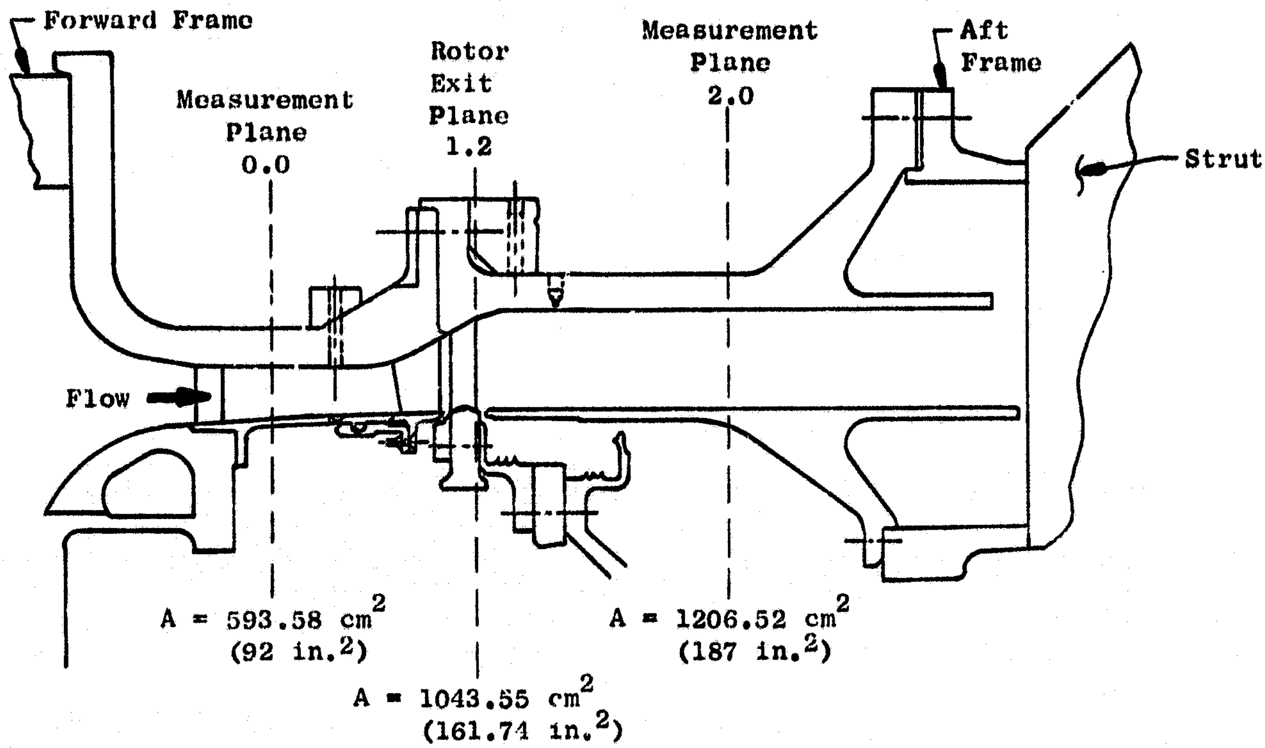


Figure 4. HLFT-IVA Low Pressure Turbine, 1-Stage Build.

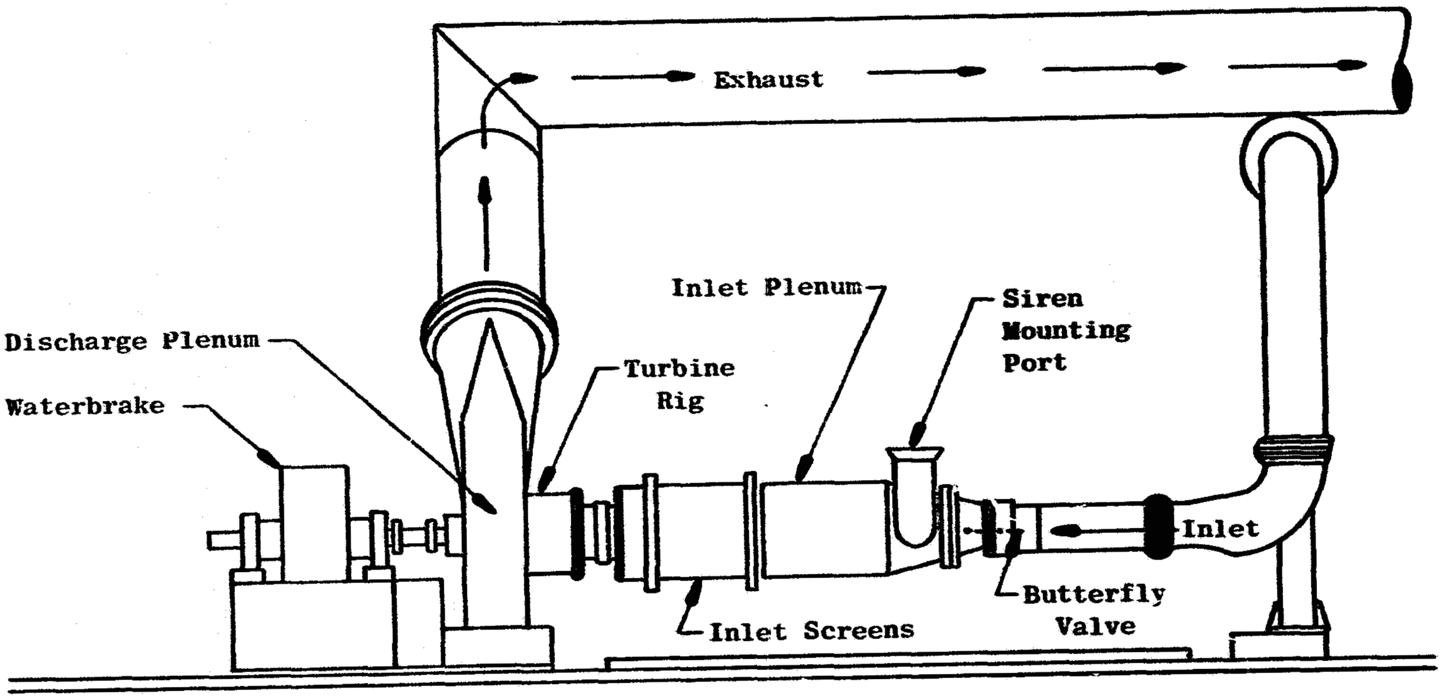


Figure 5. Warm Air Turbine Facility.

Supply System of the Component Test Complex, consisting of an arrangement of five multistage centrifugal compressors driven by synchronous motors through speed-increasing gears. Staging these compressors in series or parallel, or using them as exhaustors provides the various modes of operation normally required for turbine testing. The compressor discharge air can be directed through various auxiliary systems, providing air that is filtered to 10-micron particle size, dried to minus 226 K dewpoint, heated indirectly with steam to 450 K, or heated indirectly with natural gas to 866 K, depending on turbine requirements. The tests conducted under this NASA program were run at conditions of 275.8 and 389.5 kN/m^2 absolute inlet total pressure, and at inlet temperatures ranging from 422 to 783 K, which are well within the normal operating ranges of the facility.

After leaving the air heater, the air passes through a porous metal filter, a flow-straightening section, and a circular-arc venturi before entering the cell inlet piping system. The circular-arc venturi provides an accurate measurement of the inlet airflow rate. Prior to entering the vehicle inlet, the air passes through a 45.7 cm hydraulically actuated butterfly valve used for emergency shutoff, and then an inlet plenum which contains flow-straightening screens and egg crates which were specially designed to smooth out flow disturbances and provide a uniform stream to the test vehicle. The inlet plenum bolts directly to the vehicle forward frame, and is located on a wheeled dolly for rapid removal to access the vehicle inlet.

Air enters the first-stage nozzle through a convergent bellmouth section. Turbine discharge air leaves through a constant annular passage and expands into a discharge plenum designed to provide a uniform circumferential pressure distribution. As the air exits the vehicle it is discharged into a large exhaust scroll. A 1.067 meter exhaust pipe leaves the exhaust scroll and ducts the discharge air back to the vacuum header in the Central Air Supply System.

The generated turbine horsepower is extracted by means of a high speed waterbrake coupled to the turbine shaft by flexible couplings and a short spool piece. This waterbrake design provides excellent speed stability throughout the entire turbine operating map.

For protection against overspeed and excessive temperature or vibration, a two-level trip system is used. The Level 1 trip is signaled by an overspeed. The Level 2 trip is signaled by excessive bearing temperatures or vibrations, or critical support system temperatures or pressures. The turbine facility control console is located in the Test Cell Control Room. All necessary controls, and critical turbine or facility-monitoring instrumentation, are strategically located to enable two-operator manned control of the entire test facility. This feature is a direct result of the utilization of analog closed-loop control circuits for setting and maintaining all prime turbine variables. Turbine parameters of inlet temperature, inlet pressure, speed and discharge pressure can all be maintained automatically at preset values. The rotor net thrust, which represents the axial load on the shaft due to static pressure change across the rotating blade rows, is maintained within a specified range by controlling the air pressure in a thrust balance cavity. The cavity is enslaved within the bearing cartridge.

3.2.2 Siren Noise Source

An air-chopper siren pictured in Figure 6 was used in this program as the low frequency noise source simulating combustor noise. The range of frequencies for this investigation was from 70 to 3500 Hz. The siren consisted of a source of high pressure air, an electrically driven rotor (which interrupts the air flow at the frequency of the sound desired), and ports in a stator through which the air escapes. The siren was adapted to the warm air facility as shown in Figure 7.

The source of air was one of the air lines (620.5 kN/m^2) in the test cell which connected to the siren chamber through a 5.1 cm inlet. The pressure in the siren chamber was controlled by the upstream header pressure valves. To prevent rotor instability and excessive deflections a maximum ΔP of 137.9 kN/m^2 across the rotor was maintained for the tests. The acoustic output of the siren is a function of the chamber pressure, and this maximum ΔP produced siren tone levels of sufficient magnitude to determine the acoustic transmission loss through the turbine.

The rotor was driven by a 3.728 kW dc motor equipped with a synchronous drive speed control. A rotor disk with 20 slots was used to generate tones (a combination of fundamentals and harmonics) over the desired range of frequencies from 70 to 3500 Hz.

The aluminum stator consisted of a single disk with one slot matching the rotor slots. The stator exhausted into a 6.7 cm output port which was connected to a large transition section by a flexible coupling. The transition section, resembling a large exponential horn, was used to duct the siren tones into the facility plenum with a minimum of transmission loss.

An estimate of 10 dB transmission loss through the transition section was made, assuming a maximum siren output SPL of 160 dB at the siren exit. Measurements of the siren source level showed the peak SPL to be around 170 dB, while SPL measurements from Kulites located at the turbine inlet ranged from 138 to 165 dB.

The acoustic signal leaving the siren exhaust port traveled through the elbow shaped transition section which formed a continuous path with the inlet plenum access duct. The signal passed through the access duct, which connects radially with the facility inlet plenum upstream of the flow-straightening screens and egg crates, before reaching the bellmouth inlet of the test turbine.

The siren system was remotely controlled during the tests and was operated unchoked to give a cleaner signal and avoid excessive flow losses. Siren flow was less than 0.454 kg/sec and the chamber supply pressure was

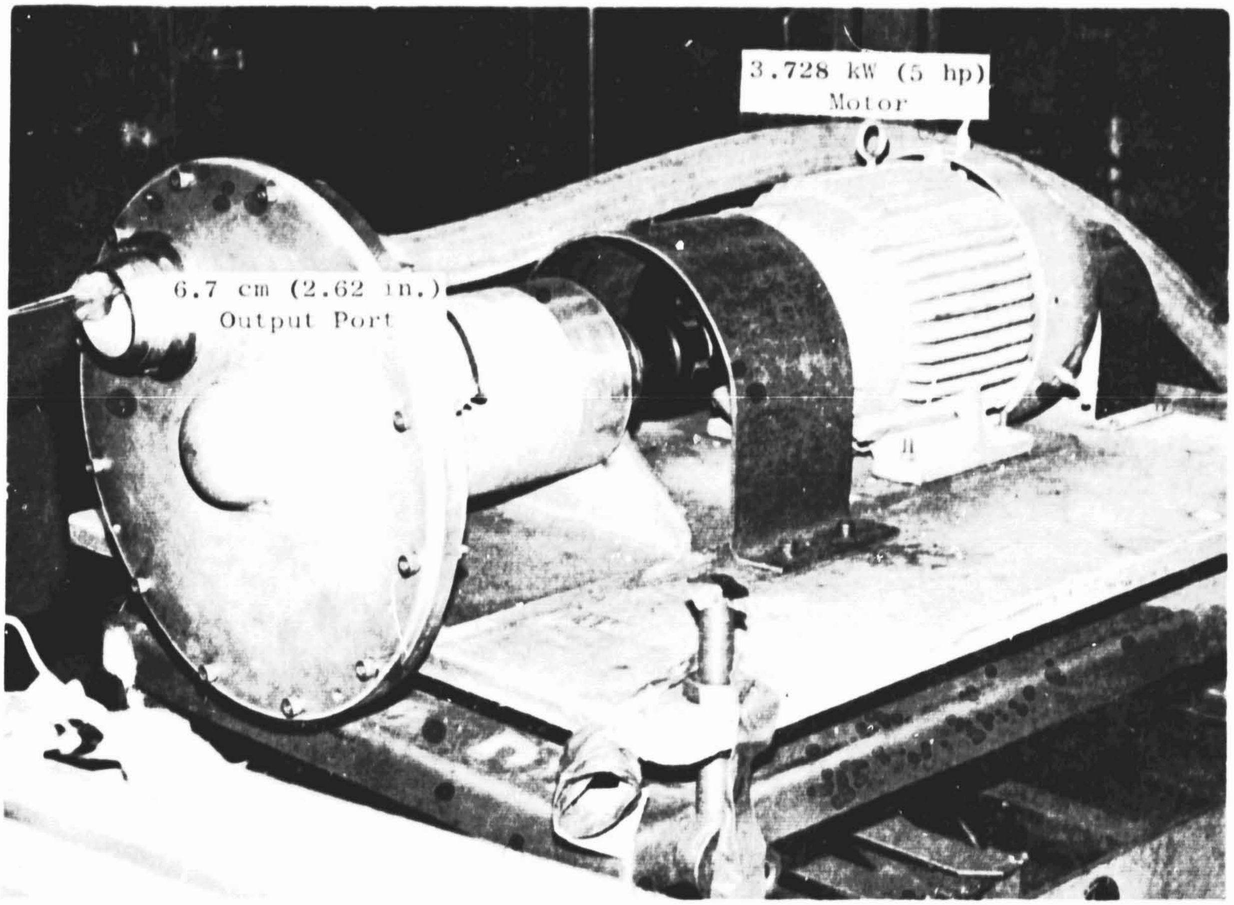


Figure 6. Siren Noise Source (C7406733).

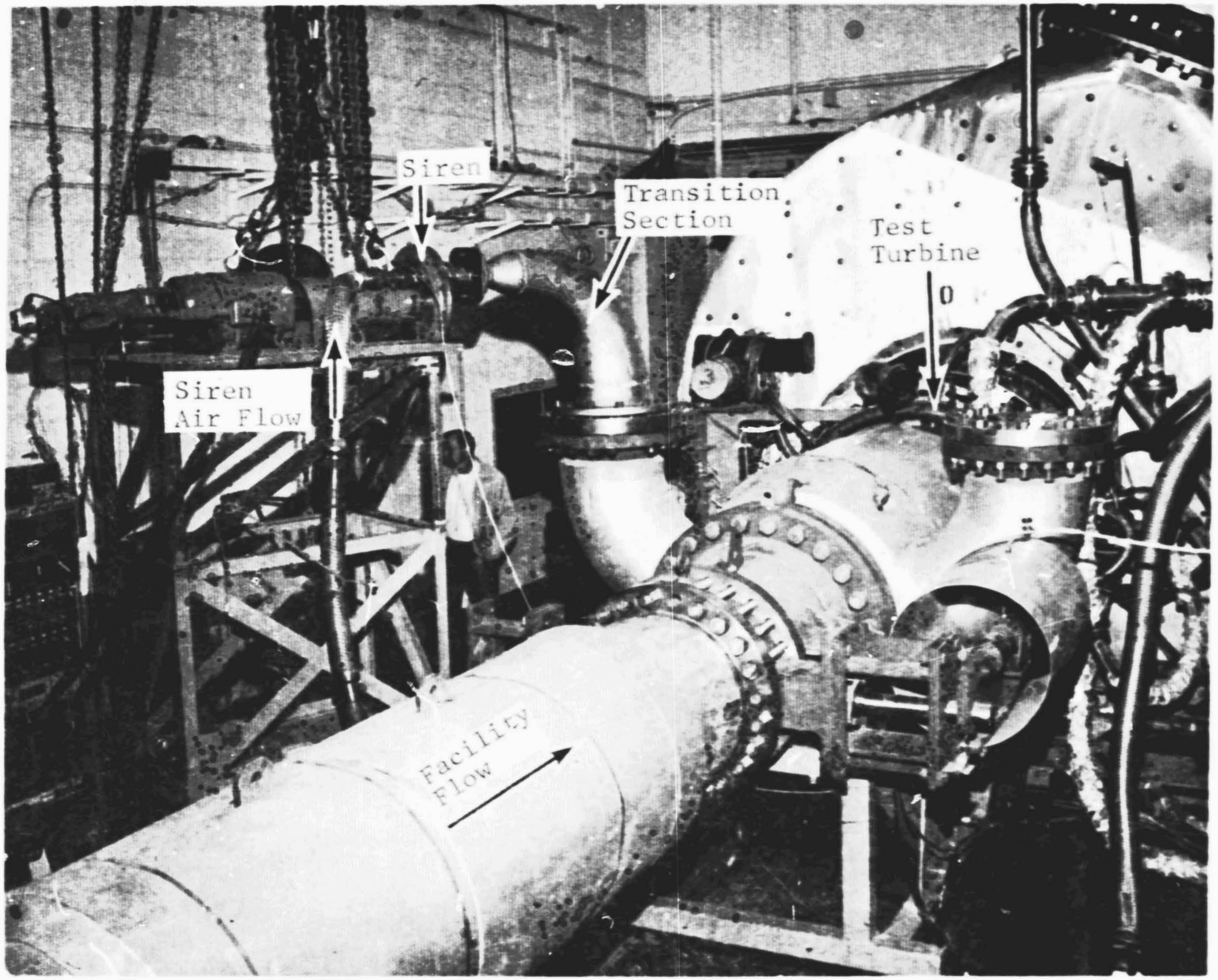


Figure 7. NASA Low Frequency Attenuation Test Setup.

maintained slightly higher (~17.2 kN/m^2) than the facility plenum pressure to ensure no reverse flow through the siren during each test.

3.3 TURBINE HARDWARE

3.3.1 High Pressure Turbine

The NASA core high pressure turbine vehicle is a model-size (scale factor ~0.67) turbine with a 50.8 cm rotor tip diameter capable of running at elevated temperatures. This turbine was used extensively in the NASA-Lewis cooling flow program NAS3-16732. The acoustic tests conducted under the low frequency noise program used the solid vane, solid blade configuration of the turbine with no cooling flows. The single-stage high pressure turbine consists of a 36-vaned stator and a rotor containing 64 blades. Other design characteristics are provided in Table 1, with details of the pitch-line blading in Table 2. The turbine inlet area is 575.39 cm^2 at the measuring plane. The turbine discharge is a straight annular section with an area of 562.48 cm^2 at the measuring plane.

3.3.2 Low Pressure Turbine

The HLFT-IVA low pressure turbine vehicle can be run as either a single-stage or three-stage machine. The turbine is highly loaded across the first two stages and contains a large number of blades in all stages. The blade numbers and other salient design characteristics are shown in Table 3. Pitch-line blade design details are given in Table 4.

The low pressure turbine three-stage build, shown in Figure 3, consists of a set of 116 preswirl vanes with radial trailing edges which orient the flow into the first-stage stator at about a 25° angle to simulate the conditions at the exit of a HP turbine. The average annulus area at the inlet measuring plane is 593.58 cm^2. The turbine discharge area is 2387.24 cm^2 in the constant annular section, which is essentially the same as at the exit from the third-stage rotor.

When the LP turbine is run as a single-stage, the last two stages are removed and both inner and outer exhaust casings are replaced with different casings, which form a smooth transition from first-stage rotor exit to turbine vehicle discharge. The exhaust annulus is straight and has an area of 1206.52 cm^2 at the measuring planes. The rotor exit area for the single-stage is 1043.55 cm^2, which represents a 15% area contraction from the measurement plane to rotor exit plane. Figure 4 shows a schematic of the single-stage build, illustrating the inlet exhaust areas.

Table 1. High Pressure Turbine Design Characteristics, (NASA Core Turbine).

Wt. Flow Function, $\frac{W\sqrt{T}}{P}$	0.81
Loading, $\frac{gJ\Delta H}{\Sigma U_p^2}$	1.66
Pressure Ratio (Total)	1.83
Speed, $N/\sqrt{T}$	362
Stator Vanes	36
Rotor Blades	64
Radius Ratio	0.85
Tip Diameter (Stage Exit), (cm)	50.8

Table 2. High Pressure Turbine Design Details (Pitchline), (NASA Core Turbine).

• Stator Vane	
Stagger Angle (deg)	44.61
Chord (cm)	5.35
Blade-to-Blade Pitch (cm)	4.10
Camber Angle (deg)	67.2
• Rotor Blade	
Stagger Angle (deg)	24
Chord (cm)	3.86
Blade-to-Blade Pitch (cm)	2.31
Camber (deg)	89.6
• Blade-Row Axial Spacing (cm)	1.31
• Flow Area at Acoustic Measuring Sections	
Inlet Area (cm^2)	575.39
Exit Area (cm^2)	562.48

Table 3. Low Pressure Turbine Design Characteristics, (Highly Loaded Fan Turbine, HLFT-IVA).

	Stage 1	Stage 2	Stage 3	Overall
Wt. Flow Function, $\frac{W\sqrt{T}}{P}$	-	-	-	1.57
Loading, $\frac{gJ\Delta H}{\Sigma U_p^2}$	3.52	3.12	1.60	2.70
Pressure Ratio (Total)	1.73	1.81	1.41	4.72
Speed, $N/\sqrt{T}$	-	-	-	204
Stator Vanes	100	144	140	-
Rotor Blades	206	190	160	-
Radius Ratio	0.811	0.735	0.663	-
Tip Diameter (Stage Exit)(cm)	63.55	69.08	73.18	-

Table 4. Low Pressure Turbine Design Details (Pitch Line), (Highly Loaded Fan Turbine, HLFT-IVA).

	Stage 1		Stage 2		Stage 3
• **Stator Vane**					
Stagger Angle	31.5°		25°		17.5°
Chord (cm)	3.25		2.26		2.51
Blade-to-Blade Pitch (cm)	2.40		1.29		1.36
Camber Angle	89.8°		110.4°		99.8°
T_{max}/Axial Chord (Pct)	14.06		9.17		7.63
• **Rotor Blade**					
Stagger Angle	16°		14°		13°
Chord (cm)	1.44		1.64		1.72
Blade-to-Blade Pitch (cm)	0.88		0.99		1.19
Camber Angle	112.5°		110.3°		83.6°
T_{max}/Axial Chord (Pct)	11.10		12.04		9.91
• **Blade-Row Axial Spacing**					
Vane-Blade Spacing (cm)	0.74		0.86		0.81
Blade-Vane Spacing (cm)		0.84		0.91	
• **Flow Area at Acoustic Measuring Sections**					
3-Stage Rig					
Inlet Area (cm^2)			593.58		
Exit Area (cm^2)			2387.24		
1-Stage Rig					
Inlet Area (cm^2)			593.58		
Exit Area (cm^2)			1206.52		

3.3.3 Turbine Frames

The turbine vehicles are supported by forward and aft frame assemblies (see Figures 2 through 4) which mount directly into the air turbine facility. The forward frame assembly consists of a 10-strut frame and outer and inner flowpath casings. Each of the 10 struts contains leading-edge instrumentation elements. Five struts contain five total pressure elements, and five struts contain five total temperature elements located at centers of five equal annular areas. The photograph in Figure 8 shows the first-stage stator of the low pressure turbine mounted to the forward frame during buildup of the vehicle.

The aft frame assembly consists of a 12-strut frame, and outer and inner flowpath casings. The aft frame mounts directly to the facility discharge plenum. Figure 9 is a photograph of the first-stage rotor and last two stages of the low pressure turbine mounted to the aft frame section.

3.4 TEST MATRICES

The acoustic tests of the component turbines were conducted over ranges of conditions with previously mapped aerodynamic performance. The tests consisted of a minimum of 15 test points (combinations of pressure ratios and speeds) which were set on each turbine build. In addition, a sufficient number of points were repeated in order to establish the data repeatability.

The inlet absolute total pressure for the high pressure turbine tests was maintained at 389.5 kN/m^2 while the inlet total temperature was set at 450 K for the cold inlet test and 783 K for the hot inlet test. The tests were conducted at four turbine pressure ratios ranging from 1.6 to 3.03 and at four speeds ranging from 70 to 110% of design speed. Table 5 shows the conditions tested along with repeat points.

The low pressure turbine was run in both three-stage and single-stage configurations. The inlet conditions for both runs were maintained constant at 275.8 kN/m^2 and 422 K. The three-stage build of the low pressure turbine was tested over a range of turbine pressure ratios from 2.0 to 5.2 and at five speeds ranging from 50 to 110% of design speed. The single-stage build was tested over the same range of turbine speeds but at four turbine pressure ratios ranging from 1.6 to 2.5. The test conditions and repeat points for both builds are shown in Table 6.

The siren was operated over a range of seven speeds to establish the test frequency matrix of 21 tones from 70 to 3500 Hz, (which was the range of the low frequency noise investigation for this program). The matrix consisted of fundamentals, second and third harmonics as shown in Table 7.

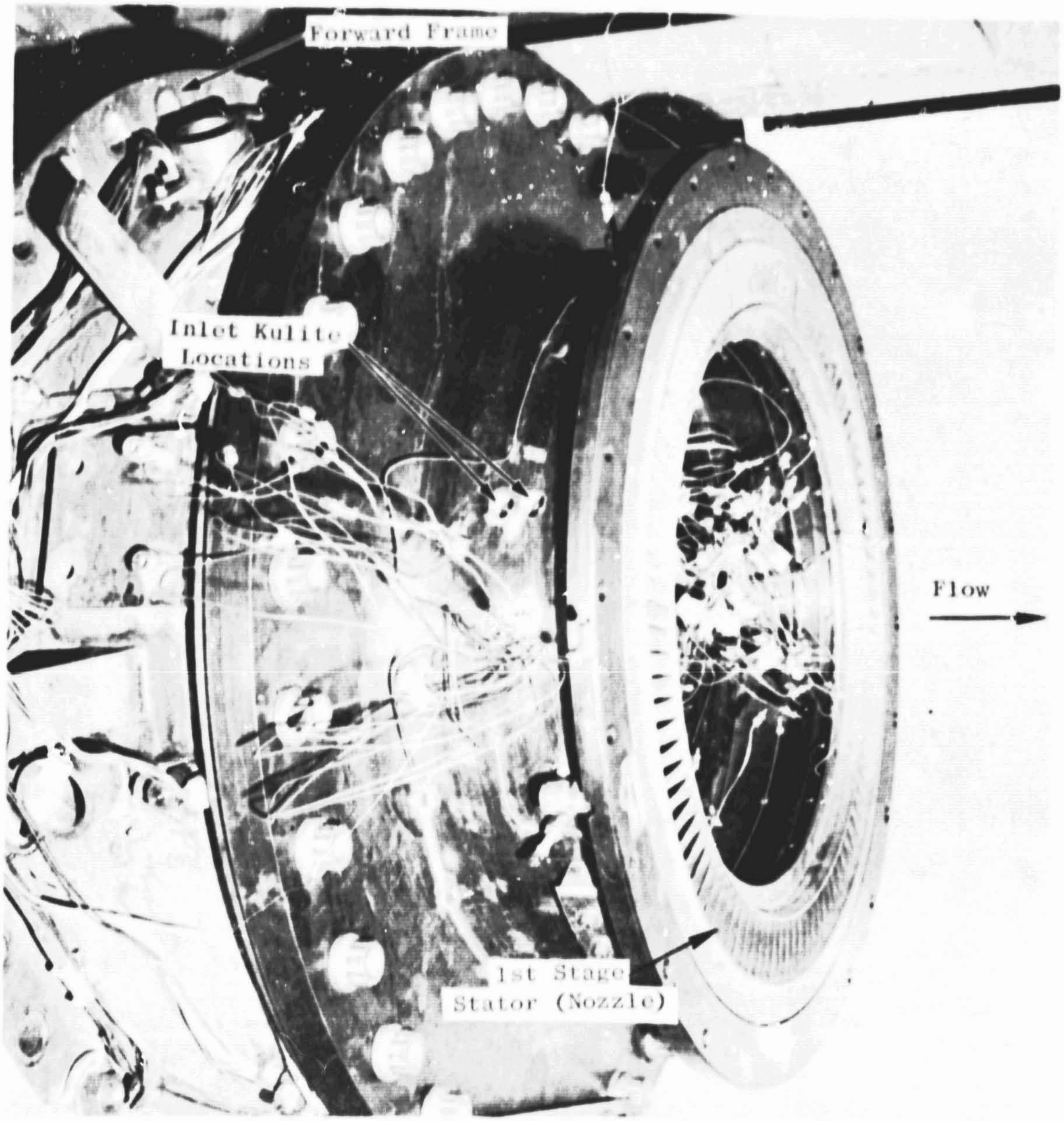


Figure 8. HLFT-IVA Low Pressure Turbine Buildup (C7607130).

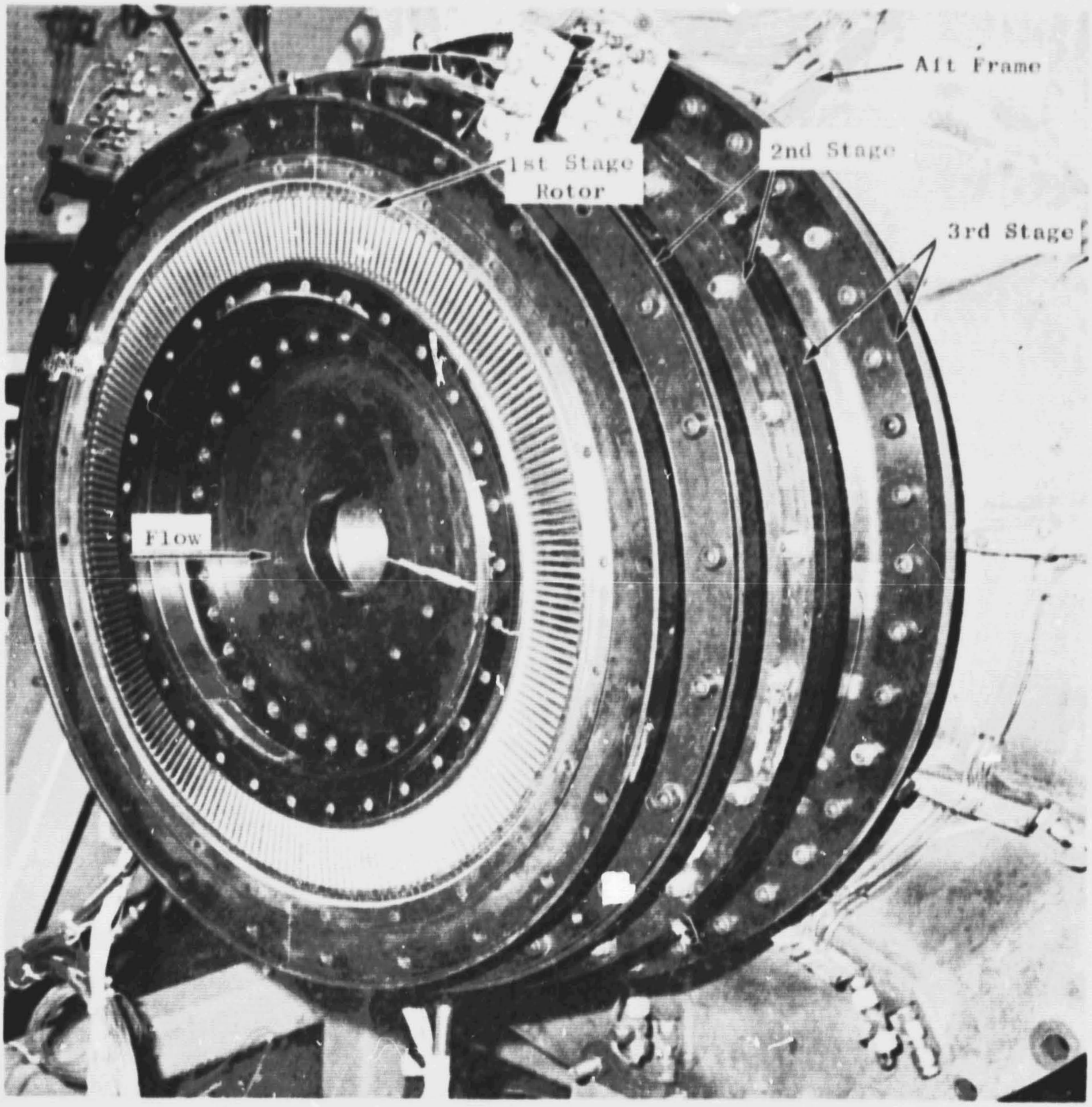


Figure 9. HLFT-IVA Low Pressure Turbine, 3-Stage Buildup (C7607129).

Table 5. High Pressure Turbine Test Matrix, (NASA Core Turbine)

- Design Speed, $N/\sqrt{T} = 362$
- Flow Function, $W\sqrt{T}/P = 0.81$
- Inlet Absolute Total Pressure, $P_{T0} = 389.5\ kN/m^2$

		Cold Inlet Test $T_{T0} = 450$ K						Hot Inlet Test $T_{T0} = 783$ K				
		P_{T0}/P_{S2}						P_{T0}/P_{S2}				
% $N/\sqrt{T}$	rpm	1.9	2.14	2.49	2.68	3.03	rpm	1.9	2.14	2.49	2.68	3.03
70	5380	X	X	X	X	–	7100	X	X	X	X	–
90	6920	X	(X)	X	X	–	9130	X	X	X	X	–
100	7690	X	(X)	(X)	–	X	10146	X	X	X	–	X
110	8460	X	(X)	X	–	X	11160	–	X	X	–	X

◯ – Repeat Point

Table 6. Low Pressure Turbine Test Matrix, (HLFT-IVA).

- Design Speed, $N/\sqrt{T}$ = 204
- Flow Function, $W\sqrt{T}/P$ = 1.57
- Inlet Total Pressure P_{TO} = 275.8 kN/m^2
- Inlet Total Temperature, T_{TO} = 422 K

% Design Speed	Speed (rpm)	Pressure Ratio (P_{TO}/P_{S2}) Single-Stage Build 1.6	1.9	2.2	2.5	Three-Stage Build 2.0	3.0	4.0	5.2
50	2100	X	-	-	-	X	-	-	-
70	2940	X	X	X	-	X	X	X	-
90	3780	X	X	(X)	X	X	(X)	X	X
100	4200	X	(X)	(X)	(X)	X	X	X	(X)
110	4615	X	X	X	X	X	(X)	X	X

○ - Repeat Point

Table 7. Siren Tonal Frequencies.

Siren Setting	Siren rpm	Fundamental Frequency (Hz)	2nd Harmonic (Hz)	3rd Harmonic (Hz)
1	250	83	167	250
2	375	125	250	375
3	900	300	600	900
4	1200	400	800	1200
5	2250	750	1500	2250
6	3000	1000	2000	3000
7	3525	1175	2350	3525

Test points were established by adjusting the turbine discharge pressure to get the proper turbine pressure ratio, P_{TO}/P_{S2} while holding the inlet conditions constant. The power absorbed by the water brake was adjusted by varying water flow rate to maintain the required turbine speed. When a point was set, the siren was set to give the desired frequency and 90 seconds of acoustic data were recorded on magnetic tape. At least seven tape recordings at different frequencies were taken at each test condition along with a digital reading of the aerodynamic vehicle and facility data prior to setting the next condition.

3.5 DATA ACQUISITION SYSTEM

The aerodynamic and acoustic instrumentation used in the tests of both the high pressure and low pressure turbines formed the first component in the data acquisition system established for this program.

The aerodynamic instrumentation was minimal in both series of tests, with only that necessary to establish the validity of the test condition when compared with existing aerodynamic performance results.

3.5.1 Acoustic Instrumentation

The acoustic instrumentation for these tests consisted of redundant pairs of Kulite pressure transducers positioned upstream and downstream of the turbine blade rows (see Figures 10 through 12). The attenuation across the blade rows was determined from the difference in SPL measurements from the upstream and downstream transducers.

The Kulite transducer is essentially a Wheatstone bridge strain gage mounted on a pressure sensitive diaphragm. A direct current power supply (batteries) excites one side of the bridge as illustrated in Figure 13. The output is taken across the other side. The electrical output signal varies in proportion to the diaphragm pressure fluctuations. A known back pressure is applied to the back of the transducer diaphragm through the back pressure tube. The output signal can then be calibrated for the known power supply voltage and applied back pressure. The calibration is in terms of millivolts output per volt of power supply per psi increase in pressure on the diaphragm. During the test, the back pressure tube is referenced to the test vehicle section pressure to prevent over-pressurizing the Kulite diaphragm and to maintain zero bias.

The upstream instrumentation consisted of four water-cooled Kulite transducers like the one shown in Figure 14. These were paired in two sets. Each set was mounted in the same axial plane on the outer casing just forward of the first stage stator and aligned axially with a 2.54 cm spacing between Kulites to permit correlation analysis of the axially propagating signals. The Kulite pairs were displaced circumferentially approximately 180° apart in both turbines.

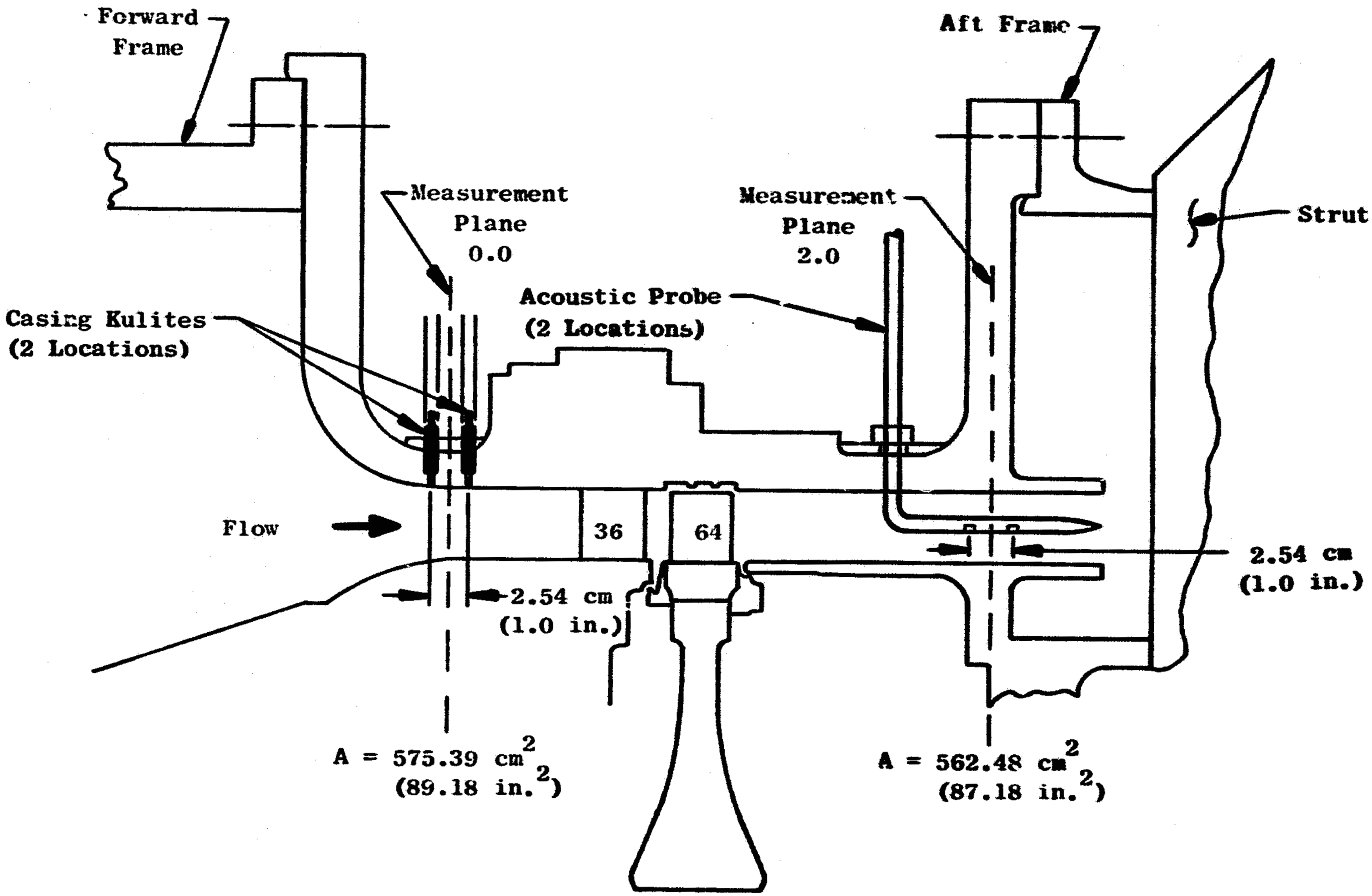


Figure 10. Schematic of NASA Core High Pressure Turbine Vehicle.

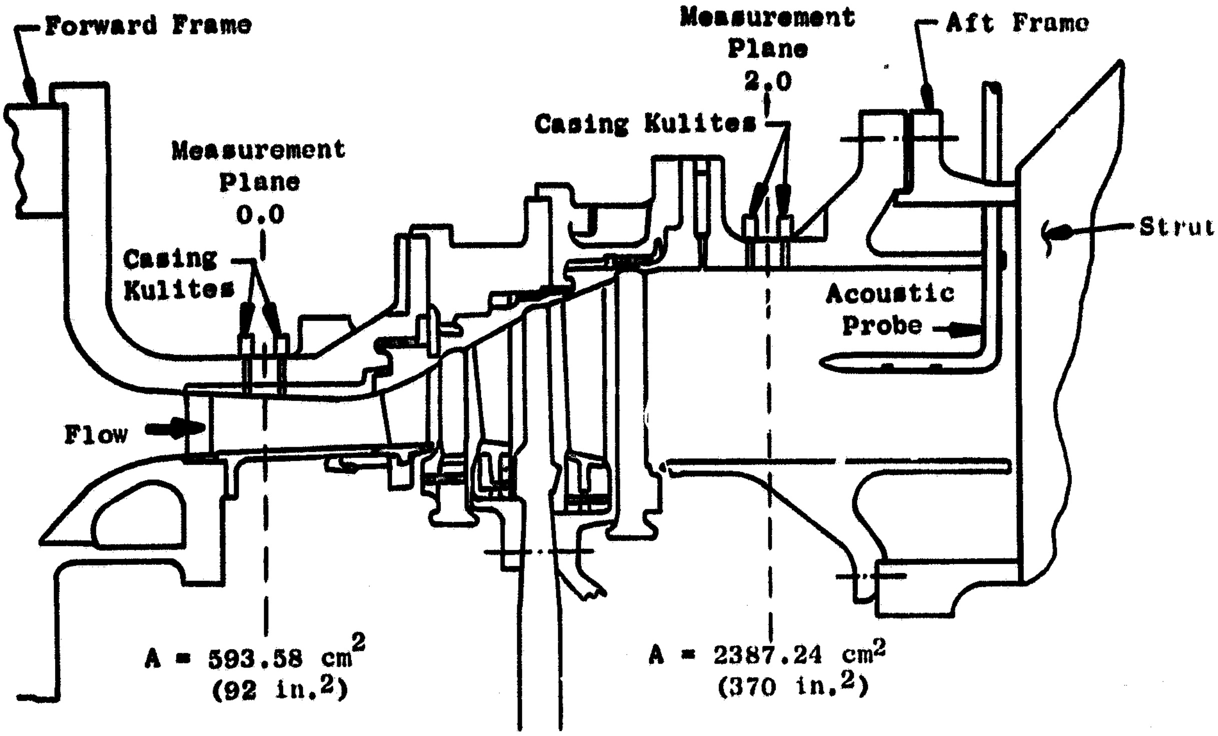


Figure 11. HLFT-IVA Low Pressure Turbine, 3-Stage Build.

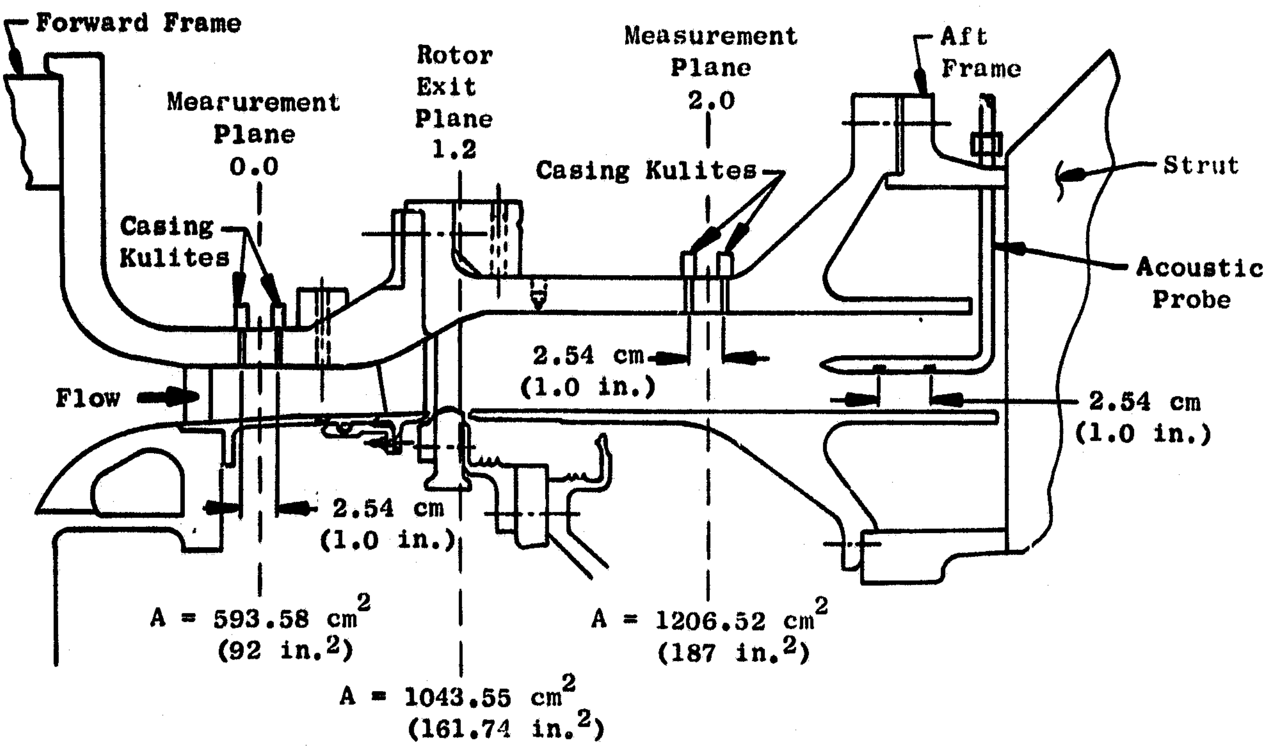


Figure 12. HLFT-IVA Low Pressure Turbine, 1-Stage Build.

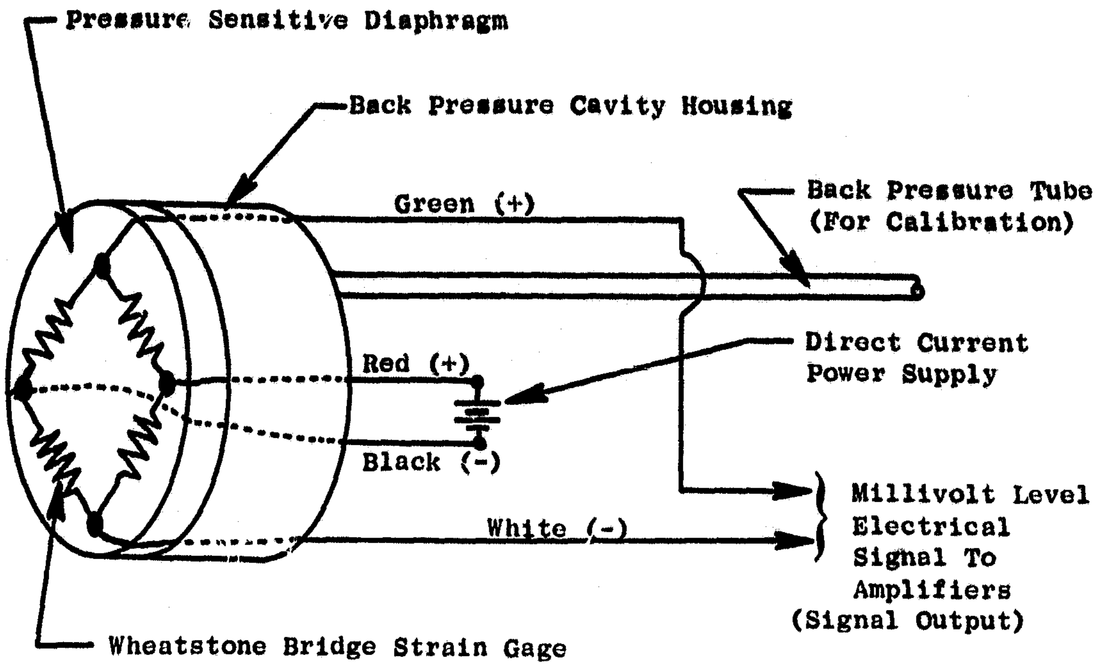


Figure 13. Kulite Pressure Transducer Schematic.

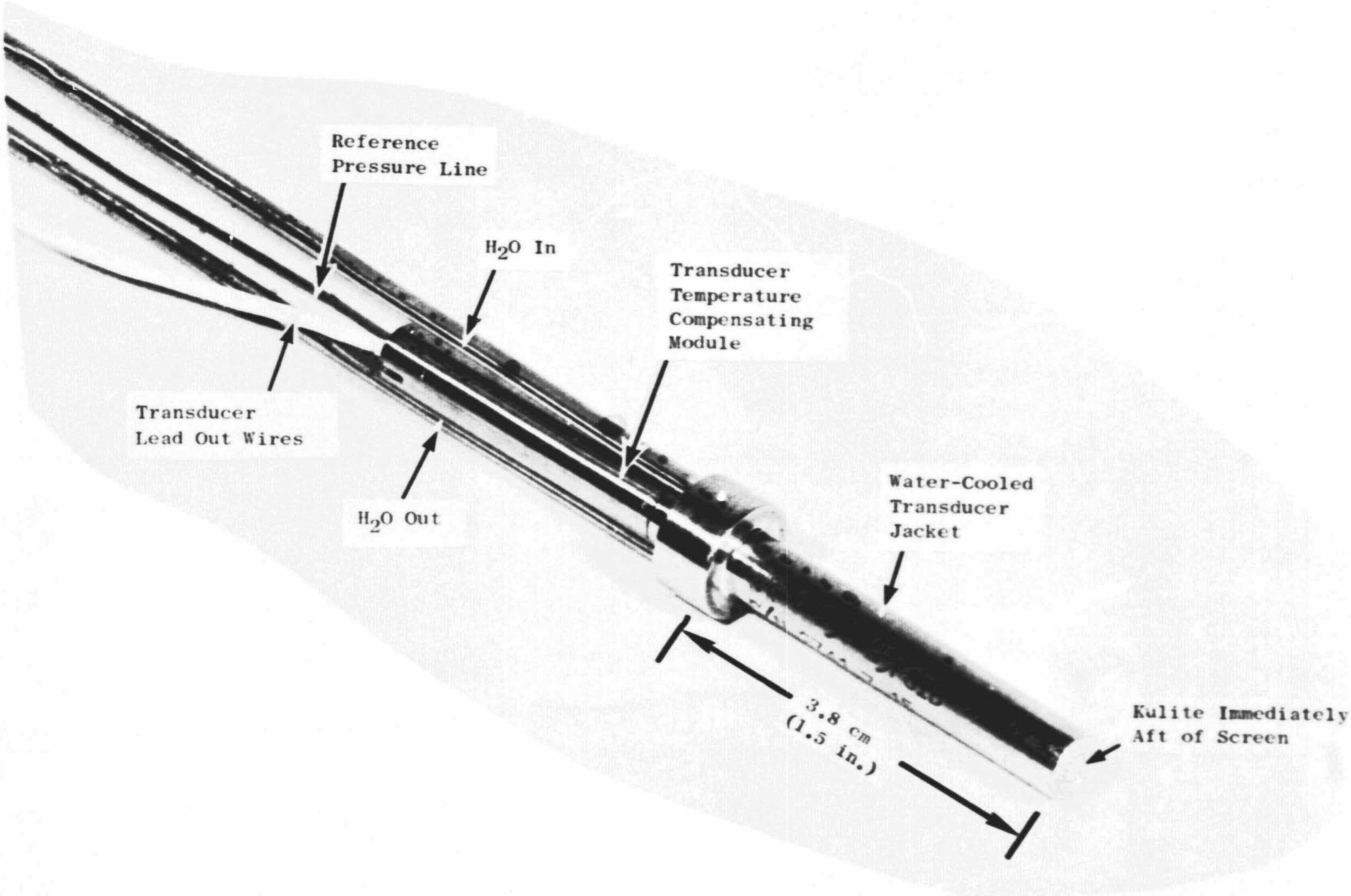


Figure 14. Water-Cooled Inlet Casing Kulite Instrumentation (C7509149).

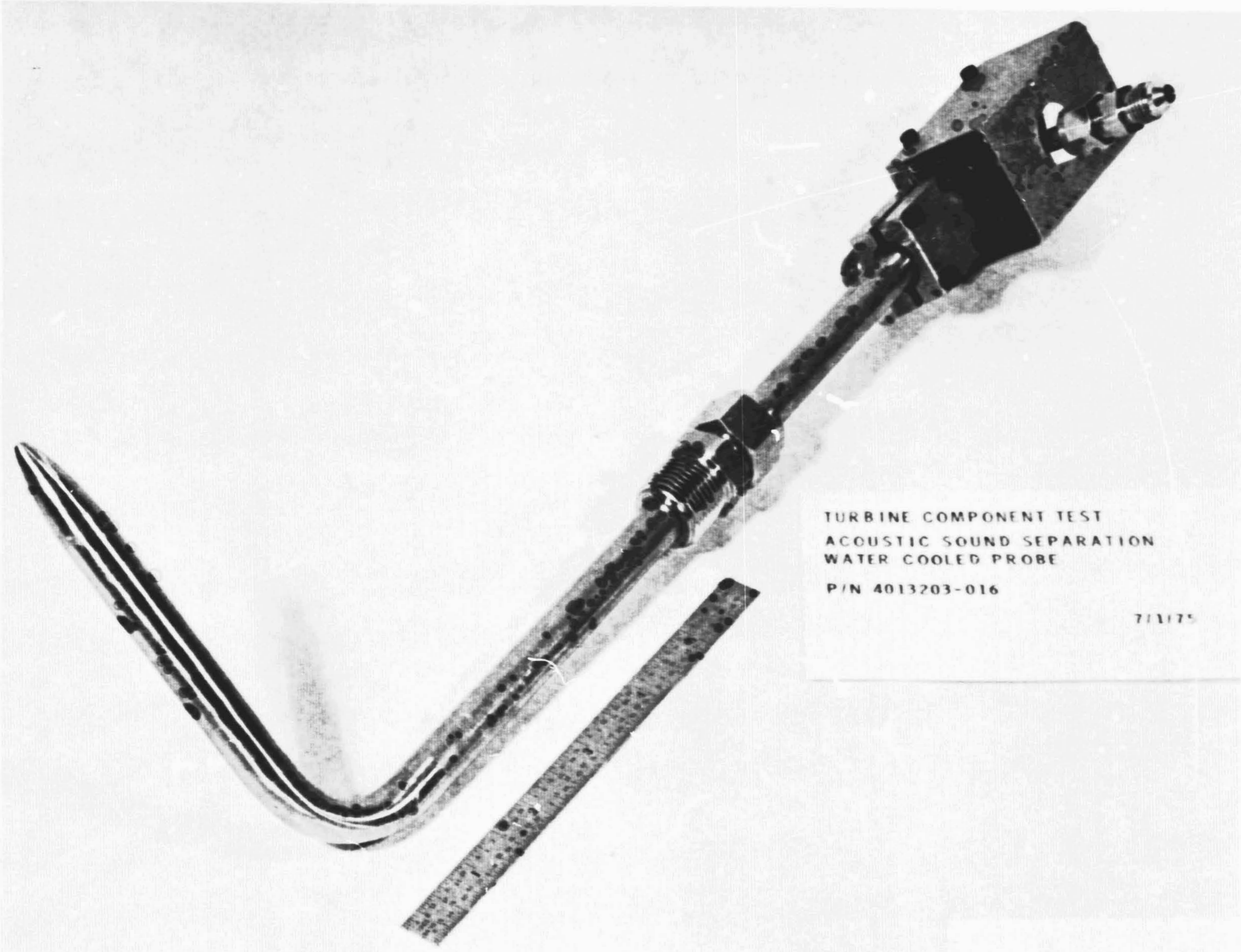


Figure 15. Sound-Separation Water-Cooled Probe (C7507025).

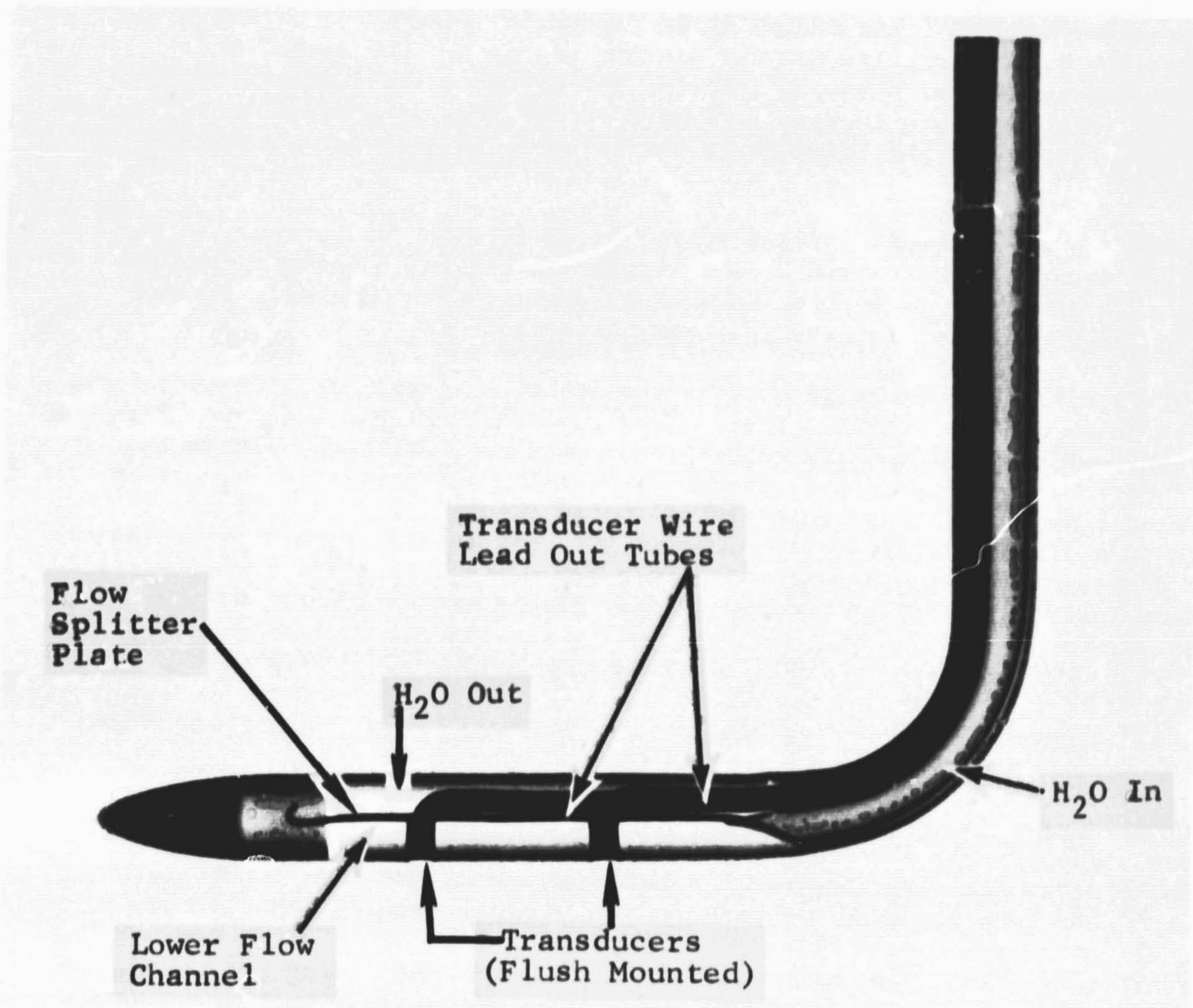


Figure 16. X-Ray Photograph of Water-Cooled Sound-Separation Probe.

The downstream instrumentation for the high pressure turbine was composed of two water-cooled sound-separation probes (Reference 7). Each probe contained two Kulites separated by 2.54 cm spacing. Figure 15 shows a photograph of one of the probes while Figure 16 is an X-ray of the probe showing the Kulite installation and cooling passages. The probes were designed to run either pointing into the low pressure turbine or away from the flow (high pressure turbine). A wind tunnel test verified that the only effect was a slight increase in the noise floor for the latter configuration.

For the low pressure turbine tests, in addition to the probes, a pair of flush-mounted wall Kulites were installed in the outer exhaust casing to serve as a check and backup to the exhaust probes. The spacing and orientation was the same as for the upstream Kulite sensors.

Figure 17 is a schematic showing the acoustic instrumentation locations for the high pressure turbine test. Note that the upstream and downstream circumferential locations are at different angular positions. Similarly, the locations of the acoustic sensors for the low pressure turbine test on the single and three-stage turbine builds are identified in Figure 18, which is a circumferential rolled-out view of the turbine vehicle with the zero degree mark corresponding to vehicle top center. For the low pressure turbine tests the upstream and downstream sensors were aligned circumferentially.

3.5.2 Acoustic Recording System

The Kulite signals measured in the vehicle in the test cell were amplified prior to being transmitted to the recording equipment to ensure proper signal strength. A schematic illustrating the general setup of the acoustic data acquisition system for this program is shown in Figure 19. All the data were recorded on magnetic tape using a Sangamo Sabre IV 28-channel recorder having a dynamic range of 48 dB and a flat frequency response to 40-kHz. The data acquisition and recording system for these acoustic tests was set up in the ac mode to record the fluctuating pressure measurements between 110 and 160 dB from the Kulite sensors. An end-to-end phase check calibration was made of the entire system while in the dc mode, which accounted for individual component sensitivites and responses (i.e., transducer, amplifier, tape recorder, and leadout cables). This ensured accurate recorded levels when the system was operated in the ac mode during a data run.

An on-line calibration of the Kulite systems was performed frequently during the course of the tests to determine changes in transducer sensitivity at operating temperature, and to maximize the use of the tape recorder dynamic range.

On-line data acquisition was conducted for a select number of upstream and downstream Kulite pairs during the high pressure turbine tests, using an EMR 1510 spectrum analyzer coupled with an X-Y plotter. This permitted

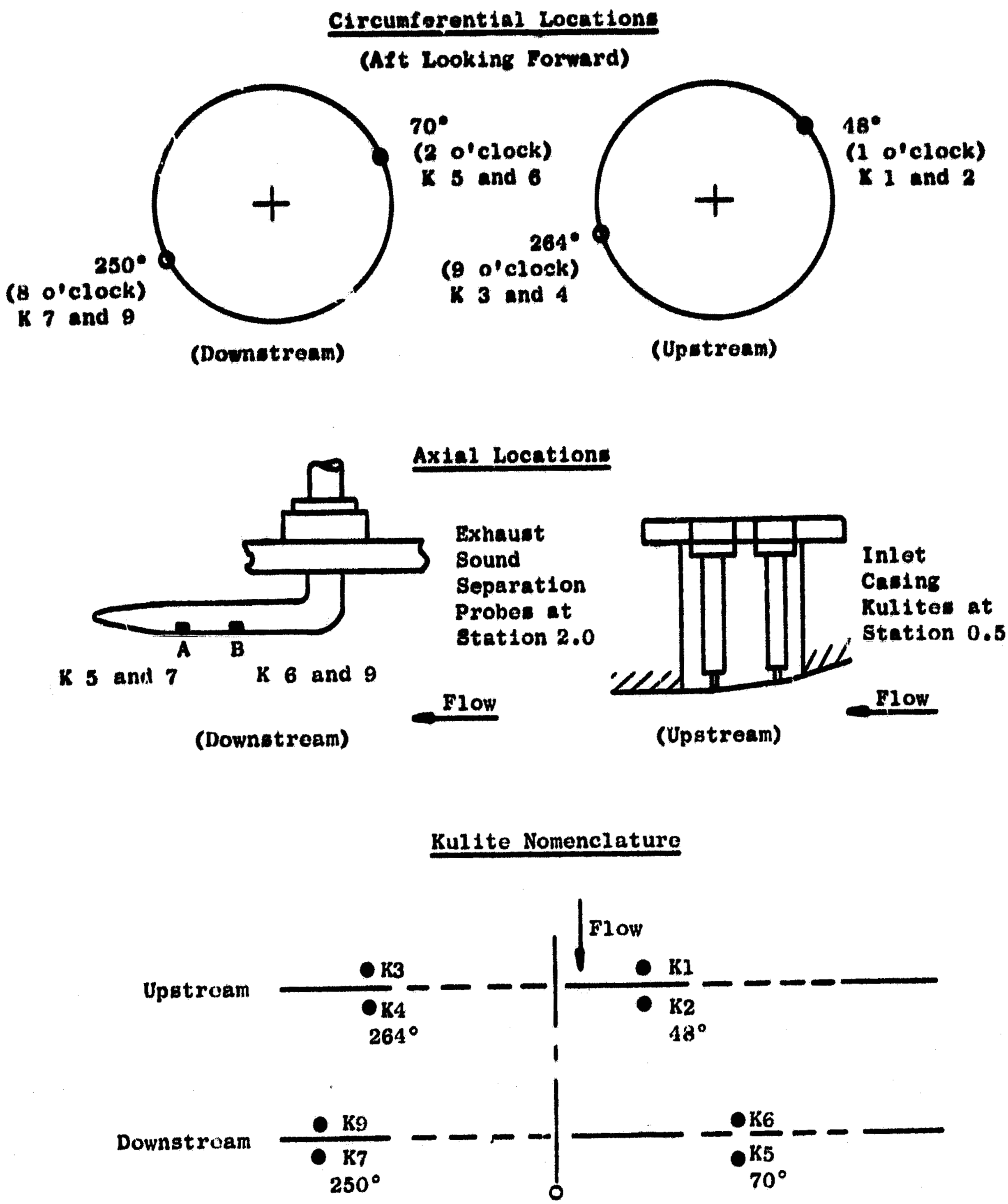


Figure 17. Acoustic Instrumentation Locations for High Pressure Turbine.

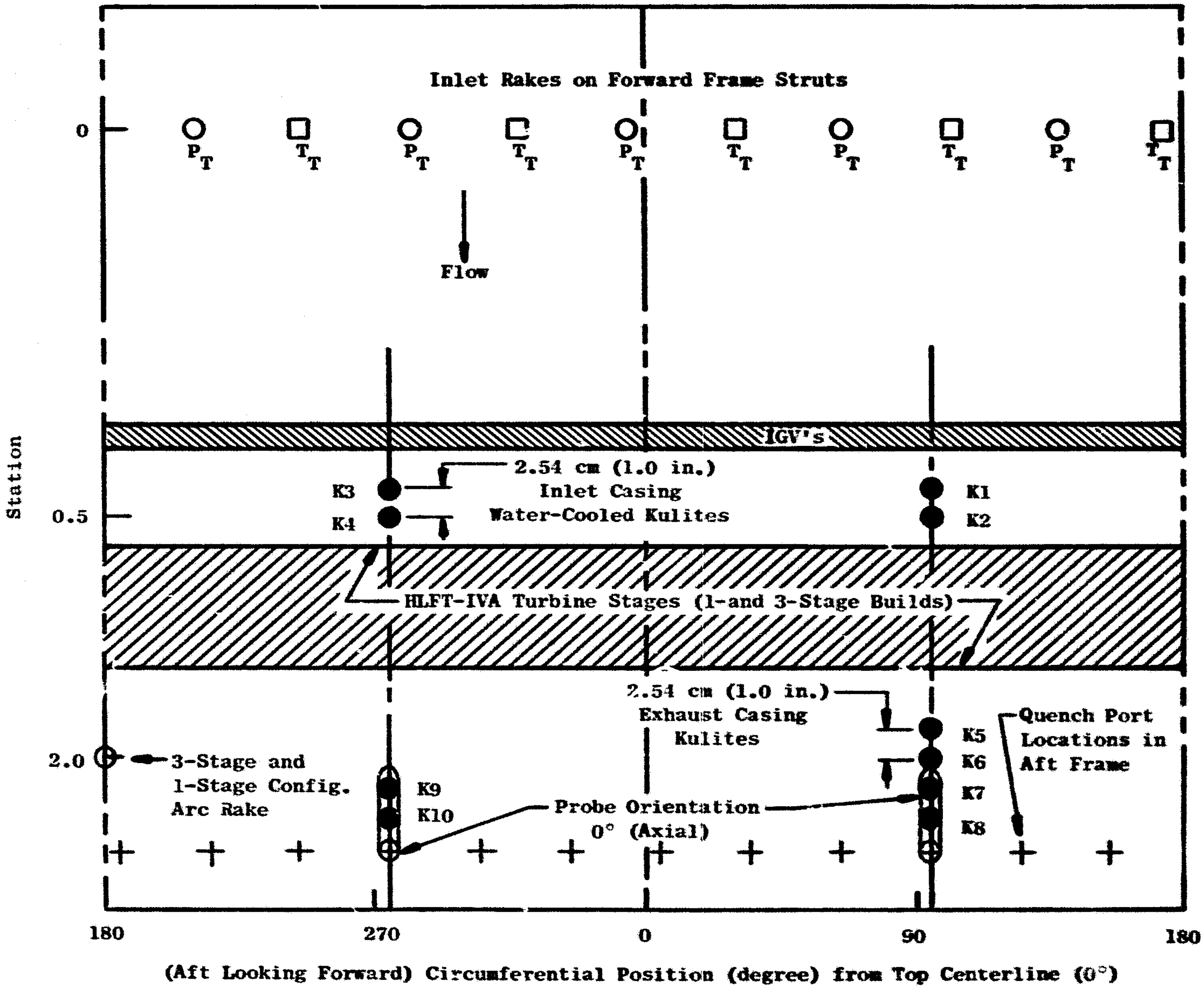


Figure 18. Acoustic Instrumentation Layout for Low Pressure Turbines.

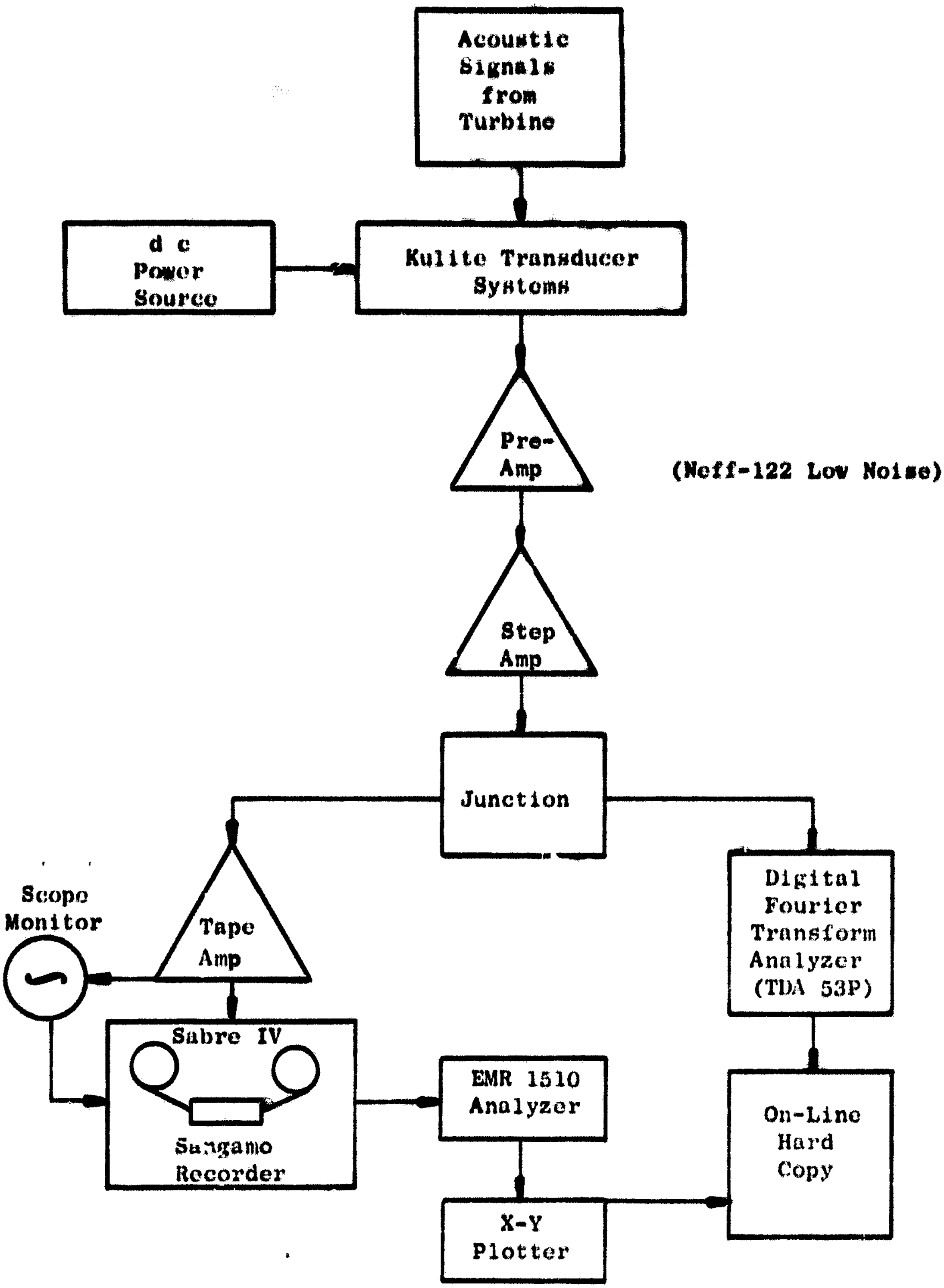


Figure 19. Acoustic Data Acquisition System.

on-line evaluation of a limited sample of results over the range of conditions tested. Further sophistication was introduced with the use of a digital Fourier transform analyzer (TDA 53P) for on-line analysis during the low pressure turbine tests. This enabled immediate determination of the turbine transfer function from a greater number of Kulite pairs, and also provided increased dynamic range (70 dB). The increased dynamic range protected against encountering the electronic noise floor if the recorded siren signal downstream of the turbine was below the turbine broadband, and required correlation techniques (sound-separation) to separate the acoustic signal from the turbulence.

3.6 DATA REDUCTION TECHNIQUES

3.6.1 Description of Techniques

The noise sources to be utilized in determining the blade-row attenuation during the performance of this program included: (1) upstream-generated siren tones and, (2) facility-generated broadband noise.

The primary method of analysis of discrete tones is generally through narrowband autospectral analysis. However, the pressure signal recorded on acoustic sensors in any flow environment includes not only the pressure perturbations associated with sound, but also those associated with the flow turbulence. Frequently, the flow turbulence, or "pseudosound", will mask the existing noise levels, both broadband and discrete frequency. The fact that the turbulence and the acoustic signal propagate with markedly different velocities can be used to separate the two signal components. This technique has been successfully developed at General Electric and is termed "sound-separation."

At times, it became necessary to distinguish not only between the turbulence and the acoustic pressures, but also between the acoustic pressures associated with the different noise sources. For example, the noise measurements downstream of the turbine will include the attenuated siren signal, the turbine-generated noise, and the facility noise. Distinction between the various sources can be achieved through the use of coherence analysis.

The data reduction methods employed to meet the objectives of this program made extensive use of the above correlation analysis techniques. Coherence was used in determining the blade-row attenuation of the siren frequencies. Cross-correlation (sound-separation) was employed to determine the composition of upstream broadband noise in order to assess the feasibility of employing facility-generated noise as a vehicle for the noise transmission work.

- **Spectral Analysis Techniques**

Narrowband spectral analysis consists of investigating a small segment of the acoustic energy using a constant bandwidth filter (for example, a bandwidth of 10 Hz for 0- to 5000-Hz, using an analog spectral analyzer). The Digital Fourier Transform Analyzer permits much finer resolution, which translates into improved signal-to-noise ratio for tones. Hence, the analysis here initially consisted of using high resolution narrowband spectra which employed bandwidths ranging from 1.0 Hz to 2.5 Hz depending on the frequency range (2000- to 5000-Hz). Corresponding sampling times ranged from 20 to 10 seconds. The results from this method proved useful in significantly improving the signal-to-noise ratio of the upstream and downstream signals. Much of the high pressure turbine results were obtained from these high resolution narrowband spectra.

- **Correlation Analysis Techniques**

While spectral analysis consists of examination of a signal content in the frequency domain, correlation analysis may well be thought of as an analogous inspection in the time domain. Correlation is used to establish the amount of similarity or coherence between two signals. These techniques of analysis provide the following information:

1. Determination of the amount of the received random signal that is coherent with any given noise source (Coherence Analysis).

2. Measurement of propagation-time-delay characteristics of a signal transmission (Cross-Correlation Analysis).

The first of these analysis techniques, coherence analysis, was used in the direct computation of the siren tone attenuation. The usual method of obtaining any transfer function amplitude as a function of the frequency is to divide the output power spectrum by the input power spectrum for the frequency range of interest. However, in this case, the turbine will add noise to the output power spectrum and thus bias the transfer function if computed by the normal means. Instead, an alternative approach uses the cross-spectrum between the input and output to reject that portion of the output power spectrum that is not related to the input. The desired transfer function then is obtained as:

$$H(f) = G(\text{in minus out})/G(\text{in.}) \qquad (1)$$

where H(f) is the transfer function amplitude versus frequency, G(in minus out) is the cross-spectrum amplitude, and G (in) is the input power spectrum. This method does not use the entire output power spectrum, only that part of the output that is coherent with the input.

The second technique, cross-correlation analysis, is used to separate the acoustic and the turbulence spectra. In cross-correlations, one signal is compared with a time-delayed second signal to determine the amount of similarity between the two signals. For a stationary signal, the cross-correlation function can be defined as:

$$R_{xy}(\tau) = \lim_{\bar{T}\to\infty} \frac{1}{\bar{T}} \int_0^{\bar{T}} g_x(t)\, g_y(t - \tau)\, dt \qquad (2)$$

where R_{xy} is the cross-correlation function

$\bar{T}$ is the integrating (averaging) time

g_x and g_y are the signals

τ is the time delay or shift

The results are displayed in the form of a graph of the similarity between the two signals as a function of the time delay (τ) between them. For example, Figure 20 displays the cross-correlation between two closely spaced sensors located in a flow. The cross-correlation function displays two peaks. The first is a signal propagating at the sound speed relative to the flow and corresponds, of course, to the acoustic perturbations. The second peak is a signal being convected by the flow and corresponds to the turbulence. Used in conjunction with the power spectrum measured by the sensors, the cross-correlation technique makes it possible to separate out the acoustic and turbulence spectra.

Similarly, by cross-correlating the signals from a reference, say an inlet Kulite, and a downstream Kulite, the amount of upstream noise propagating through the turbine may be extracted from the downstream signal. This approach will fail if the structure-transmitted or turbine-generated broadband noise dominates the transmitted facility noise levels by a large margin (in excess of 10 dB).

Instead of cross-correlating two different signals, it is possible to compare a single signal with itself. This is termed autocorrelation, and the Fourier transform of the autocorrelation function yields the power spectral density of the signal. The autocorrelation process permits the detection of periodic signals in the presence of random noise simply because, by definition, a periodic signal repeats every time period (T_p), while a random signal loses all resemblance to itself once it is time-shifted. Hence, the autocorrelation function for a periodic signal is itself periodic and, for a random signal, decays quickly to zero when a finite time delay is imposed. Carrying this concept a little further, repeated averaging of the data should then enhance the signal-to-noise ratio for tones.

Virtually all of the data reduction on both the high and low pressure component turbine tests employed the spectral and correlation analysis techniques available on the digital Fourier transform analyzer. The results from one complemented those of the other, and together, provided a powerful tool in the analysis of the data.

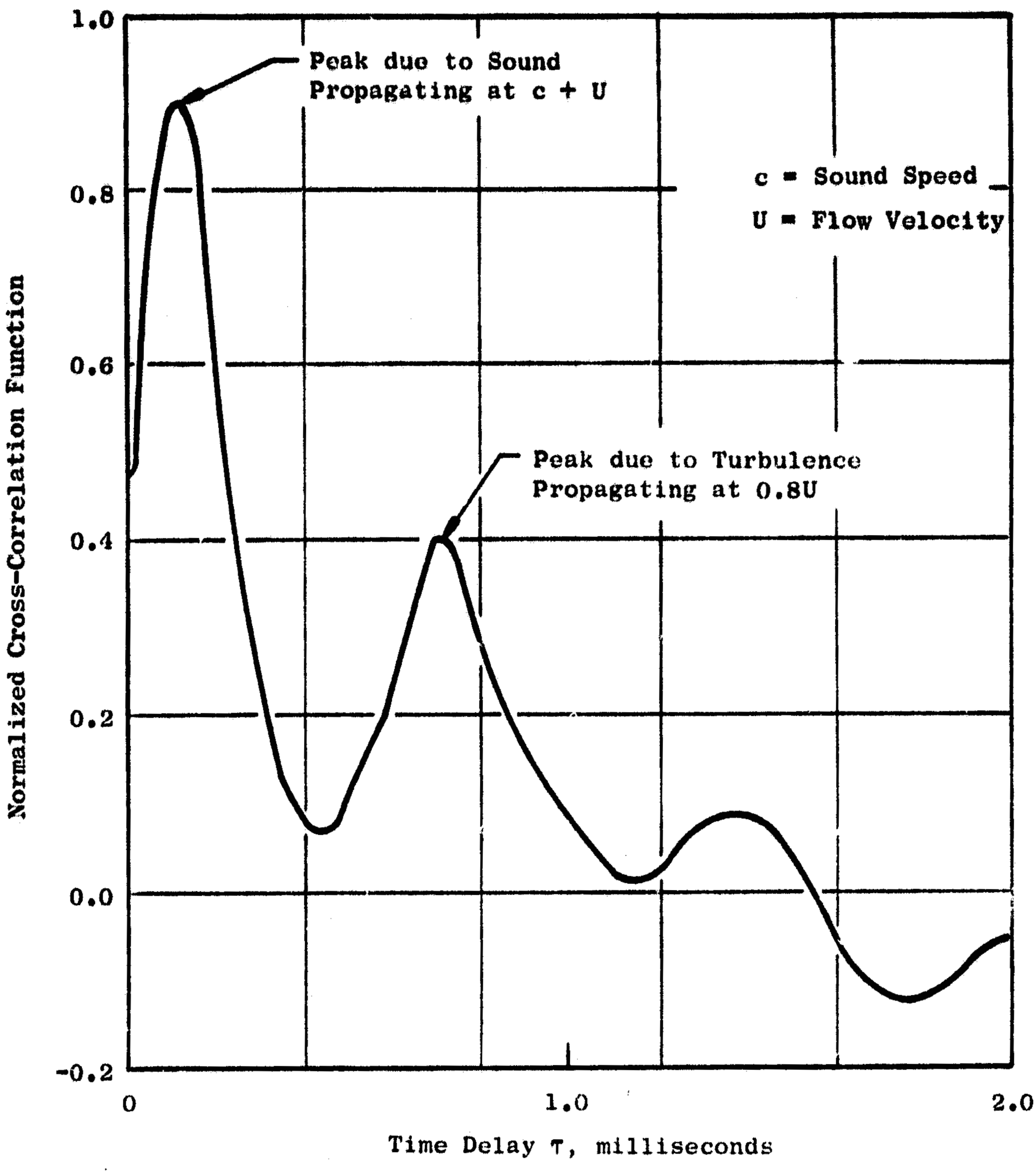


Figure 20. Typical Cross-Correlation Function for Flow with Sound Dominant.

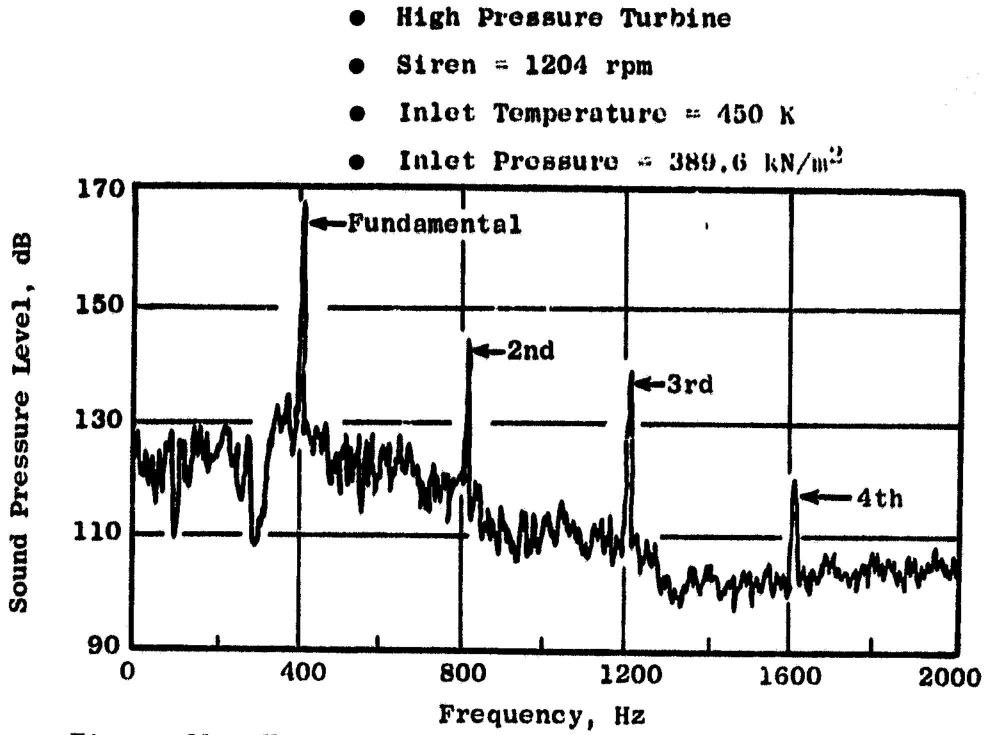


Figure 21. Upstream Kulite High Resolution Narrowband Spectrum.

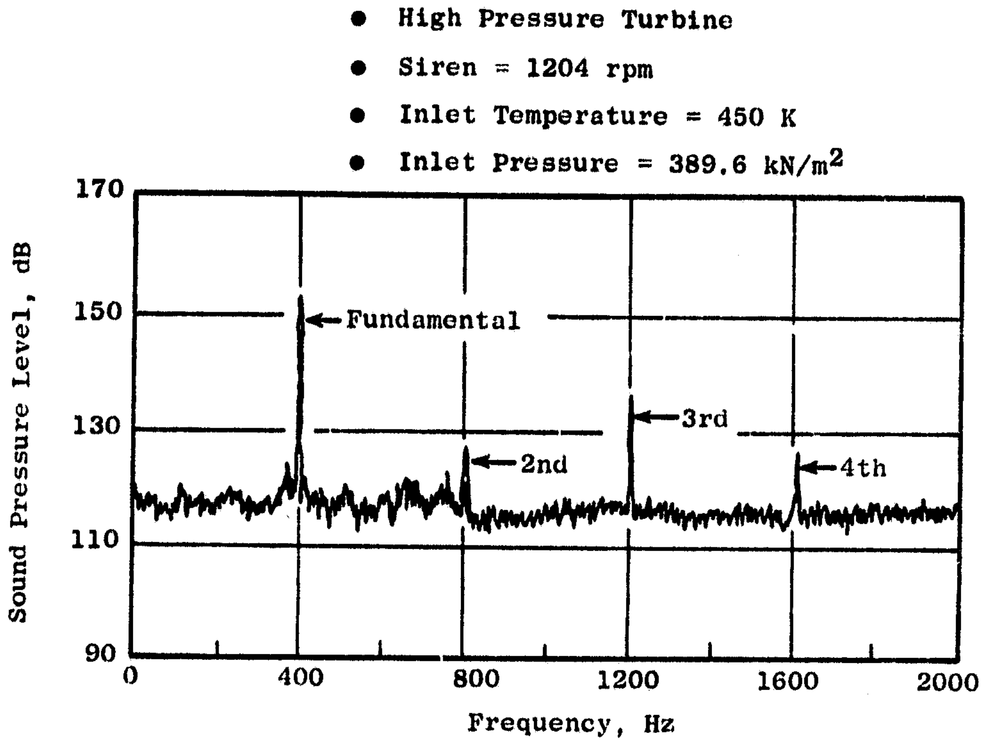


Figure 22. Downstream Kulite High Resolution Narrowband Spectrum.

3.6.2 Implementation of Techniques

- High Resolution Narrowband Spectra

Figures 21 and 22 show high resolution narrowbands with 1-Hz bandwidths for an upstream Kulite (K4) and a downstream Kulite (K7), respectively. The plots are for the high pressure turbine design point and show clearly distinguishable siren tones (fundamental and second, third, and fourth harmonics) in both upstream and downstream signals. These results are typical of both cold and hot design point conditions. More sample spectra can be found in Appendix D. Good signal-to-noise was obtained over a majority of the test points at design and off-design speeds using this method. However, some off-design conditions presented other problems (i.e., increased broadband levels) which reduced the signal-to-noise ratio and masked the downstream tones, necessitating the use of other techniques to obtain discernible tones downstream. The averaging process mentioned earlier proved cumbersome to implement and required a large number of samples to significantly improve the signal-to-noise ratio. In the end, coherence analysis provided the most satisfactory results.

- Coherence Spectral Analysis

Figure 23 gives the autospectrum for an upstream signal (Kulite 4) along with the coherent part of a downstream signal (Kulite 7). The transmission loss is the difference between the two tone levels. Note that a larger bandwidth (8 Hz) is employed here than for the high resolution narrowband spectra of Figures 21 and 22 (1 Hz). However, the tones measured with both the narrowband and coherence analysis techniques were the same.

Coherence analysis was used in conjunction with the high resolution narrowband spectra method for obtaining the attenuations for he high pressure turbine. The results were very encouraging and consequently this method was used exclusively for low pressure turbine data reduction. Typical spectra for the low pressure turbine can be found in Appendix D.

- Cross-Correlation Analysis

Part of the required attenuation analysis on this program was to see if the facility noise generated upstream of the turbine and present in the 1/3-octave band broadband noise spectra could be exploited to determine the transfer function through the turbine.

Obviously, it is first necessary to determine the level of contribution by the upstream facility-generated noise to the overall signal recorded by the upstream sensors. The other contributors of relevance here include the turbine (noise) and the flow turbulence. The facility noise and flow turbulence propagate downstream and will produce positive time-delay peaks in a cross-correlogram between a pair of upstream sensors. For the same sensor pair, the turbine-generated noise propagates in the opposite direction

- High Pressure Turbine
- Siren = 1204 rpm
- Inlet Temperature = 450 K
- Inlet Pressure = 389.6 kN/m^2

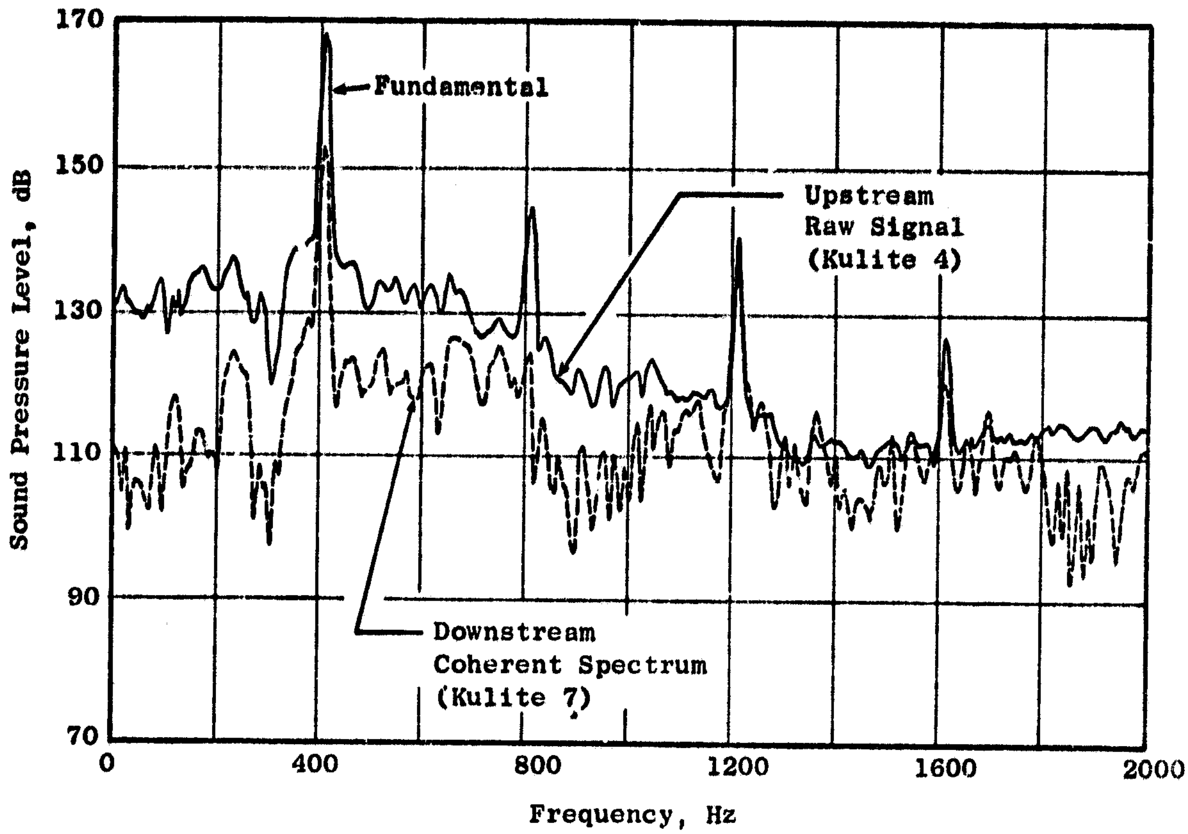


Figure 23. Coherent Spectra Comparison of Kulites 4 and 7.

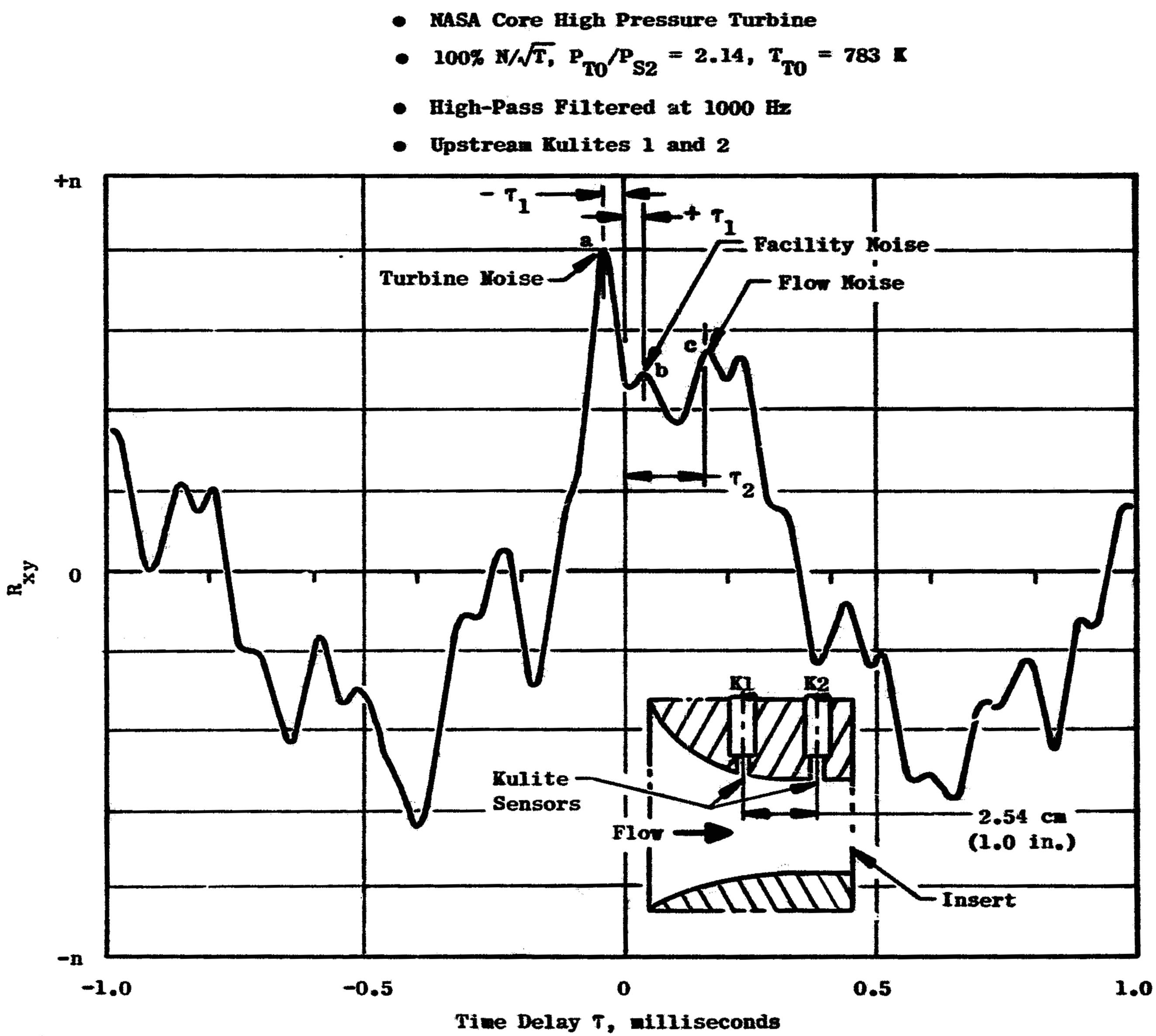


Figure 24. Cross-Correlation of Upstream Kulites for Broadband Noise Survey.

and will produce a peak at a negative time delay. The relative magnitudes of the three peaks will indicate the corresponding contributions by the three "sources" to the upstream broadband signal.

The high pressure turbine point (100% $N/\sqrt{T}$, P_{TO}/P_{S2} = 2.14) was selected for the initial evaluation. A low siren speed (250 rpm) reading was used with the data high-pass filtered above 1000 Hz to obtain essentially broadband noise free of contamination by the siren tones. The cross-correlogram for the two upstream Kulite pair K1 and K2 was obtained over a ±1 msec time interval as shown in Figure 24. The 1000 Hz filter resulted in the periodic undulations at the 1 millisecond time period. However, clearly visible are the three peaks of concern here.

The acoustic signal time delay τ_1, corresponds to peaks (a) and (b). The largest peak, (a), is at a negative τ and is attributed to the turbine generated broadband noise traveling upstream. Peak (b) is at a positive τ, indicating an acoustic signal resulting from some upstream disturbance, most probably related to the facility piping and butterfly control valve.

Flow noise is apparent at peak (c), which is at a positive τ, corresponding to the mean flow velocity.

These results show that the major contributor to the upstream broadband noise at frequenices greater than 1000 Hz is, in fact, the turbine. The facility generated broadband signal is also present but has a much smaller influence on the overall noise. The 1/3-octave band spectral analysis of the upstream broadband signal was therefore discontinued since the corresponding blade-row attenuation calculations are meaningless.

The spectra below 1000 Hz were also examined. The results at the design point for the cold and hot inlet tests of the high pressure turbine are illustrated in Figure 25a and b. The shape of the upstream spectra show a general increase in SPL with frequency up to 500 Hz. After that, the spectra drop sharply to 1500 Hz. The content of the upstream spectra of Figure 25 consists of turbine noise with facility and flow noise mixed in. The exact relationship between the three is not known.

The downstream spectra show a parallel increase in SPL up to about 400 Hz that is approximately 5 to 10 dB lower than the upstream signal. Above 400 Hz the spectra continue to climb, indicative of turbine-generated noise at those frequencies.

It appears that both the upstream and downstream broadband spectra are dominated by turbine-generated noise. While there is also facility noise content, it cannot be separated out and used for transfer function analysis. For this reason, no further analysis was conducted using the broadband portion of the spectra.

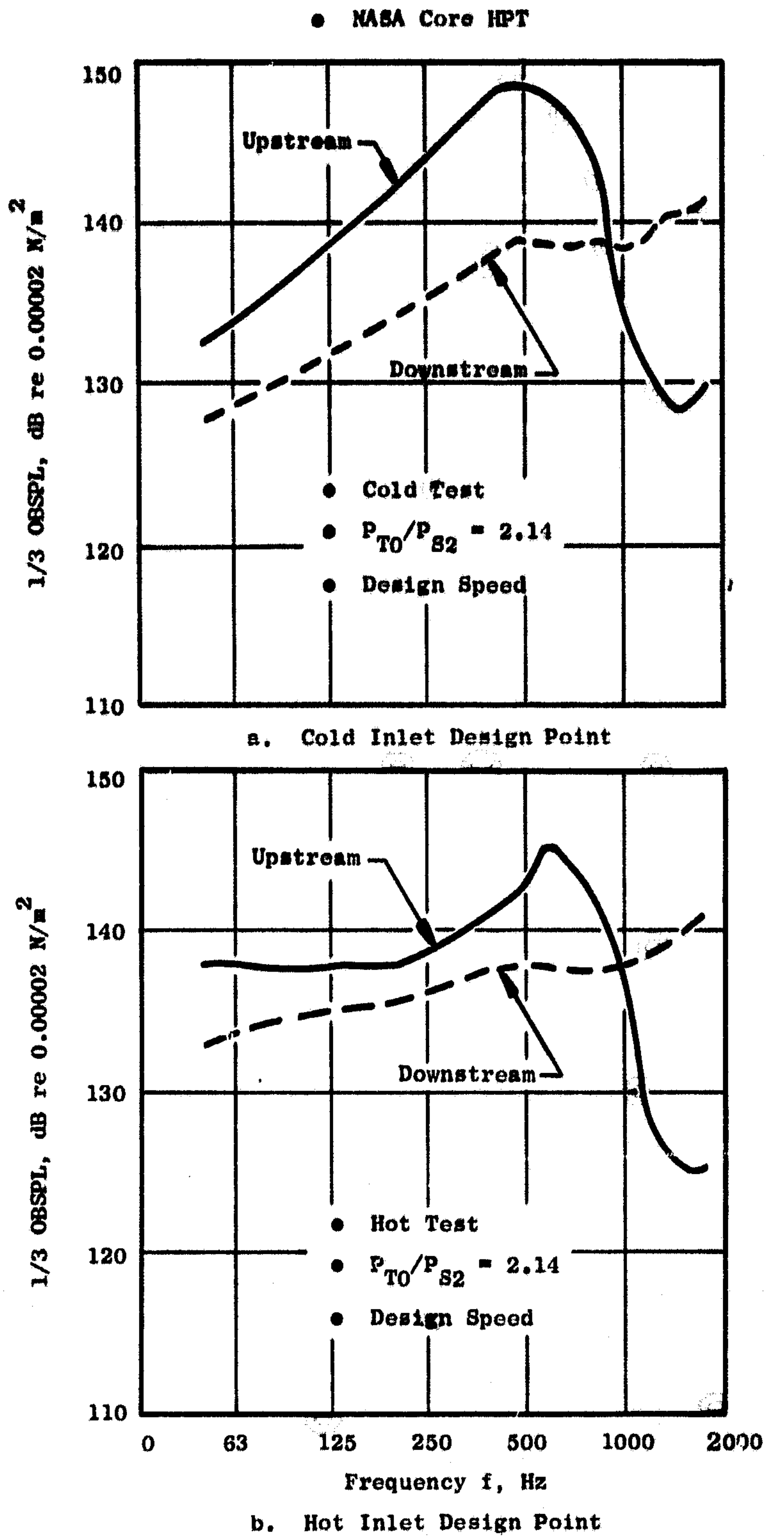


Figure 25. Comparison of Upstream and Downstream Broadband Levels.

3.7 DATA PROCESSING

The acoustic sensors were either immersed in the flow (probe Kulites) or exposed to it through a very short connecting passage (wall Kulites). Hence, the frequency response was essentially flat and no corrections were required as would be the case for wave-guide probe measurements. However in one instance, an upstream sensor had to be replaced by a Kulite mounted on a shorter bolt which created a small cavity thus altering the frequency response of the Kulite. The frequency response at ambient temperature was determined using a standard wave tube and is shown in Figure 26. A solid line is faired through the discrete data points. The resulting response curve was then shifted to a higher frequency to compensate for the higher mean cavity temperature during the turbine test. The frequency was shifted according to the ratio of the acoustic velocity in the cavity, that is

$$f_{test} = f_{cold}\sqrt{\frac{393}{288}}$$

where 288° K was the ambient temperature and 393° K was the mean cavity temperature during the test. This frequency response correction was applied to sensor K2 during the low pressure turbine tests.

The levels for the 3-stage turbine test had to be raised 5 dB to compensate for changes in the Kulite excitation voltages during the test. The initial calibrations had used 12 volts, while the voltage, which was monitored during the test, was subsequently found to be about 6.7 volts. Hence, the correction required was 20 log (12/6.7) ≃ 5 dB.

In order to allow direct comparison of the blade-row attenuations from all four test series, the data were corrected to a PWL basis. Using Blokhintsev's results (see, for example, Bekotske, K.; Reference 6), the acoustic intensity flux vector can be written:

$$\vec{I} = \frac{p^2}{\rho c^3}(c + \vec{V}\,\hat{e}_p)(c\,\hat{e}_p + \vec{V})$$

p, ρ and c are used in the conventional sense, where $\vec{V}$ is the absolute flow velocity and e_p the unit vector normal to the acoustic wave front.

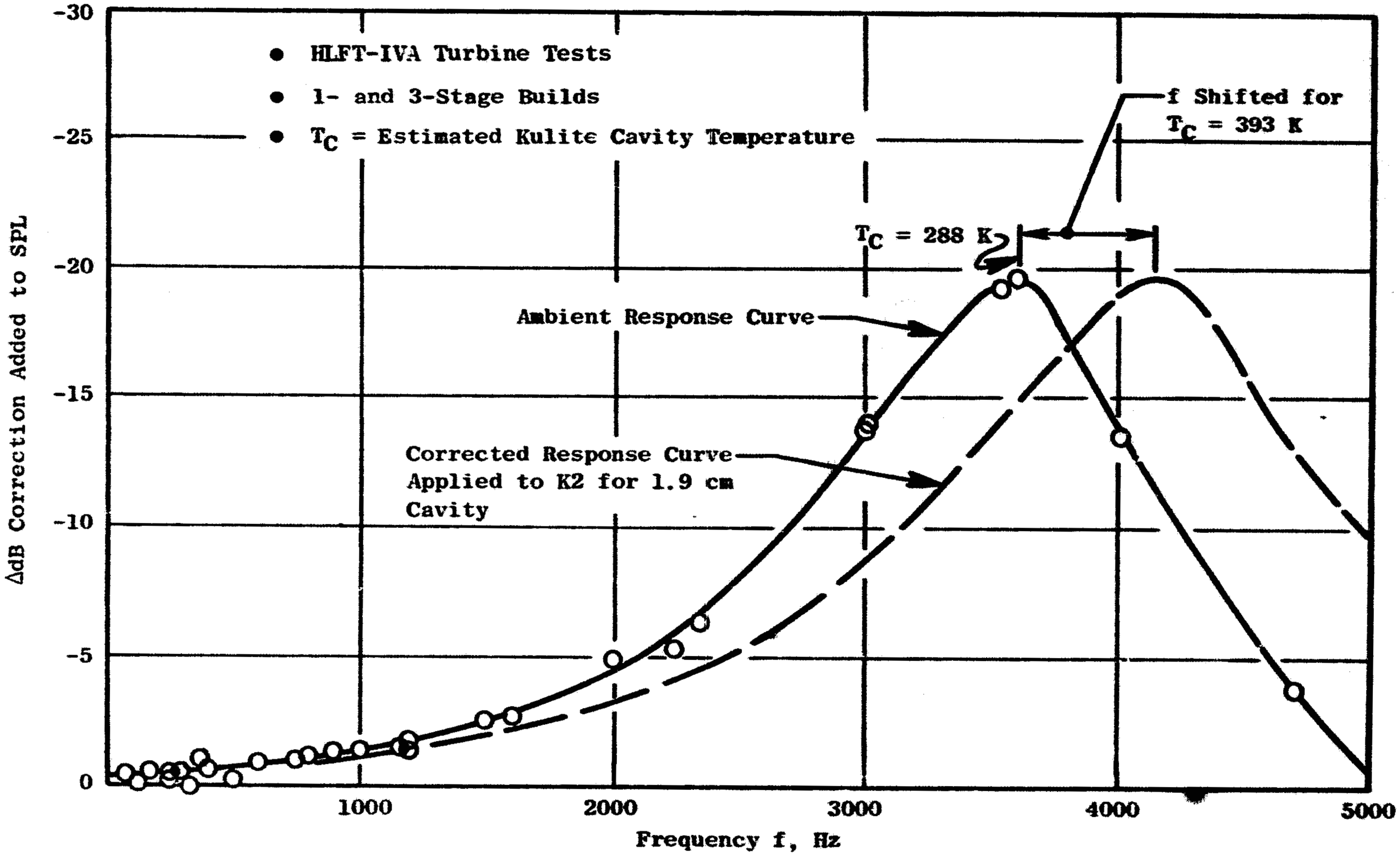


Figure 26. Frequency Response Curves for Kulite K2 Correction.

We are interested primarily in the axial component, hence

$$I_x = \vec{I} \cdot \hat{e}_x$$

$$= \frac{p^2}{\rho c^3} (c + \vec{V}.\hat{e}_p)(c\ \hat{e}_p + \vec{V}).\hat{e}_x$$

$$= \frac{p^2}{\rho c} (1 + M \cos\theta)(\cos\theta + M \cos\phi)$$

where θ and ϕ are the angles made by the acoustic wave front and the flow with the axial direction. M is the flow Mach number. The flow at the measuring planes is near axial and if a plane wave assumption is used here,

$$I_x = \frac{p^2}{\rho c} (1 + M)^2$$

The plane wave assumption also permits the acoustic power to be computed from a measurement at any point of the cross-section. Using a consistent set of reference pressure (p_o) and specific impedance ($\rho.c_o$), the acoustic power level (PWL) referenced to 10^{-13} Watts is given by:

$$PWL = SPL + 20 \log (1 + M) + 10 \log (\frac{\rho_o c_o}{\rho c}) + 10 \log A + 9.9$$

or $$PWL = SPL + 20 \log (1 + M) + 10 \log (\frac{P_o}{P_s}\sqrt{\frac{T_s}{T_o}}) + 10 \log A + 9.9$$

where SPL = sound pressure level re 2×10^{-5} N/m^2

Ps, Ts = static pressure and temperature at the measuring station

Po, To = ambient (standard day) pressure and temperature

A = cross-sectional area in m^2.

The measured attenuations and the computed transmission loss on a PWL basis are provided in Appendices A and B. Averaged conditions at the turbine inlet and exit planes were used in the PWL computations.

SECTION 4.0

ANALYSIS

4.1 THEORETICAL CONSIDERATIONS

A primary concern of the program was to check the theory used to analytically predict the attenuation of low frequency combustor noise as it propagates through the high and low pressure turbines.

The attenuation of combustor-generated noise by an engine turbine has been modeled approximately by several investigators. A rigorous analysis of the attenuation phenomenon was first performed by Bekofske (Reference 6) for subsonic relative flow. This analysis was extended under NASA funding (Reference 8) to include the case where there is subsonic relative flow at the inlet of a blade row but supersonic at the discharge side.

4.1.1 Description of Theoretical Prediction Method

The analysis examines the transmission and attenuation of sound waves through a turbine row on the basis that both the pitch and chord length of the turbine row are small compared to the wavelengths of interest here. In this limit, the turbine row may be modelled as an actuator disk which creates an abrupt discontinuity of the flow on either side of it.

The actuator disk model (Reference 8) employed uses a concept borrowed from propeller theory and applied to a blade row within an annular passage. Radial flow is assumed to be negligible, thus reducing the problem to one of two dimensions (the cascade plane).

The problem formulation follows closely an unpublished theory by Dr. R. Mani of General Electric's Research and Development Center for the discharge reflection coefficient from a blade row at low frequencies. A sound wave which impinges on the upstream side of a blade row will lead to a reflected wave on the upstream side and a transmitted wave and a vorticity wave on the downstream side of the blade row. The equations necessary to solve for the unknown wave amplitude coefficients are obtained by requiring continuity of mass flow and energy and, depending on whether the Mach number is subsonic or supersonic at the discharge of the blade row, either applying the Kutta condition at the trailing edge of the blade row, or applying the choking condition to the blade row.

The extended theory accounts for supersonic relative flow at the discharge of a blade row. Such a choked condition occurs typically in single-stage, high-pressure turbines and highly loaded fan turbines at high power settings.

Details of the complete analysis may be found in Reference 8.

4.1.2 Parametric Study

A study to determine the pertinent parameters which influence the attenuation across the turbine blade rows was conducted using the analytical method described above. The full ranges of conditions on both the HP and LP turbines were investigated, covering subsonic and supersonic regions of turbine operation. Predicted levels of blade-row attenuation were obtained for each turbine to compare with experimental results from the component tests.

Results of the blade-row attenuation study are shown in Figure 27 and Figure 28. Figure 27 provides the predicted attenuation at zero incidence for the single-stage high pressure turbine as a function of the turbine pressure ratio for both subsonic and supersonic cases. Changing the corrected turbine speed ($N/\sqrt{T}$) from 70% to 100% of the design value yields less than 0.5 dB change in the predicted attenuation. Hence the turbine speed appears to be a secondary parameter. The predicted attenuation however increases slightly with pressure ratio.

Figure 27 also provides the individual contributions of the stator and the rotating blade row. The blade-row attenuation due to the nozzle remains virtually unchanged over the mapped region. This is probably due to the fact that the nozzle pressure ratio is largely invariant in this turbine, increasing, for example, from 1.43 to 1.51 when the turbine pressure ratio is changed from 1.9 to 3.3 at 100% $N/\sqrt{T}$. The turbine pressure ratio variation is largely accomplished by increase of the rotor pressure ratio and the change in turbine attenuation is correspondingly due to change in the rotor attenuation.

Results for the low pressure turbine are shown in Figure 28. Again, the predicted attenuation increases with the turbine pressure ratio --- for all three stages. The pressure dependency becomes even clearer when the analytical prediction program is exercised over a wide pressure ratio range. The results for blade-row pressure ratios of 1.1 to 1.8 are shown in Figure 29 for all the nozzles and rotors from four turbines. The same predictions are shown in Figure 30 on a per stage (nozzle + rotor) basis. The data trend strongly suggests use of a ($\Delta T/T$) or similar work extraction parameter, where

$$\frac{\Delta T}{T} = 1 - (1/P_r)^{\frac{\gamma-1}{\gamma}} \qquad (3)$$

P_r = total-to-static pressure ratio

γ = ratio of specific heats

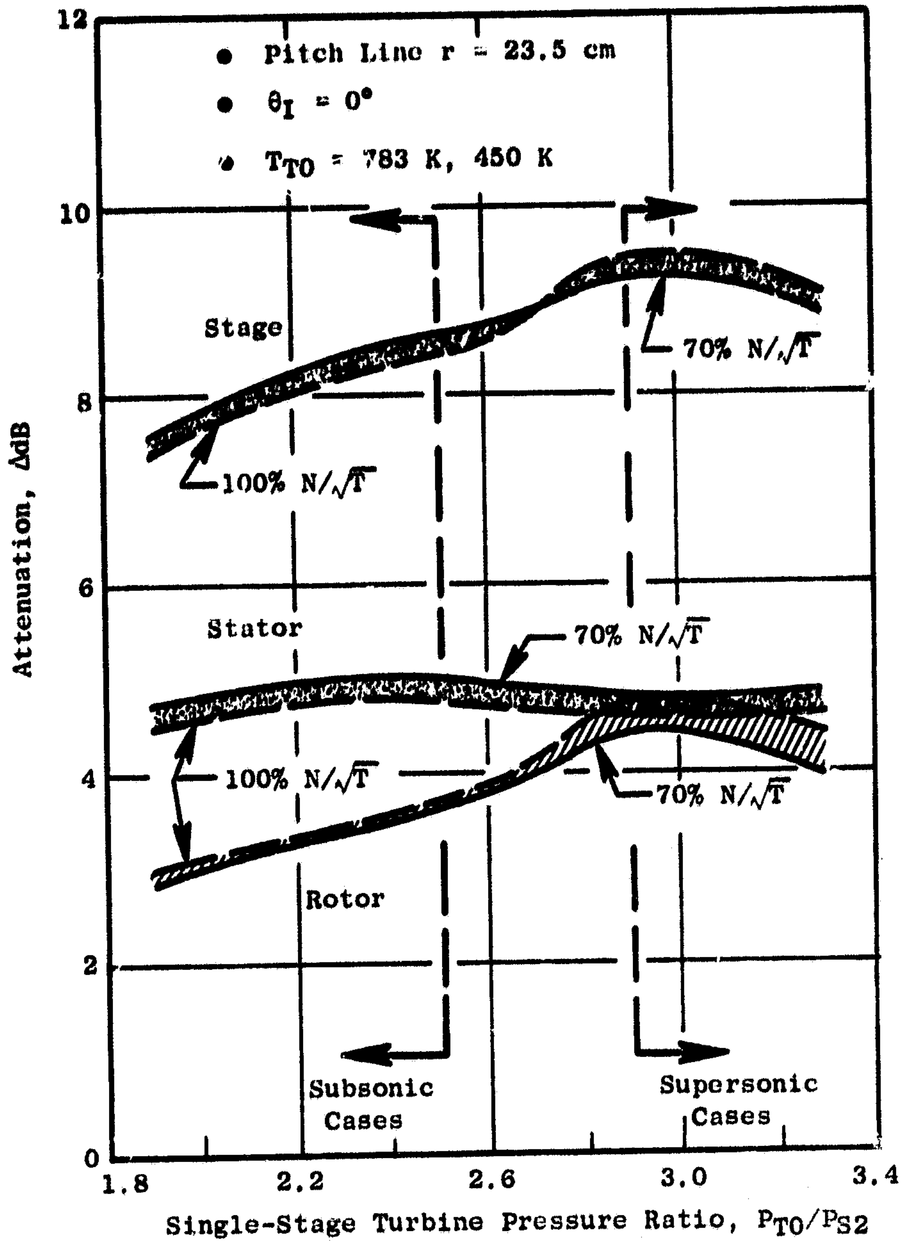


Figure 27. Blade-Row Attenuation Study (High Pressure Turbine).

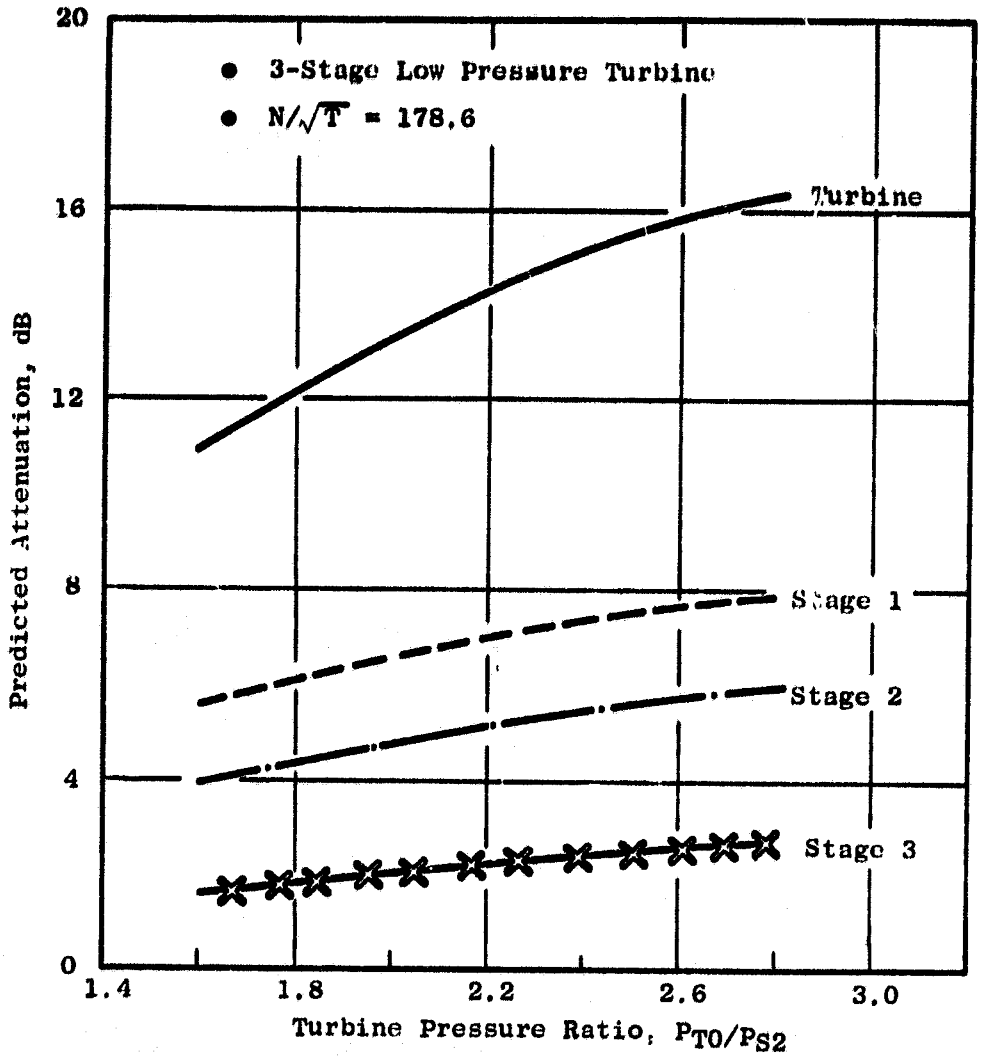


Figure 28. Variation of Predicted Low Frequency Noise Attenuation with Turbine Pressure Ratio.

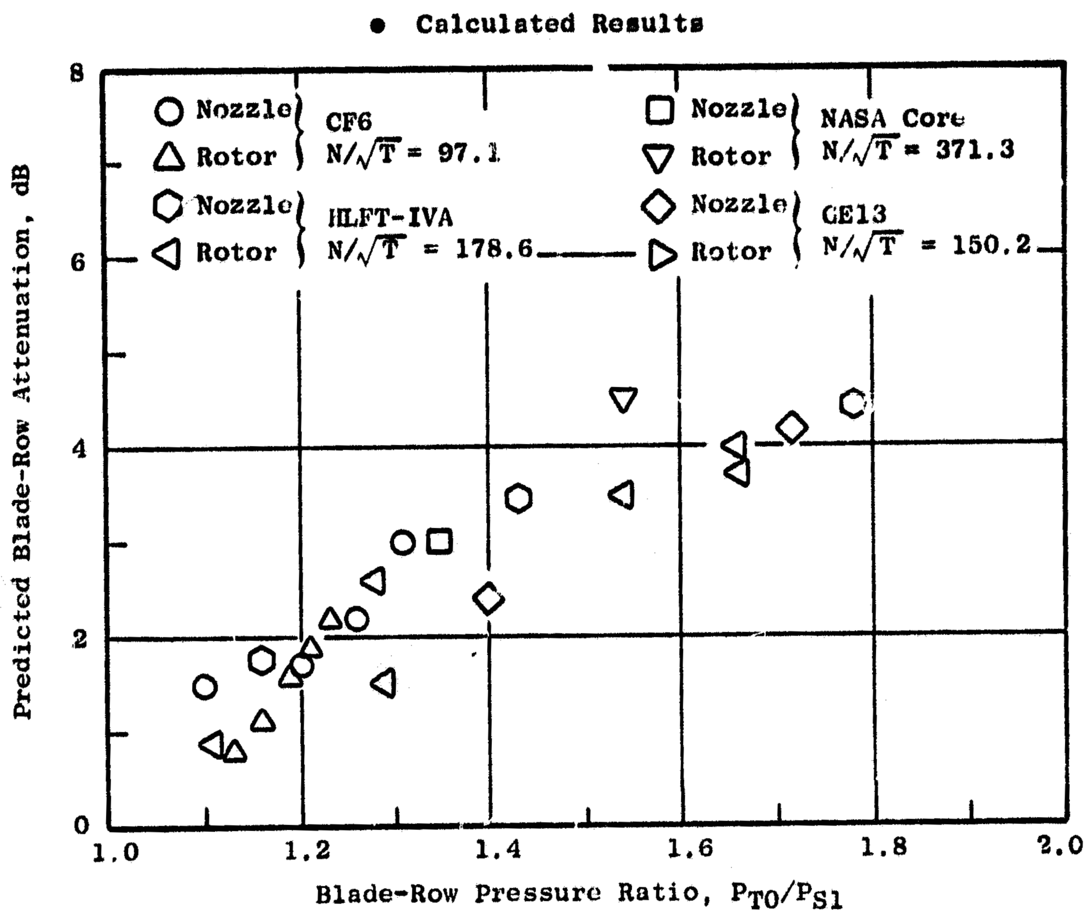


Figure 29. Dependence of Low Frequency Noise Attenuation on Blade-Row Pressure Ratio.

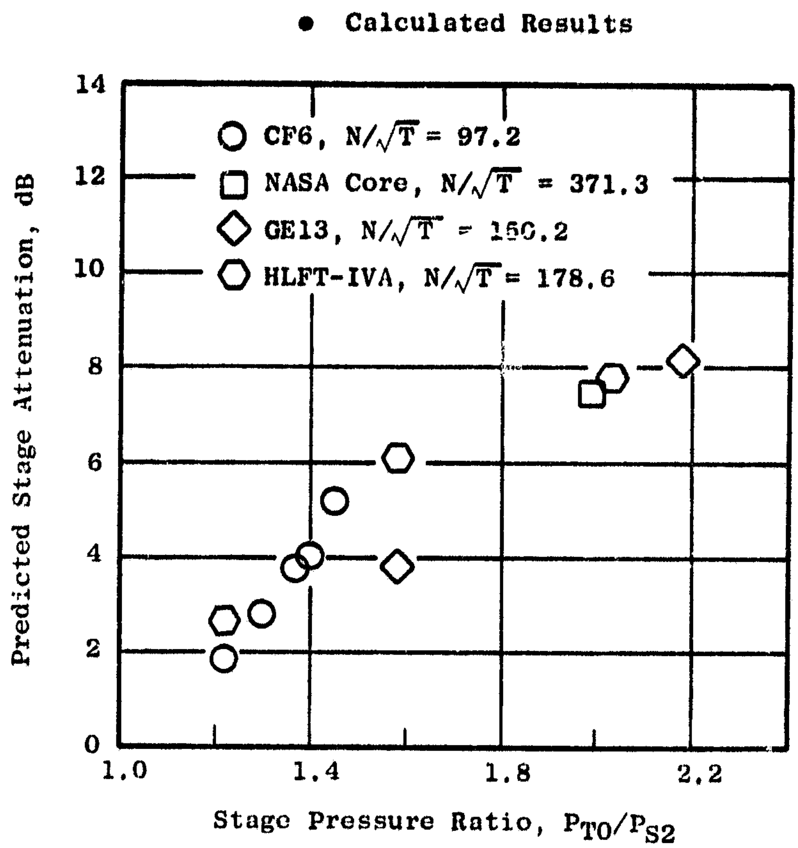


Figure 30. Dependence of Low Frequency Noise Attenuation on Stage Pressure Ratio.

The term ($\Delta T/T$) is the ideal work extraction nondimensionalized by the inlet enthalpy and was found to be a significant turbine noise generation parameter (Reference 9).

The predictions of Figure 27-30 are valid for any inlet temperature as long as $N/\sqrt{T}$ is constant, as this preserves the Mach numbers and flow angles. However, the inlet temperature would have an effect on the wave number, which must be determined solely from test data. The analysis uses an actuator disk assumption and, therefore, cannot account for either frequency or wave number phenomena.

The results of the parametric study are summarized below.

1. The attenuation for both HP and LP turbines shows a definite increasing trend with increasing turbine pressure ratio (P_{TO}/P_{S2}).

2. Speed is predicted to have only a small effect, if any, on attenuation.

3. Attenuation levels for the HP single-stage turbine are predicted at 8 to 9 dB over the pressure-ratio range.

4. The LP turbine attenuations for the single-stage are predicted at 6 to 8 dB, with the 3-stage build levels ranging from 13 to 19 dB over the test matrix.

These results are based on plane wave assumptions with zero incidence and provide a basis for comparison with the results of the acoustic tests.

4.2 EXPERIMENTAL RESULTS

4.2.1 Overview

The data from the two series for the high pressure and low pressure turbines exhibited many similar characteristics, such as increased downstream turbine broadband noise and the presence of duct phenomena, as discussed in Section 4.2.2. The increased broadband noise levels at some of the off-design conditions presented some signal-to-noise ratio difficulties which were overcome, by a large measure, through the use of coherence analysis. The presence of characteristic duct phenomena, such as higher order modes and resonances, was evident in both sets of data, which resulted in data scatter. Averaging the readings at the same frequencies from the circumferentially displaced instrumentation sets was helpful in reducing the scatter. Further averaging over a range of frequencies proved to be even more effective in minimizing the influence of the scatter and enhanced the identification of data trends. This double averaging technique was employed in evaluating the results.

The acoustic power level was computed using a plane wave assumption because of the large wave lengths involved.

4.2.2 Discussion of the Data Characteristics

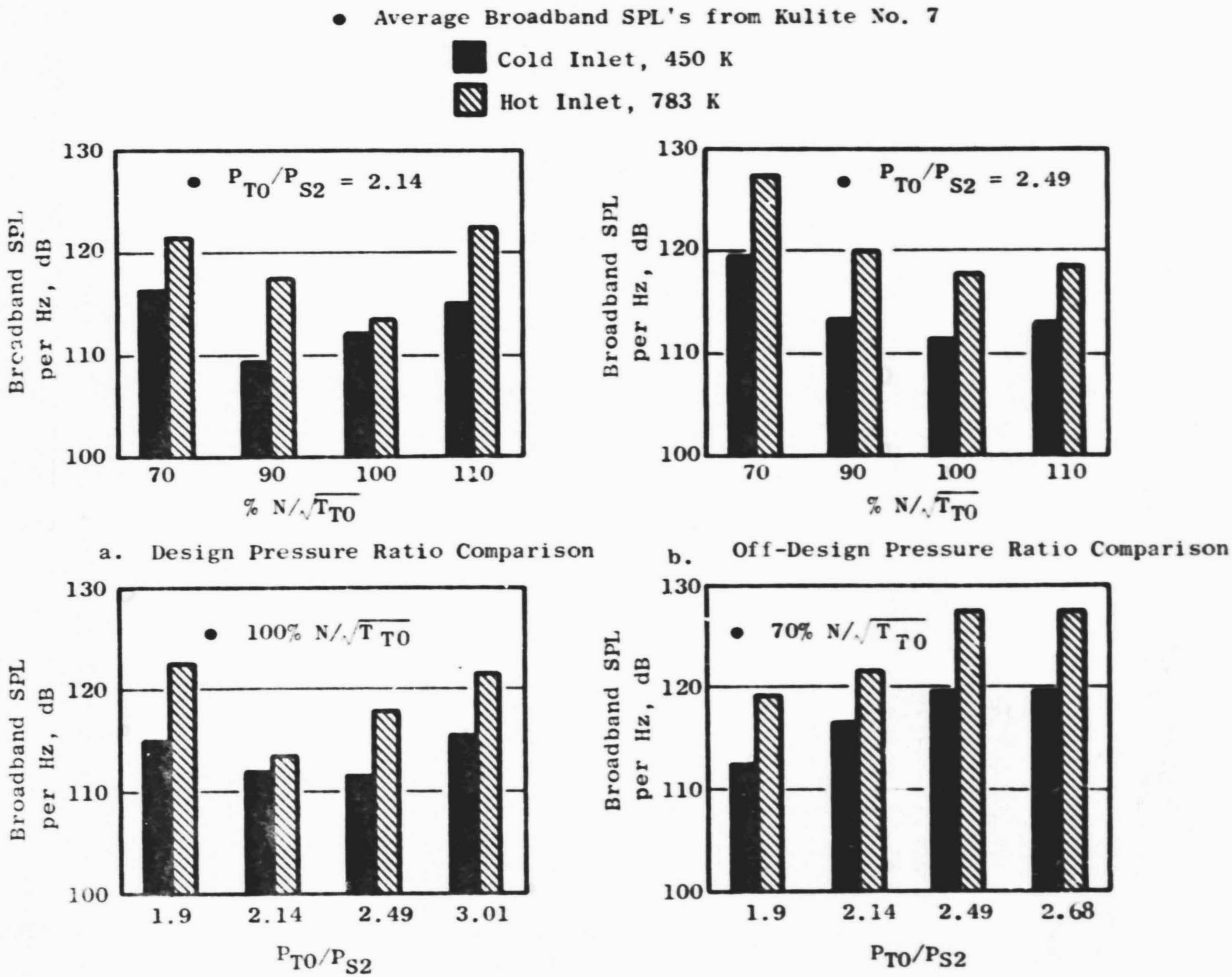
- Masking of Tones by Turbine Broadband Noise

The data from both the high pressure and low pressure turbine tests were affected in varying degrees by insufficient signal-to-noise ratio at some off-design points (see Appendix D). The insufficient signal-to-noise ratio was a consequence of increased downstream broadband levels at off-design conditions. This resulted in a masking of the siren tone at very low frequencies (below 200 Hz) and at the higher frequency end (above 2000 Hz) for both turbines, but was primarily evident in the high pressure turbine. Observations on the high pressure turbine data indicated significant increases (5 to 8 dB) in broadband levels of the downstream spectra during off-design operation, when compared to similar readings taken during the cold test. This is illustrated by the bar charts in Figure 31.

Low broadband levels at the design and near-design operating conditions in Figures 31a and 31c indicate smoother turbine operation in this optimum running region, as would be expected, while extreme conditions show an increase in broadband noise.

General Electric's experience with the high frequency (>3500 Hz) noise generation (Reference 10) indicates that, in general, turbine noise increases with pressure ratio. However, when the flow incidence increases beyond a certain range (-8° to +2°), there is a large increase in sound generation which can override the general trend with pressure ratio and speed, as occurs, for example, at extreme off-design conditions. The trends indicated by Figure 31d suggest that the signal recorded by the Kulites is turbine broadband noise, and not pseudosound due to turbulence. It is evident from a review of the results presented in these figures that the downstream broadband levels for the hot test are considerably higher than those for the cold test, especially for the extreme off-design conditions. In particular, for the hot inlet results, these off-design broadband levels are 8 to 9 dB higher than design-point levels. This caused some problems in distinguishing the siren tones at the downstream locations, particularly the second and third harmonics using the high resolution narrowband spectra.

This problem was largely eliminated through the use of coherence analysis, which was facilitated by the dual sets of acoustic sensors positioned upstream and downstream of the turbine. Over 85% of the tones were made distinguishable in the hot inlet test of the high pressure turbine, which had the lowest signal-to-noise ratio, while the low pressure data were essentially free from the "tone masking" as a result of using this analysis technique.



a. Design Pressure Ratio Comparison

b. Off-Design Pressure Ratio Comparison

c. Design Speed Comparison

d. Off-Design Speed Comparison

Figure 31. High Pressure Turbine Downstream Broadband Noise.

- **Duct Phenomena**

A second characteristic of these tests was the presence of duct phenomena. Higher order modes and resonances upstream and downstream were apparent in the measurements taken on both the high and low pressure turbines and resulted in considerable data scatter.

The effect of the higher order modes on the upstream measurements is typified in Figure 32, which shows, for the high pressure turbine, a spectral comparison of the SPL's from all four inlet Kulites obtained at the siren fundamental tones. Good agreement was obtained at frequencies below 300 Hz for all Kulites, but differences of 10 dB or more were apparent between pairs of circumferentially displaced Kulites above that frequency. The difference in levels is apparently due to a spinning mode sweeping the annulus in a helical path to produce a pattern of standing waves. This circumferential wave argument is substantiated by the fact that the cut-on frequency for the higher order modes of the turbine geometry is about 300 Hz, and that a simultaneous wave trace of the inlet Kulites shows a large phase difference between the two circumferential locations (see Figure 33).

A single spatial measurement is sufficient with zero incidence plane waves. However, because of the geometry through which the siren tone was induced, there was no way to predict the exact wave shape without extensive measurements. Therefore, the plane wave assumption was the best estimate. Instead, the instrumentation was positioned axially and circumferentially to identify the type of waves present as seen in Figure 33. To account for the effect of the circumferential modes (in Figure 32) the SPL's from at least two and as many as four of the upstream Kulites at near diametrically opposite locations were averaged.

There was no evidence of similar spinning wave structure downstream in the high pressure turbine. Figure 34 illustrates the good SPL comparison of the dual element Kulite probes for the high pressure turbine.

The frequencies of interest for combustor noise are such that higher order radial modes should not be a factor. Therefore, it should not matter at what radial immersion the measurements are made. The low pressure turbine contained two wall mounted Kulites downstream as well as the two Kulite probes. Tabular comparisons of a downstream wall Kulite (K5) with one of the Kulites (K9) on one of the probes is presented in Appendix C. Most of these comparisons show differences of 0 to 6 dB but some differences are greater. The results are difficult to explain particularly at the lower frequencies where higher order modes would not be expected in this geometry. Averaging was used to make use of all the data and to reduce the resulting scatter.

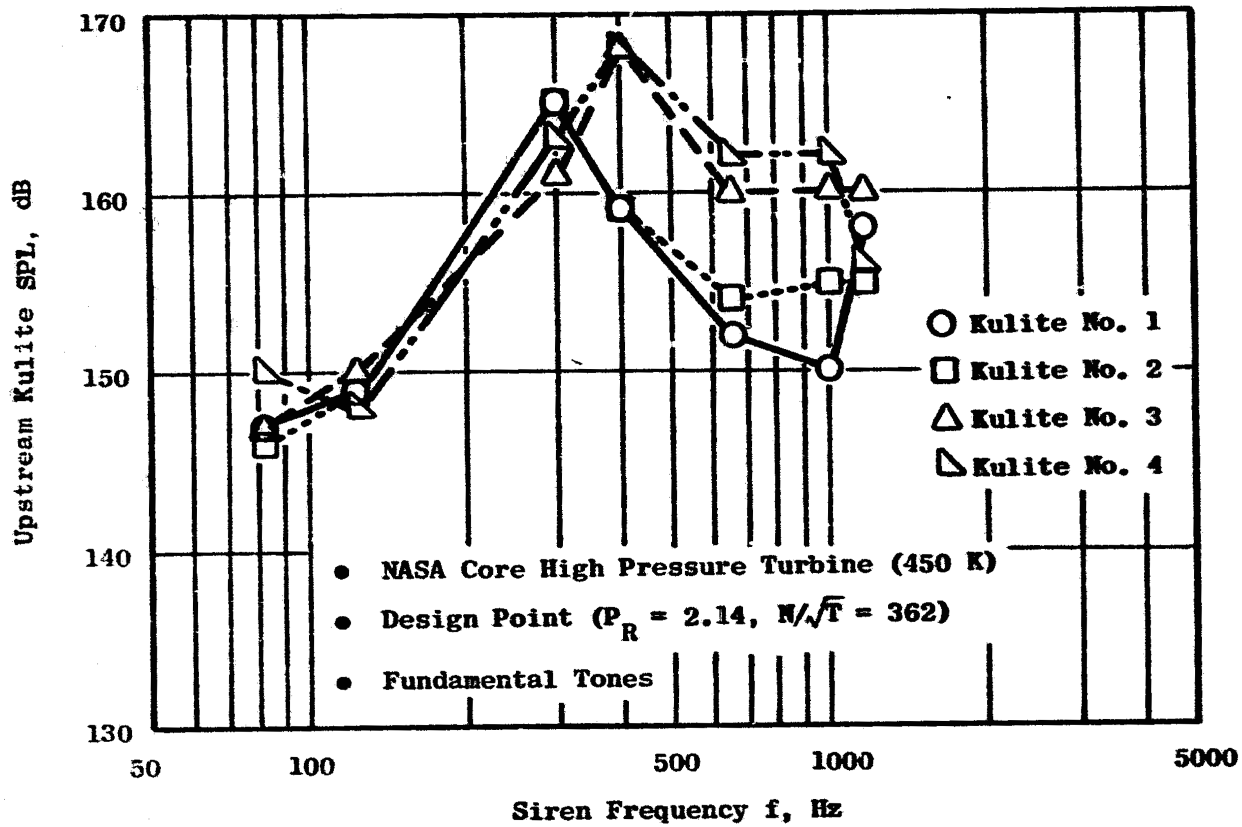


Figure 32. Comparison of Siren SPL Output for Upstream Kulites.

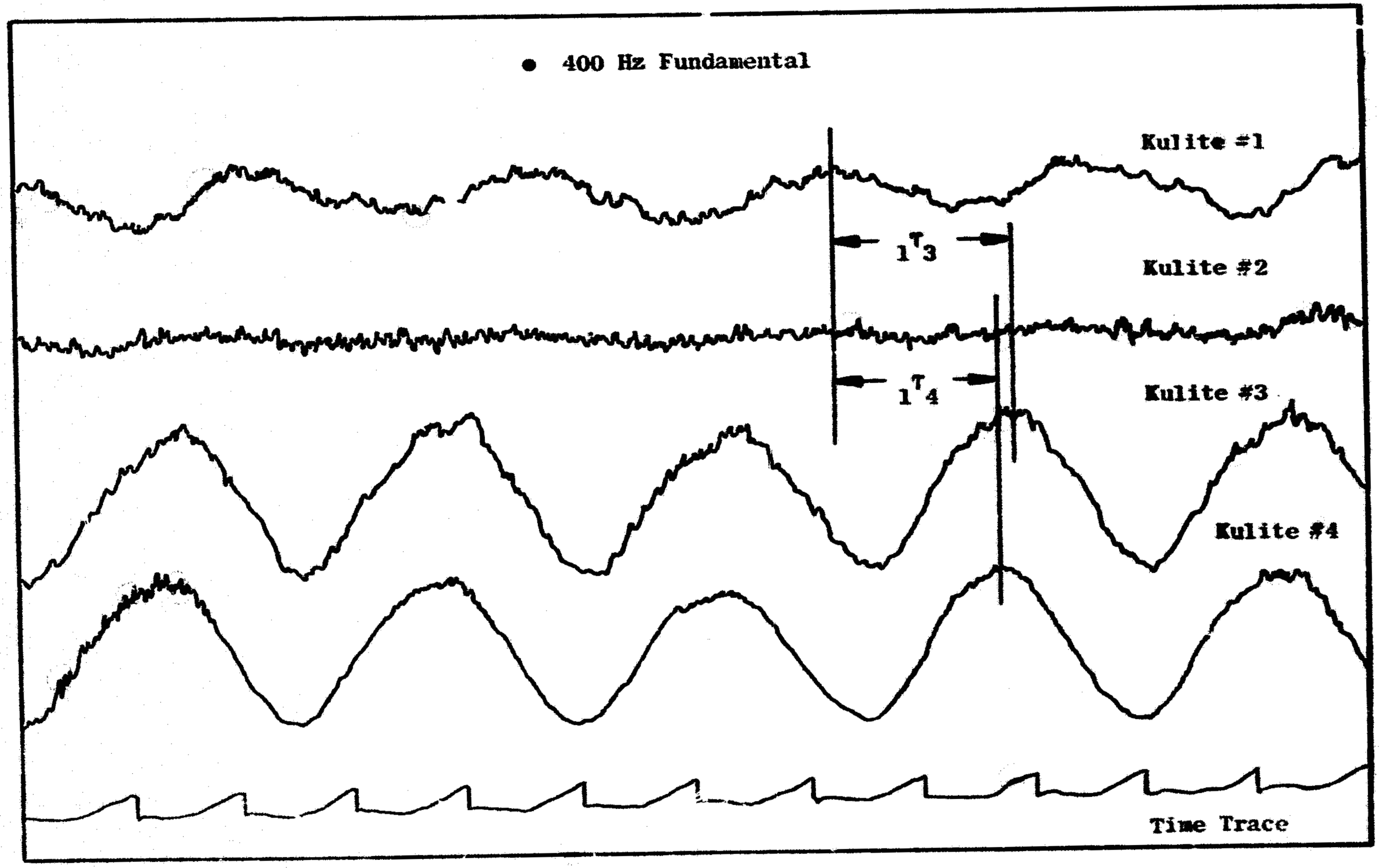


Figure 33. Simultaneous Wave Traces, Upstream.

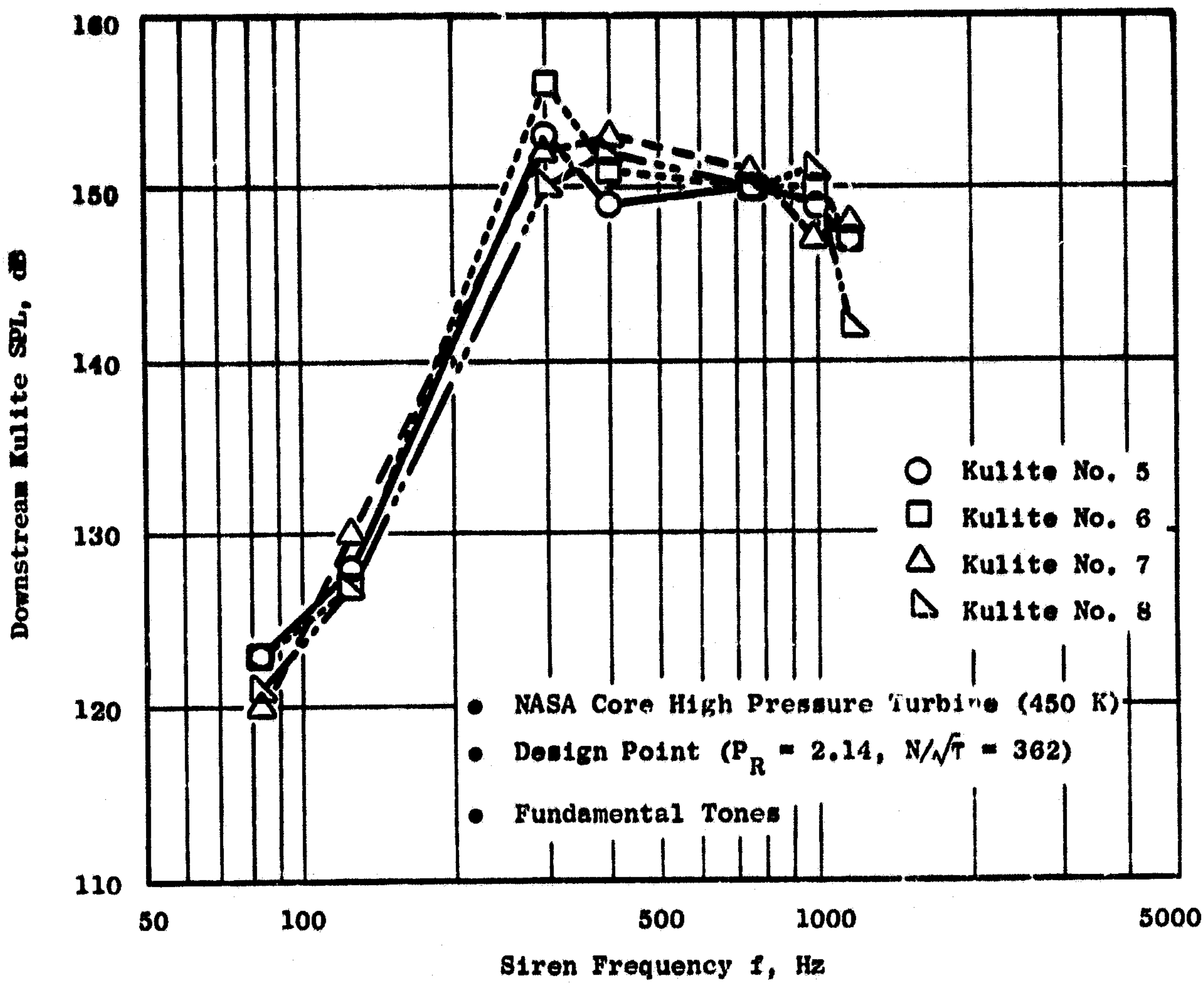


Figure 34. Comparison of Siren SPL Output for Downstream Kulites.

4.2.3 Data Analysis

To minimize the data scatter and reduce the effect of apparent resonances in all cases, an average SPL of the downstream sensors was used (as many as four Kulites from downstream probes on the high pressure turbine; average of wall and probe Kulites, where they existed, for the low pressure turbines). The blade-row attenuation over the frequency range of interest was then determined by the difference in the average SPL's calculated upstream and downstream of the turbine.

- **Bilobed Attenuation Spectra**

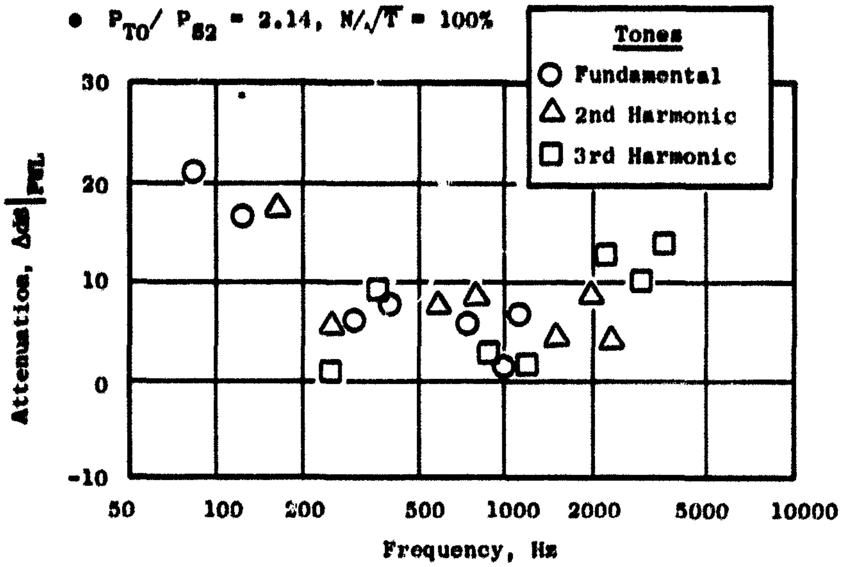
Some of the inherent scatter present when just one pair of upstream and downstream Kulites were used was reduced by this averaging procedure. Such an averaged comparison using all four sets of sensors is provided in Figure 35a for the cold HP turbine test at the design point. A bilobed attenuation spectrum is indicated from the resulting distribution. Greater than 20 dB attenuation is shown at frequencies below 200 Hz, dropping to approximately 10 dB from 250 through 2000 Hz, with minimum levels of 6 to 8 dB occurring at 250 Hz and 1175 Hz, respectively, and a small peak at 1400 Hz. An increase in the attenuation (up to 15 dB) above 2000 Hz is observed.

The averaged attenuation spectrum for the hot test at design point is shown in Figure 35b. The resulting distribution once again suggests a bilobed attenuation spectrum. The overall levels appear to be the same as for the cold test. In fact, the hot and cold transmission loss data can be collapsed by shifting the frequency scale by the square root of the inlet temperature, as is shown in Figure 36, that is, by compensating for the change in acoustic velocity.

The bilobed distribution is now clearly visible, and a line can be faired through the data points as shown in Figure 36. The attenuation for this bilobed average trend line gives minima of 7 and 8 dB at 200 and 800 Hz, respectively. Near 83, 400, and 3000 Hz, the attenuation increases to around 15 dB.

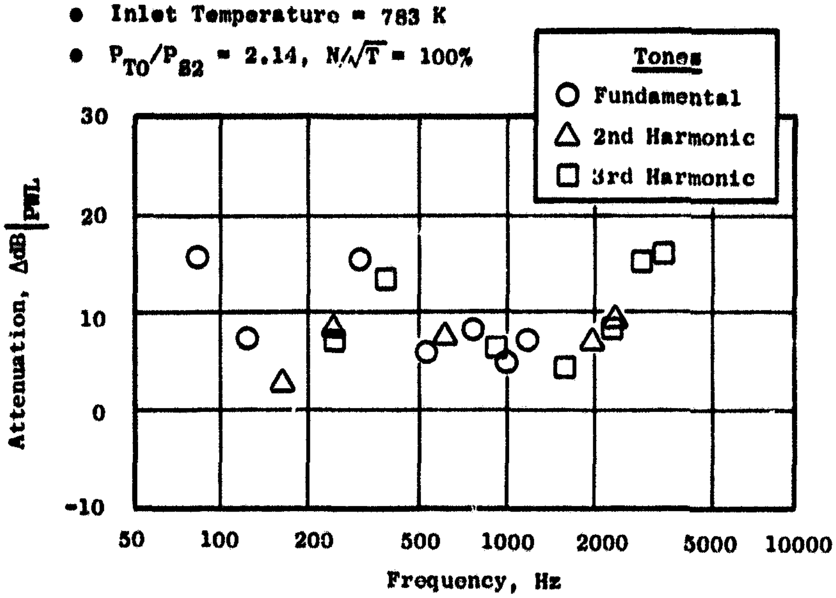
The data from the 1- and 3-stage builds of the low pressure turbine tests exhibited many of the same characteristics as had been apparent in the high pressure test results (i.e., large data scatter, presence of higher order circumferential modes, and the suggestion of a bilobed distribution of the attenuation spectra). Figure 37 shows the attenuation at the design speed for the 3-stage build at pressure ratio of 3.0, while Figure 38 illustrates typical single-stage attenuation spectra at design speed and a P_{T_0}/P_{S_2} of 1.6. Both figures illustrate the general clustering of the data around a bilobed distribution similar to the high pressure turbine results. Using the curve fit and comparing the attenuation peak in the mid frequency region, it appears that the 3 stage build exhibits a lower peak frequency (200 Hz) than does the single stage build (∿400 Hz). This shift is well within the range of data scatter encountered and hence no particular significance is attached to it.

- NASA Core High Pressure Turbine
- Averaged Values from Coherent Spectra
- Inlet Temperature = 450 K
- P_{TO}/P_{S2} = 2.14, $N/\sqrt{T}$ = 100%



a. HPT Cold Design-Point Attenuation Spectra

- NASA Core High Pressure Turbine
- Averaged Values from Coherent Spectra
- Inlet Temperature = 783 K
- P_{TO}/P_{S2} = 2.14, $N/\sqrt{T}$ = 100%



b. HPT Hot Design-Point Attenuation Spectra

Figure 35. HPT Design-Point Attenuation Spectra.

- NASA Core High Pressure Turbine
- Data Normalized to 783 K
- Averaged Values from Coherent Spectra
- P_{T0}/P_{S2} = 2.14, $N/\sqrt{T}$ = 100%

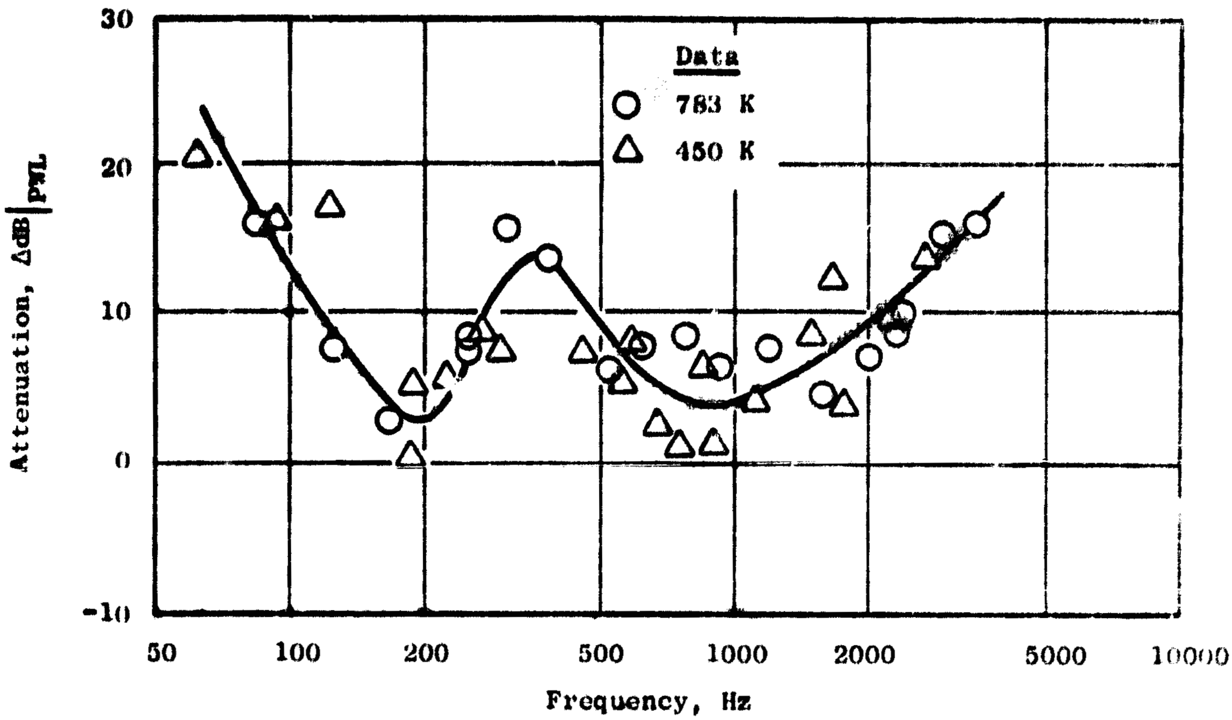


Figure 36. HPT Normalized Attenuation Spectra at Design Point.

- 3-Stage HLFT-IVA
- PWL Attenuation
- Point 3042 (100% $N/\sqrt{T}$, P_{TO}/P_{S2} = 3.0, T_{TO} = 422 K)
- Average Upstream and Downstream Kulites

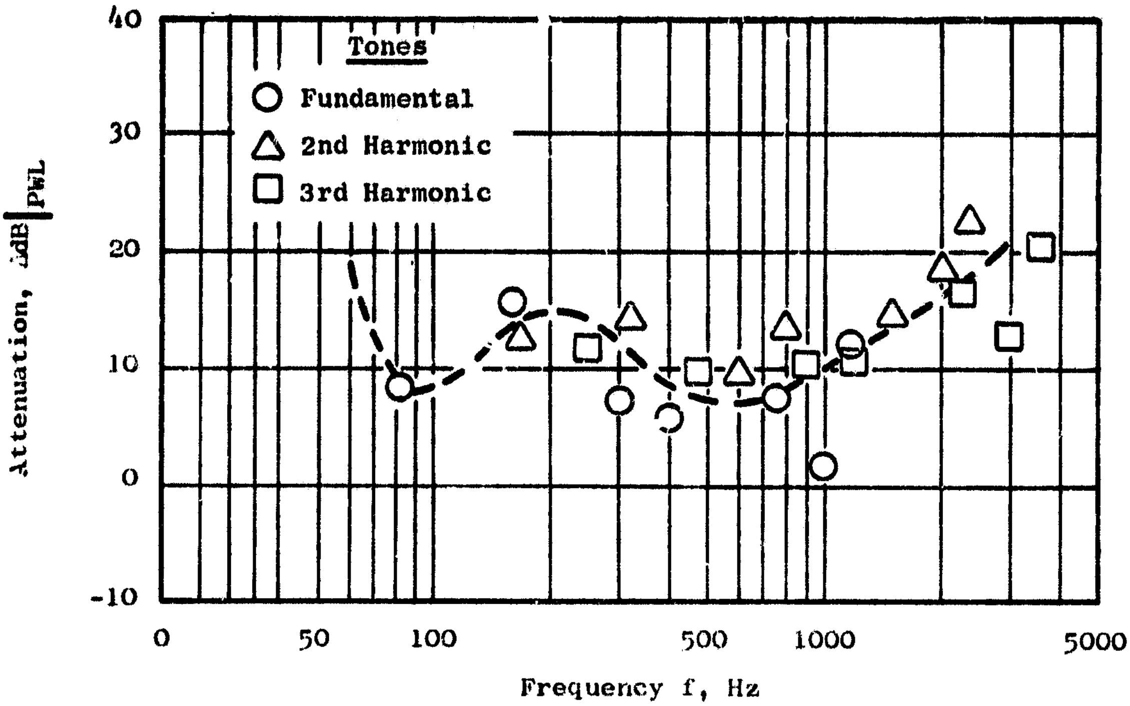


Figure 37. 3-Stage Low Pressure Turbine Attenuation Spectrum.

- 1-Stage HLFT-IVA
- PWL Attenuation
- Point 1642 (100% $N/\sqrt{T}$, P_{TO}/P_{S2} = 1.6, T_{TO} = 422 K)
- Average Upstream and Downstream Kulites

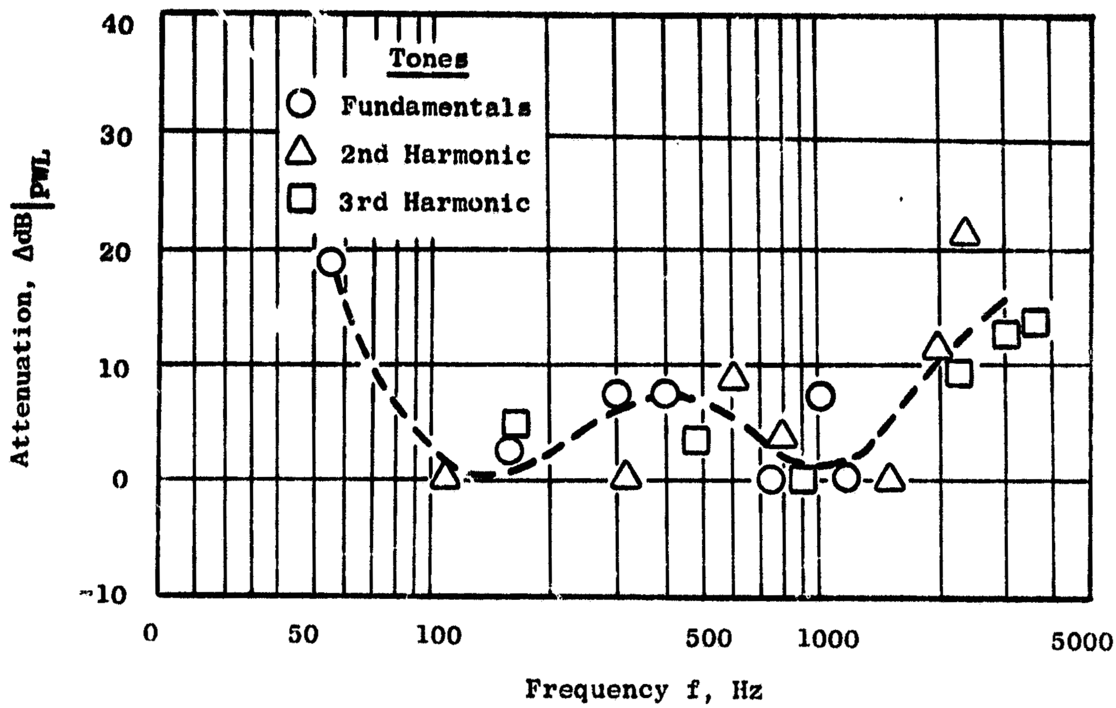


Figure 38. 1-Stage Low Pressure Turbine Attenuation Spectrum.

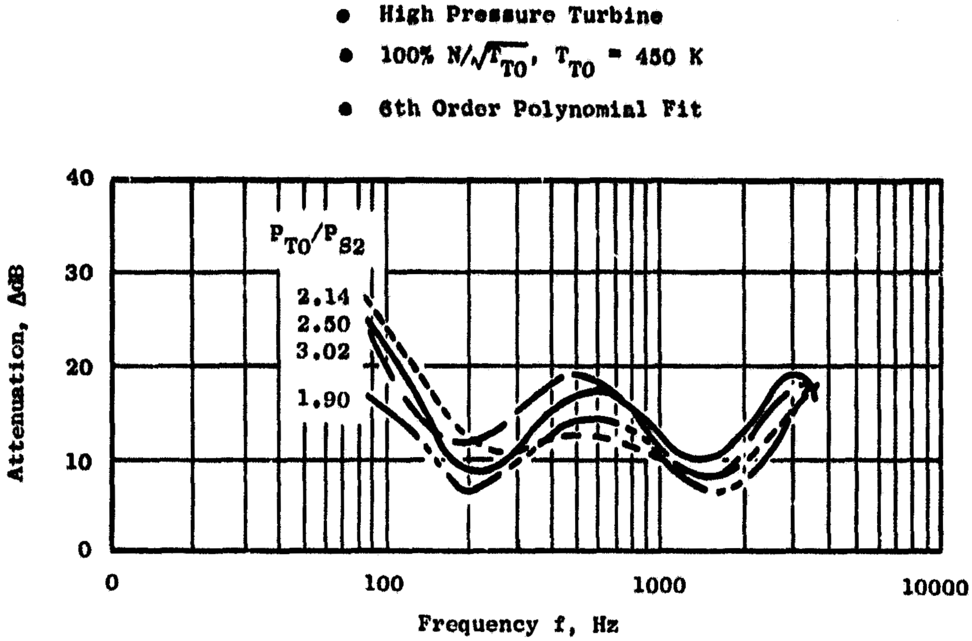
Attempts at computer curve fitting the data required grouping of frequencies within a 1/3 octave band before similar curve fits could be constructed. However, no consistent trends could be obtained using this method (see Figure 39), other than the fact that the speed effect was minimal. It was concluded that the bilobed shape was not a true low frequency noise attenuation spectrum, but it included the effects of higher order modes and other effects that may be unique to the te facility and hardware. Pursuing this point, the frequency corresponding to the first spinning mode cut-on for this facility was computed. The phase plots show a strong wave sweeping around nearly circumferentially at these frequencies, (see Figure 33). The analysis indicates that the high blade-row incidence would result in a large jump in transmission loss. Hence the mid-lobe could be a manifestation of modal cut-on.

- Bathtub Spectral Shape

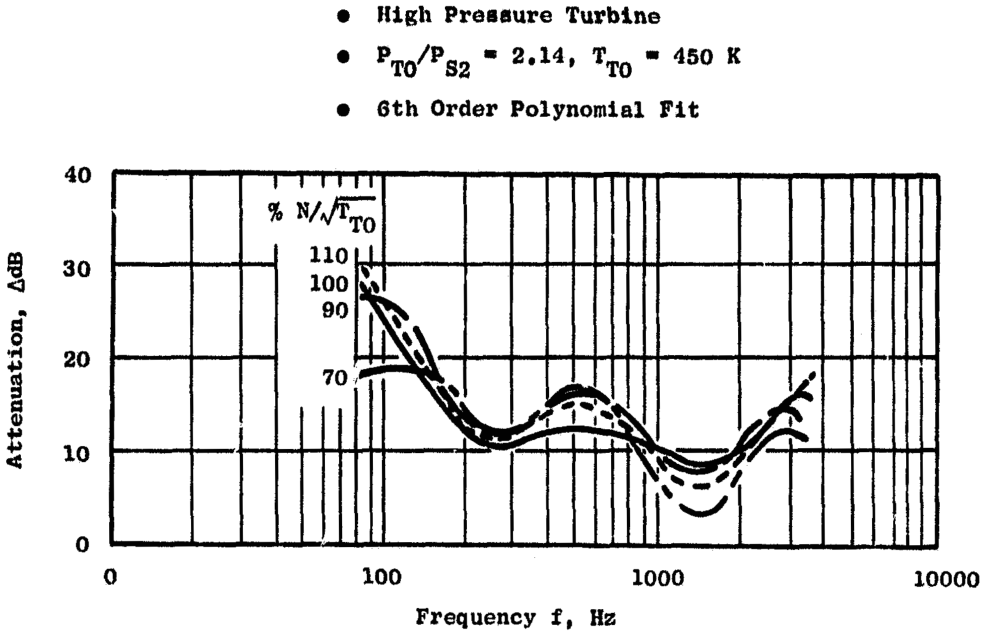
Preliminary theoretical work (conducted under NAS3-20027) aimed at explaining the mechanisms of the various levels of attenuation achieved in this program has suggested possible explanation for the increased attenuation at the low (<100 Hz) and high (>1500 Hz to 3500 Hz) frequencies termed the "bathtub" spectral shape.

The attenuation spectrum was divided into three regions as shown in Figure 40: very low frequencies (below 100 Hz), midfrequencies (200 to 1200 Hz), and high frequencies (above 1500 Hz). In essence, the attenuation mechanism assumed in the actuator-disk analysis is fully valid only for the mid-frequency region. It could be hypothesized that there are other mechanisms involved which dominate the low and high frequency ends and increase the transmission loss over that predicted by the actuator-disk model. For example, the propagation through curved passages carrying an accelerating flow could provide such an increase at the lowest frequencies. This mechanism is being investigated under Contract NAS3-20027. At the high frequency end, the attenuation could increase due to the physical blockage imposed by the turbine airfoils because the perturbation wavelengths are approaching the airfoil dimensions. This effect is also being pursued under Contract NAS3-20027. The net result is a bathtub shaped spectrum, the floor of which corresponds to the actuator-disk analysis model predictions based on the theory discussed in Reference 6. Coincidentally, the floor spans the major frequencies of interest for combustor noise.

A closer look at the midfrequency region of the transmission spectrum (Figure 40) shows that it contains primarily the attenuation based on the siren fundamentals which exhibited the least amount of scatter. An average attenuation was obtained within the midfrequency region for each test condition which compared favorably with the actuator disk analysis. The attenuation, which constituted the floor of the bathtub spectra, was determined by computing the average over this limited frequency range of all attenuation values within the region. The double averaging technique was found to be very beneficial in reducing the overall impact of higher order modes, resonances, and other duct phenomena. The term "double averaging"



a. Effect of Turbine Pressure Ratio Variation at Constant % $N/\sqrt{T}$



b. Effect of Turbine Speed Variation at Constant P_r

Figure 39. Pressure Ratio and Speed Trends with Curve Fit Spectra.

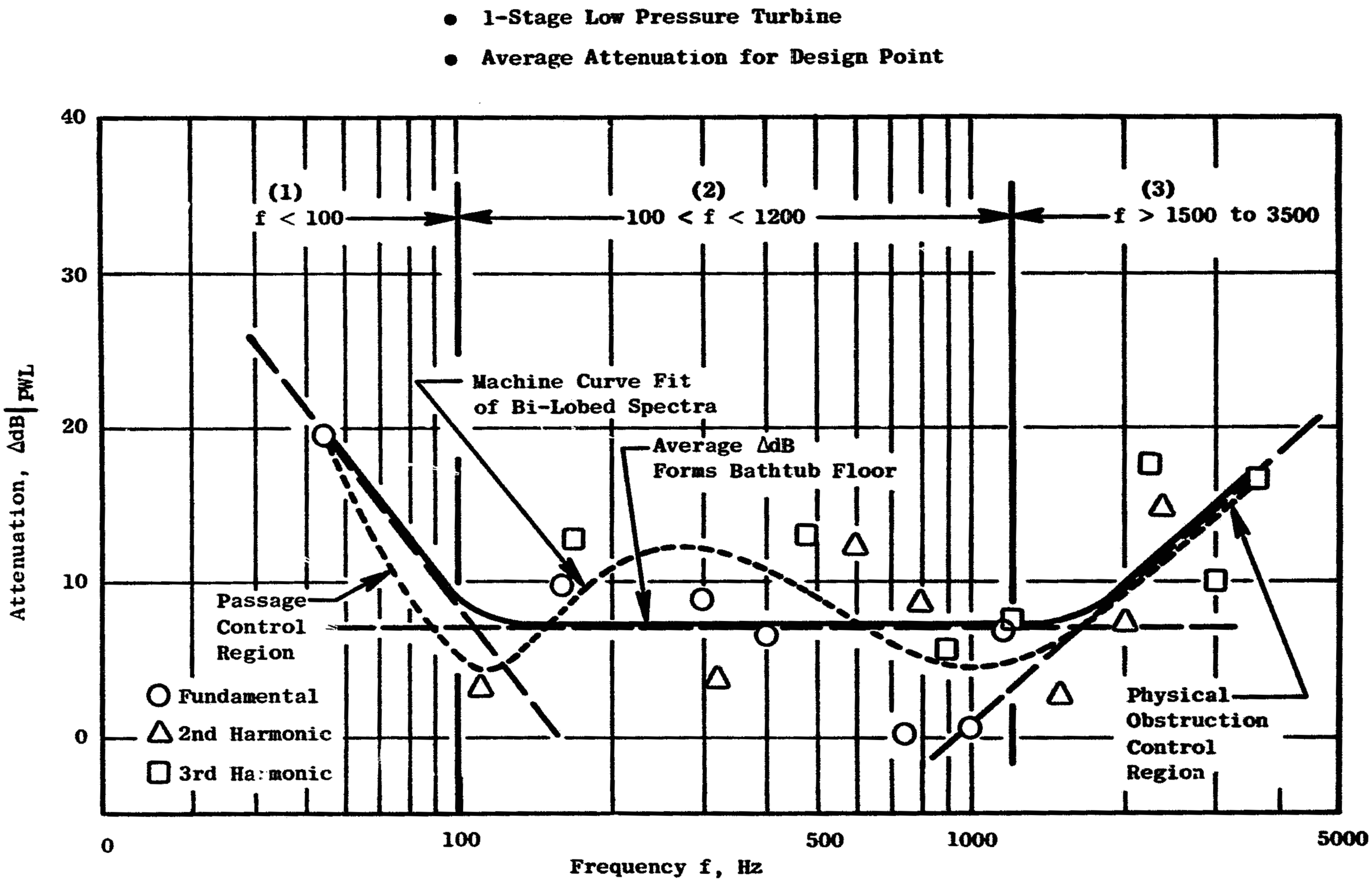


Figure 40. Bathtub Shape of Attenuation Spectra.

refers to the fact that first the upstream SPLs are averaged at each siren frequency and the PWL computed, the process repeated for the downstream sensors and the downstream PWL subtracted from the upstream PWL to obtain the attenuation at that given frequency. The double averaging results when these values for the attenuation as a function of frequency are averaged over the mid frequency range (100 to 1200 Hz) to obtain the bathtub floor.

4.2.4 Discussion of Results

This section concentrates on the attenuation results obtained from the floor of the bathtub spectrum obtained by using the double averaging method described in the previous section.

- **Low Pressure Turbine**

The average attenuation results for the single-stage LP turbine are illustrated in Figure 41. The attenuation increases with a rise in turbine pressure ratio up to a point ($P_{T0}/P_{S1.2}$ = 2.0) corresponding to choked conditions in the stator. After choking, the attenuation levels off to around 7 to 8 dB with further increases in pressure ratio. This effect is the same for all speeds tested but the reason for this is, as yet, unknown. From the tight clustering of data at all speeds, the effect of turbine speed appears to be insignificant.

The 3-stage results shown in Figure 42 clearly indicate a direct relationship between attenuation and pressure ratio. The first stage chokes at a turbine pressure ratio of about 4, but the attenuation increases beyond this, possibly because the other two stages remained unchoked. There is a larger amount of data scatter present in the average attenuations shown in Figure 42, than occurred with the single-stage. Still, no consistent trend with turbine speed is discernible.

Comparison of the 1- and 3-stage results in Figure 43 illustrates the effect of adding the second and third stages downstream of the first-stage. The single-stage attenuations are plotted at the 1-stage rotor exit pressure ratio corresponding to the 3-stage operating points. The 3-stage turbine gives an additional 3.5 dB attenuation over the 1-stage build, until the latter chokes. The added attenuation then increases with pressure ratio to 6 dB at the turbine design pressure ratio.

The results of the low pressure turbine tests to determine the effect of additional downstream stages and choking on the blade-row attenuation of low frequency noise can be summarized as follows:

1. For the 1-stage build, the attenuation increases with increasing turbine pressure ratio ($P_{T0}/P_{S1.2}$) until choking occurs, then levels off and remains constant at about 7 to 8 dB.

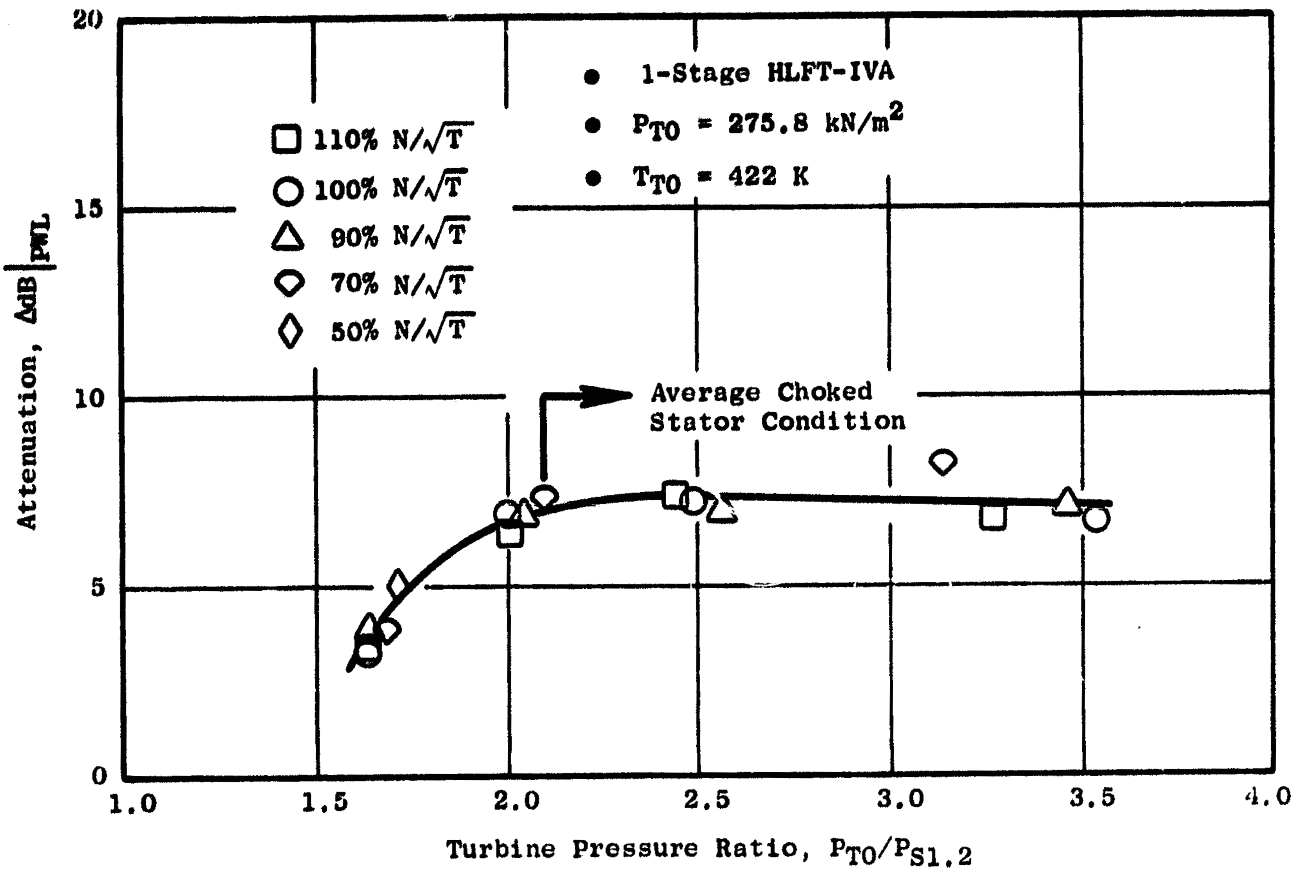


Figure 41. Effect of Turbine Pressure Ratio on Attenuation of Single-Stage Low Pressure Turbine (HLFT-IVA).

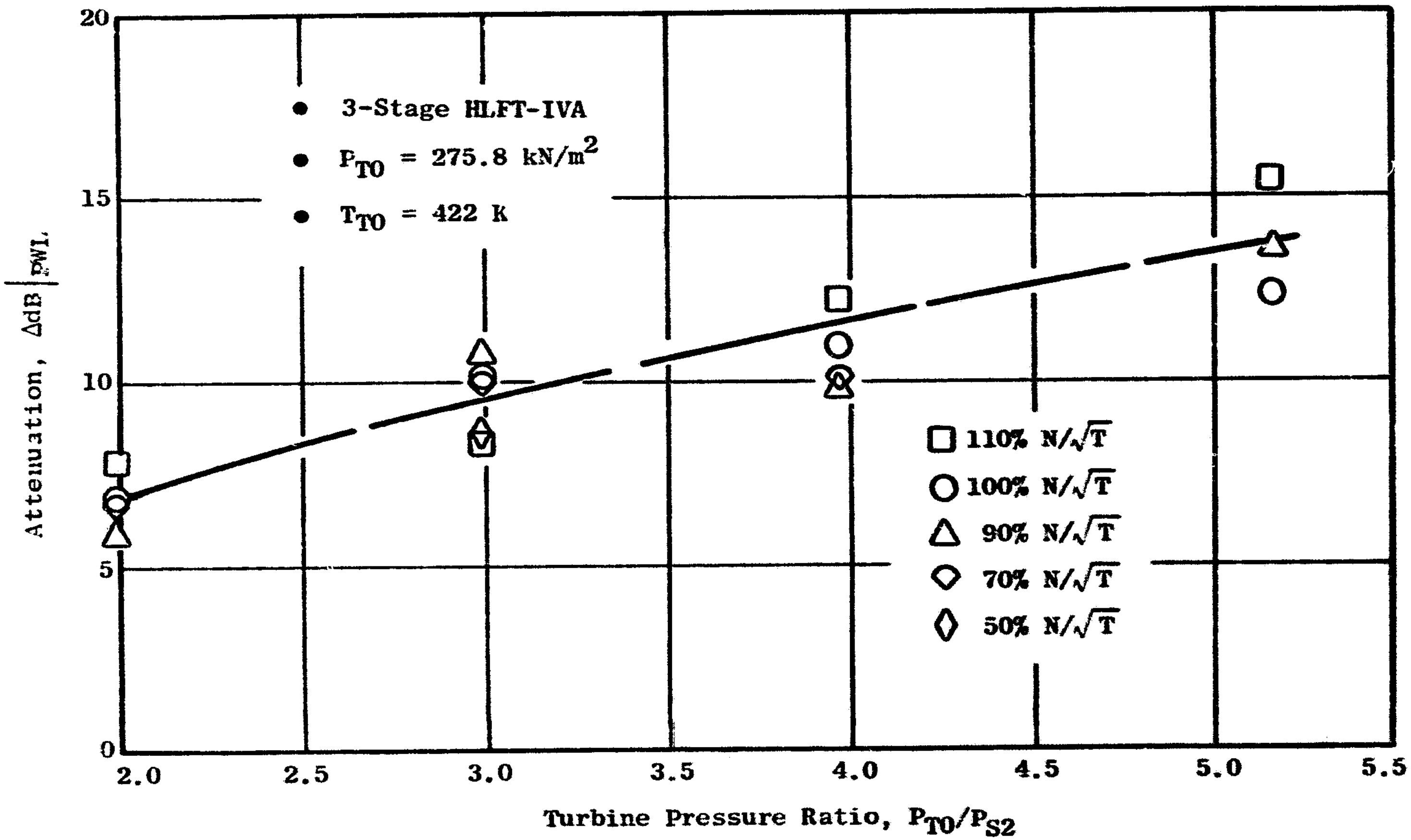


Figure 42. Effect of Turbine Pressure Ratio on Attenuation of Three-Stage Low Pressure Turbine (HLFT-IVA).

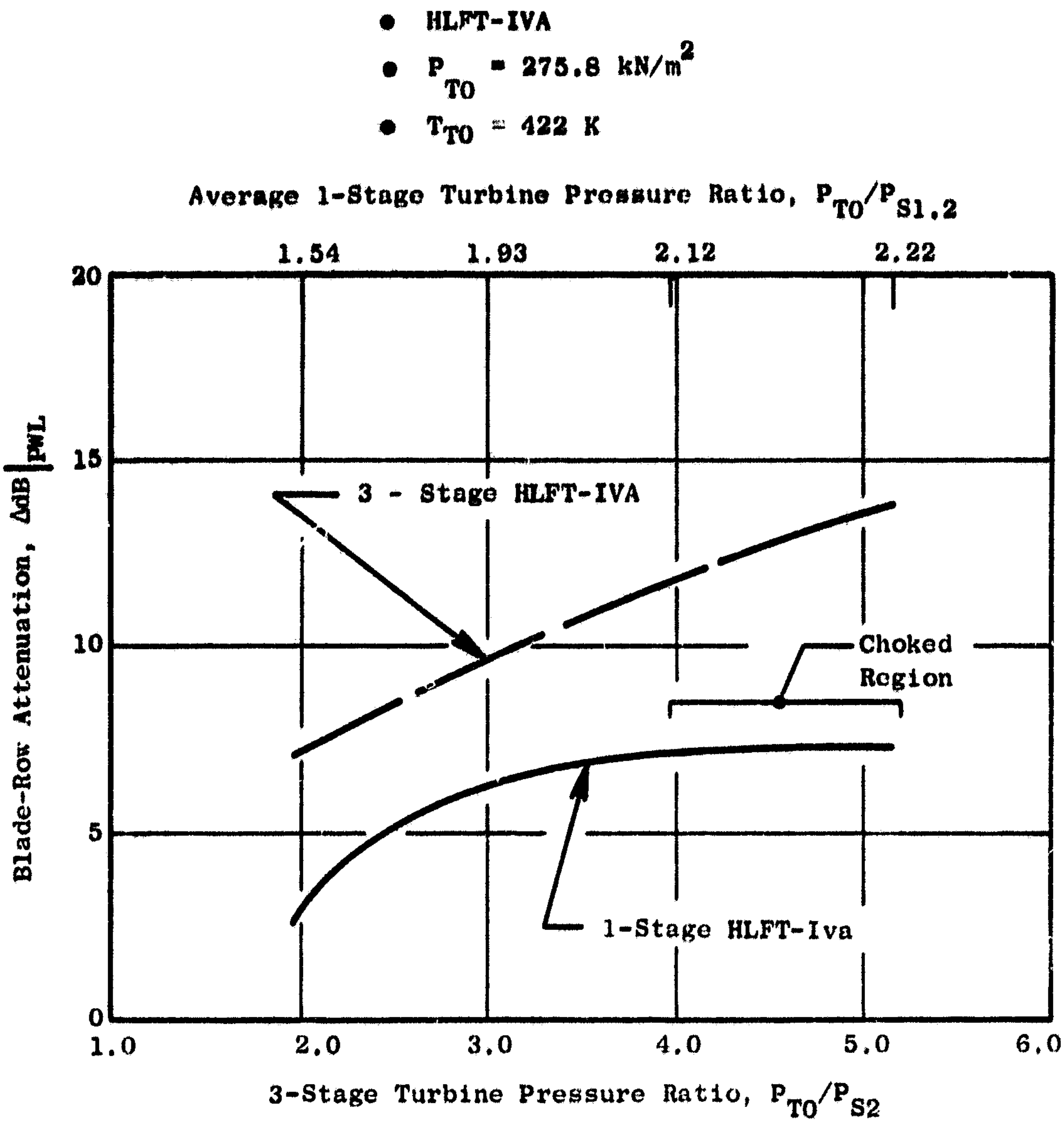


Figure 43. Attenuation Comparison of Low Pressure Turbine Results from 1- and 3-Stage Tests.

2. The effect of turbine speed on attenuation appears insignificant.

3. The effect of additional downstream stages increases the turbine attenuation from 3.5 to 4.0 dB over the unchoked single-stage results; and from 4.5 to 6.0 dB after choking of the first stage occurs.

- <u>High Pressure Turbine</u>

Results from the high pressure turbine data analysis are shown in Figure 44 for the "cold" test. A trend of attenuation increasing with pressure ratio is apparent with a leveling off after choking occurs, similar to the LPT 1-stage results. No consistent trend with turbine speed was evident.

The hot test results (Figure 45) obtained in like manner showed a general increase in attenuation with the same leveling off after choking conditions were reached. The data scatter for the hot test was greater than that for the cold. However, comparison of the hot and cold data in Figure 46 showed the hot data to be lower by less than 1 dB than the cold data for the range of pressure ratios tested when $N/\sqrt{T}$ was maintained constant. This slight decrease may suggest that attenuation decreases with increasing inlet temperature, although the difference is well within the limits of the data scatter. It should be noted that constant $N/\sqrt{T}$ means that the flow Mach numbers and velocity triangles were kept the same for the two tests.

The results of the high pressure turbine tests to determine the effect of inlet temperature and choking on the low frequency noise transmitted through the turbine are summarized as follows:

1. Attenuation increases with turbine pressure ratio in the same manner as the LP turbine results.

2. Choking limited the attenuation level to 9 to 10 dB on the HP turbine.

3. The effect of turbine speed was not significant.

4. Inlet temperature effects on attenuation were in the order of 1 dB which is well within the limits of data scatter.

Figure 47 provides a comparison of the HP turbine results with those of the single stage LP turbine. The attenuation increases with pressure ratio for both cases until choking occurs. However, the HP turbine, because of its design, chokes initially at the rotor (most turbines choke at the nozzle first) and chokes at a higher pressure ratio than does the LP turbine first stage. A higher asymptotic attenuation is therefore achieved for the HP turbine. Apparently, it is not necessary that full-span choking occur, only that the relative Mach number reach sonic conditions somewhere.

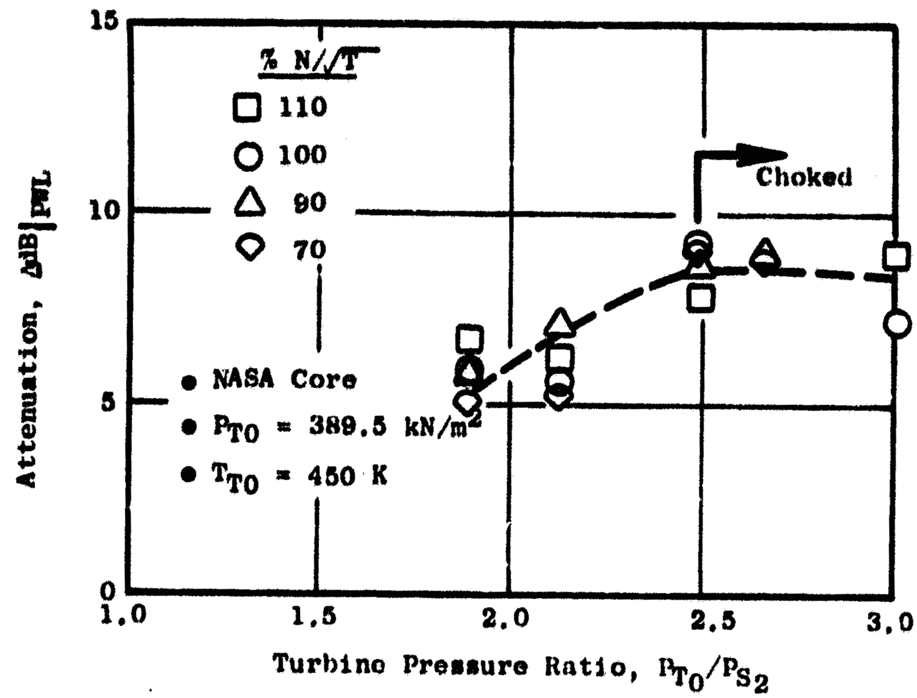


Figure 44. Effect of Turbine Pressure Ratio on Attenuation of High Pressure Turbine with Cold Inlet.

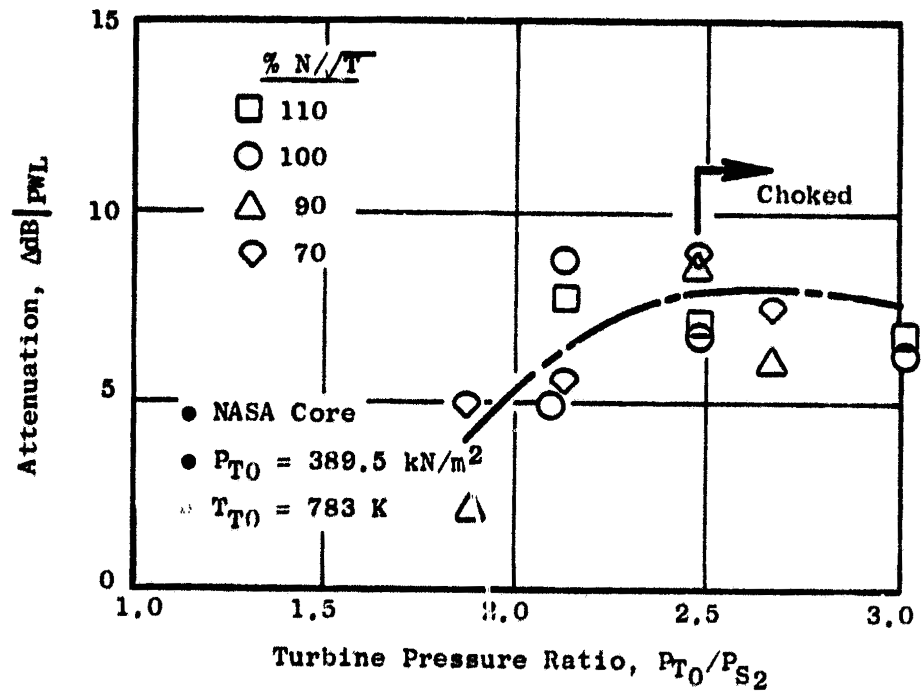


Figure 45. Effect of Turbine Pressure Ratio on Attenuation of High Pressure Turbine with Hot Inlet.

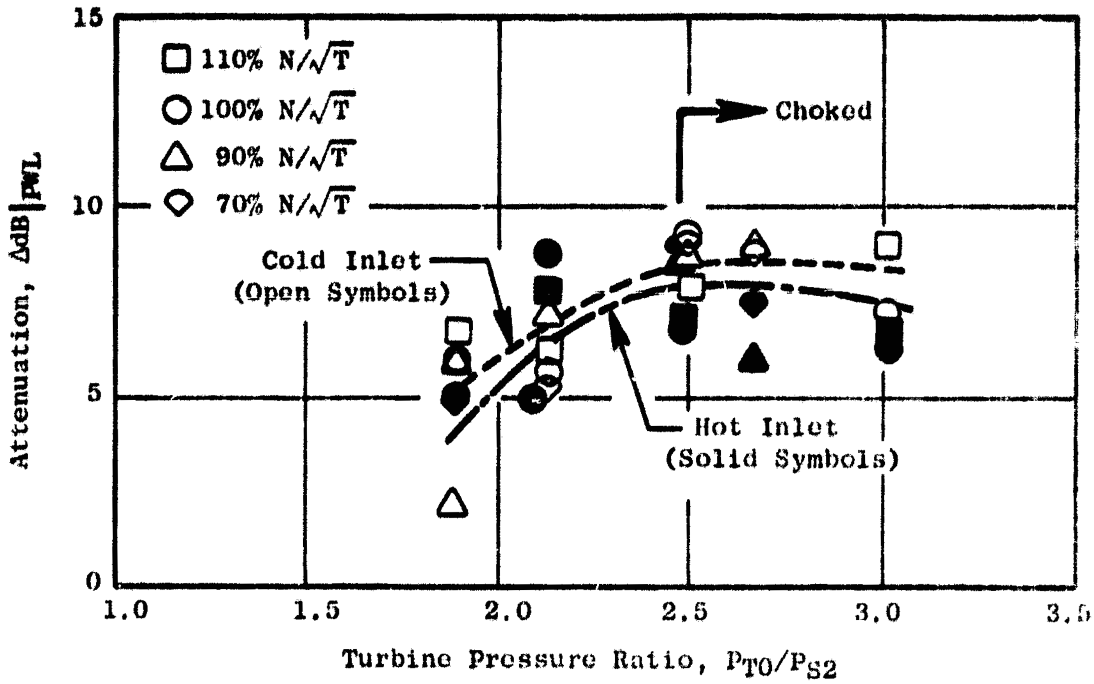


Figure 46. Effect of Turbine Inlet Temperature on High Pressure Turbine Attenuation.

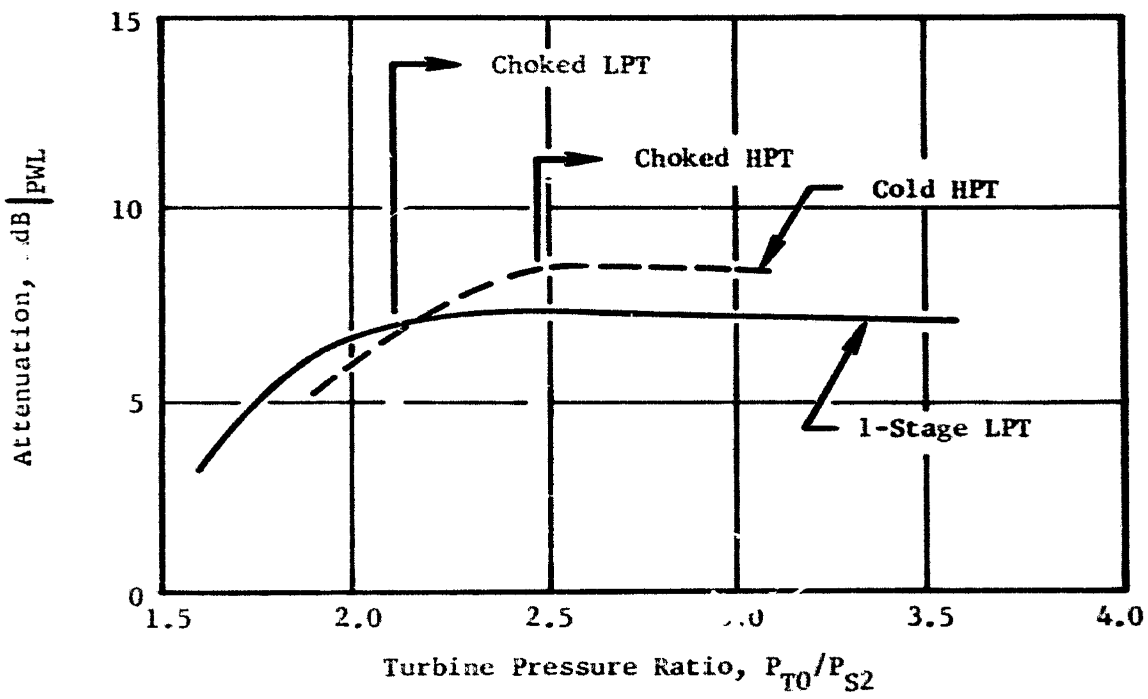


Figure 47. Comparison of Single-Stage Attenuation Results for HP and LP Turbines.

In both cases, this occurred at the hub first. A full set of aerodynamic data is provided in Appendices A and B.

Finally, a statement on the physical meaning of the measured attenuations is in order. The Δ that is actually sought is the insertion loss, that is the reduction in the sound radiated to the farfield. It can be argued that since the upstream measurements include the incident and reflected energy, the attenuation values derived are about 0 to 3 dB greater than the so called transfer function or insertion loss. Then, the effect of higher circumferential modes must be considered. The phase plots show significant spinning wave content cutting-on above 300 Hz. At the point of cut-on, a mode is spinning almost circumferentially and at about 90° to the axial direction. Consequently, the subsequent impact on the blade rows occurs at a very high incidence angle. But high incidence on approaching the turbine blades results in a complete reflection of the acoustic energy. Higher order modes are therefore characterized by a sudden increase in the measured attenuation - the exact value being a function of the energy split between the plane wave and higher order circumferential modes. Proceeding away from the cut-on point, the higher order modes assume a more axial orientation and the incidence on the blade row decreases.

The definition of the bathtub floor as the average of the attenuations for frequencies between 100 (or 200) and 1200 Hz along with the earlier sensor pair averaging helps to mitigate some of the spinning wave problems. However, if the combustor noise energy in an engine configuration remains in the form of a plane wave, attenuations measured in this program will be greater than the true insertion loss by:

1. 0 to 3 dB due to the combined incident and reflected wave measurements.

2. 1 to 2 dB due to spinning wave cut-on (an estimate based on the 300 to 400 Hz lobe in the attenuation spectra).

4.3 COMPARISON OF DATA WITH THEORY

4.3.1 Predicted and Experimental Comparisons

The predicted attenuations are compared with the data as a function of the pressure ratio at constant speed in Figures 48 through 50. In each case, the predictions are for a zero incidence acoustic wave, where the incidence angle is given by (flow angle - blade angle); (see Figure 57, Appendix A). It has previously been demonstrated that the predicted attenuation per stage is almost constant for about ±10° incidence (Reference 8). The results for the high pressure turbine are shown if Figure 48. The order of magnitude would appear to be in reasonable agreement. However, the data are about 2 dB lower than the predicted 8 to 9 dB attenuation in most incidences. The comparisons are for a single speed, but, as has been noted earlier, the turbine speed has little effect on the attenuation. Hence, the results shown here are representative of the entire operating range. The analysis does not distinguish between the hot and cold tests since $N/\sqrt{T}$, and therefore the flow triangles were maintained constant, and because the actuator disk assumption results in a loss of the wave number dependency.

The results of the comparison for the single stage build of the low pressure turbine are shown in Figure 49. Initially, at low pressure ratios, the data are 2 to 3 dB below the predictions. As the pressure ratio is increased, the measured attenuations increase at a faster rate than the predictions till the onset of choking. As was observed earlier, the measured attenuations remained virtually constant for pressure ratios higher than required for choking. However, the actuator disk analysis actually indicates a reduction in the blade row attenuation for pressure ratios greater than required for choking. The net result is than beyond $P_r = 2.5$, the measured data are higher than the prediction line, the greatest difference being about 2 dB. It is not clear how choking limits the observed attenuation. Perhaps it is the presence of a shock, or the change of impedance due to a shock, or the associate pressure discontinuity. This is under investigation under NAS3-20027. Choking implies a limitation of the flow rate and this is taken into consideration in the analysis. Both Figures 48 and 49 show the predicted attenuation levelling off and decreasing for choked turbine operation. The fact that the measured attenuation does not drop correspondingly could be a consequence of the fact that the choked condition does not extend across the full span.

The results of the comparison for the 3 stage turbine are shown in Figure 50. Also shown are the attenuations for the three individual stages (rather than the six blade rows). The predicted insertion loss for this low pressure turbine varies from 13 to 19 dB for the pressure ratio range investigated (2 to 5.2). The measured data lie 6 to 7 dB below the predicted line. But, as was explained in Section 4.2.4, the actual turbine insertion loss is 1 to 5 dB less than the measured transmission loss given by the data points. Therefore, summing the isolated blade row losses to arrive at the overall turbine loss results in at least 7 dB, and perhaps up to 12 dB over-prediction of the insertion loss due to the 3 stage turbine. On the other hand, comparison with the single stage results (Figure 48 and 49) show a much smaller discrepancy. This suggests that the net attenuation due to several blade rows in sequence will not be the straight sum of the attenuations due to individual blade rows, but rather a much smaller number due to a multi-staging effect. Physically, it can be argued that the reflected wave at each interaction other than that at the first blade row will not be lost, as is assumed in the isolated blade row analysis, but rather will be largely re-directed in the downstream direction after interaction with an upstream blade row. These multiple interactions will result in a reinforced transmitted wave and a lower overall attenuation. Investigation of this multi-staging effect is being conducted under Contract NAS3-20027.

- NASA Core High Pressure Turbine
- $N/\sqrt{T}$ = 362
- Predicted Results Based on Plane Wave, Zero Incidence Assumtions

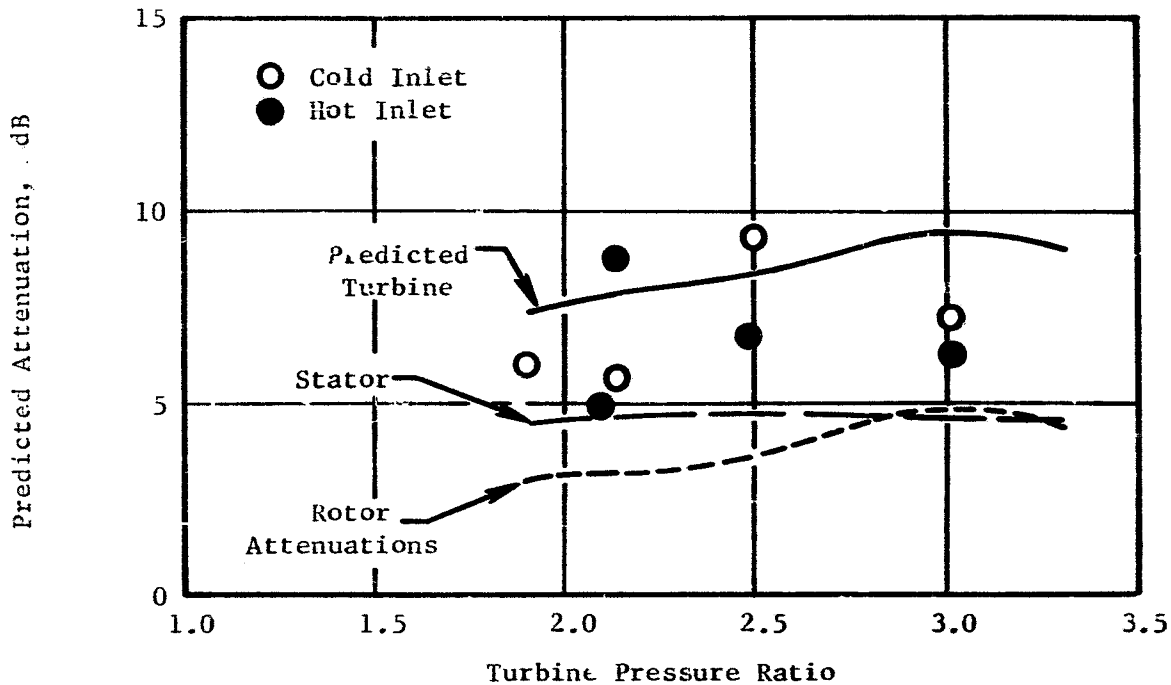


Figure 48. Comparison of High Pressure Turbine Attenuation Results with Theory.

- HLFT-IVA LPT
- $N/\sqrt{T}$ = 204
- P_{T0} = 275.8 kN/m^2, T_{T0} = 422° K
- Predicted Results Based on Plane Wave, Zero Incidence Assumptions

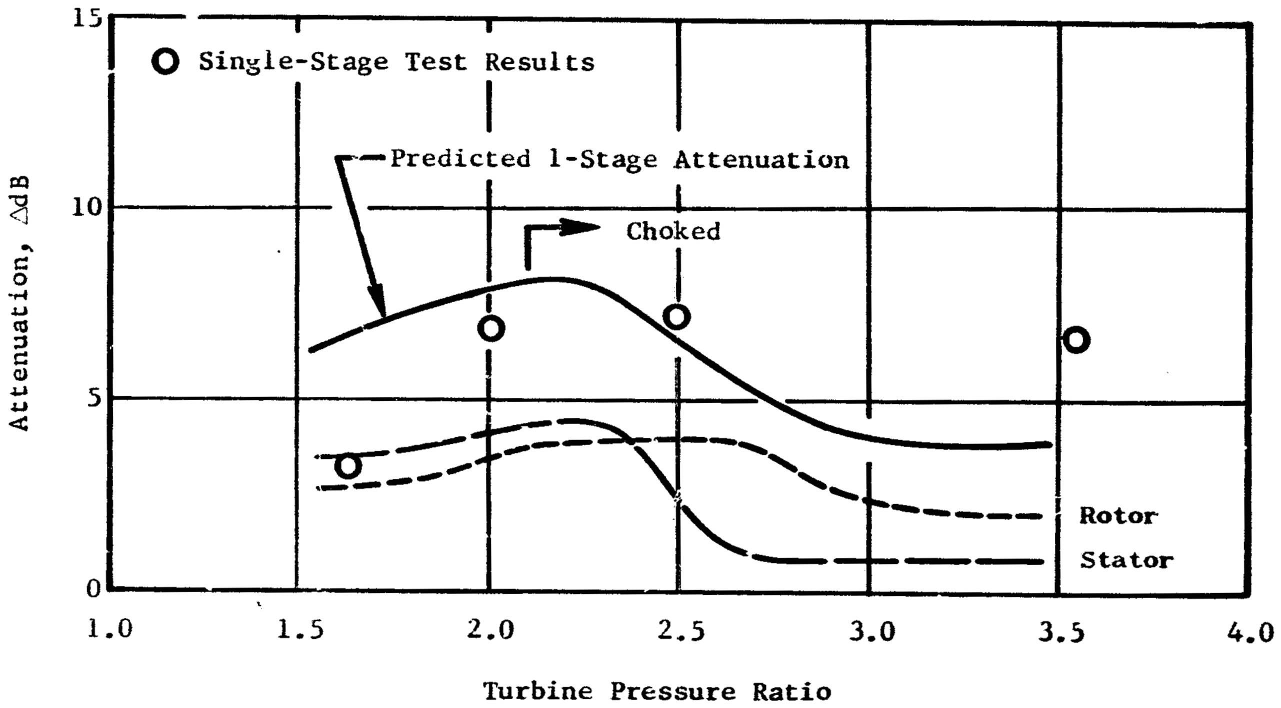


Figure 49. Comparison of Predicted and Empirical Attenuation from Single-Stage Low Pressure Turbine.

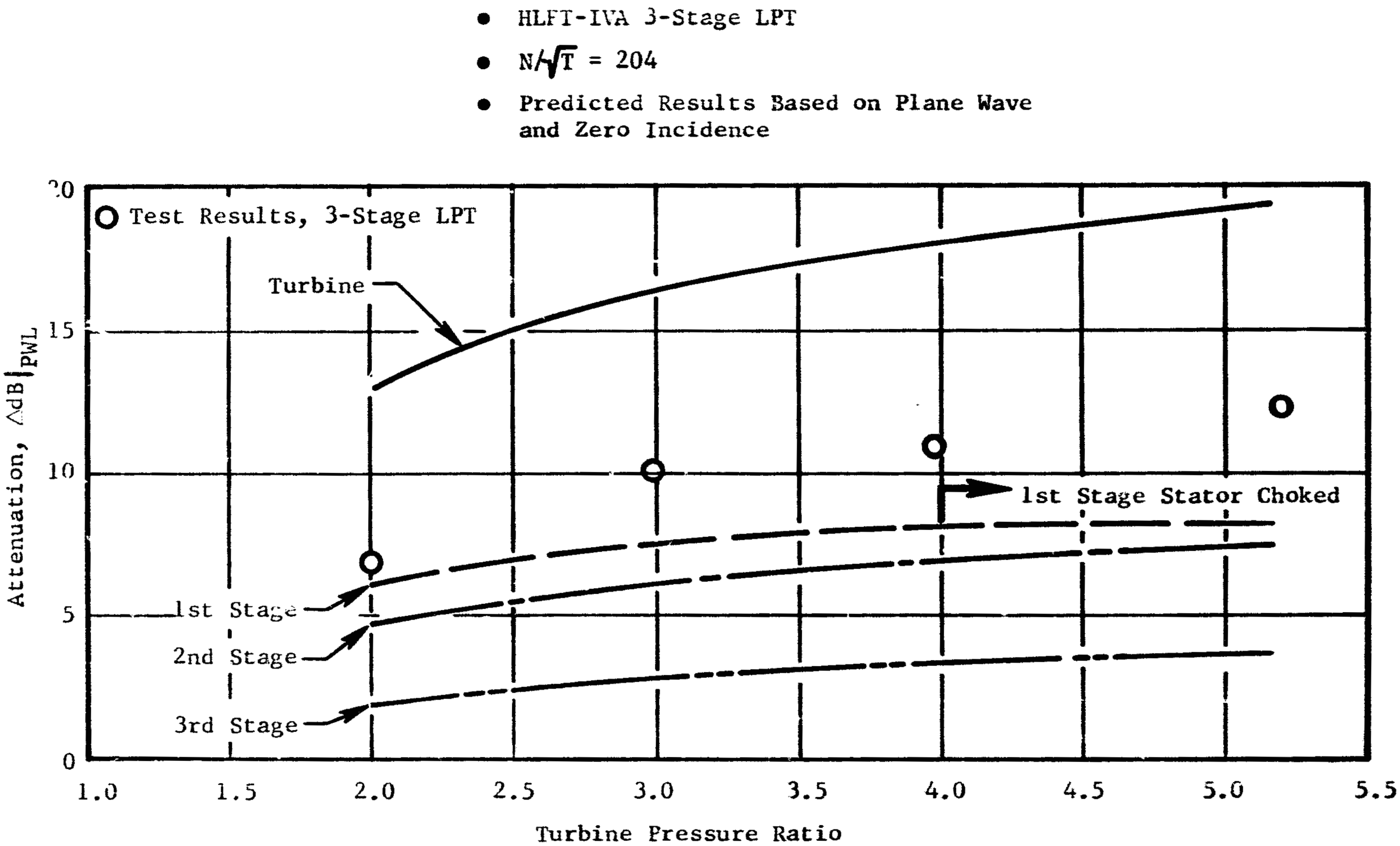


Figure 50. Comparison of Low Pressure Turbine Attenuation Results with Theory.

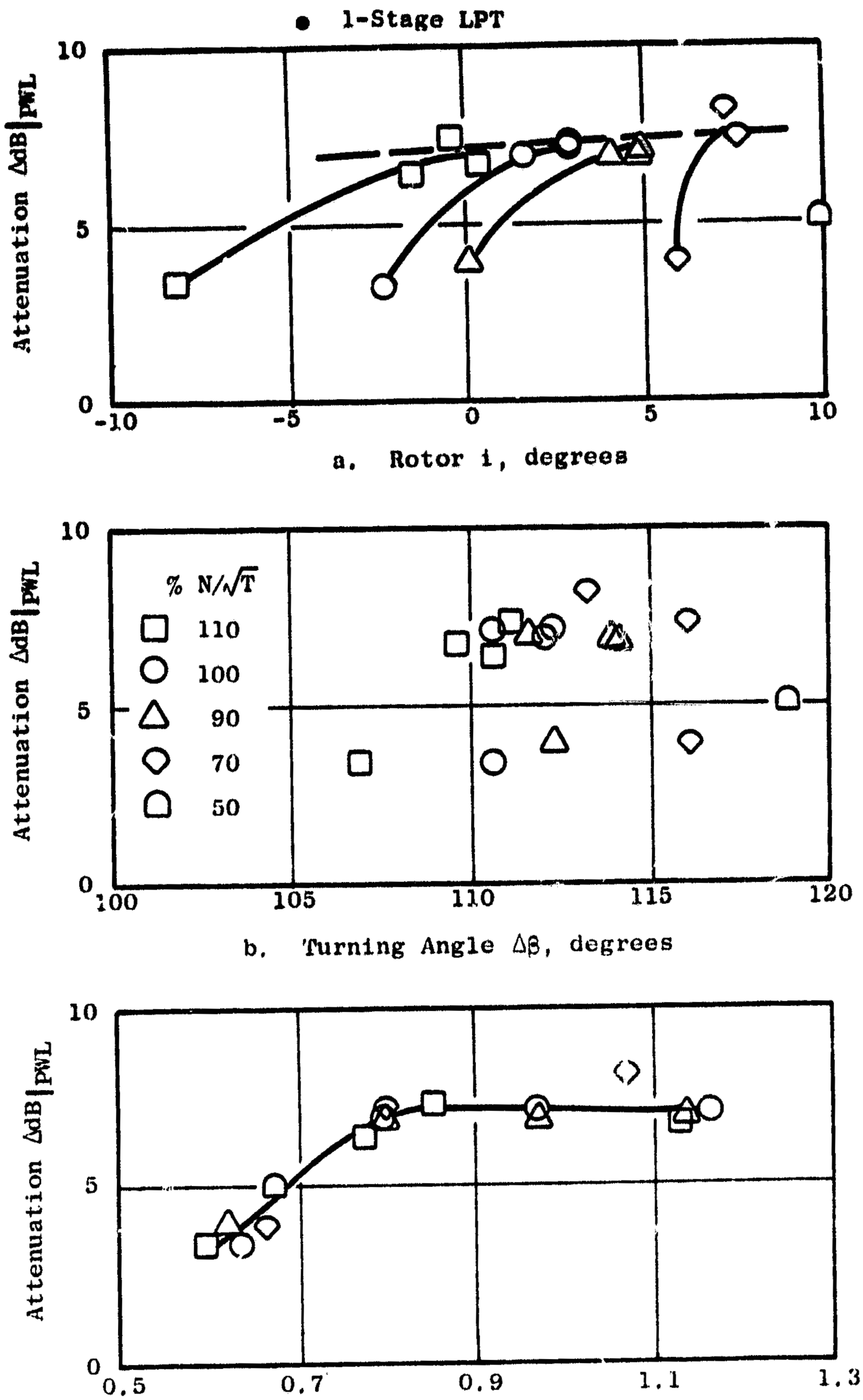
4.3.2 Evaluation of Acoustic Correlating Parameters

An investigation was conducted to identify the best correlating parameters for the measured attenuation data. Such correlating parameters would be of obvious value in formulating an empirical prediction method for low frequency noise transmission through turbine blade rows. Salient results from the study are shown in Figures 51 through 56. The performance data used in the correlations can be found in Appendices A and B. The terminology used to define the turbine flow triangles is shown in Figure 57 (Appendix A).

Previous experience with the Actuator Disk analysis (Reference 8) and combustor noise correlations (Reference 10) suggested that the parameters of interest would be blade row incidence, turning angle, relative Mach number, pressure ratio, and turbine work extraction. For example, the analysis indicated that the blade row attenuation would increase markedly if the acoustic wave incidence angle varied beyond say ±10°. As noted above, the incidence angle is defined as (flow angle - blade angle). As a first estimate, the blade angle can be taken as the flow angle at design point. If it can be assumed that the acoustic wave convects with the flow, then turbine off-design operating points could result in large attenuations due to increasing incidence. Data for the single stage low pressure turbine are plotted against the rotor incidence angle in Figure 51a. The data separate out along the different speed lines and therefore the incidence angle was rejected as a correlator.

The same data set is shown plotted as a function of the rotor turning angle in Figure 51b. There is obviously no correlation. However, when plotted against the tip relative Mach number exiting from the rotor, a good collapse results, as shown in Figure 51c. The resulting curve is similar to that obtained using the stage pressure ratio (Figure 41). The attenuation increases with the Mach number to about 0.85 and then levels off. This Mach number (0.85) corresponds to the onset of choking for the stage - which occurs initially at the stator hub. The fact that attenuation leveling off is controlled by the stator hub choke is illustrated by Figure 52. The pressure ratio normalized by the pressure ratio when choking occurs $(P_{TO}/P_{S2})/P_{TO}/P_{S2})_{\text{stator Hub Choke}}$ is not as good a correlating parameter as the rotor tip relative Mach number though, since the choking pressure ratio is a function of the turbine speed while neither the data nor the analysis indicate a speed dependency.

The rotor tip Mach number correlation of Figure 51c is repeated for the high pressure turbine data in Figures 53a and b and for the 3 stage low pressure turbine data in 53c. The correlation for cold inlet high pressure turbine is similar in that an increasing trend with Mach number is seen till choking occurs. It is interesting to note that for the high pressure turbine, choking occurs in the rotor first. It would appear that a choked condition anywhere in a stage will limit the attenuation for that particular stage. There is too much scatter in the hot inlet high pressure turbine data to draw any conclusions beyond that of Figure 53a.



a. Rotor i, degrees

b. Turning Angle Δβ, degrees

c Tip Relative Mach No., M_{2rt}

Figure 51. Aerodynamic Parameter Influence on Blade-Row Attenuation.

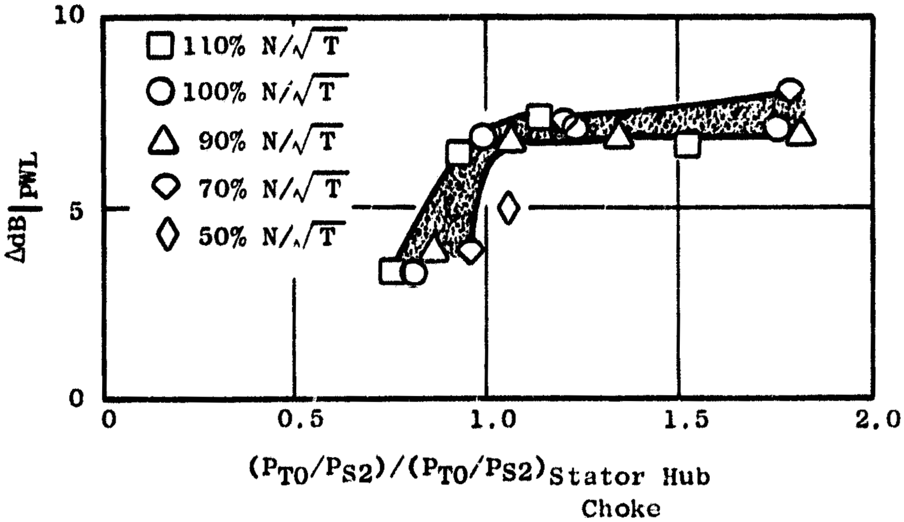


Figure 52. Dependence of Blade-Row Attenuation on Stator Hub Choke of Low Pressure Turbine.

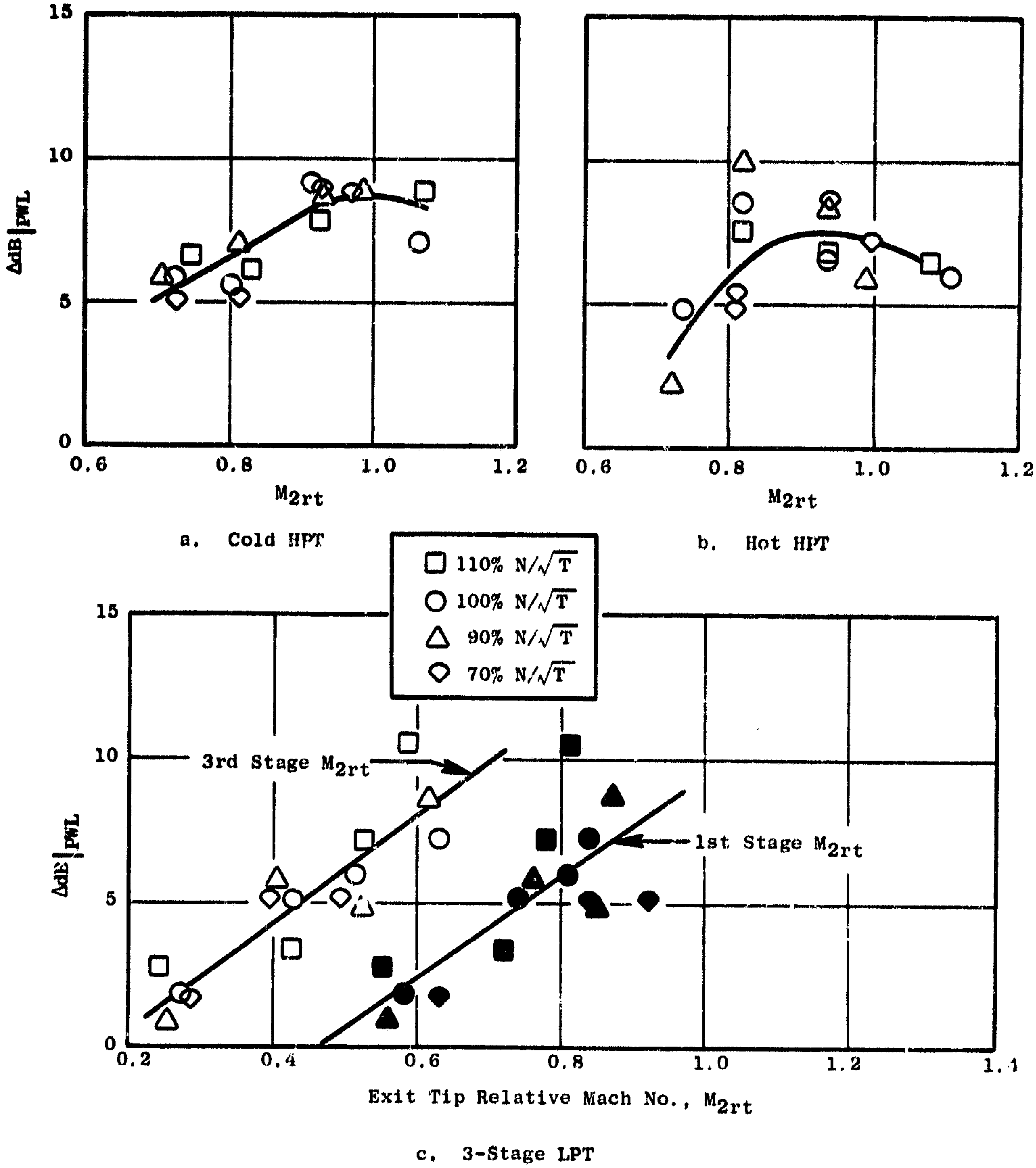


Figure 53. Exit Tip Relative Mach Number Comparisons of High and Low Pressure Turbines.

In the case of the 3 stage turbine, there is a choice of three rotor Mach numbers against which data can be correlated. Figure 53c provides the correlations for the 1st and 3rd stage rotors. The open symbols show the measured attenuations plotted as a function of tip relative Mach number at exit from the 3rd stage rotor, and the solid symbols as a function of the conditions at exit from the 1st stage rotor. There is very little to choose between the two, both providing a fair data collapse. It is clear, though, that the equation of the correlating line is a function of the blade row under consideration. That is, it is difficult to obtain a universal prediction using the rotor relative Mach number as the correlating parameter. From a study of Figures 51c and 52a, b and c, the only hope is the use of the 1st stage values.

An obvious corollary to the rotor Mach number is the stator exit Mach number. Figure 54 shows the single stage low pressure turbine data set plotted as a function of the exit Mach number at hub, pitch, and tip, respectively. All three stations produce similar plots: the data separate out along the speed lines. It is obvious that the correlation of Figure 51c is much better in achieving data collapse.

The turbine energy extraction was reviewed in the form of the turbine total temperature drop normalized by standard day temperature. Plots of the $\Delta T/T_{STD}$ versus ΔdB are presented in Figure 55a through 55c for the 3-stage and single-stage LP turbines and the cold inlet HP turbine, respectively. Again, the similarity with the pressure ratio correlations for these turbines is apparent but the data scatter is greater.

The turbine-loading parameter was eliminated as a correlating parameter, since the attenuation results obviously indicate that wheel speed is not a factor, and the work-extraction dependency is available either from the pressure ratio or ΔT plots.

The choice of a correlating parameter would appear to be between the pressure ratio, temperature drop, or rotor relative Mach number. The first two are readily available and therefore preferable. At the same time, the role played by choking must be kept in mind.

All three data sets of Figure 55 are shown on a single plot as a function of ($\Delta T/T_{STD}$) in Figure 56. The solid line in the figure is a fit through the 3 stage turbine data and the slope is roughly 20 log ($\Delta T/T_{STD}$). The data for the single stage builds lie somewhat above (1 to 2 dB) this line as a consequence possibly of the higher exhaust swirl relative to the rotor. The analysis indicates the greater this relative flow swirl angle, the larger the attenuation. The corresponding values for the 3 stage and the two single stage builds are 45.9°, 60.1° and 60.8°.

Figure 56 also illustrates the fact that the work extraction is a better determinant of low frequency noise attenuation through turbines than is the number of stages as a single stage operating at a corresponding point can provide as much attenuation as a 3 stage turbine. This has been

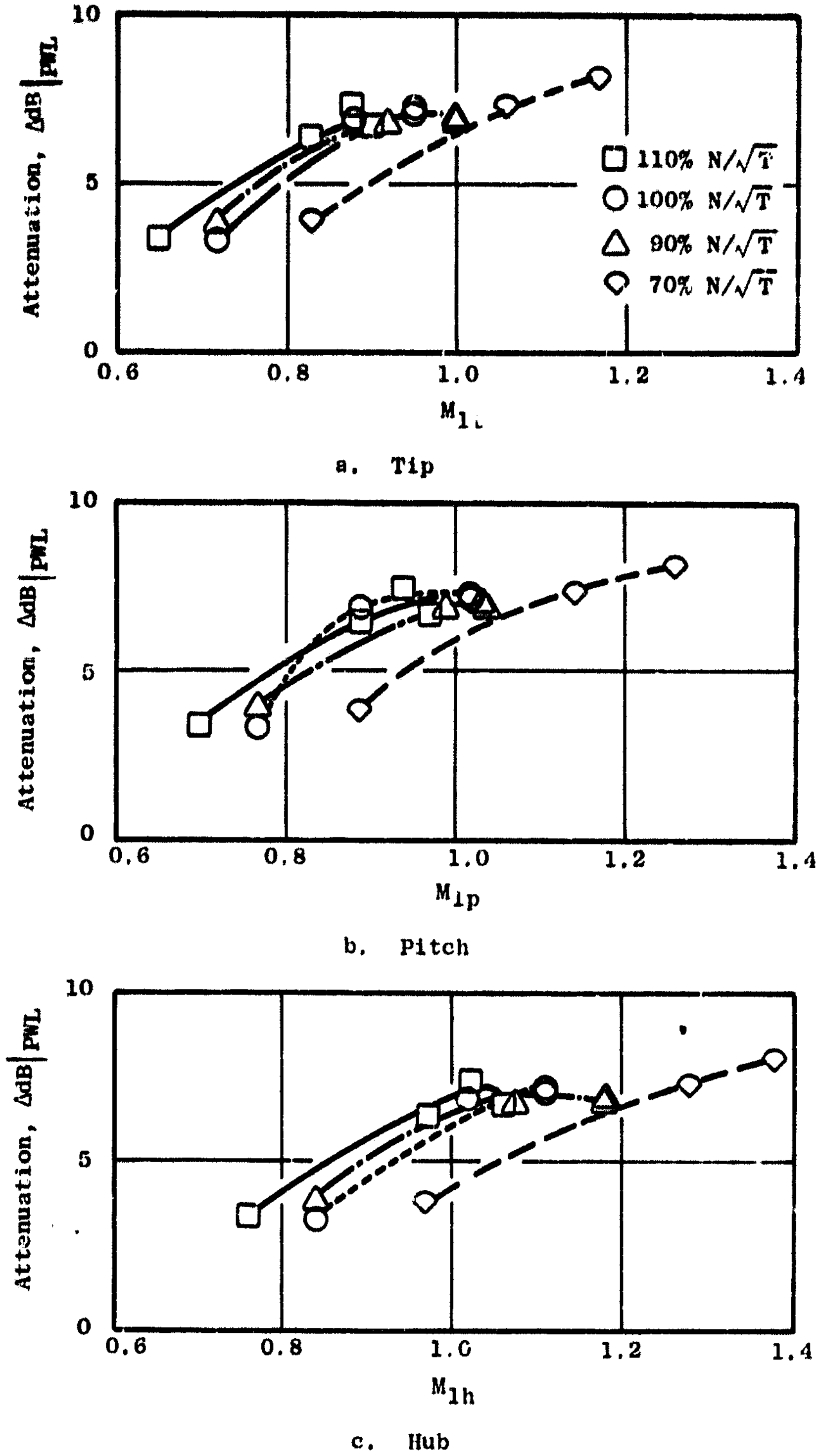


Figure 54. Comparison of Stator Exit Mach Numbers for 1-Stage Low Pressure Turbine.

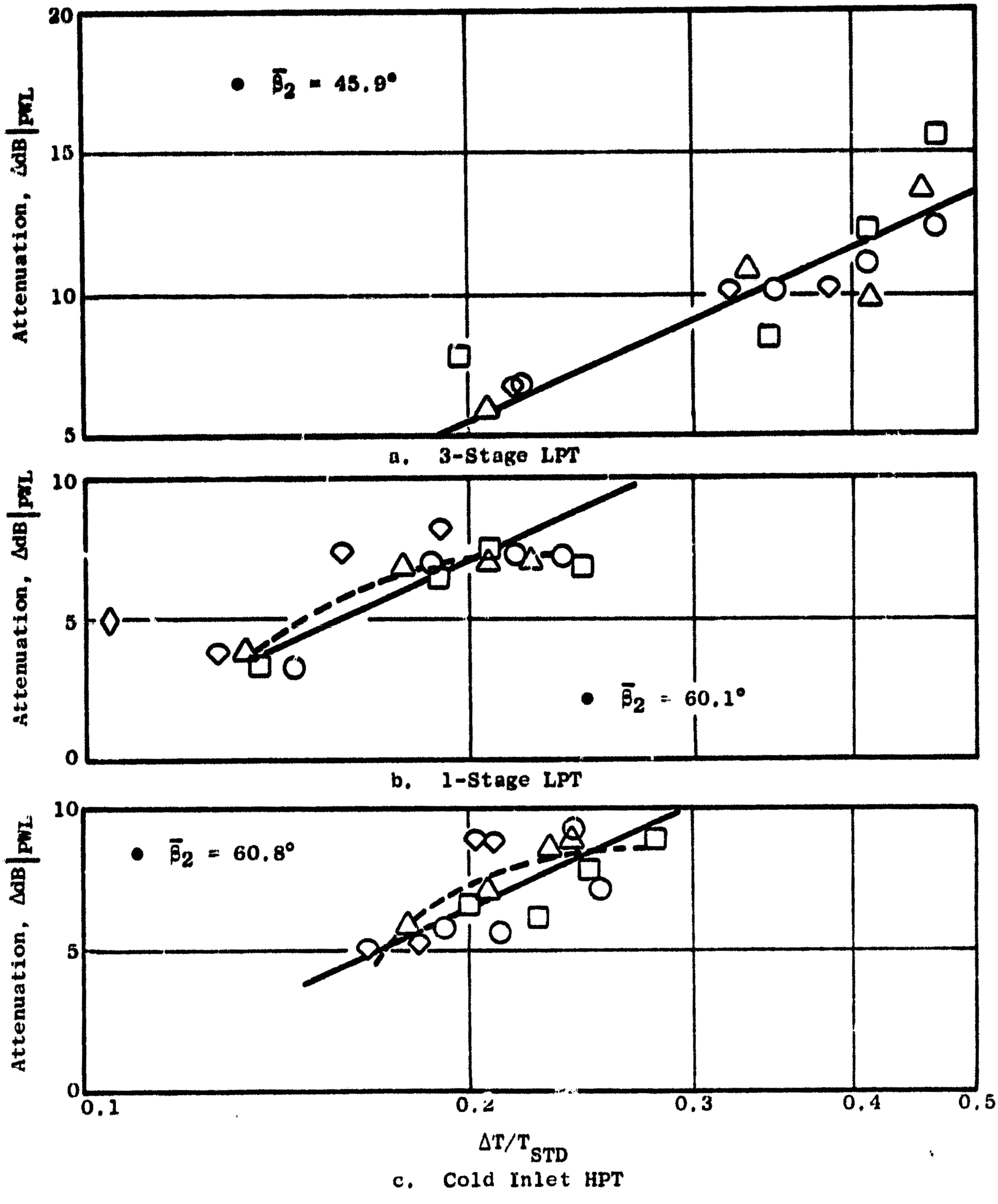


Figure 55. Influence of Turbine ΔT on Attenuation.

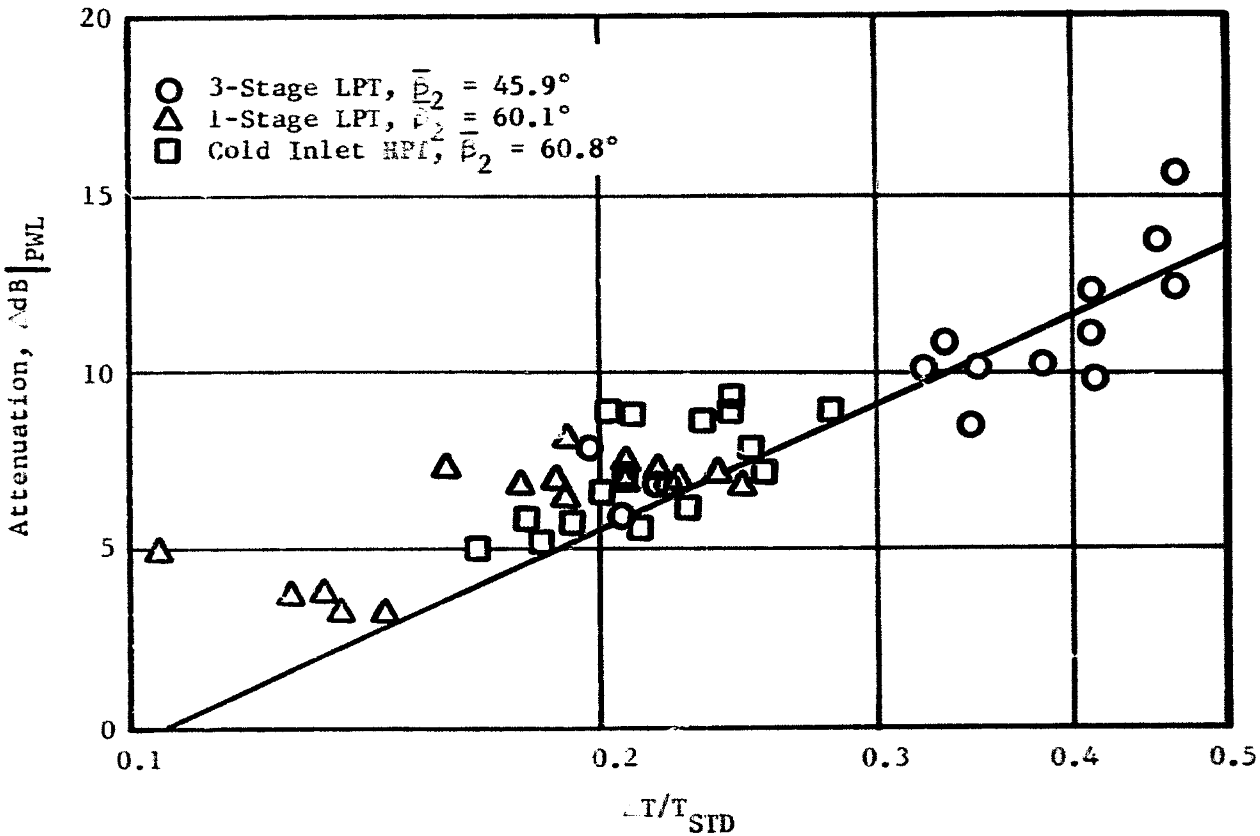


Figure 56. Data Correlation Using Turbine Temperature Extraction.

applied to the unified line core (combustor) noise prediction method evolved by General Electric (Reference 7). The method has been validated by data from turbojet, turboshaft, and turbofan engines tested by General Electric, Rolls Royce, Pratt and Whitney, Boeing, Garrett AiResearch and Allison. This method has been proposed to the SAE A21 subcommittee as a standard.

SECTION 5.0

CONCLUSIONS

5.1 BATHTUB SPECTRUM

The transmission loss spectrum determined from the turbine tests fell into three well-defined regions from 0 to 3500 Hz. A midfrequency region extends from 200 to 1200 Hz and the attenuation remains relatively constant here. The attenuation on either side increases rapidly, suggesting a bathtub shape. The very low frequency region, below 100 Hz, could be controlled by the effect of propagation through the varying-area blade passages which carry an accelerating flow. The increase in attenuation for frequencies above 1500 Hz is attributed to the physical blockage presented by the turbine blades as the wavelength is approaching the blade size. The floor region apparently is controlled by the mechanism used in the actuator disk theory. This region spans the frequencies of primary interest for combustor noise.

5.2 SUMMARY OF DATA COMPARISONS FOR THE SPECTRUM FLOOR

The results of the blade row attenuation investigation on the high and low pressure turbines yielded the following conclusions based on average attenuations for frequencies between 100 and 1200 Hz:

1. Attenuation increases with turbine pressure ratio until the blade-row (stator or rotor) chokes. After choking, the attenuation remains virtually constant for that given stage.

2. There is no significant effect of turbine speed on attenuation for any given turbine.

3. The effect of inlet temperature is not readily discernible if flow triangles are maintained constant.

4. The addition of downstream stages increases the attenuation, but by a much smaller order of magnitude than predicted by isolated blade-row theory.

5.3 SIGNIFICANCE OF FINDINGS

These conclusions clarify the regions of the attenuation spectra which directly apply to the existing prediction theory as being between 200 and 1200 Hz. Used within this range, the single-stage theory agrees well with the experimental results. A multistaging effect is evident from the overprediction of the turbine attenuation for the 3-stage LP turbine. This multistaging effect is being investigated under NASA Contract NAS3-20027, along with a new theory that will account for the increased attenuation at the two ends of the floor.

A preliminary review of the aerodynamic performance parameters shows that pressure ratio and temperature drop (work extraction) are the best correlators for empirical prediction-model use, while rotor exit tip relative Mach number appears to be another possible correlator. The attenuation varies, roughly, as 20 log (ΔT).

The measured attenuations are thought to be anywhere from 1 to 5 dB greater than the corresponding insertion losses for the turbines tested. The discrepancy is due in part to the simultaneous presence (and measurement) of the reflected and incident wave upstream of the turbine, and in part to the cut-on of spinning waves at frequencies above 300 Hz.

SECTION 6.0

SYMBOLS AND NOMENCLATURE

Symbol		Description	Units
A	-	Annulus Area	cm^2
c	-	Acoustic Velocity	m/sec
D	-	Diameter	cm
dB	-	Decibel	
f	-	Frequency	Hz
g	-	Gravitational Constant	m/sec^2
g_x, g_y	-	Input Signals	
G(In)	-	Input Power Spectrum	
G(In-Out)	-	Cross-Spectrum Amplitude	
H	-	Total Enthalpy	
H(f)	-	Transfer Function Amplitude	
HP	-	High Pressure	
HPT	-	High Pressure Turbine	
Hz	-	Hertz: cycles/second	
i	-	Rotor Incidence Angle Relative to Flow	deg
J	-	Joule's Constant	
K	-	Kulite Pressure Transducer	
LP	-	Low Pressure	
LPT	-	Low Pressure Turbine	
M	-	Mach Number	
M_{2rt}	-	Tip Relative Mach number at Rotor Exit	
n	-	Number	
N	-	Turbine Speed	rpm

Symbol		Description	Units
$N/\sqrt{T}$	-	Speed Function	rpm/$\sqrt{T}$
1/3 OBSPL	-	One-Third Octave Band Sound Pressure Level	
p	-	Acoustic Perturbation	kN/m^2
P_r	-	Total-to-Static Pressure Ratio	
P_{SH}/W_2	-	Specific Shaft Power	Btu/lbm (kJ/kg)
PWL	-	Sound Power Level, dB re: 10^{-13} watts	dB
r	-	Radius	cm
R_{xy}	-	Cross-Correlation Function	
SPL	-	Sound Pressure Level, dB re: 0.00002 N/m^2	
T	-	Temperature	K
T_{STD}	-	Standard Day Temperature	518.7° R (288.2 K)
$\bar{T}$	-	Integrating Time	sec
t	-	time	sec
T_p	-	Time Period	
T_{max}	-	Maximum Thickness	cm
U	-	Mean Flow Velocity	m/sec
U_p	-	Wheel Speed at Pitch Line	m/sec
V	-	Flow Velocity	m/sec
W	-	Weight Flow	kg/sec
W_2 CORR	-	Weight Flow Corrected to Turbine Inlet Conditions, $W\sqrt{T/T_o}/(P/P_o)$	kg/sec
β_2	-	Rotor Relative Exit Flow Angle	deg
Δ	-	Delta: Change or difference	
$\Delta\beta$	-	Rotor Turning Angle	deg

Symbol		Description	Units
γ	-	Ratio of Specific Heats	
ρ	-	Density	Kg/m^3
τ	-	Time Delay	sec.
θ	-	Acoustic Wave Propagation Angle	deg.

Subscripts

h	-	Hub
p	-	Pitch
r	-	Relative
t	-	Tip
T	-	Total Conditions
S	-	Static Conditions
o	-	Standard Atmospheric Conditions
0	-	Turbine Inlet Measuring Station
1.0	-	Stator Exit Station
1.2	-	Rotor Exit Station
2.0	-	Turbine Exit Measuring Station

APPENDIX A - LOW PRESSURE TURBINE AERO AND ACOUSTIC RESULTS

Appendix A contains tabulations of the blade-row attenuations for all test conditions over the range of frequencies explored for both the 1- and 3-stage builds of the low pressure turbine. The aerodynamic performance results are also presented along with turbine flow diagrams which include interstage and intrastage data. The vector diagram nomenclature is described in Figure 57.

• Sign Convention for Positive Flow Angles

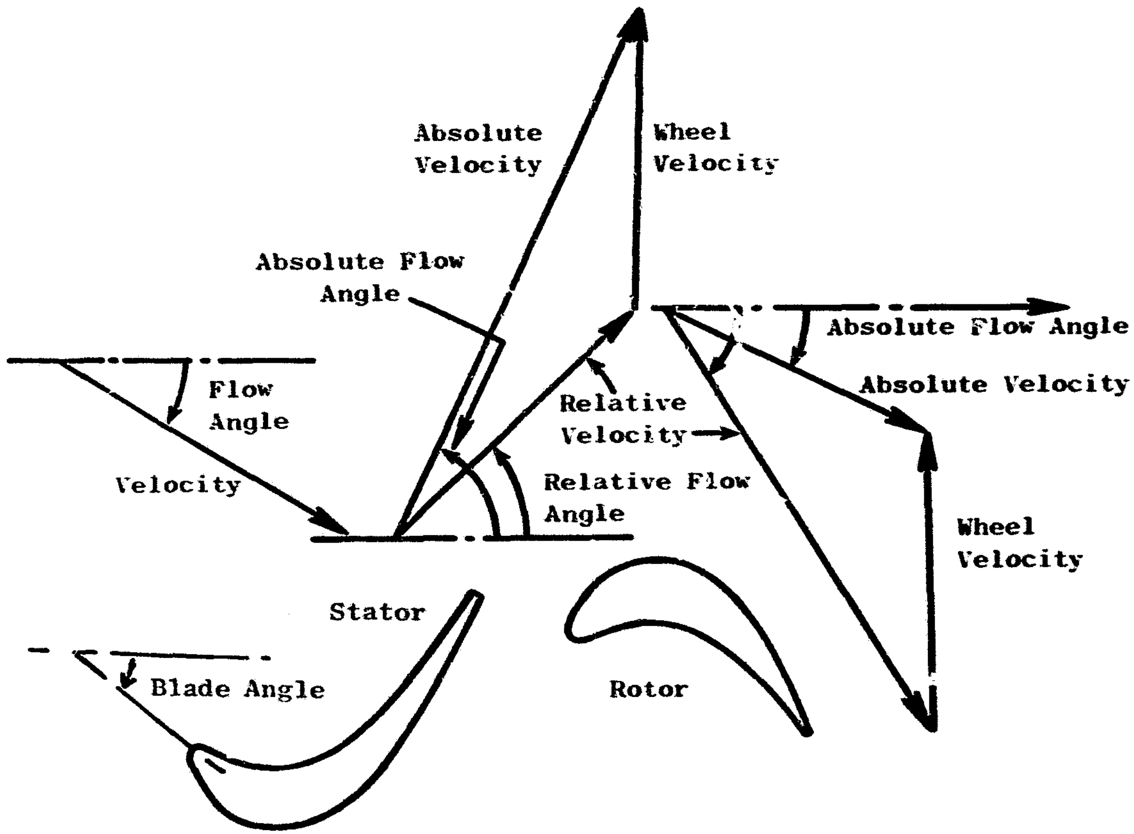


Figure 57. Vector Diagram Nomenclature.

Table 8. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 1-Stage Build, Low Pressure Turbine).

a. 110% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	2546		2246		1946		1646	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
55	-	-	25.5	20.4	27.0	21.9	22.5	17.4
83	23.0	17.9	-	-	-	-	-	-
125	14.5	9.4	-	-	-	-	-	-
164	-	-	14.5	9.4	13.0	7.9	8.5	3.4
300	7.0	1.9	15.5	10.4	23.0	17.9	10.5	5.4
400	10.5	5.4	12.5	7.4	14.0	8.9	11.0	5.9
750	5.0	0	6.0	0.9	3.5	0	3.0	0
1000	4.5	0	6.0	0.9	5.5	0.4	12.0	6.9
1175	13.2	8.2	2.8	0	4.8	0	4.2	0
2nd Harmonic, Hz								
110	-	-	9.0	3.9	7.5	2.4	7.5	2.4
167	9.0	3.9	-	-	-	-	-	-
250	9.0	3.9	-	-	-	-	-	-
328	-	-	8.0	2.9	4.5	0	2.5	0
600	15.5	10.4	22.5	17.4	17.5	12.4	8.5	3.4
800	22.5	17.4	15.0	9.9	16.0	10.9	14.5	9.4
1500	13.0	7.9	5.5	0.4	10.5	5.4	2.0	0
2000	14.2	9.2	14.2	9.2	14.2	9.2	17.2	12.2
2350	13.8	8.6	20.8	15.6	23.8	18.6	19.2	14.2
3rd Harmonic, Hz								
165	-	-	12.0	6.9	17.5	12.4	10.0	4.9
250	19.0	13.9	-	-	-	-	-	-
375	14.5	9.4	-	-	-	-	-	-
492	-	-	14.5	9.4	13.5	8.4	10.5	5.4
900	15.0	9.9	8.5	3.4	11.5	6.4	3.0	0
1200	2.2	0	25.8	20.6	6.8	1.6	5.8	0.6
2250	23.0	17.9	18.5	13.4	12.5	7.4	17.0	11.9
3000	21.5	16.4	21.0	15.9	18.0	12.9	13.0	7.9
3525	17.0	11.9	14.0	8.9	11.0	5.9	16.0	10.9
$\overline{\Delta dB}\Big\vert_{1200}^{100}$ =		6.7		7.4		6.4		3.4

Table 8. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 1-Stage Build, Low Pressure Turbine) (Continued).

b. 100% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	2542		2242		1942		1642	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
55	21.8	16.6	24.8	19.6	27.5	22.4	24.0	18.9
164	13.2	8.2	15.0	9.9	13.2	8.2	7.5	2.4
300	12.0	6.9	14.0	8.9	24.8	19.6	12.5	7.4
400	11.5	6.4	11.8	6.6	14.0	8.9	12.5	7.4
750	6.0	0.9	4.5	0	5.0	0	3.0	0
1000	3.5	0	5.5	0.4	5.0	0	12.5	7.4
1175	16.5	11.4	12.0	7.0	5.6	0.4	5.3	0.2
2nd Harmonic, Hz								
110	9.0	3.9	8.5	3.4	7.5	2.4	4.5	0
328	8.8	3.6	8.8	3.6	5.5	0.4	3.5	0
600	17.0	11.9	17.2	12.2	19.2	14.2	14.0	8.9
800	17.5	12.4	13.5	8.4	14.8	9.6	9.0	3.9
1500	9.5	4.4	7.5	2.4	6.2	1.2	1.0	0
2000	13.5	8.4	12.6	7.6	16.2	11.0	16.7	11.6
2350	17.7	12.6	20.0	14.9	19.2	14.2	26.7	21.6
3rd Harmonic, Hz								
165	13.5	8.4	18.0	12.9	15.5	10.4	10.0	4.9
492	13.0	7.9	18.2	13.2	12.0	6.9	8.5	3.4
900	11.8	6.6	10.2	5.2	14.2	9.2	5.0	0
1200	15.8	10.6	12.4	7.3	9.8	4.7	5.5	0.4
2250	15.4	10.2	22.5	17.4	23.5	18.4	14.5	9.4
3000	20.2	15.2	15.2	10.2	18.5	13.4	18.0	12.9
3525	19.5	14.4	21.8	16.6	12.2	7.2	19.0	13.9
$\Delta\overline{dB}\Big\|_{100}^{1200}$ =		7.1		7.1		6.8		3.3

Table 8. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 1-Stage Build, Low Pressure Turbine) (Continued).

c. 90% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	2537		2237		1937		1637	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
55	21.5	16.4	22.0	16.9	26.0	20.9	24.5	19.4
164	13.5	8.4	15.8	10.6	13.0	7.9	8.5	3.4
300	7.0	1.9	15.5	10.4	25.0	19.9	12.0	6.9
400	11.5	6.4	11.8	6.6	14.0	8.9	10.5	5.4
750	5.0	0	4.2	0	3.0	0	2.5	0
1000	4.5	0	3.2	0	4.5	0	9.5	4.4
1175	14.2	9.2	9.2	4.2	7.2	2.2	5.8	0.6
2nd Harmonic, Hz								
110	10.0	4.9	9.2	4.2	7.0	1.9	6.0	0.9
328	11.0	5.9	10.8	5.6	6.5	1.4	4.5	0
600	10.5	5.4	18.8	13.6	12.0	6.9	12.5	7.4
800	26.0	20.9	12.5	7.4	15.0	9.9	12.0	6.9
1500	12.0	6.9	13.8	8.6	7.0	1.9	0	0
2000	13.2	8.2	15.0	9.9	15.8	10.6	16.8	11.6
2350	21.8	16.6	13.8	8.6	16.2	11.2	17.8	12.6
3rd Harmonic, Hz								
165	14.5	9.4	15.2	10.2	19.0	13.9	10.0	4.9
492	12.5	7.4	16.5	11.4	11.5	6.4	18.0	12.9
900	16.5	11.4	9.5	4.4	9.5	4.4	4.0	0
1200	12.2	7.2	12.5	7.4	16.8	11.6	5.8	0.6
2250	14.5	9.4	21.2	16.2	16.5	11.4	19.5	14.4
3000	22.5	17.4	18.5	13.4	20.5	15.4	13.0	7.9
3525	19.5	14.4	20.2	15.2	18.5	13.4	25.0	19.9
$\overline{\Delta dB}\Big\vert_{1200}^{100}$ =		7.0		6.9		6.8		3.9

Table 8. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 1-Stage Build, Low Pressure Turbine) (Continued).

d. 70% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	2229		1929		1629	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
55	18.5	13.4	20.0	14.9	24.0	18.9
164	13.0	7.9	13.5	8.4	9.0	3.9
300	29.5	24.4	31.0	25.9	14.0	8.9
400	11.5	6.4	12.0	6.9	10.0	4.9
750	4.0	0	4.0	0	3.0	0
1000	6.5	1.4	5.5	0.4	6.5	1.4
1175	13.8	8.6	8.2	3.2	8.2	3.2
2nd Harmonic, Hz						
110	10.0	4.9	10.5	5.4	6.5	1.4
328	7.5	2.4	7.0	1.9	4.0	0
600	18.5	13.4	15.0	9.9	16.0	10.9
800	19.0	13.9	21.0	15.9	10.5	5.4
1500	4.5	0	13.0	7.9	3.5	0
2000	18.2	13.2	13.8	8.6	12.2	7.2
2350	20.2	15.2	15.8	10.6	20.8	15.6
3rd Harmonic, Hz						
165	12.5	7.4	12.0	6.9	9.5	4.4
492	11.5	6.4	10.5	5.4	9.5	4.4
900	6.0	0.9	11.0	5.9	8.5	3.4
1200	21.8	16.6	10.2	5.2	6.8	1.6
2250	19.0	13.9	22.5	17.4	19.5	14.4
3000	21.5	16.4	17.0	11.9	16.5	11.4
3525	21.5	16.4	21.5	16.4	19.0	13.9

$\overline{\Delta dB}\Big|_{1200}^{100}$ = 8.2 7.3 3.8

Table 8. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 1-Stage Build, Low Pressure Turbine) (Concluded).

c. 50% $N/\sqrt{T_{T0}}$, T_{T0} = 422 K, P_{T0} = 275.8 kN/m²

Test Point No.	1621	
Fund. Freq., Hz	ΔSPL	ΔPWL
55	22.5	17.4
164	23.0	17.9
300	13.0	7.9
400	9.5	4.4
750	2.5	0
1000	3.5	0
1175	7.2	2.2
2nd Harmonic, Hz		
110	6.5	1.4
328	9.0	3.9
600	16.5	11.4
800	9.5	4.4
1500	3.5	0
2000	10.8	5.6
2350	26.2	21.2
3rd Harmonic, Hz		
165	8.0	2.9
492	9.5	4.4
900	9.0	3.9
1200	10.2	5.2
2250	18.5	13.4
3000	19.5	14.4
3525	22.5	17.4

$$\Delta\overline{dB}\Big|_{1200}^{100} = 5.0$$

Table 9. Aerodynamic Performance Parameters, 1-Stage Low Pressure Turbine.

• P_{T0} = 275.8 kN/m^2 (40 psia), T_{T0} = 422 K (760° R)

%N/√T	Test Point	P_{T0}/P_{T2}	P_{T0}/P_{S2} Measur. Plane	$P_{T0}/P_{S1.2}$ Rotor Exit	W_2 Corr. (lbm/sec)	W_2 Corr. (kg/sec)	$N/\sqrt{T_{T0}/T_{STD}}$	P_{SH}/W_2 (Btu/lbm)	P_{SH}/W_2 (kJ/kg)
110	2546	1.916	2.479	3.26	45.77	20.76	3825	26.59	61.8
	2246	1.806	2.182	2.43	45.41	20.60	3791	24.87	57.8
	1946	1.660	1.884	2.00	45.26	20.53	3814	21.10	49.1
	1646	1.468	1.586	1.63	42.99	19.50	3458	16.13	37.5
100	2542	1.872	2.476	3.53	45.59	20.68	3467	25.80	60.0
	2542R	1.876	2.478	3.54	45.80	20.77	3468	25.70	59.8
	2242	1.774	2.181	2.49	45.38	20.58	3459	24.12	56.1
	2242R	1.779	2.181	2.48	45.69	20.72	3473	23.86	55.5
	1942	1.640	1.884	2.01	45.49	20.63	3464	20.76	48.3
	1942R	1.640	1.884	2.02	45.26	20.53	3454	21.06	49.0
	1642	1.468	1.586	1.64	43.71	19.83	3458	16.13	37.5
90	2537	1.834	2.478	3.46	45.79	20.77	3134	24.41	56.8
	2237	1.740	2.180	2.56	45.47	20.62	3111	22.86	53.2
	2237R	1.742	2.182	2.56	45.59	20.68	3127	22.82	53.1
	1937	1.618	1.884	2.04	45.34	20.57	3124	20.23	47.1
	1637	1.452	1.586	1.64	44.27	20.08	3124	15.73	36.6
70	2229	1.662	2.181	3.14	45.49	20.63	2424	19.50	45.4
	1929	1.560	1.884	2.10	45.53	20.65	2444	17.74	41.3
	1629	1.408	1.585	1.68	45.18	20.49	2418	14.10	32.8
50	1621	1.358	1.584	1.71	45.22	20.51	1738	11.72	27.3

Table 10(a). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 110% Speed.

POINT NO. 2546 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	394.	208.	367.	208.	345.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	229.7	132.4	229.7	146.9	229.7	159.0
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	347.	402.	356.	402.	364.
MACH NUMBER	:		0.519	1.057	0.519	0.972	0.518	0.904

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	279.	415.	239.	407.	210.	401.
REL. FLOW ANGLE	:	(DEGREES)	54.	56.	51.	60.	46.	63.
STATIC PRESSURE	:	(KN/M**2)	132.4	81.5	146.9	87.8	159.0	90.1
TOTAL TEMP.	:	(DEG. KELVIN)	423.	355.	423.	352.	423.	349.
STATIC TEMP.	:	(DEG. KELVIN)	347.	306.	356.	312.	364.	314.
REL. MACH NO.	:		0.745	1.191	0.627	1.160	0.547	1.136
WHEEL VELOCITY	:	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 10(a). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 2246 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	383.	208.	357.	208.	336.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	230.0	138.4	230.0	152.5	230.0	164.1
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	351.	402.	360.	402.	367.
MACH NUMBER	:		0.517	1.022	0.517	0.941	0.517	0.875

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	268.	318.	229.	317.	201.	316.
REL. FLOW ANGLE	:	(DEGREES)	54.	58.	50.	61.	45.	64.
STATIC PRESSURE	:	(KN/M**2)	138.4	122.2	152.5	125.4	164.1	126.9
TOTAL TEMP.	:	(DEG. KELVIN)	423.	365.	423.	363.	423.	362.
STATIC TEMP.	:	(DEG. KELVIN)	351.	341.	360.	343.	367.	344.
REL. MACH NO.	:		0.713	0.861	0.600	0.856	0.522	0.853
WHEEL VELOCITY	:	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 10(a). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 1946 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	206.	365.	206.	341.	206.	320.
FLOW ANGLE	;	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	230.9	148.1	230.9	161.5	230.9	172.6
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	357.	402.	366.	402.	372.
MACH NUMBER	;		0.512	0.966	0.512	0.890	0.511	0.829

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	251.	291.	214.	292.	187.	293.
REL. FLOW ANGLE	;	(DEGREES)	53.	58.	49.	61.	43.	64.
STATIC PRESSURE	;	(KN/M**2)	148.1	135.8	161.5	138.2	172.6	139.4
TOTAL TEMP.	;	(DEG. KELVIN)	423.	369.	423.	368.	423.	367.
STATIC TEMP.	;	(DEG. KELVIN)	357.	351.	366.	352.	372.	353.
REL. MACH NO.	;		0.662	0.778	0.556	0.778	0.482	0.780
WHEEL VELOCITY	;	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 10(a). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 110% Speed (Concluded).

POINT NO. 1646 — 110% SPEED

STATOR 1		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY :	(M/SEC)	186.	295.	186.	275.	186.	259.
FLOW ANGLE :	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE :	(KN/M**2)	238.8	186.1	238.8	196.3	238.8	204.6
TOTAL TEMP. :	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP. :	(DEG. KELVIN)	406.	380.	406.	386.	406.	390.
MACH NUMBER :		0.460	0.756	0.460	0.700	0.459	0.654

ROTOR 1		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL. :	(M/SEC)	184.	221.	155.	226.	133.	231.
REL. FLOW ANGLE :	(DEGREES)	50.	58.	42.	61.	34.	65.
STATIC PRESSURE :	(KN/M**2)	186.1	175.9	196.3	176.6	204.6	176.8
TOTAL TEMP. :	(DEG. KELVIN)	423.	384.	423.	383.	423.	383.
STATIC TEMP. :	(DEG. KELVIN)	380.	375.	386.	376.	390.	376.
REL. MACH NO. :		0.470	0.570	0.393	0.583	0.336	0.595
WHEEL VELOCITY :	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 10(b). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 100% Speed.

POINT NO. 2542 | 100% SPEED

STATOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	209.	410.	209.	383.	209.	360.
FLOW ANGLE	;	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	229.6	123.5	229.6	138.4	229.6	151.0
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	340.	402.	351.	402.	359.
MACH NUMBER	;		0.520	1.112	0.520	1.022	0.519	0.949

ROTOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	304.	427.	263.	416.	234.	409.
REL. FLOW ANGLE	;	(DEGREES)	55.	56.	54.	59.	49.	63.
STATIC PRESSURE	;	(KN/M**2)	123.5	77.5	138.4	84.7	151.0	87.4
TOTAL TEMP.	;	(DEG. KELVIN)	423.	358.	423.	354.	423.	352.
STATIC TEMP.	;	(DEG. KELVIN)	340.	303.	351.	309.	359.	312.
REL. MACH NO.	;		0.820	1.232	0.695	1.192	0.612	1.162
WHEEL VELOCITY	;	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 10(b). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 2242 — 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	209.	410.	209.	383.	209.	360.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	229.6	123.5	229.6	138.4	229.6	151.0
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	340.	402.	351.	402.	359.
MACH NUMBER	:		0.520	1.112	0.520	1.022	0.519	0.949

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	304.	363.	263.	357.	234.	353.
REL. FLOW ANGLE	:	(DEGREES)	55.	58.	54.	61.	49.	64.
STATIC PRESSURE	:	(KN/M**2)	123.5	102.6	138.4	107.8	151.0	110.4
TOTAL TEMP.	:	(DEG. KELVIN)	423.	363.	423.	361.	423.	358.
STATIC TEMP.	:	(DEG. KELVIN)	340.	326.	351.	330.	359.	332.
REL. MACH NO.	:		0.820	1.007	0.695	0.986	0.612	0.970
WHEEL VELOCITY	:	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 10(b). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 1942 100% SPEED

STATOR 1		HUB		PITCH		TIP	
		INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY :	(M/SEC)	208.	383.	208.	357.	208.	336.
FLOW ANGLE :	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE :	(KN/M**2)	230.0	138.4	230.0	152.5	230.0	164.1
TOTAL TEMP. :	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP. :	(DEG. KELVIN)	402.	351.	402.	360.	402.	367.
MACH NUMBER :		0.517	1.022	0.517	0.941	0.517	0.875

ROTOR 1		HUB		PITCH		TIP	
		INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL. :	(M/SEC)	278.	301.	239.	300.	211.	299.
REL. FLOW ANGLE :	(DEGREES)	55.	58.	52.	61.	47.	64.
STATIC PRESSURE :	(KN/M**2)	138.4	132.0	152.5	135.2	164.1	136.8
TOTAL TEMP. :	(DEG. KELVIN)	423.	371.	423.	369.	423.	368.
STATIC TEMP. :	(DEG. KELVIN)	351.	348.	360.	350.	367.	351.
REL. MACH NO. :		0.737	0.806	0.625	0.801	0.547	0.797
WHEEL VELOCITY :	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 10(b). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 100% Speed (Concluded).

POINT NO. 1642 | 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	195.	322.	195.	301.	195.	282.
FLOW ANGLE	;	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	235.0	171.6	235.0	183.1	235.0	192.6
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	404.	372.	404.	378.	404.	384.
MACH NUMBER	;		0.485	0.835	0.485	0.772	0.484	0.720

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	219.	242.	187.	244.	162.	246.
REL. FLOW ANGLE	;	(DEGREES)	53.	58.	48.	61.	42.	65.
STATIC PRESSURE	;	(KN/M**2)	171.6	165.7	183.1	167.2	192.6	168.0
TOTAL TEMP.	;	(DEG. KELVIN)	423.	382.	423.	381.	423.	380.
STATIC TEMP.	;	(DEG. KELVIN)	372.	369.	378.	371.	384.	371.
REL. MACH NO.	;		0.565	0.628	0.477	0.634	0.412	0.640
WHEEL VELOCITY	;	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 10(c). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 90% Speed.

POINT NO. 2537 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	209.	431.	209.	402.	209.	378.
FLOW ANGLE	;	(DEGREES)	20.	62.	20.	62.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	229.6	112.7	229.6	128.1	229.6	141.2
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	332.	402.	343.	402.	353.
MACH NUMBER	;		0.520	1.181	0.520	1.084	0.519	1.005

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	333.	430.	290.	417.	261.	408.
REL. FLOW ANGLE	;	(DEGREES)	56.	55.	56.	59.	52.	63.
STATIC PRESSURE	;	(KN/M**2)	112.7	76.7	128.1	84.6	141.2	87.8
TOTAL TEMP.	;	(DEG. KELVIN)	423.	361.	423.	358.	423.	356.
STATIC TEMP.	;	(DEG. KELVIN)	332.	303.	343.	310.	353.	312.
REL. MACH NO.	;		0.909	1.242	0.775	1.195	0.689	1.160
WHEEL VELOCITY	;	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 10(c). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 2237 | 90% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	209.	431.	209.	402.	209.	378.
FLOW ANGLE	:	(DEGREES)	20.	62.	20.	62.	20.	62.
STATIC PRESSURE	:	(KN/M□2)	229.6	112.7	229.6	128.1	229.6	141.2
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	332.	402.	343.	402.	353.
MACH NUMBER	:		0.520	1.181	0.520	1.084	0.519	1.005

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	333.	367.	290.	359.	261.	353.
REL. FLOW ANGLE	:	(DEGREES)	56.	58.	56.	61.	52.	64.
STATIC PRESSURE	:	(KN/M□2)	112.7	101.5	128.1	107.4	141.2	110.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	366.	423.	363.	423.	361.
STATIC TEMP.	:	(DEG. KELVIN)	332.	326.	343.	331.	353.	332.
REL. MACH NO.	:		0.909	1.018	0.775	0.990	0.689	0.970
WHEEL VELOCITY	:	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 10(c). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 1937 — 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	399.	208.	372.	208.	350.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	229.6	129.8	229.6	144.4	229.6	156.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	344.	402.	355.	402.	363.
MACH NUMBER	:		0.519	1.073	0.519	0.986	0.519	0.917

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	302.	303.	262.	300.	234.	299.
REL. FLOW ANGLE	:	(DEGREES)	56.	58.	55.	61.	51.	64.
STATIC PRESSURE	:	(KN/M**2)	129.8	131.8	144.4	135.6	156.6	137.7
TOTAL TEMP.	:	(DEG. KELVIN)	423.	373.	423.	372.	423.	370.
STATIC TEMP.	:	(DEG. KELVIN)	344.	349.	355.	351.	363.	352.
REL. MACH NO.	:		0.809	0.811	0.691	0.802	0.610	0.795
WHEEL VELOCITY	:	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 10(c). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 90% Speed (Concluded).

POINT NO. 1637 90% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	195.	322.	195.	301.	195.	282.
FLOW ANGLE	;	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	235.0	171.6	235.0	183.1	235.0	192.6
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	404.	372.	404.	378.	404.	384.
MACH NUMBER	;		0.485	0.835	0.485	0.772	0.485	0.720

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	228.	237.	196.	239.	172.	240.
REL. FLOW ANGLE	;	(DEGREES)	55.	58.	51.	61.	46.	64.
STATIC PRESSURE	;	(KN/M**2)	171.6	170.4	183.1	172.2	192.6	173.2
TOTAL TEMP.	;	(DEG. KELVIN)	423.	385.	423.	384.	423.	383.
STATIC TEMP.	;	(DEG. KELVIN)	372.	373.	378.	373.	384.	374.
REL. MACH NO.	;		0.588	0.614	0.501	0.618	0.436	0.620
WHEEL VELOCITY	;	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 10(d). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 70% Speed.

POINT NO. 2229 70% SPEED

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
STATOR 1								
VELOCITY	;	(M/SEC)	209.	485.	209.	454.	209.	428.
FLOW ANGLE	;	(DEGREES)	20.	59.	20.	61.	20.	61.
STATIC PRESSURE	;	(KN/M□2)	229.6	85.0	229.6	100.6	229.6	114.3
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	307.	402.	321.	402.	333.
MACH NUMBER	;		0.520	1.382	0.520	1.264	0.519	1.170
ROTOR 1								
RELATIVE VEL.	;	(M/SEC)	405.	413.	358.	396.	331.	384.
REL. FLOW ANGLE	;	(DEGREES)	56.	56.	58.	60.	56.	64.
STATIC PRESSURE	;	(KN/M□2)	85.0	85.0	100.6	93.5	114.3	98.2
TOTAL TEMP.	;	(DEG. KELVIN)	423.	371.	423.	368.	423.	366.
STATIC TEMP.	;	(DEG. KELVIN)	307.	313.	321.	321.	333.	323.
REL. MACH NO.	;		1.145	1.172	0.983	1.113	0.896	1.070
WHEEL VELOCITY	;	(M/SEC)	79.	80.	88.	89.	96.	98.

Table 10(d). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 1929 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	209.	448.	209.	418.	209.	393.
FLOW ANGLE	:	(DEGREES)	20.	61.	20.	62.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	229.6	103.7	229.6	119.3	224.6	132.8
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	324.	402.	337.	402.	347.
MACH NUMBER	:		0.520	1.242	0.520	1.138	0.519	1.055

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	369.	313.	326.	306.	297.	300.
REL. FLOW ANGLE	:	(DEGREES)	58.	58.	58.	61.	56.	64.
STATIC PRESSURE	:	(KN/M**2)	103.7	128.4	119.3	133.7	132.8	137.[illegible]
TOTAL TEMP.	:	(DEG. KELVIN)	423.	379.	423.	377.	423.	376.
STATIC TEMP.	:	(DEG. KELVIN)	324.	349.	337.	352.	347.	353.
REL. MACH NO.	:		1.017	0.839	0.878	0.816	0.792	0.80[illegible]
WHEEL VELOCITY	:	(M/SEC)	79.	80.	88.	89.	96.	96

Table 10(d). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 70% Speed (Concluded).

POINT NO. 1629 | 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	206.	365.	296.	341.	206.	320.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	230.9	148.1	230.9	161.5	230.9	172.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	357.	402.	366.	402.	372.
MACH NUMBER	:		0.512	0.966	0.512	0.890	0.511	0.829

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	289.	260.	254.	257.	228.	255.
REL. FLOW ANGLE	:	(DEGREES)	59.	58.	57.	61.	53.	64.
STATIC PRESSURE	:	(KN/M**2)	148.1	161.0	161.5	164.6	172.6	166.9
TOTAL TEMP.	:	(DEG. KELVIN)	423.	388.	423.	386.	423.	385.
STATIC TEMP.	:	(DEG. KELVIN)	357.	369.	366.	370.	372.	371.
REL. MACH NO.	:		0.760	0.675	0.659	0.670	0.587	0.663
WHEEL VELOCITY	:	(M/SEC)	79.	80.	88.	89.	96.	98.

Table 10(e). HLFT-IVA 1-Stage LP Turbine Flow Diagrams, 50% Speed.

POINT NO. 1621 — 50% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	209.	413.	209.	385.	209.	362.
FLOW ANGLE	;	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M□2)	229.6	122.2	229.6	137.2	229.6	149.9
TOTAL TEMP.	;	(DEG. KELVIN)	423	423	423	423	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	339.	402.	350.	402.	358.
MACH NUMBER	;		0.520	1.124	0.520	1.029	0.520	0.95[illegible]

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	354.	271.	317.	265.	290.	260.
REL. FLOW ANGLE	;	(DEGREES)	61.	58.	60.	61.	58.	64.
STATIC PRESSURE	;	(KN/M□2)	122.2	157.1	137.2	162.5	149.9	166.[illegible]
TOTAL TEMP.	;	(DEG. KELVIN)	423.	394.	423.	393.	423.	391.
STATIC TEMP.	;	(DEG. KELVIN)	339.	369.	350.	371.	358.	372.
REL. MACH NO.	;		0.956	0.706	0.839	0.686	0.761	0.67[illegible]
WHEEL VELOCITY	;	(M/SEC)	57.	57.	63.	64	69	70.

ORIGINAL PAGE IS OF POOR QUALITY

Table 11. Blade-Row Attenuation, ΔdB, (HL7T-IVA, 3-Stage Build, Low Pressure Turbine).

a. 110% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	5246		4046		3046		2046	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	-	-	24.0	14.9	-	-	20.5	11.4
100	-	-	-	-	13.0	3.9	-	-
125	29.0	19.9	20.0	10.9	23.5	14.4	-	-
164	-	-	-	-	-	-	17.5	8.4
300	26.0	16.9	22.0	12.9	15.0	5.9	22.0	12.9
400	21.0	11.9	26.5	17.4	17.5	8.4	17.0	7.9
750	23.0	13.9	19.5	10.4	19.0	9.9	17.0	7.9
1000	25.0	15.9	12.0	2.9	10.5	1.4	5.0	0
1175	21.8	12.6	23.2	14.2	20.8	11.6	20.8	11.6
2nd Harmonic, Hz								
167	-	-	26.5	17.4	-	-	13.0	3.9
200	-	-	-	-	12.5	3.4	-	-
250	19.0	9.9	19.5	10.4	17.0	7.9	-	-
328	-	-	-	-	-	-	20.5	11.4
600	24.5	15.4	19.5	10.4	20.0	10.9	24.5	15.4
800	26.5	17.4	23.5	14.4	23.0	13.9	21.0	11.9
1500	25.5	16.4	33.5	24.4	21.5	12.4	19.5	10.4
2000	31.2	22.2	28.2	19.2	25.2	16.2	25.8	16.6
2350	28.8	19.6	26.2	17.2	32.8	23.6	28.2	19.2
3rd Harmonic, Hz								
250	-	-	18.5	9.4	-	-	8.0	0
300	-	-	-	-	12.5	3.4	-	-
375	24.0	14.9	21.0	11.9	17.0	7.9	-	-
492	-	-	-	-	-	-	12.5	3.4
900	25.0	15.9	21.5	12.4	20.5	11.4	15.5	6.4
1200	30.2	21.2	25.2	16.2	20.8	11.6	16.8	7.6
2250	31.5	22.4	29.0	19.9	30.0	20.9	25.5	16.4
3000	30.5	21.4	23.5	14.4	22.5	13.4	19.0	9.9
3525	31.5	22.4	36.5	27.4	23.5	14.4	28.5	19.4
$\overline{\Delta dB}\Big\vert_{1200}^{100}$ =		15.5		12.2		8.4		7.8

Table 11. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 3-Stage Build, Low Pressure Turbine) (Continued).

b. 100% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	5242		4042		3042		2042	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
32	28.5	19.2	25.5	16.2	27.0	17.7	-	-
65	-	-	-	-	-	-	30.1	20.8
83	23.5	14.2	23.0	13.7	17.5	8.2	-	-
125	-	-	27.5	18.2	25.0	15.7	15.5	6.2
160	29.5	20.2	-	-	-	-	-	-
300	18.5	8.2	21.5	12.2	16.5	7.2	20.5	11.2
400	20.0	10.7	22.5	13.2	15.0	5.7	15.0	5.7
750	18.5	9.2	17.5	8.2	17.5	8.2	15.5	6.2
1000	21.5	12.2	13.5	4.2	11.0	1.7	3.5	0
1175	23.3	14.0	24.8	15.5	21.3	12.0	15.8	6.5
2nd Harmonic, Hz								
64	16.7	7.4	17.0	7.7	19.0	9.7	-	-
130	-	-	-	-	-	-	15.0	5.7
167	23.0	13.7	25.0	15.7	21.6	12.3	-	-
250	-	-	23.0	13.7	-	-	18.5	9.2
320	14.5	5.2	-	-	23.5	14.2	-	-
600	25.5	16.2	19.5	10.2	18.5	9.2	19.5	10.2
800	24.5	15.2	25.0	15.7	23.0	13.7	18.5	9.2
1500	23.5	14.2	26.5	17.2	24.0	14.7	20.0	10.7
2000	43.5	34.2	36.3	27.0	28.0	18.7	26.3	17.0
2350	36.8	27.5	22.3	13.0	31.8	22.7	28.3	19.0
3rd Harmonic, Hz								
96	18.5	9.2	5.5	0	13.0	3.7	-	-
195	-	-	-	-	-	-	15.6	6.3
250	21.5	12.2	19.5	10.2	21.0	11.7	-	-
375	-	-	18.0	8.7	-	-	15.5	6.2
480	23.0	13.7	-	-	19.0	9.7	-	-
900	18.0	8.7	19.5	10.2	19.5	10.2	15.0	5.7
1200	21.3	12.0	18.8	9.5	19.8	10.5	16.8	7.5
2250	33.5	24.2	26.5	17.2	25.5	16.2	27.8	18.5
3000	35.0	25.7	28.5	19.2	21.0	11.7	24.0	14.7
3525	32.5	23.2	27.5	18.2	29.5	20.2	24.5	15.2
$\overline{\Delta dB}\Big\vert_{1200}^{100}$ =		12.3		11.0		10.1		6.8

Table 11. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 3-Stage Build, Low Pressure Turbine) (Continued).

c. 90% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	5237		4037		3037		2037	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
70	-	-	25.0	15.9	26.5	17.4	-	-
83	23.0	13.9	-	-	-	-	15.5	6.2
125	16.0	6.9	20.0	10.9	-	-	11.5	2.2
164	-	-	-	-	30.5	21.4	-	-
300	25.5	16.4	19.5	10.4	15.5	6.4	21.5	12.2
400	23.5	14.4	22.5	13.4	15.0	5.9	14.0	4.7
750	18.0	8.9	17.0	7.9	14.5	5.4	12.5	3.2
1000	23.0	13.9	10.0	0.9	11.5	2.4	7.0	0
1175	21.8	12.6	22.2	13.2	19.2	10.2	15.2	6.0
2nd Harmonic, Hz								
140	-	-	23.5	14.4	25.0	15.9	-	-
167	26.0	16.9	-	-	-	-	19.5	10.2
250	21.0	11.9	18.5	9.4	-	-	11.5	2.2
328	-	-	-	-	20.5	11.4	-	-
600	32.0	22.9	16.5	7.4	20.5	11.4	15.0	5.7
800	21.5	12.4	24.5	15.4	24.0	14.9	15.5	6.2
1500	33.5	24.4	27.5	18.4	20.0	10.9	17.5	8.2
2000	36.8	27.6	37.2	28.2	24.8	15.6	26.2	17.0
2350	30.2	21.2	24.8	15.6	30.8	21.6	29.2	20.0
3rd Harmonic, Hz								
210	-	-	13.5	4.4	14.0	4.9	-	-
250	21.0	11.9	-	-	-	-	12.5	3.2
375	23.0	13.9	18.0	8.9	-	-	15.0	5.7
492	-	-	-	-	19.5	10.4	-	-
900	20.0	10.9	22.5	13.4	18.0	8.9	19.5	10.2
1200	26.8	17.6	16.2	7.2	20.2	11.2	20.8	11.4
2250	35.0	25.9	28.5	19.4	31.0	21.9	21.5	12.2
3000	30.5	21.4	27.5	18.4	25.5	16.4	28.5	19.2
3525	31.0	21.9	31.5	22.4	29.5	20.4	22.5	18.2
$\Delta\overline{dB}\Big\|_{1200}^{100}$ =		13.7		9.8		10.8		5.9

Table 11. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 3-Stage Build, Low Pressure Turbine) (Continued).

d. 70% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	4029		3029		2029	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	23.5	14.4	26.0	16.9	19.0	9.7
125	19.5	10.4	-	-	13.5	4.2
164	-	-	42.0	32.9	-	-
300	17.0	7.9	20.0	10.9	18.0	8.7
400	20.5	11.4	14.5	15.4	19.0	9.7
750	16.0	6.9	13.0	3.9	18.0	8.7
1000	17.5	8.4	8.0	0	12.0	2.7
1175	19.8	10.6	16.2	7.2	15.8	6.4
2nd Harmonic, Hz						
167	32.5	23.4	19.0	9.9	17.5	8.2
250	17.5	8.4	-	-	14.5	5.2
328	-	-	17.5	8.4	-	-
600	19.5	10.4	16.5	7.4	11.5	2.2
800	19.5	10.4	28.0	18.9	20.0	10.7
1500	29.5	20.4	24.0	14.9	19.0	9.7
2000	26.8	17.6	24.2	15.2	30.8	21.4
2350	23.8	14.6	15.2	6.2	22.2	13.0
3rd Harmonic, Hz						
250	18.5	9.4	16.0	6.9	10.5	1.2
375	19.0	9.9	-	-	16.5	7.2
492	-	-	15.5	6.4	-	-
900	14.5	5.4	16.5	7.4	10.0	0.7
1200	18.8	9.6	14.8	5.6	27.8	18.4
2250	31.5	22.4	31.5	22.4	22.0	12.7
3000	34.5	25.4	31.5	22.4	30.5	21.2
3525	25.5	16.4	11.5	2.4	24.0	14.7
$\overline{\Delta dB}\Big\|_{1200}^{100}$ =		10.2		10.1		6.7

Table 11. Blade-Row Attenuation, ΔdB, (HLFT-IVA, 3-Stage Build, Low Pressure Turbine) (Continued).

e. 50% $N/\sqrt{T_{TO}}$, T_{TO} = 422 K, P_{TO} = 275.8 kN/m^2

Test Point No.	3021	
Fund. Freq., Hz	ΔSPL	ΔPWL
70	24.0	14.9
155	24.0	14.9
300	24.0	14.9
400	17.0	7.9
750	11.5	2.4
1000	7.5	0
1175	21.8	12.6
2nd Harmonic, Hz		
140	27.5	18.4
310	16.0	6.9
600	15.5	6.4
800	20.0	10.9
1500	24.0	14.9
2000	22.2	13.2
2350	26.2	17.2
3rd Harmonic, Hz		
210	12.5	3.4
465	18.0	8.9
900	14.5	5.4
1200	17.8	8.6
2250	28.0	18.9
3000	25.0	15.9
3525	22.0	12.9

$$\overline{\Delta dB}\Big|_{1200}^{100} = 8.7$$

Table 12. Aerodynamic Performance Parameters, 3-Stage Low Pressure Turbine.

• P_{TO} = 275.8 kN/m^2 (40 psia), T_{TO} = 422 K (760° R)

$\%N/\sqrt{T}$	Test Point	P_{TO}/P_{T2}	P_{TO}/P_{S2} Measur. Plane	W_2 Corr (lbm/sec)	W_2 Corr (kg/sec)	$N\sqrt{\frac{T_{TO}}{T_{STD}}}$	$\frac{P_{SH}}{W_2}\left(\frac{Btu}{lbm}\right)$	$\frac{P_{SH}}{W_2}\left(\frac{kJ}{kg}\right)$
110	5246	4.812	5.162	45.70	20.73	3826	55.92	130.1
	4046	3.743	3.962	45.76	20.76	3830	48.04	111.7
	3046	2.866	2.981	45.29	20.54	3811	38.74	90.1
	3046R	2.864	2.982	45.26	20.53	3810	38.82	90.3
	2046	1.959	1.980	43.24	19.61	3817	21.84	50.8
100	5242	4.816	5.168	45.87	20.81	3487	55.72	129.6
	5242R	4.818	5.171	45.84	20.79	3480	55.73	129.6
	4042	3.780	3.964	45.88	20.81	3496	48.56	113.0
	3042	2.865	2.981	45.73	20.74	3492	39.55	92.0
	2042	1.952	1.980	44.62	20.24	3472	23.35	54.3
90	5237	4.816	5.172	45.89	20.82	3140	54.70	127.2
	4037	3.786	3.966	45.93	20.83	3124	48.10	111.9
	3037	2.873	2.983	45.91	20.82	3148	39.8	92.6
	2037	1.953	1.980	44.93	20.38	3049	25.57	59.5
70	4029	3.807	3.964	45.99	20.86	2454	44.21	102.8
	3029	2.918	2.980	45.94	20.84	2453	37.44	87.1
	3029R	2.901	2.982	45.89	20.82	2434	37.52	87.3
	2029	1.958	1.986	46.34	21.02	2380	26.37	61.3
50	3021	2.926	2.986	45.83	20.79	1754	31.92	74.2

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed.

POINT NO. 5246 | 110% SPEED

STATOR 1

		HUB		PITCH		TIP	
		INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY ;	(M/SEC)	207.	374.	207.	349.	207.	328.
FLOW ANGLE ;	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE ;	(KN/M**2)	230.4	143.5	230.4	157.3	230.4	168.6
TOTAL TEMP. ;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP. ;	(DEG. KELVIN)	402.	354.	402.	363.	402.	370.
MACH NUMBER ;		0.515	0.992	0.515	0.914	0.514	0.850

ROTOR 1

		HUB		PITCH		TIP	
		INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL. ;	(M/SEC)	260.	303.	221.	302.	194.	303.
REL. FLOW ANGLE ;	(DEGREES)	53.	58.	50.	61.	44.	64.
STATIC PRESSURE ;	(KN/M**2)	143.5	12[illegible].9	157.3	132.6	168.6	133.9
TOTAL TEMP. ;	(DEG. KELVIN)	423.	368.	423.	366.	423.	364.
STATIC TEMP. ;	(DEG. KELVIN)	354.	347.	363.	348.	370.	349.
REL. MACH NO. ;		0.686	0.813	0.577	0.811	0.501	0.811
WHEEL VELOCITY ;	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 5246 | 110% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	198.	348.	183.	313.	168.	287.
FLOW ANGLE	:	(DEGREES)	42.	64.	43.	63.	44.	61.
STATIC PRESSURE	:	(KN/M2)	130.2	80.9	132.6	92.5	138.2	101.3
TOTAL TEMP.	:	(DEG. KELVIN)	366.	366.	366.	366.	366.	366.
STATIC TEMP.	:	(DEG. KELVIN)	347.	306.	348.	318.	352.	326.
MACH NUMBER	:		0.529	0.993	0.488	0.877	0.445	0.793

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	239.	277.	187.	280.	153.	284.
REL. FLOW ANGLE	:	(DEGREES)	52.	56.	45.	59.	33.	65.
STATIC PRESSURE	:	(KN/M2)	80.9	72.4	92.5	74.2	101.3	74.7
TOTAL TEMP.	:	(DEG. KELVIN)	366.	316.	366.	315.	366.	312.
STATIC TEMP.	:	(DEG. KELVIN)	306.	298.	318.	301.	326.	301.
REL. MACH NO.	:		0.679	0.800	0.521	0.807	0.421	0.819
WHEEL VELOCITY	:	(M/SEC)	124.	123.	144.	145.	164.	166.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 5246 110% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	181.	265.	165.	232.	143.	209.
FLOW ANGLE	:	(DEGREES)	37.	57.	35.	56.	39.	59.
STATIC PRESSURE	:	(KN/M**2)	72.2	55.9	74.2	62.2	77.7	66.3
TOTAL TEMP.	:	(DEG. KELVIN)	314.	314.	314.	314.	314.	314.
STATIC TEMP.	:	(DEG. KELVIN)	298.	279.	301.	288.	304.	293.
MACH NUMBER	:		0.521	0.792	0.473	0.680	0.406	0.610

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	177.	189.	133.	202.	104.	211.
REL. FLOW ANGLE	:	(DEGREES)	37.	40.	19.	46.	1.	61.
STATIC PRESSURE	:	(KN/M**2)	55.9	53.9	62.2	53.9	66.3	53.9
TOTAL TEMP.	:	(DEG. KELVIN)	314.	288.	314.	288.	314.	283.
STATIC TEMP.	:	(DEG. KELVIN)	279.	278.	288.	277.	293.	277.
REL. MACH NO.	:		0.526	0.565	0.390	0.603	0.302	0.633
WHEEL VELOCITY	:	(M/SEC)	119.	118.	147.	147.	175.	177.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 4046 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	206.	365.	206.	[illegible]41.	206.	320.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M¤2)	230.9	148.1	230.9	161.5	230.9	172.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	357.	402.	366.	402.	372.
MACH NUMBER	:		0.512	0.966	0.512	0.890	0.511	0.829

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	251.	285.	214.	292.	187.	293.
REL. FLOW ANGLE	:	(DEGREES)	53.	58.	49.	61.	43.	64.
STATIC PRESSURE	:	(KN/M¤2)	148.1	135.8	161.5	138.2	172.6	139.4
TOTAL TEMP.	:	(DEG. KELVIN)	423.	369.	423.	368.	423.	367.
STATIC TEMP.	:	(DEG. KELVIN)	357.	351.	366.	352.	372.	353.
REL. MACH NO.	:		0.662	0.778	0.556	0.778	0.482	0.780
WHEEL VELOCITY	:	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 4046 110% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	188.	321.	173.	289.	159.	265.
FLOW ANGLE	:	(DEGREES)	41.	64.	42.	63.	43.	61.
STATIC PRESSURE	:	(KN/M**2)	136.1	92.1	138.2	103.1	143.5	111.1
TOTAL TEMP.	:	(DEG. KELVIN)	368.	368.	368.	368.	368.	368.
STATIC TEMP.	:	(DEG. KELVIN)	351.	317.	352.	327.	356.	333.
MACH NUMBER	:		0.499	0.901	0.460	0.798	0.420	0.724

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	213.	242.	166.	248.	135.	255.
REL. FLOW ANGLE	:	(DEGREES)	52.	56.	42.	59.	29.	66.
STATIC PRESSURE	:	(KN/M**2)	92.1	85.9	103.1	86.9	111.1	87.1
TOTAL TEMP.	:	(DEG. KELVIN)	368.	324.	368.	324.	368.	322.
STATIC TEMP.	:	(DEG. KELVIN)	317.	312.	327.	313.	333.	314.
REL. MACH NO.	:		0.594	0.683	0.455	0.700	0.367	0.718
WHEEL VELOCITY	:	(M/SEC)	124.	123.	144.	145.	164.	168.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 4046 — 110% SPEED

STATOR 3

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	150.	228.	138.	199.	117.	181.
FLOW ANGLE	:	(DEGREES)	32.	58.	29.	56.	33.	59.
STATIC PRESSURE	:	(KN/M**2)	86.0	70.6	86.9	76.1	89.8	79.6
TOTAL TEMP.	:	(DEG. KELVIN)	323.	323.	323.	323.	323.	323.
STATIC TEMP.	:	(DEG. KELVIN)	312.	298.	313.	304.	317.	307.
MACH NUMBER	:		0.421	0.659	0.387	0.568	0.327	0.513

ROTOR 3

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	141.	157.	110.	170.	92.	181.
REL. FLOW ANGLE	:	(DEGREES)	33.	41.	9.	46.	-13.	62.
STATIC PRESSURE	:	(KN/M**2)	70.6	68.4	76.1	68.5	79.6	68.6
TOTAL TEMP.	:	(DEG. KELVIN)	323.	303.	323.	304.	323.	301.
STATIC TEMP.	:	(DEG. KELVIN)	298.	296.	304.	296.	307.	296.
REL. MACH NO.	:		0.407	0.454	0.312	0.490	0.261	0.524
WHEEL VELOCITY	:	(M/SEC)	119.	118.	147.	147.	175.	177.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 3046 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	202.	346.	202.	322.	202.	303.
FLOW ANGLE	:	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M02)	232.5	159.0	232.5	171.6	232.5	181.9
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	403.	364.	403.	372.	403.	378.
MACH NUMBER	:		0.501	0.904	0.501	0.835	0.501	0.778

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	232.	269.	197.	271.	172.	273.
REL. FLOW ANGLE	:	(DEGREES)	52.	58.	48.	61.	41.	64.
STATIC PRESSURE	:	(KN/M02)	159.0	148.2	171.6	150.0	181.9	150.8
TOTAL TEMP.	:	(DEG. KELVIN)	423.	374.	423.	373.	423.	372.
STATIC TEMP.	:	(DEG. KELVIN)	364.	359.	372.	359.	378.	361.
REL. MACH NO.	:		0.605	0.710	0.508	0.725	0.439	0.720
WHEEL VELOCITY	:	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 1[illegible](a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 3046 110% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	168.	285.	155.	256.	142.	235.
FLOW ANGLE	;	(DEGREES)	38.	65.	39.	63.	40.	61.
STATIC PRESSURE	;	(KN/M**2)	148.6	110.4	150.0	120.1	154.6	127.1
TOTAL TEMP.	;	(DEG. KELVIN)	373.	373.	373.	373.	373.	373.
STATIC TEMP.	;	(DEG. KELVIN)	359.	333.	359.	341.	363.	346.
MACH NUMBER	;		0.440	0.778	0.407	0.692	0.370	0.630

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	177.	205.	136.	214.	112.	224.
REL. FLOW ANGLE	;	(DEGREES)	50.	56.	37.	59.	21.	67.
STATIC PRESSURE	;	(KN/M**2)	110.4	104.6	120.1	105.1	127.1	104.9
TOTAL TEMP.	;	(DEG. KELVIN)	373.	337.	373.	336.	373.	335.
STATIC TEMP.	;	(DEG. KELVIN)	333.	329.	341.	329.	346.	330.
REL. MACH NO.	;		0.482	0.564	0.367	0.589	0.299	0.614
WHEEL VELOCITY	;	(M/SEC)	124.	123.	144.	145.	164.	168.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 3046 110% SPEED

STATOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	118.	192.	111.	167.	92.	153.
FLOW ANGLE	:	(DEGREES)	24.	58.	20.	56.	24.	59.
STATIC PRESSURE	:	(KN/M□2)	104.9	90.5	105.1	95.1	107.1	98.0
TOTAL TEMP.	:	(DEG. KELVIN)	336.	336.	336.	336.	336.	336.
STATIC TEMP.	:	(DEG. KELVIN)	329.	318.	329.	322.	332.	324.
MACH NUMBER	:		0.324	0.536	0.305	0.462	0.250	0.423

ROTOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	108.	129.	92.	140.	89.	155.
REL. FLOW ANGLE	:	(DEGREES)	25.	41.	-6.	47.	-31.	63.
STATIC PRESSURE	:	(KN/M□2)	90.5	87.7	95.1	88.2	98.0	88.5
TOTAL TEMP.	:	(DEG. KELVIN)	336.	321.	336.	323.	336.	322.
STATIC TEMP.	:	(DEG. KELVIN)	318.	316.	322.	317.	324.	318.
REL. MACH NO.	:		0.302	0.363	0.253	0.391	0.244	0.432
WHEEL VELOCITY	:	(M/SEC)	119.	118.	147.	147.	175.	177.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 2046 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	176.	275.	176.	256.	176.	241.
FLOW ANGLE	;	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	242.2	196.8	242.2	206.1	242.2	213.5
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	408.	386.	408.	391.	408.	394.
MACH NUMBER	;		0.436	0.699	0.436	0.648	0.436	0.606

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	165.	204.	139.	210.	119.	215.
REL. FLOW ANGLE	;	(DEGREES)	48.	58.	39.	61.	30.	65.
STATIC PRESSURE	;	(KN/M**2)	196.8	186.5	206.1	187.0	213.5	187.0
TOTAL TEMP.	;	(DEG. KELVIN)	423.	388.	423.	388.	423.	387.
STATIC TEMP.	;	(DEG. KELVIN)	386.	381.	391.	381.	394.	382.
REL. MACH NO.	;		0.418	0.521	0.349	0.537	0.298	0.550
WHEEL VELOCITY	;	(M/SEC)	125.	125.	137.	139.	150.	154.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Continued).

POINT NO. 2046 110% SPEED

STATOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	112.	204.	104.	184.	93.	170.
FLOW ANGLE	;	(DEGREES)	25.	66.	25.	63.	25.	61.
STATIC PRESSURE	;	(KN/M**2)	187.3	159.4	187.0	165.9	189.6	170.4
TOTAL TEMP.	;	(DEG. KELVIN)	387.	387.	387.	387.	387.	387.
STATIC TEMP.	;	(DEG. KELVIN)	381.	367.	381.	371.	383.	373.
MACH NUMBER	;		0.285	0.533	0.266	0.477	0.237	0.438

ROTOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	102.	139.	82.	151.	79.	164.
REL. FLOW ANGLE	;	(DEGREES)	38.	56.	12.	59.	-13.	69.
STATIC PRESSURE	;	(KN/M**2)	159.4	152.7	165.9	153.0	170.4	152.8
TOTAL TEMP.	;	(DEG. KELVIN)	387.	366.	387.	367.	387.	367.
STATIC TEMP.	;	(DEG. KELVIN)	367.	363.	371.	364.	373.	365.
REL. MACH NO.	;		0.265	0.363	0.212	0.395	0.203	0.429
WHEEL VELOCITY	;	(M/SEC)	124.	123.	144.	145.	164.	168.

Table 13(a). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 110% Speed (Concluded).

POINT NO. 2046 — 110% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	75.	129.	77.	110.	60.	106.
FLOW ANGLE	;	(DEGREES)	-7.	60.	-13.	56.	-16.	59.
STATIC PRESSURE	;	(KN/M**2)	154.5	142.4	153.0	145.1	153.6	146.8
TOTAL TEMP.	;	(DEG. KELVIN)	367.	367.	367.	367.	367.	367.
STATIC TEMP.	;	(DEG. KELVIN)	364.	359.	364.	361.	366.	362.
MACH NUMBER	;		0.195	0.339	0.200	0.289	0.155	0.277

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	65.	96.	83.	88.	101.	93.
REL. FLOW ANGLE	;	(DEGREES)	-7.	43.	-43.	47.	-59.	60.
STATIC PRESSURE	;	(KN/M**2)	142.4	138.2	145.1	140.3	146.8	142.0
TOTAL TEMP.	;	(DEG. KELVIN)	367.	361.	367.	366.	367.	369.
STATIC TEMP.	;	(DEG. KELVIN)	359.	357.	361.	361.	362.	363.
REL. MACH NO.	;		0.170	0.252	0.218	0.230	0.264	0.243
WHEEL VELOCITY	;	(M/SEC)	119.	118.	147.	147.	175.	177.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed.

POINT NO. 5242 — 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	396.	208.	369.	208.	347.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M□2)	229.7	131.5	229.7	146.1	229.7	158.1
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	346.	402.	356.	402.	364.
MACH NUMBER	:		0.519	1.063	0.519	0.977	0.518	0.908

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	290.	317.	250.	314.	221.	313.
REL. FLOW ANGLE	:	(DEGREES)	55.	58.	53.	61.	48.	64.
STATIC PRESSURE	:	(KN/M□2)	131.5	123.5	146.1	127.2	158.1	129.1
TOTAL TEMP.	:	(DEG. KELVIN)	423.	368.	423.	366.	423.	364.
STATIC TEMP.	:	(DEG. KELVIN)	346.	343.	356.	344.	364.	346.
REL. MACH NO.	:		0.774	0.857	0.656	0.848	0.576	0.842
WHEEL VELOCITY	:	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 5242 | 100% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	219.	367.	203.	330.	187.	302.
FLOW ANGLE	:	(DEGREES)	45.	63.	47.	63.	48.	61.
STATIC PRESSURE	:	(KN/M*2)	123.5	74.3	127.2	86.6	133.5	95.8
TOTAL TEMP.	:	(DEG. KELVIN)	366.	366.	366.	366.	366.	366.
STATIC TEMP.	:	(DEG. KELVIN)	343.	299.	344.	312.	349.	321.
MACH NUMBER	:		0.589	1.058	0.544	0.932	0.498	0.841

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	266.	290.	212.	289.	175.	291.
REL. FLOW ANGLE	:	(DEGREES)	54.	56.	49.	59.	40.	65.
STATIC PRESSURE	:	(KN/M*2)	74.3	68.9	86.6	71.3	95.8	72.2
TOTAL TEMP.	:	(DEG. KELVIN)	366.	317.	366.	315.	366.	312.
STATIC TEMP.	:	(DEG. KELVIN)	299.	296.	312.	298.	321.	299.
REL. MACH NO.	:		0.765	0.843	0.595	0.839	0.485	0.841
WHEEL VELOCITY	:	(M/SEC)	113.	112.	131.	132.	149.	152.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 5242 | 100% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	200.	271.	181.	236.	158.	213.
FLOW ANGLE	:	(DEGREES)	41.	57.	39.	56.	44.	59.
STATIC PRESSURE	:	(KN/M**2)	68.4	54.5	71.3	61.0	75.3	65.2
TOTAL TEMP.	:	(DEG. KELVIN)	315.	315.	315.	315.	315.	315.
STATIC TEMP.	:	(DEG. KELVIN)	295.	278.	298.	287.	302.	292.
MACH NUMBER	:		0.579	0.809	0.522	0.695	0.453	0.620

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	188.	191.	142.	203.	107.	211.
REL. FLOW ANGLE	:	(DEGREES)	40.	40.	26.	46.	12.	61.
STATIC PRESSURE	:	(KN/M**2)	54.5	53.4	61.0	53.5	65.2	53.5
TOTAL TEMP.	:	(DEG. KELVIN)	315.	289.	315.	288.	315.	284.
STATIC TEMP.	:	(DEG. KELVIN)	278.	278.	287.	277.	292.	277.
REL. MACH NO.	:		0.562	0.569	0.416	0.608	0.312	0.629
WHEEL VELOCITY	:	(M/SEC)	108.	107.	134.	134.	159.	161.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 4042 — 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	208.	387.	208.	361.	208.	339.
FLOW ANGLE	;	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	229.9	136.3	229.9	150.5	229.9	162.4
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	349.	402.	359.	402.	366.
MACH NUMBER	;		0.518	1.034	0.518	0.952	0.517	0.885

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	281.	305.	242.	304.	214.	303.
REL. FLOW ANGLE	;	(DEGREES)	55.	58.	52.	61.	48.	64.
STATIC PRESSURE	;	(KN/M**2)	136.3	129.5	150.5	132.8	162.4	134.6
TOTAL TEMP.	;	(DEG. KELVIN)	423.	370.	423.	368.	423.	367.
STATIC TEMP.	;	(DEG. KELVIN)	349.	347.	359.	348.	366.	349.
REL. MACH NO.	;		0.748	0.820	0.634	0.814	0.556	0.810
WHEEL VELOCITY	;	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 4042 | 100% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	334.	193.	301.	178.	275.
FLOW ANGLE	:	(DEGREES)	44.	64.	46.	63.	47.	61.
STATIC PRESSURE	:	(KN/M**2)	129.5	87.4	132.8	98.8	138.9	107.2
TOTAL TEMP.	:	(DEG. KELVIN)	368.	368.	368.	368.	368.	368.
STATIC TEMP.	:	(DEG. KELVIN)	347.	313.	348.	323.	353.	331.
MACH NUMBER	:		0.557	0.943	0.514	0.834	0.471	0.755

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	234.	249.	185.	252.	152.	257.
REL. FLOW ANGLE	:	(DEGREES)	54.	56.	47.	59.	36.	66.
STATIC PRESSURE	:	(KN/M**2)	87.4	84.2	98.8	85.8	107.2	86.2
TOTAL TEMP.	:	(DEG. KELVIN)	368.	326.	368.	324.	368.	322.
STATIC TEMP.	:	(DEG. KELVIN)	313.	312.	323.	313.	331.	313.
REL. MACH NO.	:		0.658	0.703	0.510	0.713	0.413	0.724
WHEEL VELOCITY	:	(M/SEC)	113.	112.	131.	132.	149.	152.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 4042 — 100% SPEED

STATOR 3		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY :	(M/SEC)	162.	230.	148.	201.	128.	182.
FLOW ANGLE :	(DEGREES)	36.	58.	34.	56.	39.	59.
STATIC PRESSURE :	(KN/M**2)	84.0	70.5	85.8	76.2	89.0	79.8
TOTAL TEMP. :	(DEG. KELVIN)	324.	324.	324.	324.	324.	324.
STATIC TEMP. :	(DEG. KELVIN)	311.	298.	313.	304.	316.	308.
MACH NUMBER :		0.456	0.665	0.417	0.574	0.357	0.516

ROTOR 3		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL. :	(M/SEC)	149.	157.	114.	170.	90.	179.
REL. FLOW ANGLE :	(DEGREES)	36.	41.	16.	46.	-4.	62.
STATIC PRESSURE :	(KN/M**2)	70.5	69.2	76.2	69.2	79.8	69.3
TOTAL TEMP. :	(DEG. KELVIN)	324.	304.	324.	304.	324.	301.
STATIC TEMP. :	(DEG. KELVIN)	298.	297.	304.	297.	308.	297.
REL. MACH NO. :		0.430	0.452	0.324	0.491	0.256	0.518
WHEEL VELOCITY :	(M/SEC)	108.	107.	134.	134.	159.	161.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 3042 | 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	206.	365.	206.	341.	206.	320.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	230.9	148.1	230.9	161.5	230.9	172.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	357.	402.	366.	402.	372.
MACH NUMBER	:		0.512	0.966	0.512	0.890	0.511	0.829

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	261.	281.	224.	282.	197.	282.
REL. FLOW ANGLE	:	(DEGREES)	55.	58.	51.	61.	46.	64.
STATIC PRESSURE	:	(KN/M**2)	148.1	142.6	161.5	145.3	172.6	146.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	374.	423.	373.	423.	372.
STATIC TEMP.	:	(DEG. KELVIN)	357.	356.	366.	357.	372.	358.
REL. MACH NO.	:		0.685	0.746	0.581	0.745	0.507	0.745
WHEEL VELOCITY	:	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 3042 — 100% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	186.	295.	172.	265.	158.	243.
FLOW ANGLE	;	(DEGREES)	42.	65.	43.	63.	45.	61.
STATIC PRESSURE	;	(KN/M**2)	142.8	106.6	145.3	116.6	150.6	124.0
TOTAL TEMP.	;	(DEG. KELVIN)	373.	373.	373.	373.	373.	373.
STATIC TEMP.	;	(DEG. KELVIN)	356.	330.	357.	338.	361.	344.
MACH NUMBER	;		0.491	0.810	0.455	0.719	0.416	0.653

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	195.	211.	153.	218.	124.	225.
REL. FLOW ANGLE	;	(DEGREES)	52.	56.	42.	59.	29.	66.
STATIC PRESSURE	;	(KN/M**2)	106.6	103.3	116.6	104.0	124.0	104.2
TOTAL TEMP.	;	(DEG. KELVIN)	373.	337.	373.	337.	373.	335.
STATIC TEMP.	;	(DEG. KELVIN)	330.	328.	338.	329.	344.	329.
REL. MACH NO.	;		0.535	0.581	0.412	0.601	0.333	0.619
WHEEL VELOCITY	;	(M/SEC)	113.	112.	131.	132.	149.	152.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 3042 — 100% SPEED

STATOR 3

		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY :	(M/SEC)	128.	195.	119.	169.	100.	154.
FLOW ANGLE :	(DEGREES)	30.	58.	27.	56.	32.	59.
STATIC PRESSURE :	(KN/M**2)	103.3	90.2	104.0	95.0	106.6	98.0
TOTAL TEMP. :	(DEG. KELVIN)	336.	336.	336.	336.	336.	336.
STATIC TEMP. :	(DEG. KELVIN)	328.	317.	329.	322.	331.	324.
MACH NUMBER :		0.352	0.544	0.328	0.470	0.274	0.427

ROTOR 3

		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL. :	(M/SEC)	116.	130.	93.	142.	82.	151.
REL. FLOW ANGLE :	(DEGREES)	31.	41.	4.	47.	-21.	63.
STATIC PRESSURE :	(KN/M**2)	90.2	88.3	95.0	88.5	98.0	88.6
TOTAL TEMP. :	(DEG. KELVIN)	336.	321.	336.	322.	336.	320.
STATIC TEMP. :	(DEG. KELVIN)	317.	316.	322.	317.	324.	317.
REL. MACH NO. :		0.323	0.364	0.256	0.396	0.225	0.423
WHEEL VELOCITY :	(M/SEC)	108.	107.	134.	134.	159.	161.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 2042 — 100% SPEED

STATOR 1		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY :	(M/SEC)	186.	295.	186.	275.	186.	259.
FLOW ANGLE :	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE :	(KN/M**2)	238.8	186.1	238.8	196.3	238.8	204.5
TOTAL TEMP. :	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP. :	(DEG. KELVIN)	406.	380.	406.	386.	406.	390.
MACH NUMBER :		0.460	0.756	0.460	0.700	0.459	0.654

ROTOR 1		HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL. :	(M/SEC)	193.	218.	164.	222.	141.	226.
REL. FLOW ANGLE :	(DEGREES)	52.	58.	46.	61.	39.	65.
STATIC PRESSURE :	(KN/M**2)	186.1	179.5	196.3	180.5	204.5	180.8
TOTAL TEMP. :	(DEG. KELVIN)	423.	387.	423.	386.	423.	385.
STATIC TEMP. :	(DEG. KELVIN)	380.	377.	386.	378.	390.	378.
REL. MACH NO. :		0.492	0.562	0.414	0.572	0.356	0.580
WHEEL VELOCITY :	(M/SEC)	113.	114.	125.	127.	137.	140.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Continued).

POINT NO. 2042 100% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	129.	218.	120.	196.	109.	180.
FLOW ANGLE	:	(DEGREES)	34.	66.	34.	63.	35.	61.
STATIC PRESSURE	:	(KN/M□2)	180.0	152.4	180.5	159.6	183.9	164.6
TOTAL TEMP.	:	(DEG. KELVIN)	386.	386.	386.	386.	386.	386.
STATIC TEMP.	:	(DEG. KELVIN)	378.	363.	378.	367.	380.	370.
MACH NUMBER	:		0.331	0.570	0.308	0.510	0.278	0.467

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	121.	148.	94.	159.	81.	169.
REL. FLOW ANGLE	:	(DEGREES)	45.	56.	27.	59.	5.	68.
STATIC PRESSURE	:	(KN/M□2)	152.4	147.4	159.6	147.5	164.6	147.3
TOTAL TEMP.	:	(DEG. KELVIN)	386.	363.	386.	364.	386.	363.
STATIC TEMP.	:	(DEG. KELVIN)	363.	359.	367.	361.	370.	361.
REL. MACH NO.	:		0.317	0.389	0.244	0.418	0.209	0.445
WHEEL VELOCITY	:	(M/SEC)	113.	112.	131.	132.	149.	152.

Table 13(b). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 100% Speed (Concluded).

POINT NO. 2042 | 100% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	79.	136.	78.	118.	61.	111.
FLOW ANGLE	:	(DEGREES)	8.	59.	3.	56.	4.	59.
STATIC PRESSURE	:	(KN/M**2)	148.4	136.8	147.5	139.9	148.6	141.7
TOTAL TEMP.	:	(DEG. KELVIN)	363.	363.	363.	363.	363.	363.
STATIC TEMP.	:	(DEG. KELVIN)	361.	354.	361.	357.	362.	357.
MACH NUMBER	:		0.207	0.360	0.205	0.309	0.158	0.290

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	69.	93.	75.	94.	86.	103.
REL. FLOW ANGLE	:	(DEGREES)	8.	41.	-30.	47.	-50.	62.
STATIC PRESSURE	:	(KN/M**2)	136.8	133.6	139.9	134.9	141.7	135.9
TOTAL TEMP.	:	(DEG. KELVIN)	363.	356.	363.	361.	363.	361.
STATIC TEMP.	:	(DEG. KELVIN)	354.	353.	357.	356.	357.	357.
REL. MACH NO.	:		0.181	0.247	0.196	0.248	0.226	0.270
WHEEL VELOCITY	:	(M/SEC)	108.	107.	134.	134.	159.	161.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed.

POINT NO. 5237 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	209.	421.	209.	393.	209.	369.
FLOW ANGLE	;	(DEGREES)	20.	62.	20.	62.	20.	62.
STATIC PRESSURE	;	(KN/M□2)	229.6	118.0	229.6	133.1	229.6	145.9
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	336.	402.	347.	402.	356.
MACH NUMBER	;		0.520	1.147	0.520	1.053	0.519	0.977

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	324.	329.	282.	324.	253.	321.
REL. FLOW ANGLE	;	(DEGREES)	56.	58.	55.	61.	52.	64.
STATIC PRESSURE	;	(KN/M□2)	118.0	118.0	133.1	122.6	145.9	125.2
TOTAL TEMP.	;	(DEG. KELVIN)	423.	369.	423.	367.	423.	366.
STATIC TEMP.	;	(DEG. KELVIN)	336.	339.	347.	342.	356.	343.
REL. MACH NO.	;		0.878	0.895	0.749	0.878	0.664	0.867
WHEEL VELOCITY	;	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 5237 — 90% SPEED

STATOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	239.	380.	221.	342.	204.	312.
FLOW ANGLE	;	(DEGREES)	48.	63.	50.	62.	52.	61.
STATIC PRESSURE	;	(KN/M**2)	118.0	70.4	122.6	83.0	129.8	92.6
TOTAL TEMP.	;	(DEG. KELVIN)	367.	367.	367.	367.	367.	367.
STATIC TEMP.	;	(DEG. KELVIN)	339.	296.	342.	309.	347.	319.
MACH NUMBER	;		0.645	1.102	0.595	0.969	0.547	0.871

ROTOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	288.	301.	233.	297.	194.	295.
REL. FLOW ANGLE	;	(DEGREES)	56.	56.	52.	59.	44.	65.
STATIC PRESSURE	;	(KN/M**2)	70.4	67.3	83.0	70.5	92.6	71.8
TOTAL TEMP.	;	(DEG. KELVIN)	367.	319.	367.	318.	367.	316.
STATIC TEMP.	;	(DEG. KELVIN)	296.	294.	309.	297.	319.	299.
REL. MACH NO.	;		0.833	0.878	0.656	0.863	0.539	0.855
WHEEL VELOCITY	;	(M/SEC)	102.	101.	118.	119.	134.	137.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 5237 | 90% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	217.	274.	196.	239.	173.	213.
FLOW ANGLE	:	(DFGREES)	43.	56.	43.	56.	48.	59.
STATIC PRESSURE	:	(KN/M**2)	66.9	55.5	70.5	62.0	75.0	66.2
TOTAL TEMP.	:	(DEG. KELVIN)	318.	318.	318.	318.	318.	318.
STATIC TEMP.	:	(DEG. KELVIN)	294.	280.	297.	289.	303.	295.
MACH NUMBER	:		0.633	0.818	0.569	0.701	0.496	0.620

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	198.	193.	150.	204.	113.	208.
REL. FLOW ANGLE	:	(DFGREFS)	42.	40.	30.	46.	19.	60.
STATIC PRESSURF	:	(KN/M**2)	55.5	55.1	62.0	55.2	66.2	55.3
TOTAL TEMP.	:	(DEG. KELVIN)	318.	294.	318.	292.	318.	288.
STATIC TEMP.	:	(DEG. KELVIN)	280.	282.	289.	281.	295.	281.
REL. MACH NO.	:		0.592	0.574	0.440	0.609	0.328	0.619
WHFEL VELOCITY	:	(M/SEC)	97.	97.	120.	121.	143.	145.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 4037 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	209.	417.	209.	390.	209.	366.
FLOW ANGLE	:	(DEGREES)	20.	62.	20.	62.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	229.6	119.6	229.6	134.8	229.6	147.5
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	337.	402.	348.	402.	357.
MACH NUMBER	:		0.520	1.136	0.520	1.043	0.519	0.968

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	321.	324.	279.	320.	250.	317.
REL. FLOW ANGLE	:	(DEGREES)	56.	58.	55.	61.	51.	64.
STATIC PRESSURE	:	(KN/M**2)	119.6	120.4	134.8	124.9	147.5	127.5
TOTAL TEMP.	:	(DEG. KELVIN)	423.	370.	423.	368.	423.	366.
STATIC TEMP.	:	(DEG. KELVIN)	337.	341.	348.	344.	357.	345.
REL. MACH NO.	:		0.867	0.879	0.740	0.864	0.656	0.855
WHEEL VELOCITY	:	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 4037 90% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	234.	356.	217.	320.	200.	292.
FLOW ANGLE	;	(DEGREES)	48.	63.	49.	63.	51.	61.
STATIC PRESSURE	;	(KN/M**2)	120.4	79.0	124.9	91.0	132.0	100.0
TOTAL TEMP.	;	(DEG. KELVIN)	368.	368.	368.	368.	368.	368.
STATIC TEMP.	;	(DEG. KELVIN)	341.	306.	344.	317.	348.	326.
MACH NUMBER	;		0.631	1.017	0.582	0.896	0.535	0.807

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	264.	261.	213.	262.	176.	263.
REL. FLOW ANGLE	;	(DEGREES)	56.	56.	51.	59.	42.	65.
STATIC PRESSURE	;	(KN/M**2)	79.0	79.8	91.0	82.0	100.0	82.9
TOTAL TEMP.	;	(DEG. KELVIN)	368.	326.	368.	324.	368.	322.
STATIC TEMP.	;	(DEG. KELVIN)	306.	308.	317.	310.	326.	311.
REL. MACH NO.	;		0.753	0.743	0.592	0.744	0.484	0.745
WHEEL VELOCITY	;	(M/SEC)	102.	101.	118.	119.	134.	137.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 4037 | 90% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	180.	237.	164.	207.	144.	186.
FLOW ANGLE	;	(DEGREES)	41.	57.	40.	56.	45.	59.
STATIC PRESSURE	;	(KN/M**2)	79.3	68.0	82.0	73.8	85.6	77.5
TOTAL TEMP.	;	(DEG. KELVIN)	324.	324.	324.	324.	324.	324.
STATIC TEMP.	;	(DEG. KELVIN)	308.	296.	310.	303.	314.	307.
MACH NUMBER	;		0.512	0.687	0.465	0.592	0.404	0.529

ROTOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	162.	160.	123.	174.	93.	180.
REL. FLOW ANGLE	;	(DEGREES)	40.	41.	24.	46.	9.	62.
STATIC PRESSURE	;	(KN/M**2)	68.0	67.6	73.8	67.6	77.5	67.6
TOTAL TEMP.	;	(DEG. KELVIN)	324.	304.	324.	304.	324.	301.
STATIC TEMP.	;	(DEG. KELVIN)	296.	297.	303.	296.	307.	296.
REL. MACH NO.	;		0.470	0.463	0.351	0.502	0.265	0.522
WHEEL VELOCITY	;	(M/SEC)	97.	97.	120.	121.	143.	145.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 3037 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	208.	383.	208.	357.	208.	336.
FLOW ANGLE	:	(DEGREES)	20.	63.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	230.0	138.4	230.0	152.5	230.0	164.1
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	402.	351.	402.	360.	402.	367.
MACH NUMBER	:		0.517	1.022	0.517	0.941	0.517	0.875

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	287.	289.	249.	287.	221.	285.
REL. FLOW ANGLE	:	(DEGREES)	56.	58.	54.	61.	50.	64.
STATIC PRESSURE	:	(KN/M**2)	138.4	140.0	152.5	143.4	164.1	145.3
TOTAL TEMP.	:	(DEG. KELVIN)	423.	376.	423.	374.	423.	373.
STATIC TEMP.	:	(DEG. KELVIN)	351.	354.	360.	356.	367.	357.
REL. MACH NO.	:		0.762	0.766	0.651	0.761	0.573	0.756
WHEEL VELOCITY	:	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 3037 | 90% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	200.	295.	186.	265.	172.	243.
FLOW ANGLE	:	(DEGREES)	45.	65.	47.	63.	49.	61.
STATIC PRESSURE	:	(KN/M**2)	139.9	107.7	143.4	118.0	149.4	125.3
TOTAL TEMP.	:	(DEG. KELVIN)	374.	374.	374.	374.	374.	374.
STATIC TEMP.	:	(DEG. KELVIN)	354.	331.	356.	339.	359.	345.
MACH NUMBER	:		0.530	0.810	0.492	0.719	0.452	0.652

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	205.	208.	162.	213.	132.	218.
REL. FLOW ANGLE	:	(DEGREES)	54.	56.	46.	59.	35.	66.
STATIC PRESSURE	:	(KN/M**2)	107.7	107.1	118.0	108.2	125.3	108.4
TOTAL TEMP.	:	(DEG. KELVIN)	374.	341.	374.	341.	374.	339.
STATIC TEMP.	:	(DEG. KELVIN)	331.	332.	339.	333.	345.	333.
REL. MACH NO.	:		0.560	0.569	0.437	0.584	0.353	0.597
WHEEL VELOCITY	:	(M/SEC)	102.	101.	118.	119.	134.	137.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 3037 — 90% SPEED

STATOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	131.	189.	122.	164.	104.	149.
FLOW ANGLE	;	(DEGREES)	34.	58.	31.	56.	37.	59.
STATIC PRESSURE	;	(KN/M**2)	107.0	95.6	108.2	100.3	110.8	103.2
TOTAL TEMP.	;	(DEG. KELVIN)	341.	341.	341.	341.	341.	341.
STATIC TEMP.	;	(DEG. KELVIN)	332.	323.	333.	327.	335.	329.
MACH NUMBER	;		0.359	0.523	0.332	0.453	0.281	0.409

ROTOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	116.	125.	91.	136.	76.	146.
REL. FLOW ANGLE	;	(DEGREES)	34.	41.	10.	47.	-13.	63.
STATIC PRESSURE	;	(KN/M**2)	95.6	94.3	100.3	94.4	103.2	94.5
TOTAL TEMP.	;	(DEG. KELVIN)	341.	327.	341.	327.	341.	325.
STATIC TEMP.	;	(DEG. KELVIN)	323.	322.	327.	322.	329.	323.
REL. MACH NO.	;		0.322	0.346	0.250	0.378	0.208	0.403
WHEEL VELOCITY	;	(M/SEC)	97.	97.	120.	121.	143.	145.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 2037 — 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	186.	295.	186.	275.	186.	259.
FLOW ANGLE	:	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	238.8	186.1	238.8	196.3	238.8	204.5
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	406.	380.	406.	386.	406.	390.
MACH NUMBER	:		0.460	0.756	0.460	0.700	0.459	0.654

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	201.	215.	173.	218.	150.	221.
REL. FLOW ANGLE	:	(DEGREES)	54.	58.	49.	61.	43.	65.
STATIC PRESSURE	:	(KN/M**2)	186.1	183.3	196.3	184.6	204.5	185.2
TOTAL TEMP.	:	(DEG. KELVIN)	423.	389.	423.	388.	423.	388.
STATIC TEMP.	:	(DEG. KELVIN)	380.	379.	386.	380.	390.	381.
REL. MACH NO.	:		0.515	0.552	0.437	0.560	0.378	0.565
WHEEL VELOCITY	:	(M/SEC)	102.	103.	113.	114.	123.	126.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Continued).

POINT NO. 2037 — 90% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	133.	211.	124.	190.	113.	175.
FLOW ANGLE	:	(DEGREES)	37.	66.	38.	63.	40.	61.
STATIC PRESSURE	:	(KN/M**2)	183.6	159.1	184.6	166.0	188.1	170.8
TOTAL TEMP.	:	(DEG. KELVIN)	388.	388.	388.	388.	388.	388.
STATIC TEMP.	:	(DEG. KELVIN)	380.	367.	380.	371.	382.	373.
MACH NUMBER	:		0.340	0.551	0.317	0.493	0.288	0.451

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	124.	143.	96.	153.	80.	161.
REL. FLOW ANGLE	:	(DEGREES)	48.	56.	32.	59.	12.	68.
STATIC PRESSURE	:	(KN/M**2)	159.1	155.5	166.0	155.7	170.8	155.5
TOTAL TEMP.	:	(DEG. KELVIN)	388.	368.	388.	368.	388.	368.
STATIC TEMP.	:	(DEG. KELVIN)	367.	365.	371.	365.	373.	366.
REL. MACH NO	:		0.321	0.372	0.247	0.398	0.206	0.421
WHEEL VELOCITY	:	(M/SEC)	102.	101.	118.	119.	134.	137.

Table 13(c). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 90% Speed (Concluded).

POINT NO. 2037 — 90% SPEED

STATOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	78.	129.	76.	112.	59.	105.
FLOW ANGLE	:	(DEGREES)	13.	59.	9.	56.	12.	59.
STATIC PRESSURE	:	(KN/M□2)	156.1	145.9	155.7	148.8	156.8	150.6
TOTAL TEMP.	:	(DEG. KELVIN)	368.	368.	368.	368.	368.	368.
STATIC TEMP.	:	(DEG. KELVIN)	365.	360.	365.	362.	366.	363.
MACH NUMBER	:		0.202	0.340	0.197	0.293	0.153	0.274

ROTOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	67.	87.	68.	90.	76.	99.
REL. FLOW ANGLE	:	(DEGREES)	13.	41.	-25.	47.	-47.	63.
STATIC PRESSURE	:	(KN/M□2)	145.9	143.2	148.8	144.2	150.6	145.0
TOTAL TEMP.	:	(DEG. KELVIN)	368.	362.	368.	364.	368.	364.
STATIC TEMP.	:	(DEG. KELVIN)	360.	358.	362.	361.	363.	361.
REL. MACH NO.	:		0.174	0.229	0.177	0.236	0.197	0.259
WHEEL VELOCITY	:	(M/SEC)	97.	97.	120.	121.	143.	145.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed.

POINT NO. 4029 — 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	209.	484.	209.	453.	209.	427.
FLOW ANGLE	;	(DEGREES)	20.	59.	20.	61.	20.	61.
STATIC PRESSURE	;	(KN/M**2)	229.6	85.4	229.6	101.0	229.6	114.8
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	307.	402.	322.	402.	333.
MACH NUMBER	;		0.520	1.378	0.520	1.261	0.519	1.167

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	404.	363.	357.	349.	330.	340.
REL. FLOW ANGLE	;	(DEGREES)	56.	58.	58.	61.	56.	64.
STATIC PRESSURE	;	(KN/M**2)	85.4	105.3	101.0	112.3	114.8	116.4
TOTAL TEMP.	;	(DEG. KELVIN)	423.	374.	423.	372.	423.	370.
STATIC TEMP.	;	(DEG. KELVIN)	307.	331.	322.	336.	333.	338.
REL. MACH NO.	;		1.142	0.998	0.980	0.955	0.893	0.925
WHEEL VELOCITY	;	(M/SEC)	79.	80.	88.	89.	96.	98.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 4029 — 70% SPEED

STATOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	287.	407.	264.	365.	245.	332.
FLOW ANGLE	:	(DEGREES)	52.	62.	54.	62.	57.	61.
STATIC PRESSURE	:	(KN/M□2)	105.1	63.1	112.3	76.2	121.1	86.4
TOTAL TEMP.	:	(DEG. KELVIN)	372.	372.	372.	372.	372.	372.
STATIC TEMP.	:	(DEG. KELVIN)	331.	290.	336.	306.	342.	317.
MACH NUMBER	:		0.786	1.192	0.718	1.042	0.659	0.930

ROTOR 2			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	333.	282.	276.	275.	235.	270.
REL. FLOW ANGLE	:	(DEGREES)	58.	57.	56.	59.	51.	65.
STATIC PRESSURE	:	(KN/M□2)	63.1	75.3	76.2	78.9	86.4	80.8
TOTAL TEMP.	:	(DEG. KELVIN)	372.	333.	372.	331.	372.	329.
STATIC TEMP.	:	(DEG. KELVIN)	290.	308.	306.	311.	317.	313.
REL. MACH NO.	:		0.974	0.801	0.782	0.778	0.654	0.763
WHEEL VELOCITY	:	(M/SEC)	79.	79.	92.	93.	104.	107.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 4029 70% SPEED

STATOR 3			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	215.	243.	194.	211.	173.	186.
FLOW ANGLE	:	(DEGREES)	47.	57.	47.	56.	53.	59.
STATIC PRESSURE	:	(KN/M**2)	74.6	68.4	78.9	74.4	83.5	78.2
TOTAL TEMP.	:	(DEG. KELVIN)	331.	331.	331.	331.	331.	331.
STATIC TEMP.	:	(DEG. KFLVIN)	308.	304.	311.	309.	316.	313.
MACH NUMBER	:		0.611	0.696	0.548	0.598	0.483	0.524

ROTOR 3			HUB		PITCH		TIP	
			INLET	FXIT	INLET	EXIT	INLET	EXIT
RELATIVE VFL.	:	(M/SEC)	182.	160.	139.	173.	104.	173.
REL. FLOW ANGLE	:	(DFGREES)	46.	41.	35.	46.	27.	61.
STATIC PRFSSURF	:	(KN/M**2)	68.4	69.7	74.4	69.9	78.2	70.0
TOTAL TEMP.	:	(DEG. KELVIN)	331.	314.	331.	312.	331.	309.
STATIC TEMP.	:	(DEG. KFLVIN)	304.	306.	309.	304.	313.	305.
REL. MACH NO.	:		0.522	0.456	0.395	0.495	0.290	0.493
WHEEL VELOCITY	:	(M/SEC)	76.	75.	94.	94.	112.	113.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 3029 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	209.	467.	209.	436.	209.	410.
FLOW ANGLE	;	(DEGREES)	20.	60.	20.	61.	20.	62.
STATIC PRESSURE	;	(KN/M**2)	229.6	94.1	229.6	109.7	229.6	123.5
TOTAL TEMP.	;	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	;	(DEG. KELVIN)	402.	316.	402.	329.	402.	339.
MACH NUMBER	;		0.520	1.312	0.520	1.201	0.519	1.112

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	387.	331.	342.	321.	314.	314.
REL. FLOW ANGLE	;	(DEGREES)	57.	58.	58.	61.	56.	64.
STATIC PRESSURE	;	(KN/M**2)	94.1	119.4	109.7	125.3	123.5	128.9
TOTAL TEMP.	;	(DEG. KELVIN)	423.	377.	423.	375.	423.	373.
STATIC TEMP.	;	(DEG. KELVIN)	316.	343.	329.	346.	339.	348.
REL. MACH NO.	;		1.081	0.896	0.931	0.865	0.843	0.844
WHEEL VELOCITY	;	(M/SEC)	79.	80.	88.	89.	96.	98.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 3029 — 70% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	257.	326.	237.	292.	221.	265.
FLOW ANGLE	;	(DEGREES)	52.	64.	53.	63.	56.	61.
STATIC PRESSURE	;	(KN/M□2)	119.1	94.0	125.3	105.1	133.3	113.3
TOTAL TEMP.	;	(DEG. KELVIN)	375.	375.	375.	375.	375.	375.
STATIC TEMP.	;	(DEG. KELVIN)	342.	323.	346.	333.	351.	340.
MACH NUMBER	;		0.694	0.905	0.637	0.799	0.587	0.717

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	253.	222.	207.	223.	172.	222.
REL. FLOW ANGLE	;	(DEGREES)	58.	56.	53.	59.	47.	65.
STATIC PRESSURE	;	(KN/M□2)	94.0	101.0	105.1	103.2	113.3	104.2
TOTAL TEMP.	;	(DEG. KELVIN)	375.	344.	375.	343.	375.	342.
STATIC TEMP.	;	(DEG. KELVIN)	323.	332.	333.	332.	340.	333.
REL. MACH NO.	;		0.702	0.609	0.563	0.611	0.462	0.606
WHEEL VELOCITY	;	(M/SEC)	79.	79.	92.	93.	104.	107.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 3029 — 70% SPEED

STATOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	158.	196.	146.	171.	128.	153.
FLOW ANGLE	;	(DEGREES)	43.	58.	42.	56.	47.	59.
STATIC PRESSURE	;	(KN/M**2)	100.6	93.1	103.2	98.0	106.4	101.0
TOTAL TEMP.	;	(DEG. KELVIN)	343.	343.	343.	343.	343.	343.
STATIC TEMP.	;	(DEG. KELVIN)	331.	324.	332.	329.	336.	332.
MACH NUMBER	;		0.433	0.542	0.399	0.468	0.347	0.417

ROTOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	136.	127.	104.	140.	78.	144.
REL. FLOW ANGLE	;	(DEGREES)	43.	41.	27.	47.	14.	62.
STATIC PRESSURE	;	(KN/M**2)	93.1	93.5	98.0	93.5	101.0	93.5
TOTAL TEMP.	;	(DEG. KELVIN)	343.	331.	343.	330.	343.	328.
STATIC TEMP.	;	(DEG. KELVIN)	324.	326.	329.	325.	332.	326.
REL. MACH NO.	;		0.376	0.349	0.284	0.386	0.212	0.398
WHEEL VELOCITY	;	(M/SEC)	76.	75.	94.	94.	112.	113.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 2029 | 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	202.	346.	292.	322.	202.	303.
FLOW ANGLE	:	(DEGREES)	20.	64.	20.	63.	20.	62.
STATIC PRESSURE	:	(KN/M**2)	232.5	159.0	232.5	171.6	232.5	181.9
TOTAL TEMP.	:	(DEG. KELVIN)	423.	423.	423.	423.	423.	423.
STATIC TEMP.	:	(DEG. KELVIN)	403.	364.	493.	372.	403.	378.
MACH NUMBER	:		0.502	0.904	0.502	0.835	0.501	0.778

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	269.	246.	236.	245.	211.	243.
REL. FLOW ANGLE	:	(DEGREES)	58.	58.	56.	61.	53.	64.
STATIC PRESSURE	:	(KN/M**2)	159.0	169.5	171.6	172.6	181.9	174.6
TOTAL TEMP.	:	(DEG. KELVIN)	423.	389.	423.	388.	423.	388.
STATIC TEMP.	:	(DEG. KELVIN)	364.	373.	372.	374.	378.	375.
REL. MACH NO.	:		0.702	0.635	0.609	0.633	0.540	0.627
WHEEL VELOCITY	:	(M/SEC)	79.	80.	88.	89.	96.	98.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Continued).

POINT NO. 2029 — 70% SPEED

STATOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	176.	236.	165.	212.	154.	193.
FLOW ANGLE	;	(DEGREES)	47.	65.	49.	63.	51.	61.
STATIC PRESSURE	;	(KN/M**2)	169.2	149.1	172.6	157.3	178.0	163.0
TOTAL TEMP.	;	(DEG. KELVIN)	388.	388.	388.	388.	388.	388.
STATIC TEMP.	;	(DEG. KELVIN)	373.	361.	374.	367.	377.	371.
MACH NUMBER	;		0.455	0.619	0.426	0.552	0.394	0.500

ROTOR 2			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	164.	158.	131.	164.	106.	168.
REL. FLOW ANGLE	;	(DEGREES)	56.	56.	47.	59.	36.	67.
STATIC PRESSURE	;	(KN/M**2)	149.1	150.6	157.3	151.3	163.0	151.6
TOTAL TEMP.	;	(DEG. KELVIN)	388.	368.	388.	368.	388.	367.
STATIC TEMP.	;	(DEG. KELVIN)	361.	363.	367.	363.	371.	364.
REL. MACH NO.	;		0.431	0.414	0.341	0.429	0.275	0.438
WHEEL VELOCITY	;	(M/SEC)	79.	79.	92.	93.	104.	107.

Table 13(d). HLFT-IVA 3-Stage LP Turbine Flow Diagrams, 70% Speed (Concluded).

POINT NO. 2029 — 70% SPEED

STATOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	99.	140.	93.	122.	78.	111.
FLOW ANGLE	:	(DEGREES)	33.	59.	31.	56.	37.	59.
STATIC PRESSURE	:	(KN/M**2)	150.5	142.5	151.3	145.9	153.3	148.0
TOTAL TEMP.	:	(DEG. KELVIN)	368.	368.	368.	368.	368.	368.
STATIC TEMP.	:	(DEG. KELVIN)	363.	358.	363.	361.	365.	362.
MACH NUMBER	:		0.259	0.370	0.243	0.321	0.204	0.291

ROTOR 3			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	84.	91.	67.	100.	58.	106.
REL. FLOW ANGLE	:	(DEGREES)	33.	41.	6.	47.	-18.	64.
STATIC PRESSURE	:	(KN/M**2)	142.5	141.5	145.9	141.7	148.0	141.8
TOTAL TEMP.	:	(DEG. KELVIN)	368.	361.	368.	361.	368.	359.
STATIC TEMP.	:	(DEG. KELVIN)	358.	358.	361.	358.	362.	358.
REL. MACH NO.	:		0.221	0.238	0.176	0.262	0.151	0.279
WHEEL VELOCITY	:	(M/SEC)	76.	75.	94.	94.	112.	113.

APPENDIX B - HIGH PRESSURE TURBINE AERO AND ACOUSTIC RESULTS

Appendix B contains the blade-row attenuations for all the test conditions on the high pressure turbine with cold and hot inlet temperatures. Aerodynamic performance results from both runs are presented. The turbine flow diagrams including interstage and intrastage data are also presented.

Table 14. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine).

a. 110% $N/\sqrt{T_{TO}}$, T_{TO} = 450 K, P_{TO} = 389.5 kN/m^2

Test Point No.	3084		2484		2184*		1984	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	18.0	13.4	24.0	19.4	30.2	25.6	18.0	13.4
125	19.0	14.4	16.5	11.9	15.0	10.4	10.0	5.4
301	14.0	9.4	11.0	6.4	10.0	5.4	9.0	4.4
334	---	---	---	---	---	---	23.0	18.4
401	---	---	18.0	13.4	18.0	13.4	---	---
526	15.0	10.4	---	---	---	---	---	---
752	22.0	17.4	17.0	12.4	10.0	5.4	9.0	4.4
1008	11.0	6.4	11.0	6.4	8.5	3.9	19.0	14.4
1175	15.0	10.4	13.0	8.4	13.2	8.6	16.0	11.4
2nd Harmonic, Hz								
167	21.0	16.4	25.0	20.4	22.8	18.2	4.0	0
250	12.0	7.4	9.0	4.4	8.0	3.4	5.0	0.4
602	19.0	14.4	18.0	13.4	15.5	10.9	16.0	11.4
667	---	---	---	---	---	---	19.0	14.4
803	---	---	19.0	14.4	15.0	10.4	---	---
1052	9.0	4.4	---	---	---	---	---	---
1503	7.0	2.4	-7.0	0	-3.5	0	-2.0	0
2015	15.0	10.4	9.0	4.4	12.0	7.4	12.0	7.4
2350	13.0	8.4	6.0	1.4	14.2	9.6	6.0	1.4
3rd Harmonic, Hz								
250	11.0	6.4	13.0	8.4	15.8	11.2	1.0	0
375	19.0	14.4	11.0	6.4	14.0	9.4	12.0	7.4
903	2.0	0	2.0	0	-4.5	0	4.0	0
1001	---	---	---	---	---	---	3.0	0
1204	---	---	7.0	2.4	0	0	---	---
1578	-6.0	0	---	---	---	---	---	---
2255	8.0	3.4	2.0	0	6.5	1.9	10.0	5.4
3023	21.0	16.4	4.0	0	14.5	9.9	25.0	20.4
3526	6.0	1.4	0	0	16.5	11.9	15.0	10.4
$\overline{\Delta dB}\Big\|_{1200}^{200}$ =		9.2		8.0		6.8		7.2

*Repeat points averaged

Table 14. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine) (Continued).

b. 100% $N/\sqrt{T_{TO}}$, T_{TO} = 450 K, P_{TO} = 389.5 kN/m^2

Test Point No.	3076		2476*		2176*		1976	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	25.0	20.4	25.0	20.4	27.9	23.3	17.0	12.4
125	11.0	6.4	18.5	13.9	19.5	14.9	12.0	7.4
301	14.0	9.4	11.5	6.9	10.4	5.8	9.0	4.4
375	---	---	---	---	---	---	14.0	9.4
401	---	---	17.5	12.9	13.1	8.5	---	---
477	17.0	12.4	---	---	---	---	---	---
752	18.0	13.4	24.5	19.9	10.1	5.5	10.0	5.4
1008	10.0	5.4	16.4	11.9	10.0	5.4	16.0	11.4
1175	11.0	6.4	25.0	20.4	9.6	5.0	15.0	10.4
2nd Harmonic, Hz								
167	17.0	12.4	10.5	5.9	17.5	12.9	10.0	5.4
250	13.0	8.4	12.5	7.9	9.5	4.9	6.0	1.4
602	17.0	12.4	13.0	8.4	13.6	9.0	17.0	12.4
750	---	---	---	---	---	---	11.0	6.4
803	---	---	16.5	1[illegible]	15.5	10.9	---	---
955	9.0	4.4	---	---	---	---	---	---
1503	4.0	0	3.0	0	1.5	0	-5.0	0
2015	18.0	13.4	18.0	13.4	14.6	10.0	11.0	6.4
2350	12.0	7.4	17.5	12.9	5.8	1.2	8.0	3.4
3rd Harmonic, Hz								
250	-3.0	0	3.5	0	7.1	2.5	4.0	0
375	21.0	16.4	16.5	11.9	15.4	10.8	17.0	12.4
903	-6.0	0	0.5	0	0.1	0	1.0	0
1126	---	---	---	---	---	---	6.0	1.4
1204	---	---	8.0	3.4	5.0	0.4	---	---
1432	5.0	0.4	---	---	---	---	---	---
2255	9.0	4.4	14.5	9.9	12.6	8.0	9.0	4.4
3023	28.0	23.4	17.0	12.4	6.8	2.2	16.0	11.4
3526	9.0	4.4	17.5	12.9	5.8	1.2	19.0	14.4
$\Delta\overline{dB}\Big\|_{1200}^{200}$ =		8.1		9.6		5.7		6.2

*Repeat points averaged

Table 14. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine) (Continued).

c. 90% $N/\sqrt{T_{TO}}$, T_{TO} = 450 K, P_{TO} = 389.5 kN/m^2

Test Point No.	2667		2469		2169*		1969	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	21.0	16.4	24.0	19.4	26.5	21.9	28.0	23.4
125	19.0	14.4	23.0	18.4	23.5	18.9	13.0	8.4
301	12.0	7.4	12.0	7.4	9.5	4.9	9.0	4.4
401	---	---	16.0	11.4	15.5	10.9	---	---
457	15.0	10.4	---	---	---	---	---	---
526	---	---	---	---	---	---	9.0	4.4
752	27.0	22.4	33.0	28.4	14.5	9.9	11.0	6.4
1008	9.0	4.4	12.0	7.4	9.0	4.4	13.0	8.4
1175	8.0	3.4	21.0	16.4	15.5	10.9	17.0	12.4
2nd Harmonic, Hz								
167	17.0	12.4	13.0	8.4	18.5	13.9	20.0	15.4
250	14.0	9.4	11.0	6.4	11.5	6.9	8.0	3.4
602	19.0	14.4	16.0	11.4	16.5	11.9	16.0	11.4
803	---	---	12.0	7.4	17.0	12.4	---	---
914	17.0	12.4	---	---	---	---	---	---
1052	---	---	---	---	---	---	9.0	4.4
1503	5.0	0.4	3.0	0	-3.5	0	-7.0	0
2015	15.0	10.4	13.0	8.4	14.0	9.4	22.0	17.4
2350	10.0	5.4	10.0	5.4	11.0	6.4	13.0	8.4
3rd Harmonic, Hz								
250	8.0	3.4	7.0	2.4	11.5	6.9	10.0	5.4
375	17.0	12.4	16.0	11.4	18.0	13.4	12.0	7.4
903	3.0	0	1.0	0	-3.0	0	2.0	0
1204	---	---	3.0	0	1.5	0	---	---
1371	-10.0	0	---	---	---	---	---	---
1578	---	---	---	---	---	---	5.0	0.4
2255	16.0	11.4	15.0	10.4	10.5	5.9	13.0	8.4
3025	14.0	9.4	16.0	11.4	7.0	2.4	18.0	13.4
3526	11.0	6.4	22.0	17.4	8.8	4.2	18.0	13.4
$\overline{\Delta dB}\Big\|_{1200}^{200}$ =		9.1		9.2		7.7		6.2

*Repeat points averaged

Table 14. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine) (Concluded).

d. 70% $N/\sqrt{T_{TO}}$, T_{TO} = 450 K, P_{TO} = 389.5 kN/m^2

Test Point No.	2653		2453		2153		1953	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	27.0	22.4	25.0	20.4	18.0	13.4	22.0	17.4
125	21.0	16.4	27.0	22.4	---	---	15.0	10.4
301	13.0	8.4	12.0	7.4	11.0	6.4	10.0	5.4
401	---	---	16.0	11.4	16.0	11.4	---	---
477	16.0	11.4	---	---	---	---	---	---
526	---	---	--	---	---	---	8.0	3.4
752	23.0	18.4	26.0	21.4	20.0	15.4	18.0	13.4
1008	11.0	6.4	11.0	6.4	4.0	0	11.0	6.4
1175	17.0	12.4	18.0	13.4	8.5	3.9	12.0	7.4
2nd Harmonic, Hz								
167	25.0	20.4	25.0	20.4	17.5	12.9	13.0	8.4
250	11.0	6.4	15.0	10.4	---	---	7.0	2.4
602	15.0	10.4	18.0	13.4	16.0	11.4	13.0	8.4
803	---	---	12.0	7.4	12.0	7.4	---	---
955	9.0	4.4	---	---	---	---	---	---
1052	---	---	---	---	---	---	7.0	2.4
1503	-1.0	0	-2.0	0	-2.0	0	-3.0	0
2015	17.0	12.4	20.0	15.4	13.5	8.9	27.0	22.4
2350	11.0	6.4	11.0	11.4	2.5	0	15.0	10.4
3rd Harmonic, Hz								
250	16.0	11.4	9.0	4.4	10.0	5.4	6.0	1.4
375	16.0	11.4	16.0	11.4	---	---	11.0	6.4
903	-4.0	0	0	0	-6.0	0	3.0	0
1204	---	---	9.0	4.4	0	0	---	---
1432	8.0	3.4	---	---	---	---	---	---
1578	---	---	---	---	---	---	8.0	3.4
2255	8.0	3.4	11.0	6.4	5.0	0.4	15.0	10.4
3023	10.0	5.4	10.0	5.4	7.0	2.4	19.0	14.4
3526	15.0	10.4	17.0	12.4	10.0	5.4	13.0	8.4
$\overline{\Delta dB}\Big\|_{1200}^{200}$ =		9.2		9.3		6.1		5.2

Table 15. Aerodynamic Performance Parameters, Cold High Pressure Turbine.

• P_{T0} = 389.5 kN/m^2 (56.5 psia), T_{T0} = 450 K (810° R)

%N/√T	Test Point	P_{T0}/P_{T2}	P_{T0}/P_{T2} Measur. Plane	W_2 Corr. (lbm/sec)	W_2 Corr. (kg/sec)	$N/\sqrt{T_{T0}/T_{STD}}$	P_{SH}/W_2 (Btu/lbm)	P_{SH}/W_2 (kJ/kg)
110	3084	2.235	3.02	34.59	15.69	6768.4	34.04	79.2
	2484	2.055	2.50	34.55	15.67	6764.7	30.75	71.5
	2184	1.88	2.14	34.42	15.61	6770.2	26.90	62.6
	2184	1.88	2.14	34.31	15.56	6771.8	26.95	62.7
	1984	1.745	1.90	33.64	15.26	6775.0	23.40	54.6
100	3076	2.20	3.02	34.73	15.75	6156.8	32.92	76.6
	2476	2.04	2.50	34.51	15.65	6159.9	30.05	69.9
	2476	2.04	2.50	34.62	15.70	6159.7	29.91	69.6
	2176	1.865	2.14	34.55	15.67	6161.7	26.50	61.6
	2176	1.865	2.14	34.55	15.67	6161.7	26.50	61.6
	1976	1.72	1.90	33.95	15.40	6156.0	23.28	54.1
90	2669	2.06	2.68	34.80	15.78	5538.6	29.93	69.6
	2469	2.00	2.50	34.88	15.82	5547.9	28.79	67.0
	2169	1.845	2.15	34.94	15.85	5541.1	25.66	59.7
	2169	1.84	2.14	34.70	15.74	5547.0	25.76	59.9
	1969	1.705	1.90	34.10	15.47	5544.5	22.83	53.1
70	2653	1.92	2.67	35.11	15.92	4680.3	27.60	64.2
	2453	1.88	2.50	35.13	15.93	4524.3	26.30	61.2
	2153	1.77	2.14	35.41	16.06	4316.5	22.80	53.0
	1953	1.67	1.90	34.69	15.74	4315.7	20.87	48.5

Table 16(a). NASA Core HP Turbine Flow Diagrams - Cold Test, 110% Speed.

POINT NO. 3084 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	91.	328.	91.	306.	91.	287.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M□2)	377.3	237.4	377.3	253.0	377.3	265.8
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	396.	444.	403.	444.	408.
MACH NUMBER	;		0.215	0.825	0.215	0.762	0.214	0.711

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	166.	386.	140.	390.	122.	394.
REL. FLOW ANGLE	;	(DEGREES)	44.	62.	32.	61.	19.	60.
STATIC PRESSURE	;	(KN/M□2)	237.4	127.1	253.0	129.3	265.8	130.8
TOTAL TEMP.	;	(DEG. KELVIN)	448.	367.	448.	368.	448.	369.
STATIC TEMP.	;	(DEG. KELVIN)	396.	336.	403.	337.	408.	338.
REL. MACH NO.	;		0.415	1.053	0.347	1.061	0.300	1.069
WHEEL VELOCITY	;	(M/SEC)	192.	192.	209.	209.	225.	225.

Table 16(a). NASA Core HP Turbine Flow Diagrams - Cold Test, 110% Speed (Continued).

POINT NO. 2584 110% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	90.	324.	90.	302.	90.	283.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.6	241.0	377.6	256.4	377.6	268.9
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	397.	444.	404.	444.	409.
MACH NUMBER	:		0.213	0.811	0.213	0.750	0.213	0.699

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	161.	335.	136.	342.	119.	346.
REL. FLOW ANGLE	:	(DEGREES)	44.	62.	31.	61.	17.	60.
STATIC PRESSURE	:	(KN/M**2)	241.0	156.5	256.4	157.7	268.9	158.6
TOTAL TEMP.	:	(DEG. KELVIN)	448.	376.	448.	377.	448.	377.
STATIC TEMP.	:	(DEG. KELVIN)	397.	354.	404.	355.	409.	356.
REL. MACH NO.	:		0.403	0.891	0.338	0.908	0.293	0.918
WHEEL VELOCITY	:	(M/SEC)	192.	192.	209.	209.	225.	225.

Table 16(a). NASA Core HP Turbine Flow Diagrams - Cold Test, 110% Speed (Continued).

POINT NO. 2184 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	90.	317.	90.	296.	90.	278.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.6	246.0	377.6	260.9	377.6	273.2
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	399.	444.	406.	444.	411.
MACH NUMBER	;		0.211	0.793	0.211	0.733	0.211	0.684

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	155.	301.	131.	3[illegible].	115.	314.
REL. FLOW ANGLE	;	(DEGREES)	43.	62.	30.	61.	15.	60.
STATIC PRESSURE	;	(KN/M**2)	246.0	177.1	260.9	177.7	273.2	178.2
TOTAL TEMP.	;	(DEG. KELVIN)	448.	383.	448.	383.	448.	384.
STATIC TEMP.	;	(DEG. KELVIN)	399.	367.	406.	367.	411.	367.
REL. MACH NO.	;		0.388	0.786	0.325	0.809	0.283	0.819
WHEEL VELOCITY	;	(M/SEC)	192.	192.	209.	209.	225.	225.

Table 16(a). NASA Core HP Turbine Flow Diagrams - Cold Test, 110% Speed (Concluded).

POINT NO. 1984 110% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	87.	303.	87.	282.	87.	265.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	378.3	256.7	378.3	270.7	378.3	282.2
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	404.	444.	409.	444.	414.
MACH NUMBER	;		0.206	0.752	0.206	0.696	0.206	0.650

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	142.	270.	121.	281.	108.	283.
REL. FLOW ANGLE	;	(DEGREES)	40.	62.	26.	61.	10.	60.
STATIC PRESSURE	;	(KN/M**2)	256.7	198.6	270.7	198.8	282.2	199.0
TOTAL TEMP.	;	(DEG. KELVIN)	448.	390.	448.	391.	448.	392.
STATIC TEMP.	;	(DEG. KELVIN)	404.	378.	409.	378.	414.	378.
REL. MACH NO.	;		0.353	0.694	0.298	0.723	0.264	0.726
WHEEL VELOCITY	;	(M/SEC)	192.	192.	209.	209.	225.	225.

Table 16(b). NASA Core E^3 Turbine Flow Diagrams - Cold Test, 100% Speed.

POINT NO. 3076 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	91.	332.	91.	310.	91.	291.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.2	234.3	377.2	250.1	377.2	263.2
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	394.	444.	401.	444.	407.
MACH NUMBER	;		0.216	0.837	0.216	0.773	0.215	0.721

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	182.	362.	154.	366.	132.	369.
REL. FLOW ANGLE	;	(DEGREES)	49.	62.	39.	61.	29.	60.
STATIC PRESSURE	;	(KN/M**2)	234.3	141.7	250.1	143.9	263.2	145.7
TOTAL TEMP.	;	(DEG. KELVIN)	448.	375.	448.	375.	448.	375.
STATIC TEMP.	;	(DEG. KELVIN)	394.	346.	401.	347.	407.	348.
REL. MACH NO.	;		0.457	0.971	0.384	0.981	0.326	0.989
WHEEL VELOCITY	;	(M/SEC)	174.	174.	190.	190.	205.	205.

Table 16(b). NASA Core HP Turbine Flow Diagrams - Cold Test, 100% Speed (Continued).

POINT NO. 2476 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	91.	330.	91.	308.	91.	289.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M¤2)	377.3	236.1	377.3	251.8	377.3	264.8
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	395.	444.	402.	444.	407.
MACH NUMBER	;		0.215	0.831	0.215	0.768	0.215	0.716

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	180.	336.	152.	342.	131.	346.
REL. FLOW ANGLE	;	(DEGREES)	48.	62.	39.	61.	28.	60.
STATIC PRESSURE	;	(KN/M¤2)	236.1	156.6	251.8	158.3	264.8	159.6
TOTAL TEMP.	;	(DEG. KELVIN)	448.	379.	448.	379.	448.	379.
STATIC TEMP.	;	(DEG. KELVIN)	395.	356.	402.	356.	407.	357.
REL. MACH NO.	;		0.452	0.890	0.379	0.905	0.323	0.914
WHEEL VELOCITY	;	(M/SEC)	174.	174.	190.	190.	205.	205.

Table 16(b). NASA Core HP Turbine Flow Diagrams - Cold Test, 100% Speed (Continued).

POINT NO. 2176 | 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	90.	317.	90.	296.	90.	278.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.7	246.0	377.7	260.9	377.7	273.2
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	399.	444.	406.	444.	411.
MACH NUMBER	:		0.211	0.793	0.211	0.733	0.211	0.684

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	168.	293.	142.	302.	122.	305.
REL. FLOW ANGLE	:	(DEGREES)	47.	62.	37.	61.	24.	60.
STATIC PRESSURE	:	(KN/M**2)	246.0	184.1	260.9	185.0	273.2	185.6
TOTAL TEMP.	:	(DEG. KELVIN)	448.	387.	448.	387.	448.	388.
STATIC TEMP.	:	(DEG. KELVIN)	399.	371.	406.	371.	411.	371.
REL. MACH NO.	:		0.418	0.760	0.351	0.783	0.300	0.792
WHEEL VELOCITY	:	(M/SEC)	174.	174.	190.	190.	205.	205.

Table 16(b). NASA Core HP Turbine Flow Diagrams - Cold Test, 100% Speed (Concluded).

POINT NO. 1976 — 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	87.	303.	87.	282.	87.	265.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	378.3	256.7	378.3	270.7	378.3	282.2
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	404.	444.	409.	444.	414.
MACH NUMBER	:		0.206	0.752	0.206	0.696	0.206	0.650

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	154.	266.	130.	276.	113.	278.
REL. FLOW ANGLE	:	(DEGREES)	45.	62.	33.	61.	20.	60.
STATIC PRESSURE	:	(KN/M**2)	256.7	203.7	270.7	204.1	282.2	204.5
TOTAL TEMP.	:	(DEG. KELVIN)	448.	393.	448.	393.	448.	394.
STATIC TEMP.	:	(DEG. KELVIN)	404.	381.	409.	381.	414.	381.
REL. MACH NO.	:		0.382	0.680	0.321	0.707	0.277	0.712
WHEEL VELOCITY	:	(M/SEC)	174.	174.	190.	190.	205.	205.

Table 16(c). NASA Core HP Turbine Flow Diagrams - Cold Test, 90% Speed.

POINT NO. 2669 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	92.	337.	92.	314.	92.	295.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.1	231.2	377.1	247.3	377.1	260.6
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	393.	444.	400.	444.	406.
MACH NUMBER	;		0.217	0.849	0.217	0.784	0.217	0.731

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	199.	363.	170.	366.	146.	368.
REL. FLOW ANGLE	;	(DEGREES)	52.	62.	45.	61.	36.	60.
STATIC PRESSURE	;	(KN/M**2)	231.2	142.4	247.3	145.3	260.6	147.7
TOTAL TEMP.	;	(DEG. KELVIN)	448.	379.	448.	379.	448.	379.
STATIC TEMP.	;	(DEG. KELVIN)	393.	348.	400.	348.	406.	349.
REL. MACH NO.	;		0.502	0.972	0.424	0.979	0.362	0.984
WHEEL VELOCITY	;	(M/SEC)	157.	157.	171.	171.	185.	185.

Table 16(c). NASA Core HP Turbine Flow Diagrams - Cold Test, 90% Speed (Continued).

POINT NO. 2469 90% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	92.	334.	92.	311.	92.	292.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.2	233.4	377.2	249.4	377.2	262.5
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	394.	444.	401.	444.	407.
MACH NUMBER	;		0.216	0.841	0.216	0.778	0.216	0.724

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	196.	343.	168.	347.	144.	350.
REL. FLOW ANGLE	;	(DEGREES)	52.	62.	45.	61.	36.	60.
STATIC PRESSURE	;	(KN/M**2)	233.4	154.4	249.4	156.8	262.5	158.8
TOTAL TEMP.	;	(DEG. KELVIN)	448.	382.	448.	382.	448.	382.
STATIC TEMP.	;	(DEG. KELVIN)	394.	355.	401.	355.	407.	356.
REL. MACH NO.	;		0.495	0.909	0.418	0.921	0.356	0.927
WHEEL VELOCITY	;	(M/SEC)	157.	157.	171.	171.	185.	185.

Table 16(c). NASA Core HP Turbine Flow Diagrams - Cold Test, 90% Speed (Continued).

POINT NO. 2169 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	90.	323.	90.	301.	90.	282.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M¤2)	377.5	241.8	377.5	257.0	377.5	269.6
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	397.	444.	404.	444.	409.
MACH NUMBER	:		0.213	0.809	0.213	0.748	0.213	0.698

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	186.	300.	158.	307.	136.	311.
REL. FLOW ANGLE	:	(DEGREES)	51.	62.	43.	61.	34.	60.
STATIC PRESSURE	:	(KN/M¤2)	241.8	181.2	257.0	182.8	269.6	183.9
TOTAL TEMP.	:	(DEG. KELVIN)	448.	389.	448.	389.	448.	389.
STATIC TEMP.	:	(DEG. KELVIN)	397.	370.	404.	369.	409.	370.
REL. MACH NO.	:		0.466	0.779	0.393	0.799	0.335	0.807
WHEEL VELOCITY	:	(M/SEC)	157.	157.	171.	171.	185.	185.

Table 16(c). NASA Core HP Turbine Flow Diagrams - Cold Test, 90% Speed (Concluded).

POINT NO. 1969 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	87.	303.	87.	282.	87.	265.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	378.3	256.7	378.3	270.7	378.3	282.2
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	404.	444.	409.	444.	414.
MACH NUMBER	:		0.206	0.752	0.206	0.696	0.206	0.650

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	167.	261.	141.	271.	121.	274.
REL. FLOW ANGLE	:	(DEGREES)	49.	62.	40.	61.	29.	60.
STATIC PRESSURE	:	(KN/M**2)	256.7	208.8	270.7	209.6	282.2	210.2
TOTAL TEMP.	:	(DEG. KELVIN)	448.	397.	448.	397.	448.	397.
STATIC TEMP.	:	(DEG. KELVIN)	404.	383.	409.	383.	414.	383.
REL. MACH NO.	:		0.414	0.666	0.348	0.692	0.297	0.697
WHEEL VELOCITY	:	(M/SEC)	157.	157.	171.	171.	185.	185.

C-3

Table 16(d). NASA Core HP Turbine Flow Diagrams - Cold Test, 70% Speed

POINT NO. 2653 — 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	93.	346.	93.	323.	93.	303.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	376.9	224.1	376.9	240.7	376.9	254.5
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	389.	444.	397.	444.	403.
MACH NUMBER	;		0.219	0.877	0.219	0.810	0.219	0.754

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	237.	366.	207.	366.	181.	366.
REL. FLOW ANGLE	;	(DEGREES)	58.	62.	53.	61.	49.	60.
STATIC PRESSURE	;	(KN/M**2)	224.1	143.7	240.7	148.3	254.5	152.0
TOTAL TEMP.	;	(DEG. KELVIN)	448.	389.	448.	388.	448.	388.
STATIC TEMP.	;	(DEG. KELVIN)	389.	352.	397.	352.	403.	353.
REL. MACH NO.	;		0.600	0.974	0.519	0.973	0.450	0.972
WHEEL VELOCITY	;	(M/SEC)	122.	122.	133.	133.	144.	144.

Table 16(d). NASA Core HP Turbine Flow Diagrams - Cold Test, 70% Speed (Continued).

POINT NO. 2453 | 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	93.	345.	93.	321.	93.	302.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	376.9	225.4	376.9	241.5	376.9	255.7
TOTAL TEMP.	:	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	:	(DEG. KELVIN)	444.	390.	444.	398.	444.	404.
MACH NUMBER	:		0.219	0.872	0.219	0.805	0.219	0.750

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	236.	352.	206.	353.	180.	353.
REL. FLOW ANGLE	:	(DEGREES)	58.	62.	53.	61.	48.	60.
STATIC PRESSURE	:	(KN/M**2)	225.4	152.1	241.5	156.4	255.7	159.7
TOTAL TEMP.	:	(DEG. KELVIN)	448.	391.	448.	390.	448.	389.
STATIC TEMP.	:	(DEG. KELVIN)	390.	357.	398.	357.	404.	358.
REL. MACH NO.	:		0.596	0.930	0.515	0.932	0.446	0.933
WHEEL VELOCITY	:	(M/SEC)	122.	122.	133.	133.	144.	144.

Table 16(d). NASA Core HP Turbine Flow Diagrams - Cold Test, 70% Speed (Continued).

POINT NO. 2153 | 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	91.	333.	91.	311.	91.	292.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.2	233.9	377.2	249.8	377.2	262.9
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	394.	444.	401.	444.	407.
MACH NUMBER	;		0.216	0.839	0.216	0.783	0.216	0.723

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	225.	308.	196.	313.	171.	315.
REL. FLOW ANGLE	;	(DEGREES)	58.	62.	53.	61.	47.	60.
STATIC PRESSURE	;	(KN/M**2)	233.9	179.5	249.8	182.6	262.9	185.0
TOTAL TEMP.	;	(DEG. KELVIN)	448.	396.	448.	396.	448.	395.
STATIC TEMP.	;	(DEG. KELVIN)	394.	372.	401.	372.	407.	372.
REL. MACH NO.	;		0.565	0.798	0.487	0.810	0.422	0.815
WHEEL VELOCITY	;	(M/SEC)	122.	122.	133.	133.	144.	144.

Table 16(d). NASA Core HP Turbine Flow Diagrams - Cold Test, 70% Speed (Concluded).

POINT NO. 1953 — 70% SPEED

STATOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	90.	317.	90.	296.	90.	278.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.7	246.0	377.7	260.9	377.7	273.2
TOTAL TEMP.	;	(DEG. KELVIN)	448.	448.	448.	448.	448.	448.
STATIC TEMP.	;	(DEG. KELVIN)	444.	399.	444.	406.	444.	411.
MACH NUMBER	;		0.211	0.793	0.211	0.733	0.211	0.684

ROTOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	208.	275.	181.	282.	157.	285.
REL. FLOW ANGLE	;	(DEGREES)	57.	62.	51.	61.	45.	60.
STATIC PRESSURE	;	(KN/M**2)	246.0	202.5	260.9	204.6	273.2	206.4
TOTAL TEMP.	;	(DEG. KELVIN)	448.	401.	448.	401.	448.	400.
STATIC TEMP.	;	(DEG. KELVIN)	399.	383.	406.	382.	411.	382.
REL. MACH NO.	;		0.521	0.703	0.448	0.721	0.387	0.728
WHEEL VELOCITY	;	(M/SEC)	122.	122.	133.	133.	144.	144.

Table 17. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine).

a. 110% $N/\sqrt{T_{TO}}$, T_{TO} = 783 K, P_{TO} = 389.5 kN/m^2

Test Point No.	3011		2411		2111	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	17.0	12.2	33.0	28.2	15.5	10.7
125	---	---	---	---	14.0	9.2
150	21.0	16.2	24.0	19.2	---	---
300	---	---	---	---	16.0	11.2
401	13.0	8.2	11.0	6.2	---	---
525	18.0	13.2	17.0	12.2	15.0	10.2
750	21.0	16.2	13.0	8.2	---	---
770	---	---	---	---	16.0	11.2
1000	11.0	6.2	17.0	12.2	14.0	9.2
1175	14.0	9.2	17.0	12.2	11.0	6.2
2nd Harmonic, Hz						
167	0	0	21.0	16.2	8.0	3.2
250	---	---	---	---	11.0	6.2
300	4.0	0	5.0	0.2	---	---
600	---	---	---	---	12.0	7.2
802	18.0	13.2	16.0	11.2	---	---
1050	6.0	1.2	9.0	4.2	15.0	10.2
1500	15.0	10.2	3.0	0	---	---
1539	---	---	---	---	1.0	0
2000	10.0	5.2	15.0	10.2	17.0	12.2
2350	13.0	8.2	18.0	13.2	11.0	6.2
3rd Harmonic, Hz						
250	10.0	5.2	11.0	6.2	4.0	0
375	---	---	---	---	15.0	10.2
450	12.0	7.2	10.0	5.2	---	---
900	---	---	---	---	7.0	2.2
1204	0	0	4.0	0	---	---
1575	-15.0	0	13.0	8.2	-1.0	0
2250	2.0	0	8.0	3.2	---	---
2309	---	---	---	---	9.0	4.2
3000	19.0	14.2	18.0	13.2	13.0	8.2
3525	22.0	17.2	32.0	27.2	18.0	13.2
$\overline{\Delta dB}\Big\|_{1200}^{200}$ =		7.3		7.1		7.6

Table 17. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine)(Continued).

b. 100% $N/\sqrt{T_{TO}}$, T_{TO} = 783 K, P_{TO} = 389.5 kN/m^2

Test Point No.	3010		2410		2110		1910	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	28.0	23.2	22.0	17.2	20.7	15.9	---	---
125	---	---	---	---	12.7	7.9	---	---
150	26.0	21.2	28.0	23.2	---	---	19.0	14.2
300	16.0	11.2	---	---	20.7	15.9	---	---
401	---	---	11.0	6.2	---	---	12.0	7.2
525	19.0	14.2	15.0	10.2	11.0	6.2	14.0	9.2
750	13.0	8.2	---	---	---	---	20.0	15.2
770	---	---	12.0	7.2	13.3	8.5	---	---
1000	9.0	4.2	12.0	7.2	10.0	5.2	12.0	7.2
1175	15.0	10.2	23.0	18.2	12.3	7.5	7.0	2.2
2nd Harmonic, Hz								
167	17.0	12.2	10.0	5.2	7.7	2.9	---	---
250	---	---	---	---	13.3	8.5	---	---
300	8.0	3.2	9.0	4.2	---	---	7.0	2.2
600	19.0	14.2	---	---	12.7	7.9	---	---
802	---	---	13.0	8.2	---	---	11.0	6.2
1050	-8.0	0	8.0	3.2	12.0	7.2	6.0	1.2
1500	2.0	0	---	---	---	---	0	0
1539	---	---	3.0	0	2.6	0	---	---
2000	14.0	9.2	18.0	13.2	12.0	7.2	10.0	5.2
2350	15.0	10.2	17.0	12.2	14.7	9.9	8.0	3.2
3rd Harmonic, Hz								
350	11.0	6.2	11.0	6.2	12.3	7.5	---	---
375	---	---	---	---	18.4	13.6	---	---
450	10.0	5.2	10.0	5.2	---	---	8.0	3.2
900	1.0	0	---	---	11.3	6.5	---	---
1204	---	---	2.0	0	---	---	-3.0	0
1575	-29.0	0	-13.0	0	9.3	4.5	-16.0	0
2250	6.0	1.2	---	---	---	---	2.0	0
2309	---	---	7.0	2.2	13.6	8.8	---	---
3000	20.0	15.2	22.0	17.2	20.3	15.5	12.0	7.2
3525	26.0	21.2	33.0	28.2	21.0	16.2	19.0	14.2
$\overline{\Delta dB}\Big\vert_{1200}^{200}$ =		7.0		6.9		8.6		5.4

Table 17. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine) (Continued).

c. 90% $N/\sqrt{T_{TO}}$, T_{TO} = 783 K, P_{TO} = 389.5 kN/m^2

Test Point No.	2691		2491		2191		1991	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	---	---	20.0	15.2	19.0	14.2	---	---
125	---	---	---	---	19.0	14.2	---	---
150	13.0	8.2	19.0	14.2	---	---	16.0	11.2
300	---	---	---	---	22.0	17.2	---	---
401	13.0	8.2	10.0	5.2	---	---	10.0	5.2
525	17.0	12.2	16.0	11.2	14.0	9.2	12.0	7.2
750	16.0	11.2	10.0	5.2	12.0	7.2	---	---
770	---	---	---	---	---	---	---	---
1000	10.0	5.2	12.0	7.2	12.0	7.2	---	---
1175	15.0	10.2	22.0	17.2	24.0	19.2	---	---
2nd Harmonic, Hz								
167	---	---	13.0	8.2	17.0	12.2	---	---
250	---	---	---	---	13.0	8.2	---	---
300	2.0	0	20.0	15.2	---	---	6.0	1.2
600	---	---	---	---	10.0	5.2	---	---
802	17.0	12.2	13.0	8.2	---	---	1.0	6.2
1050	7.0	2.2	11.0	6.2	20.0	15.2	-3.0	0
1500	3.0	0	8.0	3.2	5.0	0.2	---	---
1539	---	---	---	---	---	---	---	---
2000	13.0	8.2	19.0	14.2	21.0	16.2	---	---
2350	17.0	12.2	17.0	12.2	12.0	7.2	---	---
3rd Harmonic, Hz								
250	---	---	9.0	4.2	9.0	4.2	---	---
375	---	---	---	---	18.0	13.2	---	---
450	10.0	5.2	12.0	7.2	---	---	9.0	4.2
900	---	---	---	---	20.0	15.2	---	---
1204	1.0	0	11.0	6.2	---	---	2.0	0
1575	-13.0	0	3.0	0	5.0	0.2	-23.0	0
2250	5.0	0.2	11.0	6.2	14.0	9.2	---	---
2309	---	---	---	---	---	---	---	---
3000	12.0	7.2	13.0	8.2	19.0	14.2	---	---
3525	21.0	16.2	23.0	18.2	27.0	22.2	---	---
$\Delta\overline{dB}\Big\vert_{1200}^{200}$ =		6.7		8.5		11.0		3.7

Table 17. Blade-Row Attenuation, ΔdB, (NASA Core High Pressure Turbine)(Concluded).

d. 70% $N/\sqrt{T_{TO}}$, T_{TO} = 783 K, P_{TO} = 389.5 kN/m^2

Test Point No.	2671		2471		2171		1971	
Fund. Freq., Hz	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL	ΔSPL	ΔPWL
83	---	---	16.0	11.2	15.0	10.2	---	---
125	---	---	---	---	13.0	8.2	---	---
150	31.0	26.2	31.0	26.2	---	---	23.0	18.2
300	---	---	---	---	16.0	11.2	---	---
401	13.0	8.2	11.0	6.2	10.0	5.2	11.0	6.2
525	15.0	10.2	14.0	9.2	---	---	13.0	8.2
750	17.0	12.2	15.0	10.2	4.0	0	12.0	7.2
770	---	---	---	---	---	---	---	---
1000	10.0	5.2	13.0	8.2	9.0	4.2	12.0	7.2
1175	11.0	6.2	11.0	6.2	15.0	10.2	14.0	9.2
2nd Harmonic, Hz								
167	---	---	15.0	10.2	12.0	7.2	---	---
250	---	---	---	---	11.0	6.2	---	---
300	17.0	12.2	25.0	20.2	---	---	4.0	0
600	---	---	---	---	11.0	6.2	---	---
802	15.0	10.2	13.0	8.2	9.0	4.2	12.0	7.2
1050	2.0	0	6.0	1.2	---	---	8.0	3.2
1500	6.0	1.2	3.0	0	9.0	4.2	-3.0	0
1539	---	---	---	---	---	---	---	---
2000	1.0	0	21.0	16.2	16.0	11.2	17.0	12.2
2350	13.0	8.2	4.0	0	19.0	14.2	12.0	7.2
3rd Harmonic, Hz								
250	---	---	12.0	7.2	6.0	1.2	---	---
375	---	---	---	---	14.0	9.2	---	---
450	17.0	12.0	18.0	13.2	---	---	8.0	3.2
900	---	---	---	---	13.0	8.2	---	---
1204	5.0	0.2	12.0	7.2	6.0	1.2	-1.0	0
1575	-20.0	0	-3.0	0	---	---	-12.0	0
2250	-1.0	0	30.0	25.2	17.0	12.2	6.0	1.2
2309	---	---	---	---	---	---	---	---
3000	4.0	0	13.0	8.2	24.0	19.2	19.2	14.2
3525	20.0	15.2	14.0	9.2	34.0	29.2	24.0	19.2
$\Delta\overline{dB}\Big\|_{1200}^{200}$ =		7.7		8.8		5.6		5.2

Table 18. Aerodynamic Performance Parameters, Hot High Pressure Turbine.

- P_{T0} = 389.5 kN/m^2 (56.5 psia), T_{T0} = 783 K (1410° R)

%N/$\sqrt{T}$	Test Point	P_{T0}/P_{T2}	P_{T0}/P_{T2} Measur. Plane	W_2 Corr. (lbm/sec)	W_2 Corr. (kg/sec)	$N/\sqrt{T_{T0}/T_{STD}}$	P_{SH}/W_2 (Btu/lbm)	P_{SH}/W_2 (kJ/kg)
110	3011	2.235	3.02	26.27	11.92	6684.2	58.86	136.9
	2411	2.05	2.48	26.26	11.91	6675.7	58.93	123.1
	2111	1.88	2.13	25.99	11.79	6679.7	46.84	108.9
100	3010	2.20	3.01	26.30	11.93	6160.0	57.29	133.3
	2410	2.03	2.48	26.35	11.95	6163.8	51.66	120.2
	2110	1.86	2.13	26.11	11.84	6167.9	46.11	107.3
	1910	1.84	2.13	25.72	11.67	6174.8	40.08	93.2
90	2691	2.055	2.67	26.41	11.98	5565.7	51.86	120.6
	2491	1.995	2.49	26.14	11.86	5548.3	50.78	118.1
	2191	1.83	2.13	26.20	11.88	5553.6	44.69	103.9
	1991	1.70	1.69	25.64	11.63	5571.4	39.74	92.4
70	2671	1.92	2.67	26.62	12.07	4360.8	45.58	106.0
	2471	1.87	2.48	26.71	12.12	4320.0	44.44	103.4
	2171	1.77	2.13	26.70	12.11	4313.8	40.89	93.7
	1971	1.665	1.89	26.21	11.89	4329.9	36.28	84.4

Table 19(a). NASA Core HP Turbine Flow Diagrams - Hot Test, 110% Speed.

POINT NO. 3011 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	118.	428.	118.	399.	118.	375.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.5	238.9	377.5	254.3	377.5	267.1
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	686.	764.	697.	764.	706.
MACH NUMBER	;		0.216	0.827	0.216	0.765	0.215	0.713

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	214.	507.	181.	512.	157.	517.
REL. FLOW ANGLE	;	(DEGREES)	44.	62.	32.	61.	18.	60.
STATIC PRESSURE	;	(KN/M**2)	238.9	128.5	254.3	130.6	267.1	132.2
TOTAL TEMP.	;	(DEG. KELVIN)	771.	639.	771.	640.	771.	641.
STATIC TEMP.	;	(DEG. KELVIN)	686.	587.	697.	589.	706.	592.
REL. MACH NO.	;		0.413	1.055	0.346	1.063	0.299	1.071
WHEEL VELOCITY	;	(M/SEC)	253.	253.	275.	275.	297.	297.

Table 19(a). NASA Core HP Turbine Flow Diagrams - Hot Test, 110% Speed (Continued).

POINT NO. 2411 110% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	118.	423.	118.	394.	118.	370.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M□2)	377.7	242.1	377.7	257.4	377.7	269.8
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	688.	764.	699.	764.	708.
MACH NUMBER	;		0.215	0.815	0.215	0.754	0.213	0.703

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	209.	440.	177.	449.	154.	455.
REL. FLOW ANGLE	;	(DEGREES)	43.	62.	31.	[illegible]	16.	60.
STATIC PRESSURE	;	(KN/M□2)	242.1	157.5	257.4	158.6	269.8	159.5
TOTAL TEMP.	;	(DEG. KELVIN)	771.	653.	771.	654.	771.	656.
STATIC TEMP.	;	(DEG. KELVIN)	688.	618.	699.	618.	708.	620.
REL. MACH NO.	;		0.403	0.894	0.337	0.912	0.293	0.922
WHEEL VELOCITY	;	(M/SEC)	253.	253.	275.	275.	297.	297.

Table 19(a). NASA Core HP Turbine Flow Diagrams - Hot Test, 110% Speed (Concluded).

POINT NO. 2111 110% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	116.	410.	116.	382.	116.	358.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M2)	378.0	249.8	378.0	264.3	378.0	276.3
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	693.	764.	704.	764.	712.
MACH NUMBER	:		0.211	0.786	0.211	0.728	0.210	0.679

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	197.	386.	167.	399.	147.	403.
REL. FLOW ANGLE	:	(DEGREES)	41.	62.	28.	61.	13.	60.
STATIC PRESSURE	:	(KN/M2)	249.8	183.0	264.3	183.5	276.3	183.9
TOTAL TEMP.	:	(DEG. KELVIN)	771.	667.	771.	668.	771.	669.
STATIC TEMP.	:	(DEG. KELVIN)	693.	642.	704.	642.	712.	643.
REL. MACH NO.	:		0.378	0.769	0.318	0.794	0.279	0.801
WHEEL VELOCITY	:	(M/SEC)	253.	253.	275.	275.	297.	297.

Table 19(b). NASA Core HP Turbine Flow Diagrams - Hot Test, 100% Speed.

POINT NO. 3010 | 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	119.	434.	119.	404.	119.	380.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.4	235.9	377.4	251.6	377.4	264.5
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	684.	764.	696.	764.	704.
MACH NUMBER	:		0.217	0.838	0.217	0.775	0.216	0.723

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	236.	524.	199.	526.	171.	528.
REL. FLOW ANGLE	:	(DEGREES)	48.	62.	39.	61.	28.	60.
STATIC PRESSURE	:	(KN/M**2)	235.9	122.8	251.6	125.7	264.5	128.0
TOTAL TEMP.	:	(DEG. KELVIN)	771.	642.	771.	643.	771.	643.
STATIC TEMP.	:	(DEG. KELVIN)	684.	581.	696.	584.	704.	586.
REL. MACH NO.	:		0.455	1.094	0.381	1.097	0.325	1.100
WHEEL VELOCITY	:	(M/SEC)	230.	230.	250.	250.	270.	270.

Table 19(b). NASA Core HP Turbine Flow Diagrams - Hot Test, 100% Speed (Continued).

POINT NO. 2410 — 100% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	;	(M/SEC)	118.	428.	118.	399.	118.	374.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M□2)	377.5	239.5	377.5	255.0	377.5	267.6
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	687.	764.	697.	764.	706.
MACH NUMBER	;		0.216	0.825	0.216	0.763	0.214	0.712

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	;	(M/SEC)	230.	444.	194.	451.	167.	456.
REL. FLOW ANGLE	;	(DEGREES)	48.	62.	38.	61.	26.	60.
STATIC PRESSURE	;	(KN/M□2)	239.5	157.3	255.0	159.0	267.6	160.4
TOTAL TEMP.	;	(DEG. KELVIN)	771.	658.	771.	658.	771.	659.
STATIC TEMP.	;	(DEG. KELVIN)	687.	618.	697.	619.	706.	620.
REL. MACH NO.	;		0.443	0.901	0.371	0.916	0.317	0.924
WHEEL VELOCITY	;	(M/SEC)	230.	230.	250.	250.	270.	270.

Table 19(b). NASA Core HP Turbine Flow Diagrams - Hot Test, 100% Speed (Continued).

POINT NO. 2110 | 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	117.	416.	117.	388.	117.	364.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.8	246.1	377.8	260.9	377.8	273.2
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	691.	764.	702.	764.	709.
MACH NUMBER	;		0.213	0.801	0.213	0.741	0.212	0.691

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	219.	389.	185.	400.	160.	405.
REL. FLOW ANGLE	;	(DEGREES)	47.	62.	36.	61.	24.	60.
STATIC PRESSURE	;	(KN/M**2)	246.1	182.6	260.9	183.5	273.2	184.2
TOTAL TEMP.	;	(DEG. KELVIN)	771.	669.	771.	670.	771.	671.
STATIC TEMP.	;	(DEG. KELVIN)	691.	642.	702.	642.	709.	64[illegible].
REL. MACH NO.	;		0.421	0.774	0.353	0.797	0.302	0.806
WHEEL VELOCITY	;	(M/SEC)	230.	230.	250.	250.	270.	270.

Table 19(b). NASA Core HP Turbine Flow Diagrams - Hot Test, 100% Speed (Concluded).

POINT NO. 1910 | 100% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	114.	397.	114.	370.	114.	347.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	378.4	256.8	378.4	270.7	378.3	282.2
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	765.	698.	765.	708.	765.	715.
MACH NUMBER	;		0.208	0.760	0.208	0.703	0.207	0.657

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	201.	351.	170.	365.	148.	368.
REL. FLOW ANGLE	;	(DEGREES)	45.	62.	33.	61.	20.	60.
STATIC PRESSURE	;	(KN/M**2)	256.8	202.8	270.7	203.4	282.2	203.7
TOTAL TEMP.	;	(DEG. KELVIN)	771.	680.	771.	681.	771.	681.
STATIC TEMP.	;	(DEG. KELVIN)	698.	659.	708.	659.	715.	659.
REL. MACH NO.	;		0.385	0.690	0.323	0.717	0.279	0.722
WHEEL VELOCITY	;	(M/SEC)	230.	230.	250.	250.	270.	270.

Table 19(c). NASA Core HP Turbine Flow Diagrams - Hot Test, 90% Speed.

POINT NO. 2691 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	120.	440.	120.	410.	120.	385.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.3	232.5	377.3	248.4	377.3	261.6
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	682.	764.	693.	764.	702.
MACH NUMBER	;		0.218	0.852	0.218	0.788	0.217	0.734

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	259.	475.	221.	479.	189.	482.
REL. FLOW ANGLE	;	(DEGREES)	52.	62.	45.	61.	36.	60.
STATIC PRESSURE	;	(KN/M**2)	232.5	144.0	248.4	146.8	261.6	149.1
TOTAL TEMP.	;	(DEG. KELVIN)	771.	658.	771.	657.	771.	657.
STATIC TEMP.	;	(DEG. KELVIN)	682.	607.	693.	608.	702.	610.
REL. MACH NO.	;		0.501	0.972	0.424	0.979	0.361	0.984
WHEEL VELOCITY	;	(M/SEC)	207.	207.	225.	225.	243.	243.

Table 19(c). NASA Core HP Turbine Flow Diagrams - Hot Test, 90% Speed (Continued).

POINT NO. 2491 | 90% SPEED

STATOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	119.	437.	119.	407.	119.	382.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.3	234.3	377.3	250.1	377.3	263.2
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	683.	764.	694.	764.	703.
MACH NUMBER	;		0.218	0.845	0.218	0.781	0.217	0.729

ROTOR 1

			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	256.	451.	218.	457.	187.	460.
REL. FLOW ANGLE	;	(DEGREES)	52.	62.	44.	61.	36.	60.
STATIC PRESSURE	;	(KN/M**2)	234.3	154.8	250.1	157.2	263.2	159.1
TOTAL TEMP.	;	(DEG. KELVIN)	771.	662.	771.	662.	771.	662.
STATIC TEMP.	;	(DEG. KELVIN)	683.	618.	694.	618.	703.	619.
REL. MACH NO.	;		0.495	0.915	0.418	0.927	0.356	0.933
WHEEL VELOCITY	;	(M/SEC)	207.	207.	225.	225.	243.	243.

Table 19(c). NASA Core HP Turbine Flow Diagrams - Hot Test, 90% Speed (Continued).

POINT NO. 2191 | 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	118.	422.	118.	393.	118.	369.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.7	243.0	377.7	258.1	377.7	270.6
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	689.	764.	699.	764.	708.
MACH NUMBER	:		0.214	0.812	0.214	0.751	0.213	0.701

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	242.	394.	205.	403.	176.	408.
REL. FLOW ANGLE	:	(DEGREES)	51.	62.	43.	61.	33.	60.
STATIC PRESSURE	:	(KN/M**2)	243.0	182.1	258.1	183.6	270.6	184.7
TOTAL TEMP.	:	(DEG. KELVIN)	771.	674.	771.	674.	771.	674.
STATIC TEMP.	:	(DEG. KELVIN)	689.	643.	699.	643.	708.	643.
REL. MACH NO.	:		0.465	0.784	0.392	0.803	0.334	0.811
WHEEL VELOCITY	:	(M/SEC)	207.	207.	225.	225.	243.	243.

Table 19(c). NASA Core HP Turbine Flow Diagrams - Hot Test, 90% Speed (Concluded).

POINT NO. 1991 — 90% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	114.	397.	114.	370.	114.	347.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	378.4	256.8	378.4	270.4	378.4	282.2
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	765.	698.	765.	708.	765.	715.
MACH NUMBER	:		0.208	0.760	0.208	0.703	0.207	0.657

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	218.	345.	185.	358.	159.	361.
REL. FLOW ANGLE	:	(DEGREES)	49.	62.	40.	61.	29.	60.
STATIC PRESSURE	:	(KN/M**2)	256.8	208.1	270.4	208.9	282.2	209.5
TOTAL TEMP.	:	(DEG. KELVIN)	771.	686.	771.	686.	771.	686.
STATIC TEMP.	:	(DEG. KELVIN)	698.	664.	708.	664.	715.	664.
REL. MACH NO.	:		0.416	0.676	0.350	0.701	0.299	0.707
WHEEL VELOCITY	:	(M/SEC)	207.	207.	225.	225.	243.	243.

Table 19(d). NASA Core HP Turbine Flow Diagrams - Hot Test, 70% Speed.

POINT NO. 2671 | 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	;	(M/SEC)	121.	453.	121.	422.	121.	396.
FLOW ANGLE	;	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	;	(KN/M**2)	377.0	225.5	377.0	242.1	377.0	255.7
TOTAL TEMP.	;	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	;	(DEG. KELVIN)	764.	676.	764.	689.	764.	698.
MACH NUMBER	;		0.220	0.879	0.220	0.812	0.219	0.757

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	;	(M/SEC)	309.	488.	269.	488.	235.	487.
REL. FLOW ANGLE	;	(DEGREES)	58.	62.	53.	61.	48.	60.
STATIC PRESSURE	;	(KN/M**2)	225.5	141.4	242.1	146.1	255.7	149.9
TOTAL TEMP.	;	(DEG. KELVIN)	771.	673.	771.	672.	771.	672.
STATIC TEMP.	;	(DEG. KELVIN)	676.	609.	689.	611.	698.	613.
REL. MACH NO.	;		0.600	0.998	0.518	0.995	0.450	0.933
WHEEL VELOCITY	;	(M/SEC)	161.	161.	175.	175.	189.	189.

Table 19(d). NASA Core HP Turbine Flow Diagrams - Hot Test, 70% Speed (Continued).

POINT NO. 2471 | 70% SPEED

STATOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
VELOCITY	:	(M/SEC)	121.	451.	121.	421.	121.	395.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.1	226.5	377.1	242.9	377.1	256.6
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	677.	764.	689.	764.	699.
MACH NUMBER	:		0.220	0.876	0.220	0.809	0.219	0.754

ROTOR 1			HUB INLET	HUB EXIT	PITCH INLET	PITCH EXIT	TIP INLET	TIP EXIT
RELATIVE VEL.	:	(M/SEC)	307.	461.	268.	463.	234.	464.
REL. FLOW ANGLE	:	(DEGREES)	58.	62.	53.	61.	48.	60.
STATIC PRESSURE	:	(KN/M**2)	226.5	153.1	242.9	157.3	256.6	160.6
TOTAL TEMP.	:	(DEG. KELVIN)	771.	677.	771.	676.	771.	675.
STATIC TEMP.	:	(DEG. KELVIN)	677.	621.	689.	622.	699.	623.
REL. MACH NO.	:		0.596	0.933	0.516	0.936	0.4[illegible]7	0.937
WHEEL VELOCITY	:	(M/SEC)	161.	161.	175.	175.	189.	189.

Table 19(d). NASA Core HP Turbine Flow Diagrams - Hot Test, 70% Speed (Continued).

POINT NO. 2171 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	119.	434.	119.	404.	119.	380.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M*2)	377.4	236.2	377.4	251.9	377.4	264.9
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	684.	764.	696.	764.	704.
MACH NUMBER	:		0.217	0.838	0.217	0.775	0.216	0.723

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	290.	397.	253.	403.	220.	407.
REL. FLOW ANGLE	:	(DEGREES)	58.	62.	52.	61.	47.	60.
STATIC PRESSURE	:	(KN/M*2)	236.2	183.9	251.9	186.7	264.9	189.0
TOTAL TEMP.	:	(DEG. KELVIN)	771.	687.	771.	686.	771.	686.
STATIC TEMP.	:	(DEG. KELVIN)	684.	649.	696.	649.	704.	649.
REL. MACH NO.	:		0.561	0.786	0.484	0.799	0.419	0.805
WHEEL VELOCITY	:	(M/SEC)	161.	161.	175.	175.	189.	189.

Table 19(d). NASA Core HP Turbine Flow Diagrams - Hot Test, 70% Speed (Concluded).

POINT NO. 1971 — 70% SPEED

STATOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
VELOCITY	:	(M/SEC)	117.	416.	117.	388.	117.	364.
FLOW ANGLE	:	(DEGREES)	20.	69.	20.	68.	20.	67.
STATIC PRESSURE	:	(KN/M**2)	377.8	246.1	377.8	260.9	377.8	273.2
TOTAL TEMP.	:	(DEG. KELVIN)	771.	771.	771.	771.	771.	771.
STATIC TEMP.	:	(DEG. KELVIN)	764.	691.	764.	702.	764.	709.
MACH NUMBER	:		0.213	0.801	0.213	0.741	0.212	0.691

ROTOR 1			HUB		PITCH		TIP	
			INLET	EXIT	INLET	EXIT	INLET	EXIT
RELATIVE VEL.	:	(M/SEC)	273.	364.	237.	373.	206.	376.
REL. FLOW ANGLE	:	(DEGREES)	57.	62.	51.	61.	45.	60.
STATIC PRESSURE	:	(KN/M**2)	246.1	201.8	260.9	203.9	273.2	205.7
TOTAL TEMP.	:	(DEG. KELVIN)	771.	693.	771.	693.	771.	692.
STATIC TEMP.	:	(DEG. KELVIN)	691.	663.	702.	663.	709.	663.
REL. MACH NO.	:		0.525	0.713	0.452	0.730	0.390	0.737
WHEEL VELOCITY	:	(M/SEC)	161.	161.	175.	175.	189.	189.

APPENDIX C - COMPARISON OF DOWNSTREAM WALL AND PROBE KULITE MEASUREMENTS

Appendix C contains comparisons of the wall and probe Kulite measurements downstream of the 3-stage low pressure turbine.

Table 20. Three-Stage Low Pressure Turbine, Point 3042.

Fund. Freq., Hz	Downstream SPL Wall K5	Probe K9	$\overline{SPL}$
83	115	113	114
160	126	126	126
300	144	134	139
400	150	150	150
750	143	136	139.5
1,000	139	141	140
1,175	136	123	129.5
2nd Harmonic Hz	K5	K9	$\overline{SPL}$
167	(103)	(105)	104
320	127	110	118.5
600	128	122	125
800	118	124	121
1,500	120	126	123
2,000	125	115	120
2,350	123	119	121

Table 21. Three-Stage Low Pressure Turbine, Point 4042.

Fund. Freq., Hz	Downstream SPL Wall K5	Probe K9	$\overline{SPL}$
83	118	114	116
125	129	117	123
300	141	127	134
400	147	138	142.5
750	140	141	140.5
1,000	139	141	140
1,175	120	129	124.5
2nd Harmonic, Hz	K5	K9	$\overline{SPL}$
167	106	104	105
250	127	118	122.5
600	122	122	122
800	117	118	117.5
1,500	119	125	122
2,000	112	113	112.5
2,350	126	114	120

( ) Broadband Level

APPENDIX D - TYPICAL HIGH RESOLUTION NARROWBAND SPECTRA AND TYPICAL COHERENCE SPECTRA

Appendix D contains typical high resolution narrowband spectra from cold inlet and hot inlet high pressure turbine tests and typical coherence spectra from 1-stage and 3-stage low pressure turbine tests.

- High Pressure Turbine
- Siren = 375 RPM
- Inlet Temperature = 450° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.1 ; $N/\sqrt{T}$ = 100%

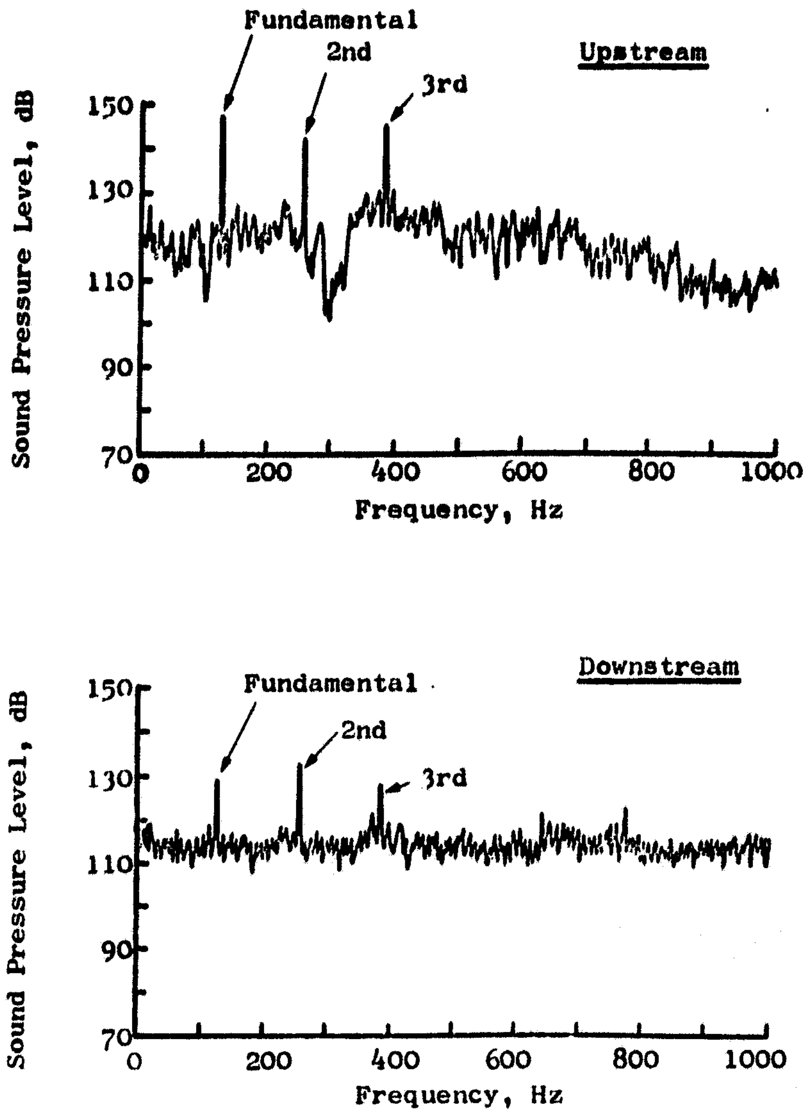


Figure 58. Typical High Resolution Narrowband Spectra (Cold Inlet HPT).

- High Pressure Turbine
- Siren = 900 RPM
- Inlet Temperature = 450° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.1 ; $N/\sqrt{T}$ = 90%

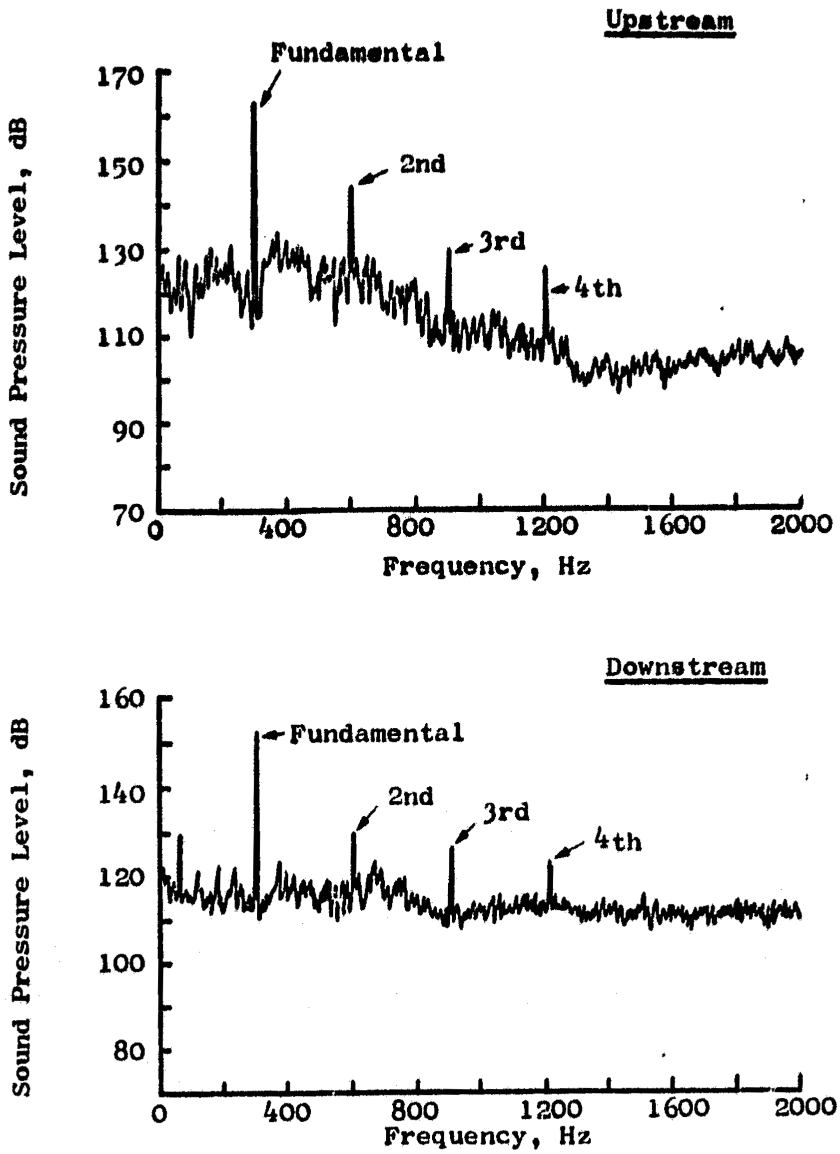


Figure 59. Typical High Resolution Narrowband Spectra (Cold Inlet HPT).

- High Pressure Turbine
- Siren = 3525 RPM
- Inlet Temperature = 450° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.4 ; N/$\sqrt{T}$ = 100%

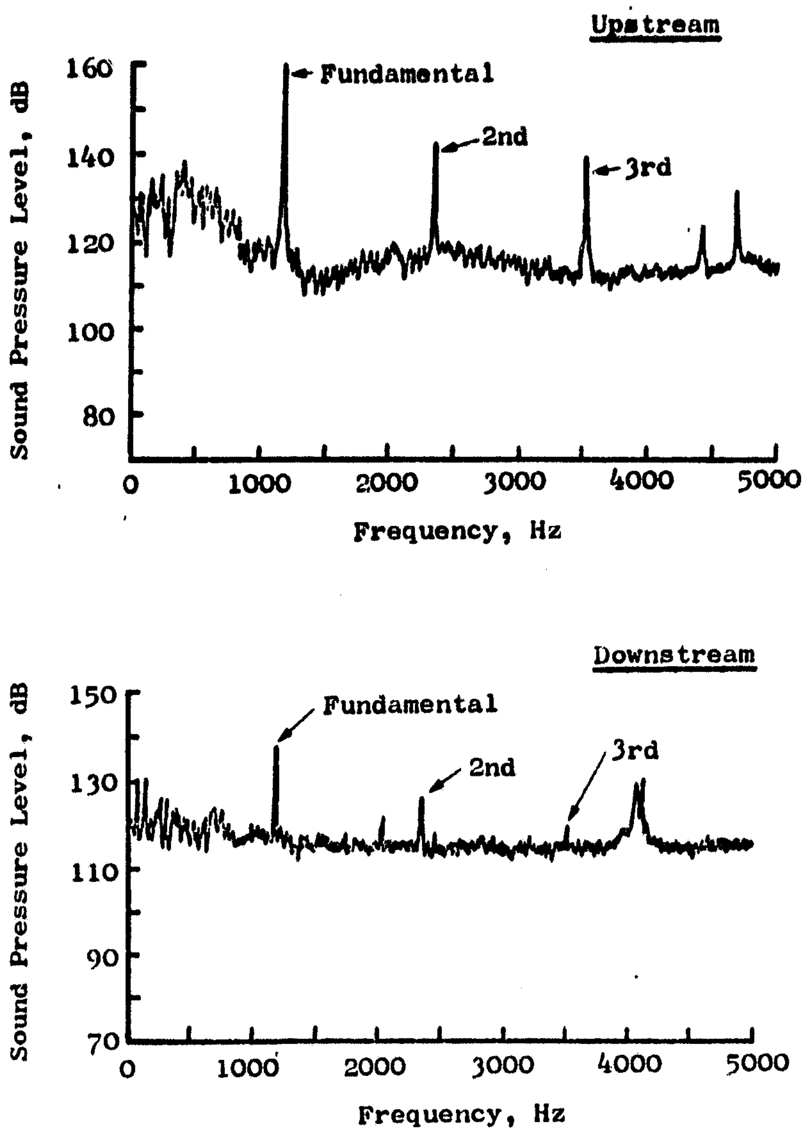


Figure 60. Typical High Resolution Narrowband Spectra (Cold Inlet HPT).

- High Pressure Turbine
- Siren = 2250 RPM
- Inlet Temperature = 783° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.1 ; $N/\sqrt{T}$ = 100%

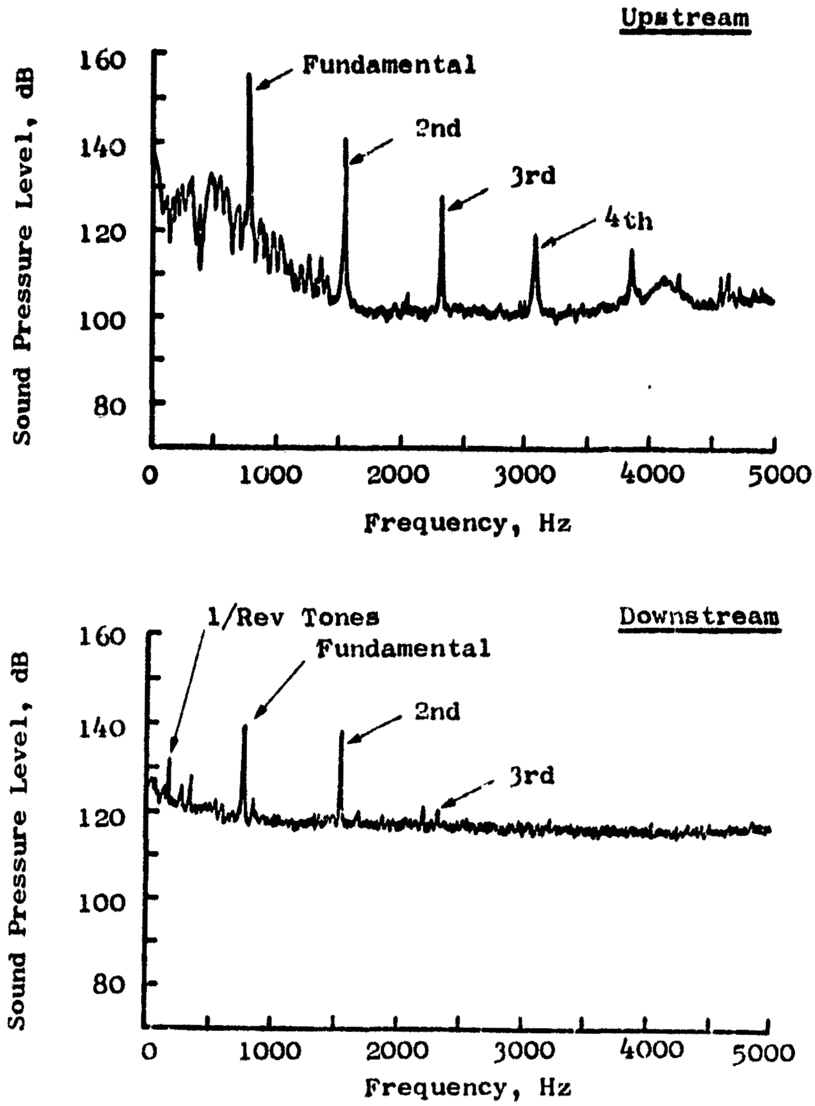


Figure 61. Typical High Resolution Narrowband Spectra (Hot Inlet HPT).

- High Pressure Turbine
- Siren = 2250 RPM
- Inlet Temperature = 783° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.6 ; $N/\sqrt{T}$ = 70%

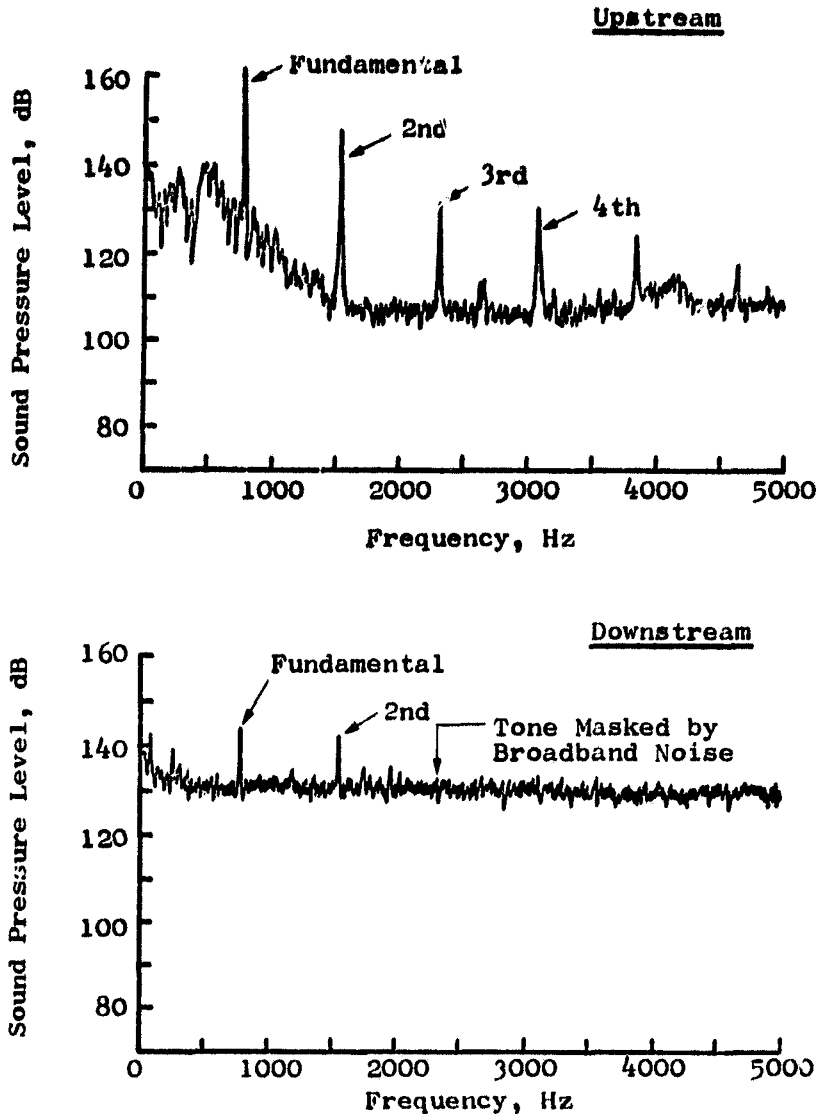
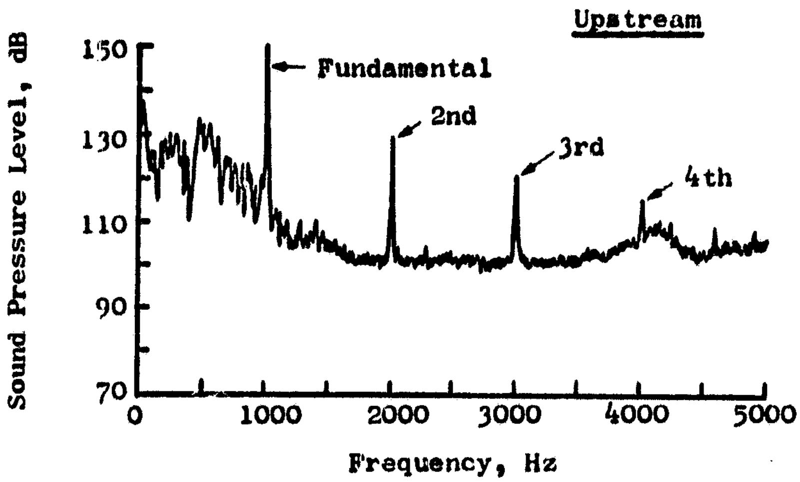


Figure 62. Typical High Resolution Narrowband Spectra (Hot Inlet HPT).

- High Pressure Turbine
- Siren = 3000 RPM
- Inlet Temperature = 783° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.1 ; $N/\sqrt{T}$ = 100%



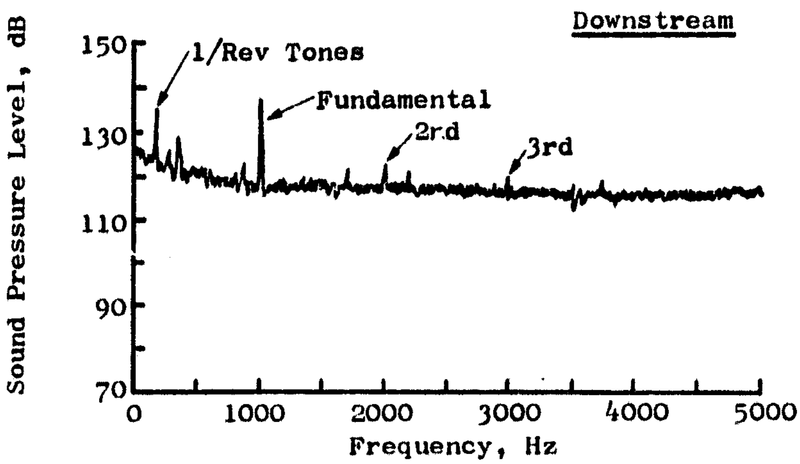


Figure 63. Typical High Resolution Narrowband Spectra (Hot Inlet HPT).

- High Pressure Turbine
- Siren = 3000 RPM
- Inlet Temperature = 783° K
- Inlet Pressure = 389.6 kN/m^2
- P_R = 2.1 ; $N/\sqrt{T}$ = 110%

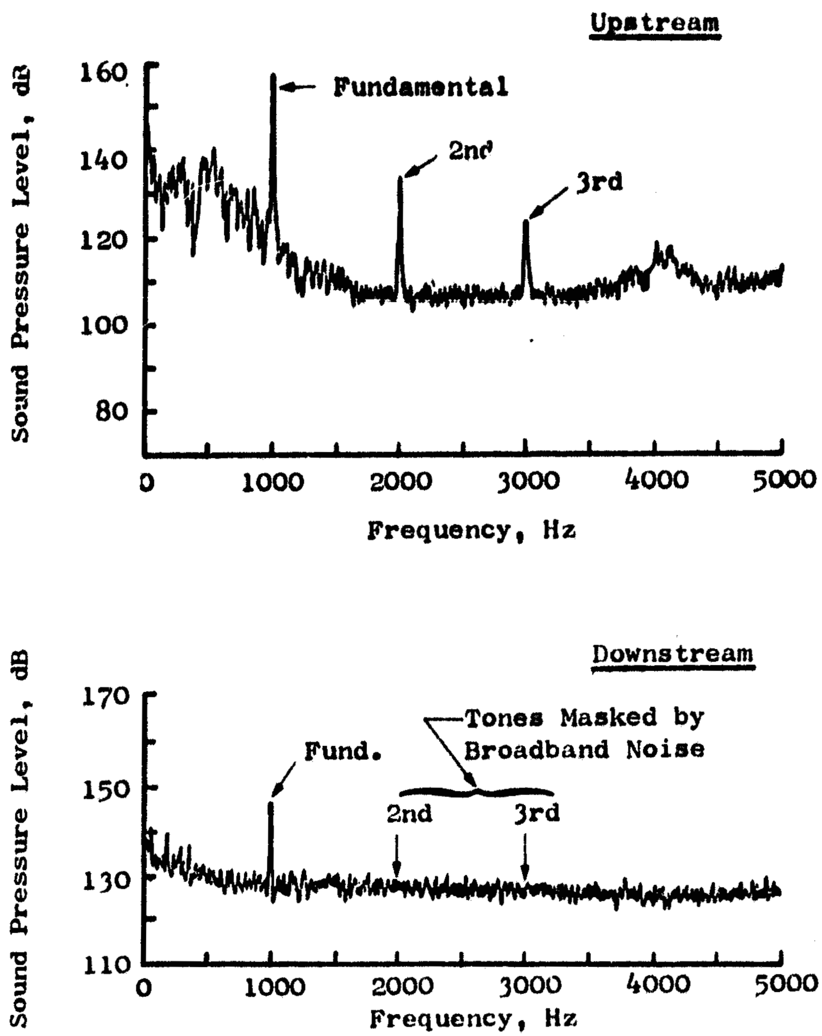


Figure 64. Typical High Resolution Narrowband Spectra (Hot Inlet HPT).

- Low Pressure Turbine - Single Stage
- Inlet Temperature = 422° K
- Inlet Pressure = 275.8 kN/m^2

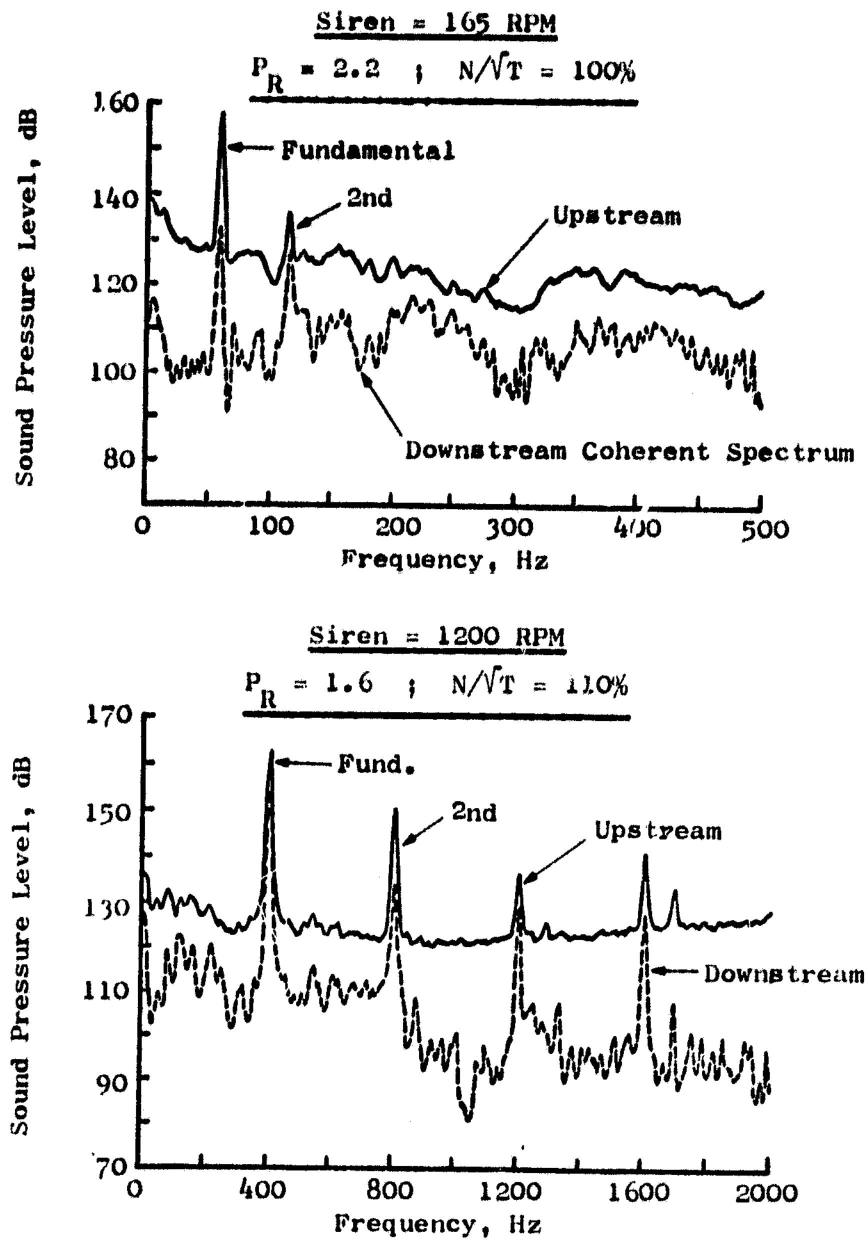


Figure 65. Typical Coherence Spectra (1-Stage LPT).

- Low Pressure Turbine - Three Stage
- Inlet Temperature = 422° K
- Inlet Pressure = 275.8 kN/m^2
- P_R = 3.0 ; $N/\sqrt{T}$ = 50%

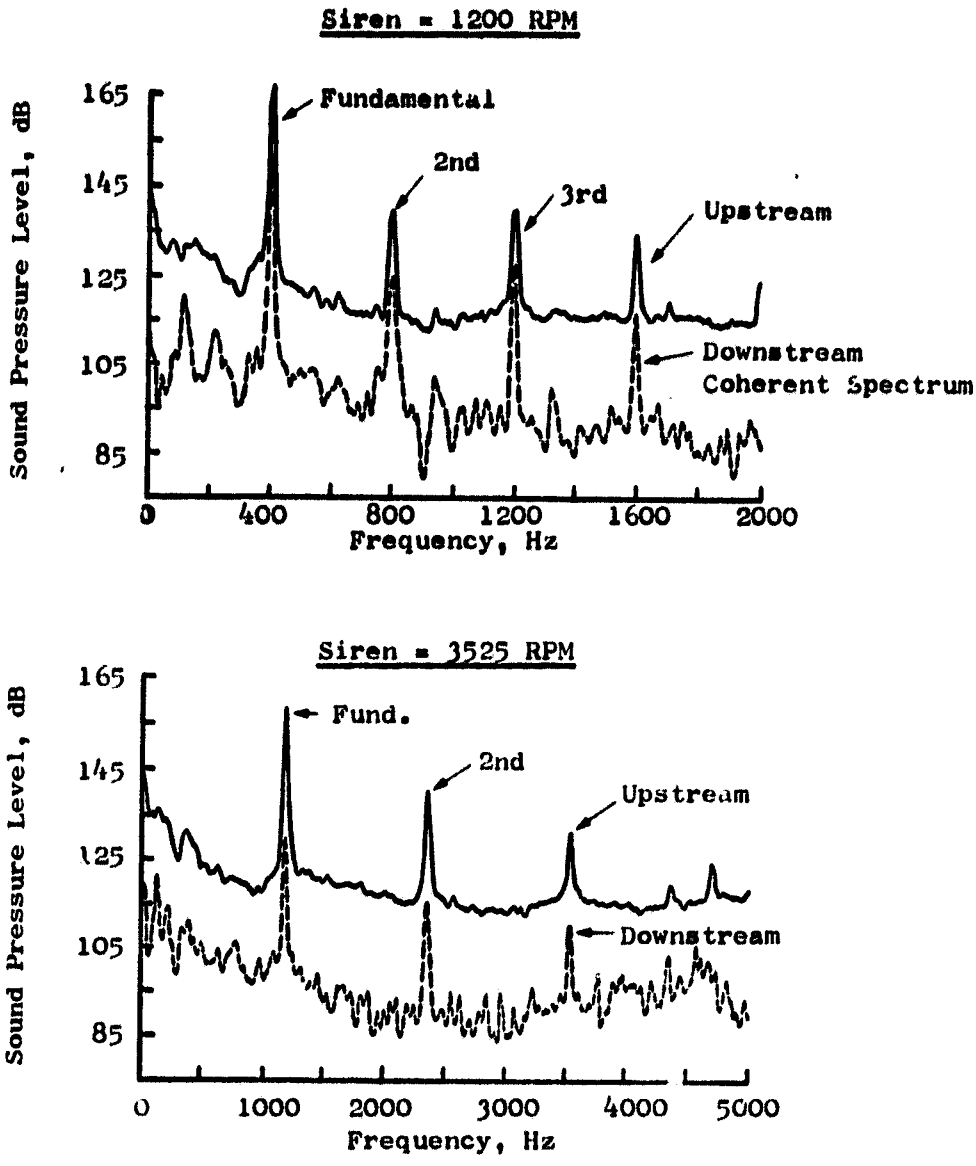


Figure 66. Typical Coherence Spectra (3-Stage LPT).

- Low Pressure Turbine - Three Stage
- Inlet Temperature = 422° K
- Inlet Pressure = 275.8 kN/m^2
- P_R = 5.2 ; $N/\sqrt{T}$ = 100%

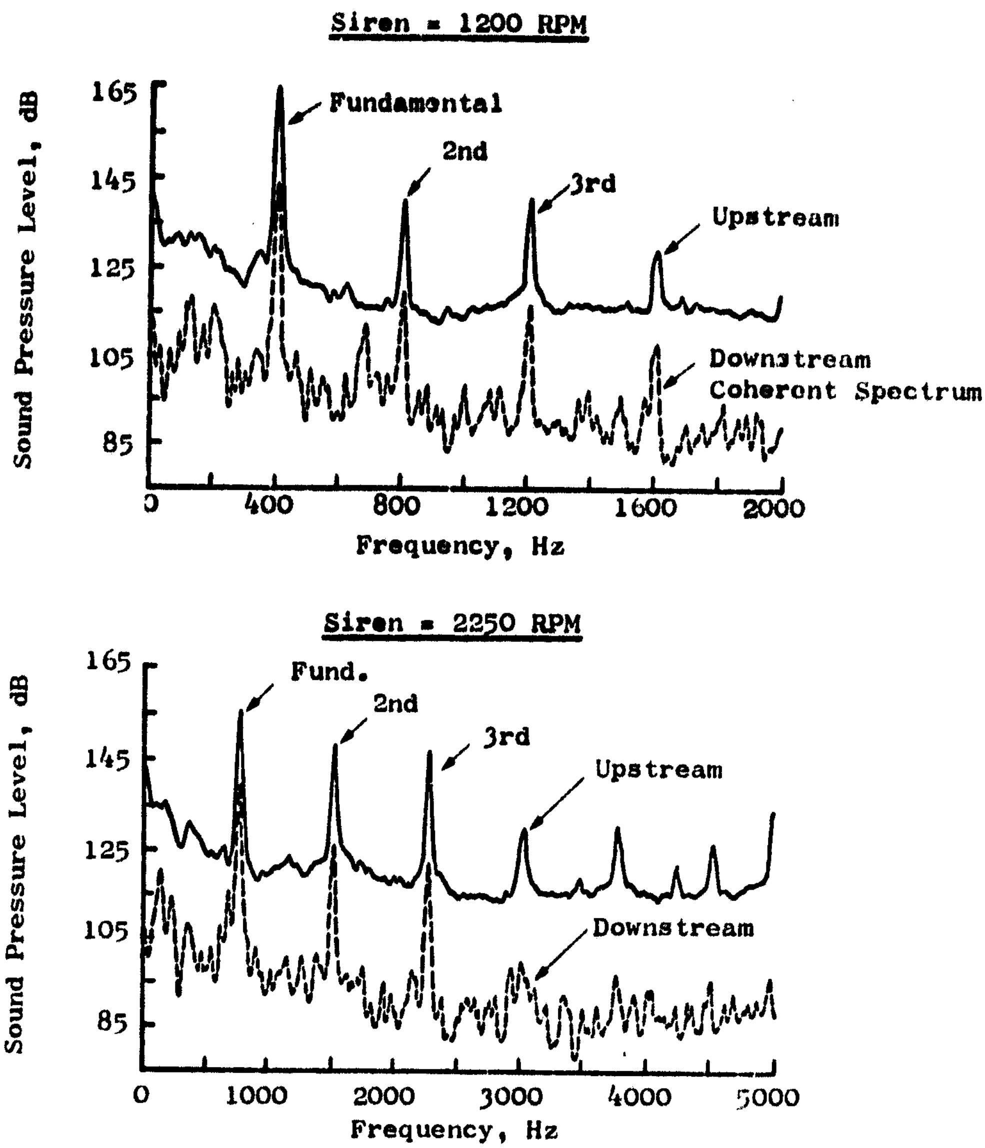


Figure 67. Typical Coherence Spectra (3-Stage LPT).

REFERENCES

1. Gerend, R.P., Kumasaka, H.P., Roundhill, J.P.; "Core Engine Noise," AIAA Aero-Acoustics Conference, Paper No. 73-1027, October 1973.

2. Chiu, H.H., Plett, E.G., Summerfield, M.; "Noise Generation by Ducted Combustion Systems," AIAA Aero-Acoustics Conference, Paper No. 73-1024, October, 1973.

3. Ho, P.Y., and Tedrick, R.N.; "Combustion Noise Prediction Techniques for Small Gas Turbine Engines," Garrett-AiResearch Report No. SD-8006, May 1972.

4. Arnold, J.S.; "Generation of Combustion Noise," J. Acoust. Soc. Am., Vol. 52, No. 1, July 1972.

5. Motsinger, R.; "Prediction of Engine Combustor Noise and Correlation with T64 Engine Low Frequency Noise," G.E. Report No. R72AEG313, October 1972.

6. Bekofske, K.; "Attenuation of Acoustic Energy Across a Blade Row," Report No. 73CRD342, General Electric Company, December 1973.

7. Matta, R.K., Sandusky, G.T., and Doyle, V.L., "Core Engine Noise Investigation Program - Low Emission Engines," General Electric Company, DOT/FAA Report No. FAA-RD-77-4, February 1977.

8. Emmerling, J.J. and Bekofske, K.L., "Experimental Clean Combustor Program Phase II, Noise Measurement Addendeum," NASA CR 135045, January 1976.

9. Kazin, S.B. and Matta, R.K., "Turbine Noise Generation, Reduction and Prediction." AIAA Paper 75-449, March 1975.

10. Kazin, S.B., Matta, R.K., et al.; "Core Engine Noise Control Program, Vol. III - Prediction Methods," General Electric Company, DOT/FAA Report No. FAA-RD-74-125, III, August 1974.