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USB ENVIRONMENT MEASUREMENTS BASED ON FULL-SCALE STATIC ENGINE GROUND TESTS

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SUMMARY

Flow turning parameters, static pressures, surface temperatures, surface fluctuating pressures and acceleration levels were measured in the environment of a full-scale upper surface blowing (USB) propulsive-lift test configuration. The test components included a flightworthy CF6-50D engine, nacelle and USB flap assembly utilized in conjunction with ground verification testing of the USAF YC-14 Advanced Medium STOL Transport propulsion system. Results, based on a preliminary analysis of the data, generally show reasonable agreement with predicted levels based on model data. However, additional detailed analysis is required to confirm the preliminary evaluation, to help delineate certain discrepancies with model data and to establish a basis for future flight test comparisons.

INTRODUCTION

Recently for both military and commercial powered-lift airplane concepts, attention has been directed to the use of upper surface blowing (USB) for propulsive lift. The present USB technology base has been developed through extensive model- and small-scale tests of general research configurations and is currently being applied to the USAF YC-14 Advanced Medium STOL Transport (AMST). Results of these small-scale studies have provided an initial understanding of such key powered-lift technology areas as: achievement of adequate structures in areas subject to the difficult environment of the engine exhaust; definition of the external and internal acoustic environment; achievement of adequate exhaust flow turning at low speed; and integration of the engine exhaust system with the airframe. Further progress is anticipated through development of a data base of full-scale hardware and comparison of this data with the model measurements.

The National Aeronautics and Space Administration (NASA) has undertaken, in conjunction with broad base technology development, some large-scale USB technology efforts which will be valuable in defining successful design approaches. In particular, NASA is participating with the U.S. Air Force to develop technology during both full-scale ground and flight testing associated with the USAF YC-14 prototype airplane development. Another notable example is the recently initiated NASA Quiet Short-Haul Research Airplane (QSRA) program.

The present program, an integrated ground and flight test technology program to study the USB environment, has been undertaken by NASA as part of their AMST efforts. The program was structured to utilize prototype YC-14 airplane hardware and to accomplish all measurements on a piggyback, noninterference basis.

It was planned that the ground test hardware would incorporate, where possible, instrumentation identical to that designated for the subsequent flight test. The combined ground/flight test program was then planned in an integrated framework.

The general objectives of the program were the following:

- To achieve the planning, design and fabrication of certain modifications required of the YC-14 prototype airplane no. , to permit subsequent flexibility for flight test experiments of interest to the NASA
- To accomplish early, full-scale engine ground test of the critical aerodynamic and structural technologies unique to the USB concept using a test article (including engine/nacelle/wing/flap/body section) of which significant portions are actual flightworthy, YC-14 prototype airplane hardware instrumented for ground test identically to the flight test vehicle
- To accomplish initial flight testing of the structural and acoustic technology items for which these instrumentation modifications have been incorporated
- To integrate the ground and flight test programs in order that: (1) certain complex flight instrumentation systems are thoroughly checked out in the ground test prior to flight; and (2) that costs are reduced through the use of common design efforts and instrumentation

The present paper provides results together with a preliminary analysis of the full-scale engine static ground test. The results are preliminary in that plans call for future detailed analysis of the ground test data together with acquisition of and comparative analysis with flight results, testing for which is planned for August, 1976.

DESCRIPTION OF THE GROUND TEST

The NASA-funded ground test efforts were accomplished as part of the basic YC-14 program engine verification test conducted at the Boeing Tulalip test facilities from December 1975 to February 1976.

Testing was accomplished on a specially constructed engine test stand which features a considerably open support structure to provide sufficient clearance for a full-scale USB installation including nacelle, USB flaps and simulated fuselage segment (fig. 1). A photograph of the test rig is given in figure 2. The entire test article was installed on top of a specially designed six-component force balance which provided strain-gauged-flexure output proportional to forces in the thrust, lift and side directions together with moments about the three principal axes. Two of the five CF6-50D engines designated to support the YC-14 flight test program were used, consecutively, during the ground test. Similarly, airplane flightworthy nacelle and USB flap hardware were incorporated as major elements of the ground test configuration. To help relate the test geometry to that of the flight vehicle, figure 3 shows the features of the no. 1 prototype airplane as visible during airplane final assembly in Seattle.

The technical objectives of the NASA-funded portion of the ground test are summarized in figure 4. Principal test parameter variations related to the NASA measurements included the following: engine power setting, angle of USB flap deployment, position of USB mixed-flow nozzle auxiliary takeoff door, position of USB flap vortex generators. In addition, related to the basic YC-14 program development objectives, variations of engine bleed flow rates, level of thrust reverse and bellmouth/flight-inlet engine intake configurations were tested. These latter measurements are beyond the scope of the present paper. Also, the reader is directed to references 1 through 4 for information related to design and development of the YC-14 USB installations.

INSTRUMENTATION

Approximately 150 channels of instrumentation were incorporated to assess the USB environment for the NASA-funded measurements. The approximate sensor locations for the static pressures, surface air temperatures, microphones, and accelerometers are shown in figure 5. The first two of these groups were treated as steady state measurements, whereas the latter two measurements were handled as instantaneous or high frequency data. Test objectives call for maximum commonality between flight and ground test instrumentation. The following were two exceptions to this commonality: (1) Provisions for four additional microphones, located on and near the wing-body fairing were added for the ground test, (2) Static pressures were measured only on the USB flap/wing upper surface. Flight test static pressure measurements will include undersurface measurements.

In addition to the NASA instrumentation, extensive instrumentation of the engine, outdoor environment, and other pertinent test information was made available by the YC-14 program. Of particular interest is that instrumentation associated with the engine operation which includes: shaft speeds, exhaust stream charging pressures and temperatures, primary and secondary airflows and others. Instrumentation was also provided for model overall thrust, lift and pitching moment forces.

Conventional type transducers were used for measurement of the various steady state parameters of interest. The flight inlet, the fan duct, and nozzle ramp area sound level were measured internally by flush-mounted microphones, Photocon no. 524. The upper wing surface sound levels were measured by flush-mounted Kulite miniature microphones. The flap area sound levels were measured by flush-mounted Photocon no. 765 and 524 microphones. The body area sound levels were measured by flush-mounted microphones including Photocon no. 524 and B & K no. 41[illegible] types. Endevco Accelerometers model no. 2229C were principally used for the flap vibration measurements. These are a microminiature design with flat charge and voltage response over a broad temperature range.

All steady state performance data were acquired through a Beckman 210 Digital Data system. This is a high-speed, high-accuracy data acquisition system which contains a stable dc amplifier for each analog channel. Microphone and accelerometer measurements were acquired on separate wide band FM tape recorders outfitted with appropriate individual channel signal conditioning. The systems provided flat response through a frequency range of 20 to 10 000 Hz for the microphones and 5 to 2500 Hz for the accelerometers.

NASA-LANGLEY GROUND TEST

It should be noted that a contractually unrelated but coordinated static ground test program has been undertaken at NASA-Langley. The Langley testing used a 0.25 scale test article with identical USB nozzle/flap/fuselage geometry together with a United Aircraft of Canada JT15D engine (see fig. 6). It is intended that subsequent scale effect assessments will include comparisons with the Langley 0.25 scale program. Such comparisons are beyond the scope of this paper.

PRINCIPAL TEST RESULTS

Preliminary results and conclusions, developed during a two month posttest documentation period, are summarized below. These are subject to modification upon further detailed data reduction and analysis.

Flow Turning

Figure 7 summarizes the USB nozzle/flap flow turning results for the two flaps-down configurations tested. Flow turning angle as measured by the lift and thrust components of the six-component force balance is plotted against fan pressure ratio for both the full-down (41°/70°) and intermediate (31.5°/54°) flaps. The numbers in parentheses refer to the incremental rotation from flaps-up of the main and aft flap segments respectively. Figure 8 provides additional information on the flow turning results in terms of a polar plot. The axial and vertical force balance readings are normalized by the ideal thrust computed from the actual primary and secondary stream airflows and nozzle pressure ratios determined by internal pressure rakes upstream of the mixed flow exhaust nozzle. The data illustrates that as turning is increased, the ratio of total resultant force to the ideal thrust decreases. This is due primarily to the increased scrubbing losses incurred on the USB flap system as additional USB flap area is wetted. Key results of the flow turning assessment from the data given here and other data provided in Boeing document D748-10113-1 "YC-14 Ground and Flight Experiments for NASA–Ground Test Final Report" April 1976 were these:

- Flow turning angles of between 60° and 63° were achieved for full-down flaps. A preliminary comparison of these values with Boeing 1/15-scale model measurements shows good agreement, with the full-scale turning angles exceeding the model measurements by about 2-1/2°. This level of turning was accomplished after flap-to-flap and flap-to-fuselage sealing procedures used for the ground test were brought up to design standards. Flow turning angles of about 50° to 52° were obtained for the intermediate flap setting. The takeoff configuration (flaps up, nozzle door open) produced about 13° of turning. Preliminary comparison shows good agreement with Boeing model data.

- Retraction of the vortex generators and closure of the auxiliary nozzle door (both failure conditions for airplane operation with USB flaps deployed) exacted flow turning penalties, relative to the design condition, of about 11° and 16° respectively for full-down flaps.

- All flow turning measurements were performed with the test article installed at a fixed height above ground (engine ℄ height = 5.8 m) duplicative of installation during airplane taxi. Existing *model* data suggests the presence of "ground effect" impacting the data by loss of several degrees of flow turning and between 3% to 10% of resultant thrust when compared to free field measurements. Resultant velocity coefficients of about 0.75 and 0 78 were measured at Tulalip for the full-down and intermediate flaps cases, respectively. (The Boeing velocity coefficient parameter accounts for internal duct and mixing losses, nozzle losses and losses associated with flow turning and scrubbing over the USB flap and fuselage surfaces.) The reader is cautioned that certain of the instrumentation supporting the measured velocity coefficients are currently under review and accordingly are subject to some minor changes.

Pressure Environment

Figure 9 is representative of the pressure distribution data acquired during the testing. Both chordwise and spanwise pressure profiles are shown in this particular comparison which illustrates the loss of suction pressure over the aft portion of the USB flap system upon retraction of the vortex generators(VG). Assessment of all the pressure distribution data provides the following principal results:

- All pressure profile data were quite orderly and consistent in reflecting the integrated changes in flow turning recorded by the force balance instrumentation. Increased flow turning due to improvements in flap sealing was evidenced primarily by increased suction pressures on the aft USB flap segment

- A drop in the chordwise suction pressure profile between the main and aft USB flap, initially attributed to flap-to-flap seal leakage, was subsequently judged to be primarily a result of local surface curvature changes

- Detailed comparisons of the full-scale pressure distributions with model data have not been made. However, preliminary review suggests that the aft flap suction pressures do not exhibit close agreement with the available model data and further evaluation of these data are recommended

Temperature Environment

Figure 10 provides a comparison of temperature distribution contours (based on model data) used for design requirements for the intermediate flap setting at an engine fan pressure ratio of 1.52. This condition provided the highest measured full-scale flap temperature (155.6° C) of any of the test conditions run. As noted on the figure, an adjustment to the measured full-scale levels of approximately 44° C has been applied to bring these temperatures to a common reference level of maximum takeoff power on a hot day (39.4° C ambient). The primary conclusions drawn from these and other temperature measurements (not shown) are as follows:

- Maximum flap temperatures tend to occur somewhat outboard of the engine centerline on the aft USB flap. Decreasing power setting tends to shift the line of peak temperatures slightly inboard

- **Maximum measured internal, upper-surface nozzle temperature was 251.7° C which occurred in the flaps-up, door-open (i.e., takeoff) configuration at an engine power setting corresponding to fan pressure ratio = 1.71**

- **Recorded fuselage temperatures were generally quite cool with the highest level exceeding ambient by only ≈ 28° C. These levels were recorded at the most downstream portion of the simulated fuselage section**

- **Preliminary comparison with model data from two sources indicates fair agreement in both temperature level and distribution. The full-scale temperature distribution tended to show peak temperatures somewhat further inboard than the most recent model data.**

Acoustic Environment

Figures 11 to 13 are representative summaries of the fluctuating pressure (i.e., acoustic) data. Figure 11 gives overall fluctuating pressure level trends against a calculated, average mixed flow jet velocity for various geometric groups of microphones. The maximum recorded dB level on the flaps was on the order of 165dB. This level was also reached by certain fuselage microphones which were in the vicinity of the flap trailing edge region. Figures 12 and 13 give a representation of the frequency distribution of the acoustic energy as defined by 1/3-octave band analysis. The principal features of this acoustic data and the other data analyzed to date can be summarized as:

- Overall fluctuating pressures on the wing/flap/fuselage in excess of 160 dB tend to be contained within the flow-scrubbed regions on the USB flaps or the adjacent fiberglass fairing between the wing and fuselage

- Overall fluctuating pressure levels on the fuselage itself tend to remain less than 155-dB (fuselage section below the fiberglass fairing) or less than 150 dB (fuselage section above the fiberglass fairing)

- Overall fluctuating pressure levels measured in the fan duct and on the nozzle wall did not exceed 155 dB

- Preliminary comparisons of overall sound pressure level between full-scale and Boeing 1/8-scale model data show quite good agreement with respect to the wing and fuselage regions; measurements in the USB flap region agree reasonably well

- 1/3-octave band spectral analysis shows low frequency activity in the neighborhood of 80 to 100 Hz corresponding to a Strouhal number of approximately 0.35. Peak energy in this frequency is measured on the fuselage region near the flap trailing edge, on the flaps and on the wing trailing edge panel. Activity in this Strouhal number range is consistent with previous model-scale investigations of near-field acoustic measurements for USB propulsive lift installations and is associated with the jet/wing-surface interaction shear regions

- An indication that fuselage microphones near the flaps are directly exposed to the flow scrubbing is that higher levels of low frequency activity (approximately 10 dB) are measured than in more distant regions. The level of activity in the frequency band of 30 to 50 Hz is slightly higher than indicated by model data but detailed assessment must await a narrow band analysis

- Another apparent peak in the spectra is in the 300- to 400-Hz range corresponding to a Strouhal number of approximately 1.5. This frequency band is predominant in nozzle, wing, and flap regions and is associated with the exhaust-jet/ambient-air shear regions. This pattern of acoustic energy is also consistent with observations of previous model experiments

- Retraction of the vortex generators at full-down flaps and high power setting produced a considerable (approximately 5 dB) decrease of noise in the neighborhood of 90 to 100 Hz. This characteristic was noticeable in both the wing and nozzle microphone measurements

- Engine fan tone noise is evident in the high frequency end of the spectrum (1500 to 5000 Hz) for measurements in the fan duct and in the nozzle wall region and is also prominent in some of the wing microphone data. However, the levels tend to be considerably less evident downstream of the wing in the flap and fuselage regions where the broad band noise of the jet mixing region determines the noise level at these higher frequencies

Acceleration Environment

Figures 14 to 16 are representative summaries of the USB flap acceleration data for the flaps down test condition analyzed. Figure 14 gives overall vibration levels in g's rms for several chordwise locations at the spanwise position of the outboard hinge fitting. The direction of the accelerometer sensor is indicated by the arrows. Figure 15 gives the results of an engine-off test where the installed flaps were subjected to inputs from an electromagnetic shaker over a range of frequencies from 0 to 500 Hz. The engine-off tests were intended to help interpret the resulting engine-on accelerometer measurements in terms of the flap-assembly natural modes. Figure 16 gives frequency spectra for several accelerometers illustrating the variation in energy distribution with downstream location. The primary features of this data and the other accelerometer data analyzed to date are summarized below:

- Only a small portion of the acquired accelerometer data was able to be analyzed in the allotted time. However, all of the data examined appeared to be orderly and self-consistent with respect to power setting, geometric location and expectations based upon the engine-off, shake test

- Overall vibration levels of 3 to 4 g's rms (parallel) and 7 to 9 g's rms (transverse to the flap chord) were measured on both flaps at the inboard and outboard attachment points of the primary flap structural components. Higher overall levels of 14 and 38 g's rms were measured normal to the skin of the aft flap downstream of the hinge arm support structure but at the same spanwise location. One accelerometer, on an aft flap skin panel outboard of the hinge arm, measured 56 g's rms

- Numerous frequency peaks are evident in the various spectra examined. The most dominant activity appeared to take place in 3 separate frequency ranges: 20 to 30 Hz, 90 to 110 Hz and 250 to 350 Hz

- The 20- to 30-Hz activity is evident in both the main and aft flaps for those accelerometers located at the principal attachment points of the primary flap structural components. This suggests that the activity is associated with a response mode of the overall flap assembly

- The 90- to 110-Hz activity is also visible in many of the accelerometers but tends to be dominant in the aft flap sensors. This vibration activity is increased the higher the power setting and the further downstream on the flap the measurement is made. These characteristics together with the trend of increasing overall rms acceleration level in the downstream direction suggest a pitching-motion-type flap response at this frequency

- Activity in the 250- to 350-Hz range is dominant in the acceleration response of the sensor located on one of the upper surface, aft flap skin panels and was judged to be primarily panel response

- Vibration activity in the frequency bands noted above is consistent with USB exhaust jet pressure fluctuations determined by acoustic microphone measurement and associated with various of the noise source shear regions typical of a USB installation as discussed previously

- The above conclusions are based on a preliminary examination of portions of the available data. Additional detailed data analysis could be profitable pursued to: (1) complete analysis of data not yet examined, and (2) extend comparisons with the acoustic measurements to more fully understand the nature of the fluctuating loads and the flap response

Instrumentation Verification

All of the steady state pressure and temperature instrumentation as well as the high frequency accelerometers performed well during the ground test and with the possible exception of some minor location changes are considered satisfactory for flight testing. Of the 36 microphone installations, all but the 7-USB flap upper surface measurements were considered satisfactory for flight. Problems with the latter microphone installations (see fig. 17) during the first part of the ground test were attributed to a combination of: microphone quality control and mechanical construction of the special cable and cable connectors. Subsequent vendor refurbishment and onsite repairs provided satisfactory measurements during the remainder of the ground test. However, in view of the decreased instrumentation accessibility and the increased cost of flight test delays, it has been recommended that the flap microphone installations be reevaluated and compared with alternate installations.

FOLLOW-ON DATA ANALYSIS

Based upon the preliminary data analysis, recommendations for detailed analysis of this ground test data are deemed appropriate. The principal elements of these recommendations include:

- Further analysis of the full-scale Tulalip data to include additional test conditions not yet analyzed
- Additional interpretation of the data by integrated assessment of the microphone, accelerometer and steady state measurements
- Extending comparisons of the full-scale data to those of Boeing 1/16-scale and NASA-Langley 1/4-scale JT15D static tests in order to assess scaling relationships

CONCLUDING REMARKS

Conclusions based upon the preliminary data analysis are given in figure 18. In summary, all of the principal objectives of the ground test measurements have been accomplished. The material and data developed will provide a sound basis for both: (1) extending the preliminary analysis presented herein to help evaluate scaling relationships, and (2) serving as a guide for accomplishing satisfactory flight test measurements.

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1. J. K. Wimpress, "Upper Surface Blowing Technology as Applied to the YC-14 Airplane," SAE Paper 730916, October, 1973.

2. H. Skavdahl, T. Wang and W. J. Hirt, "Nozzle Development for the Upper Surface Blown Jet Flap on the YC-14 Airplane," SAE Paper 740469, April, 1974.

3. F. W. May and G. E. Bean, "Aerodynamic Design of The Boeing YC-14 Advanced Medium STOL Transport (AMST)," AIAA Paper no. 75-1015, August, 1975.

4. C. A. Crotz, "Development of the YC-14 Propulsion System," AIAA Paper no. 75-1314, September, 1975.

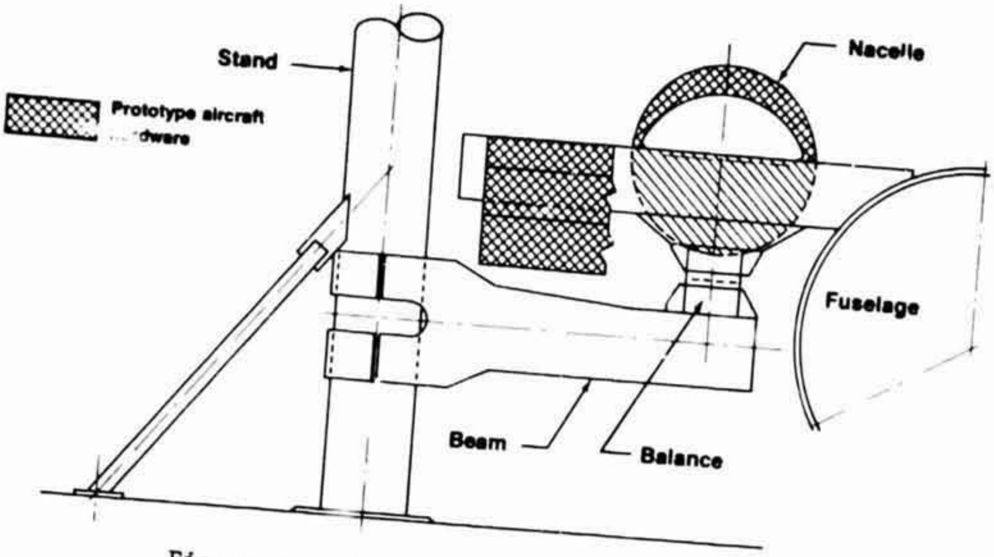


Figure 1.- YC-14 ground test installation.

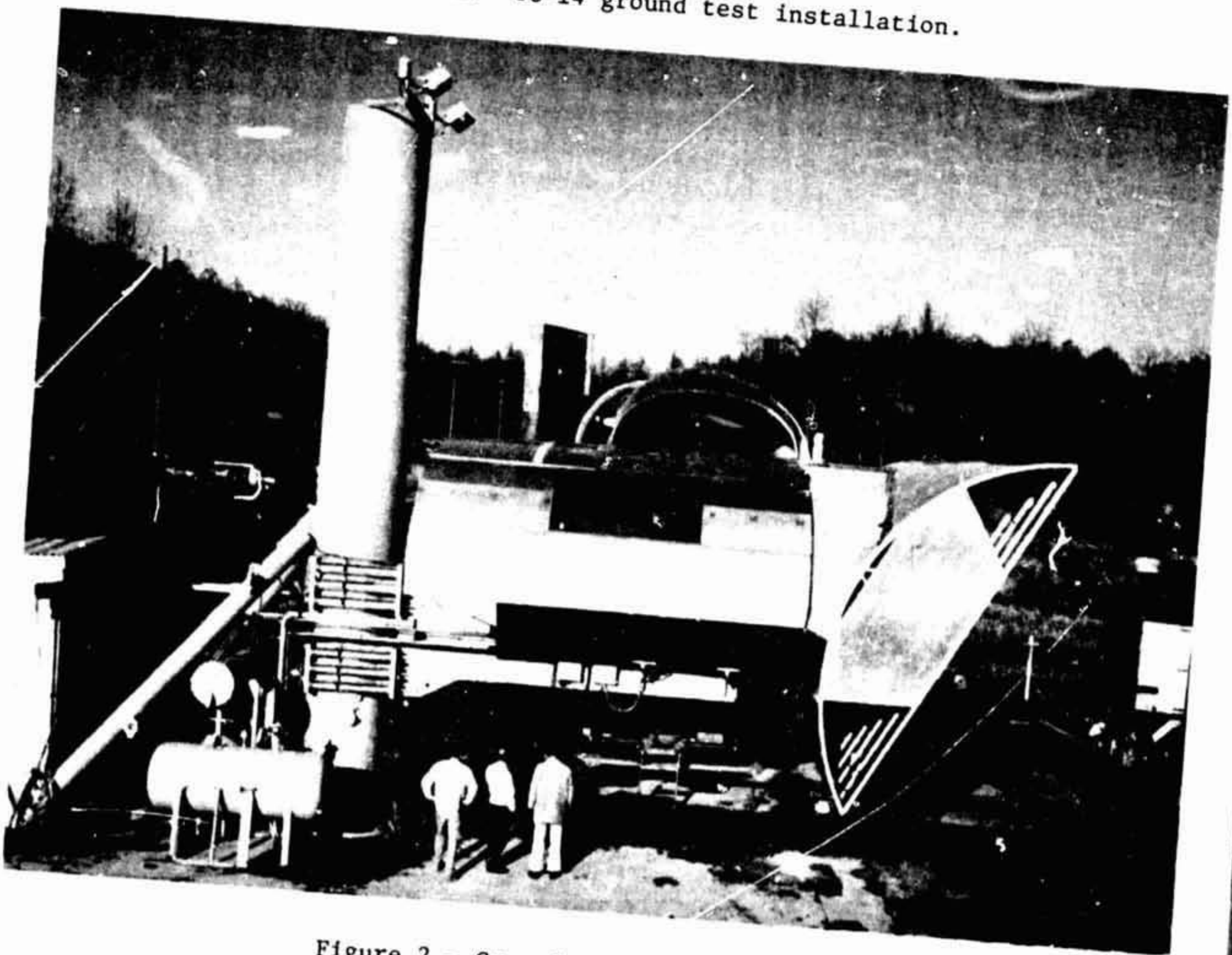


Figure 2.- Ground test installation.

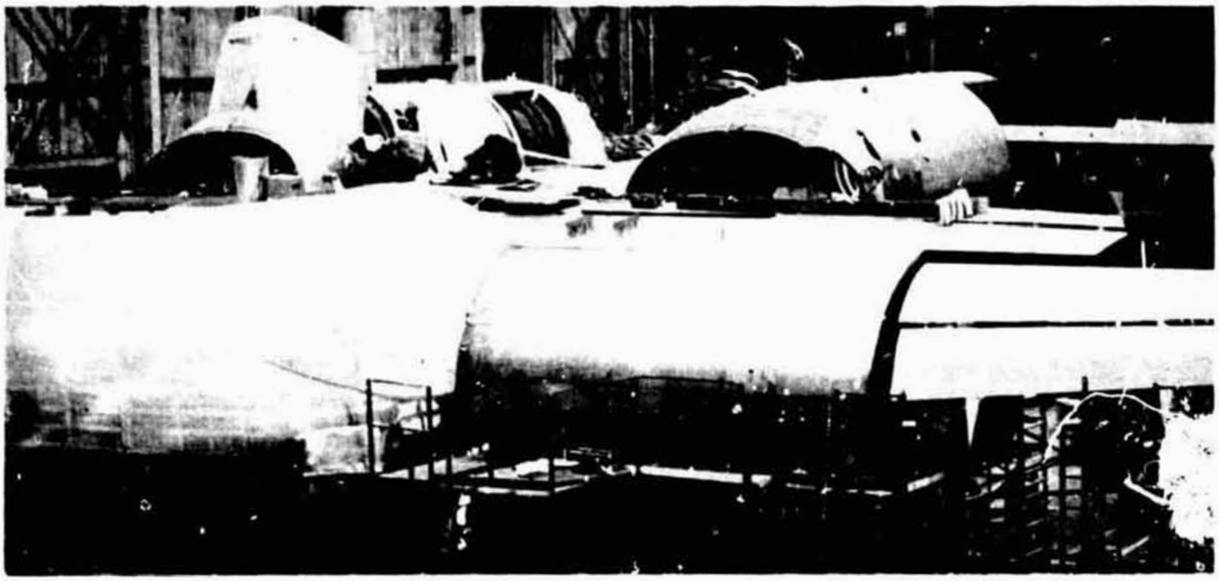


Figure 3.- YC-14 prototype no. 1 - final assembly, February 1976.

1. Assess USB structural environment
   Pressure, thermal, fatigue loads
2. Assess USB flap structural response
3. Identify USB noise sources
   Near-field assessment
4. Assess static aerodynamic flow turning
5. Assess fuselage noise environment
6. Assess nacelle acoustics
7. Develop preflight instrumentation verification
8. Develop data for ground/flight correlation
9. Develop data for scaling correlations

Figure 4.- Ground test technical objectives.

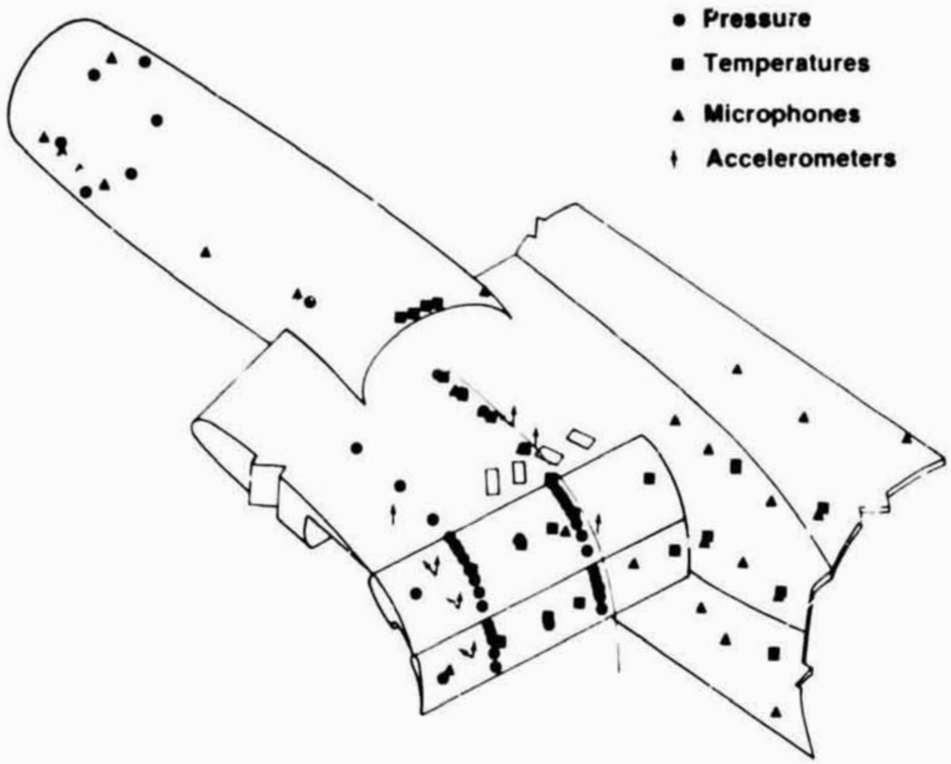


Figure 5.- Ground test instrumentation.

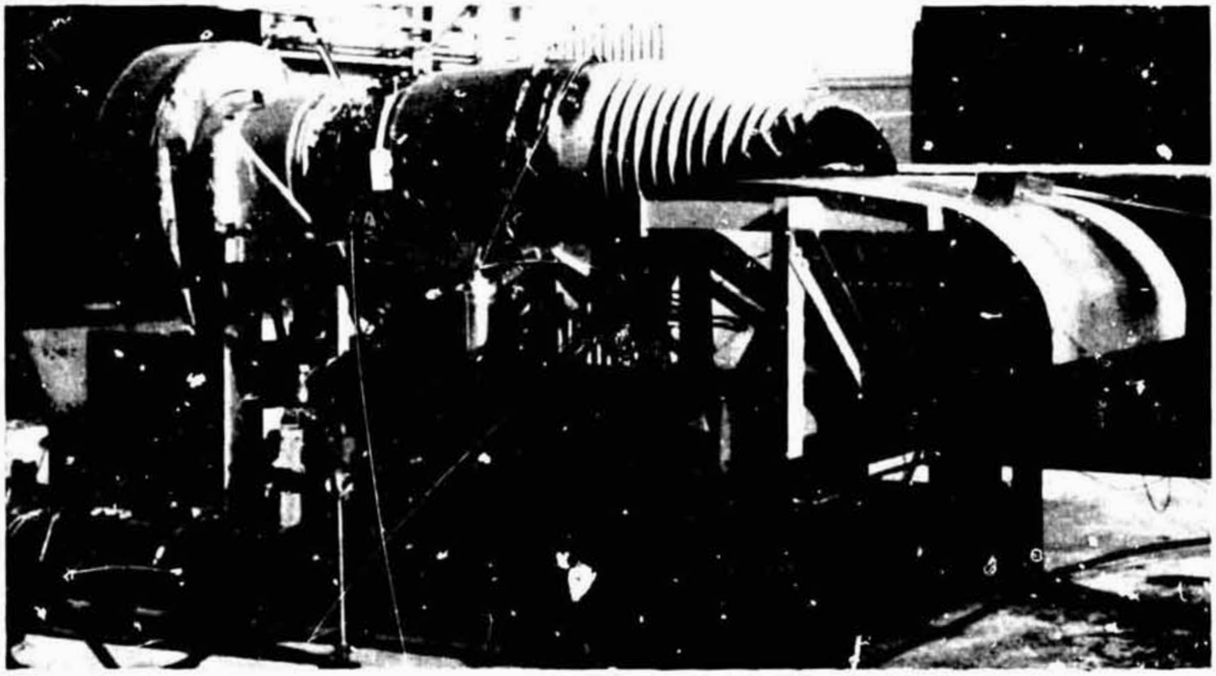


Figure 6.- NASA Langley JT15D static test rig.

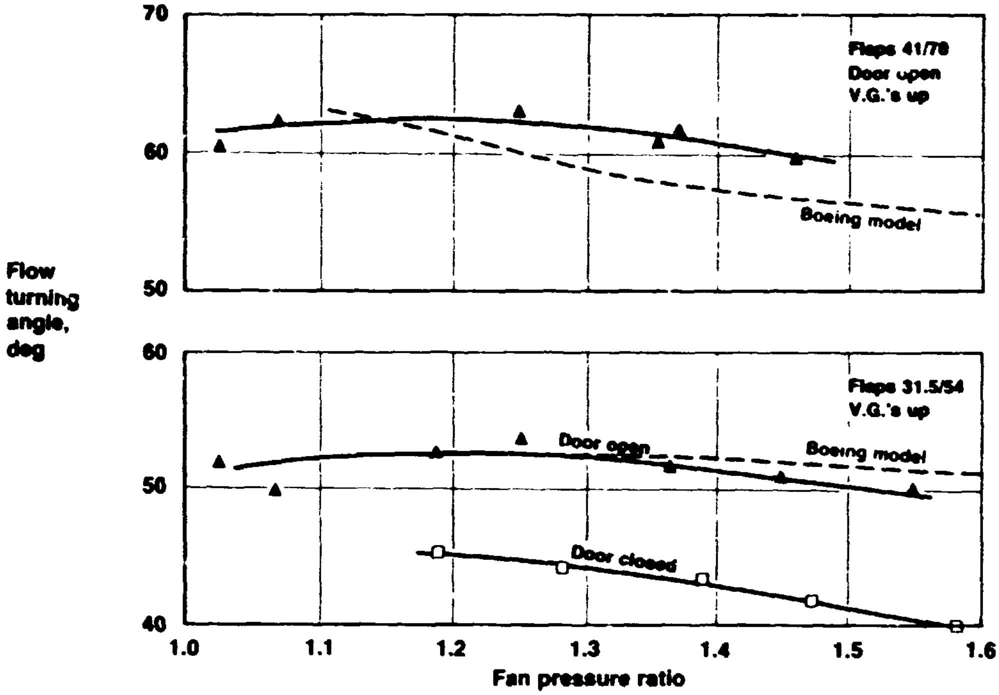


Figure 7.- Static flow turning data - intermediate and full-down USB flaps.

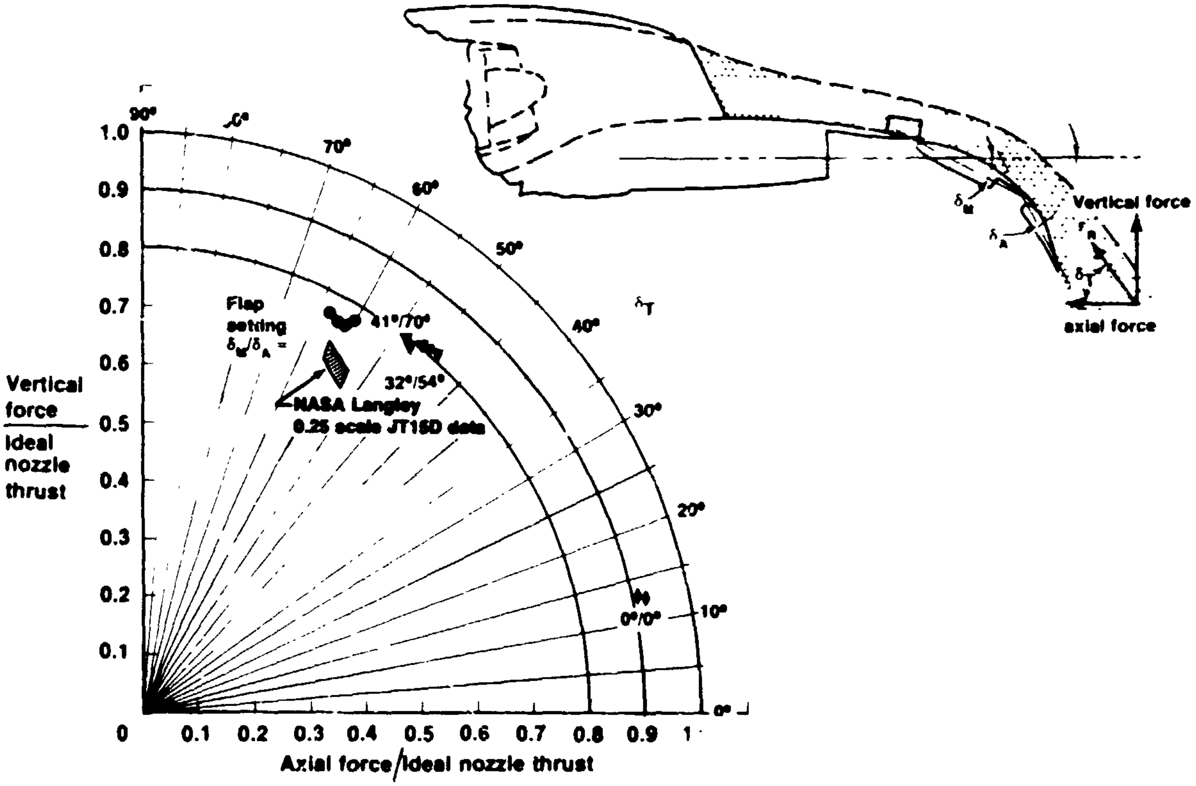


Figure 8.- USB flap static turning performance.

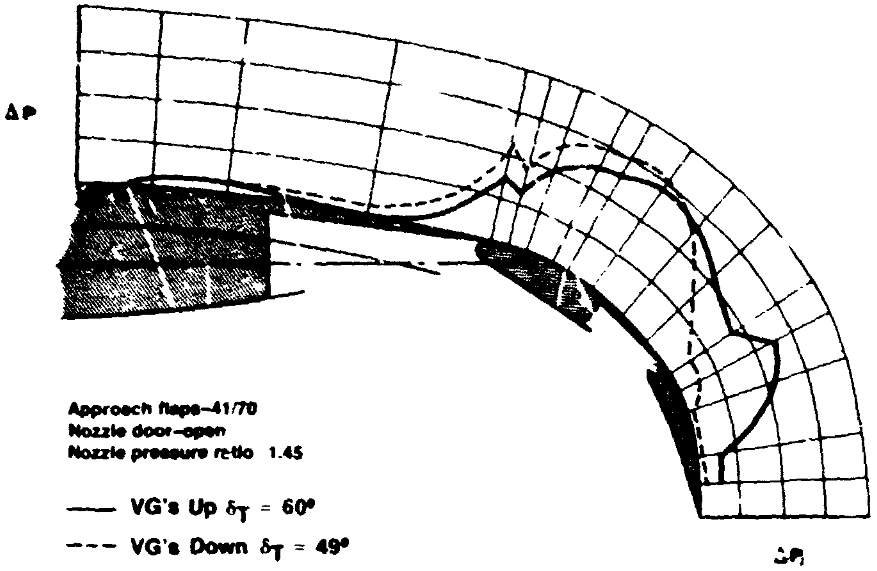


Figure 9.- Chordwise upper surface pressures along engine centerline.

°F	°C	°F	°C
50	10.0	260	126.7
80	26.7	273	133.9
103	39.4	299	148.4
173	78.3	300	148.9
175	79.5	305	151.7
180	82.2	312	155.6
188	86.7	344	173.4
200	93.3	390	198.9
208	97.8	393	200.6
209	98.3	400	204.5
219	103.3	405	207.2
240	115.6	415	212.8
256	124.5	450	232.2

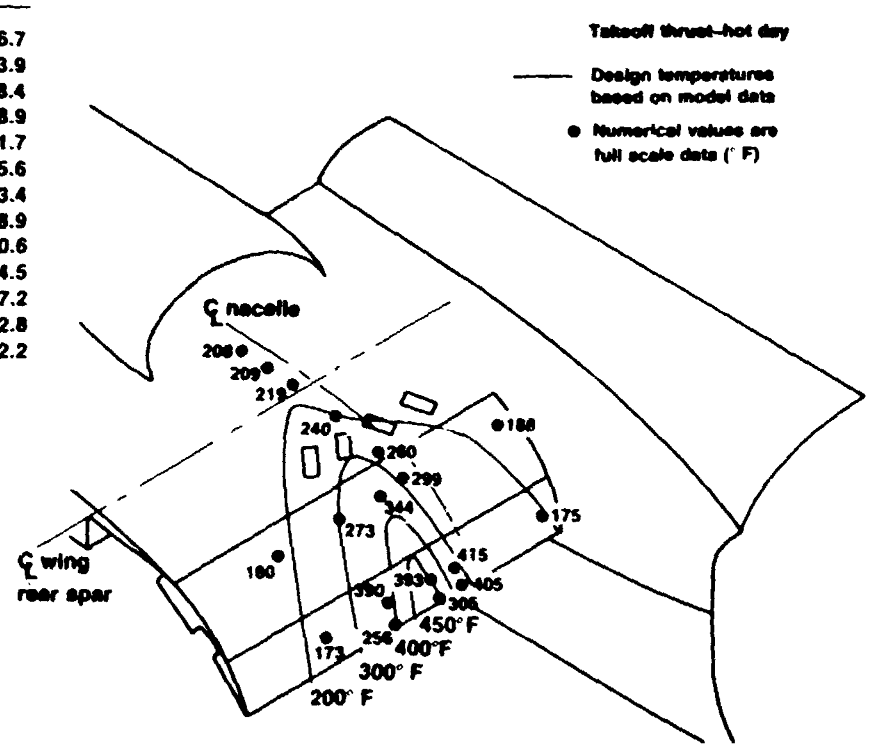
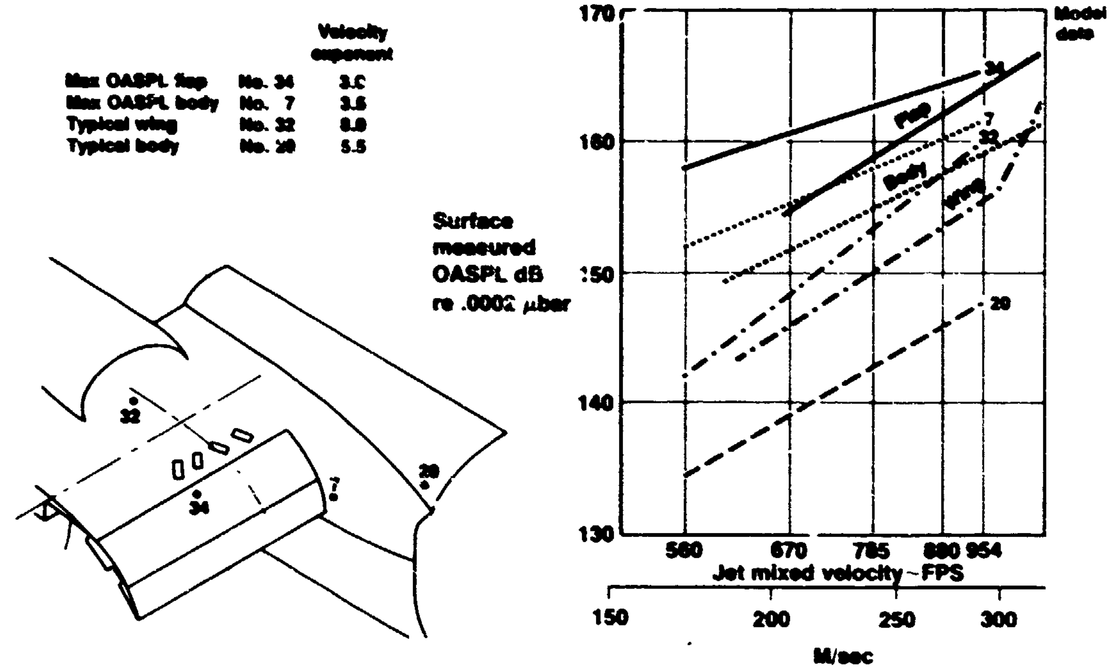


Figure 10.- USB flap temperature distributions.



		Velocity exponent
Max OASPL flap	No. 34	3.0
Max OASPL body	No. 7	3.6
Typical wing	No. 32	8.0
Typical body	No. 20	5.5

Figure 11.- Surface measured fluctuating pressures.

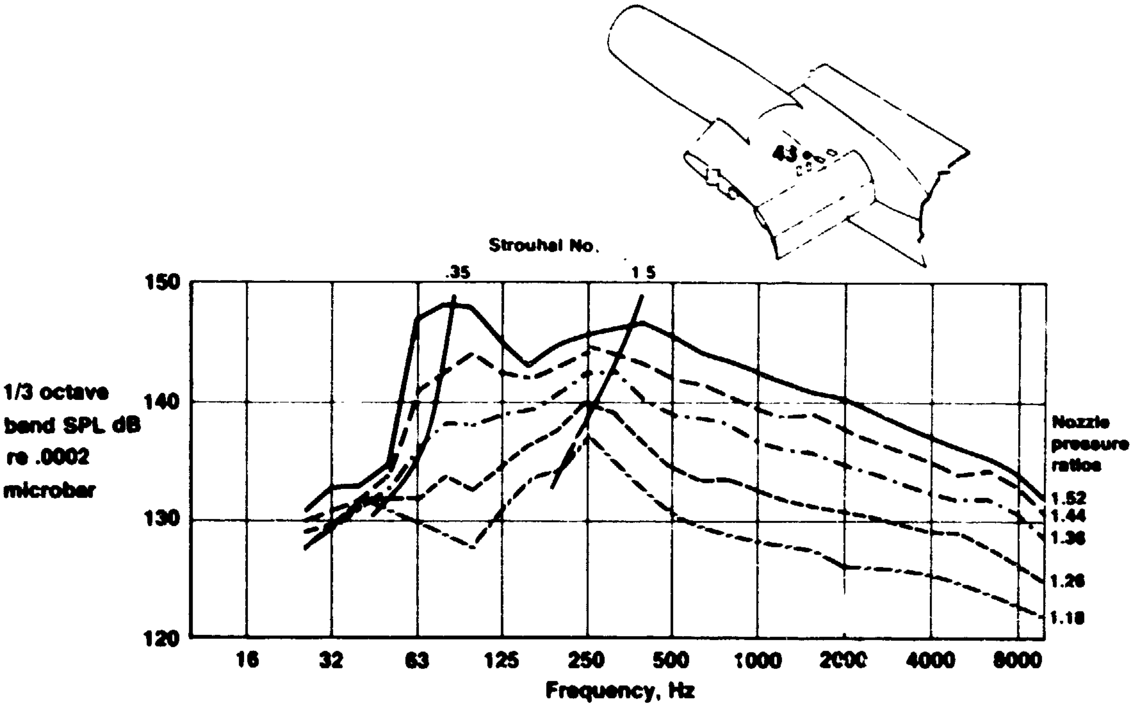


Figure 12.- Typical 1/3-octave band spectra.

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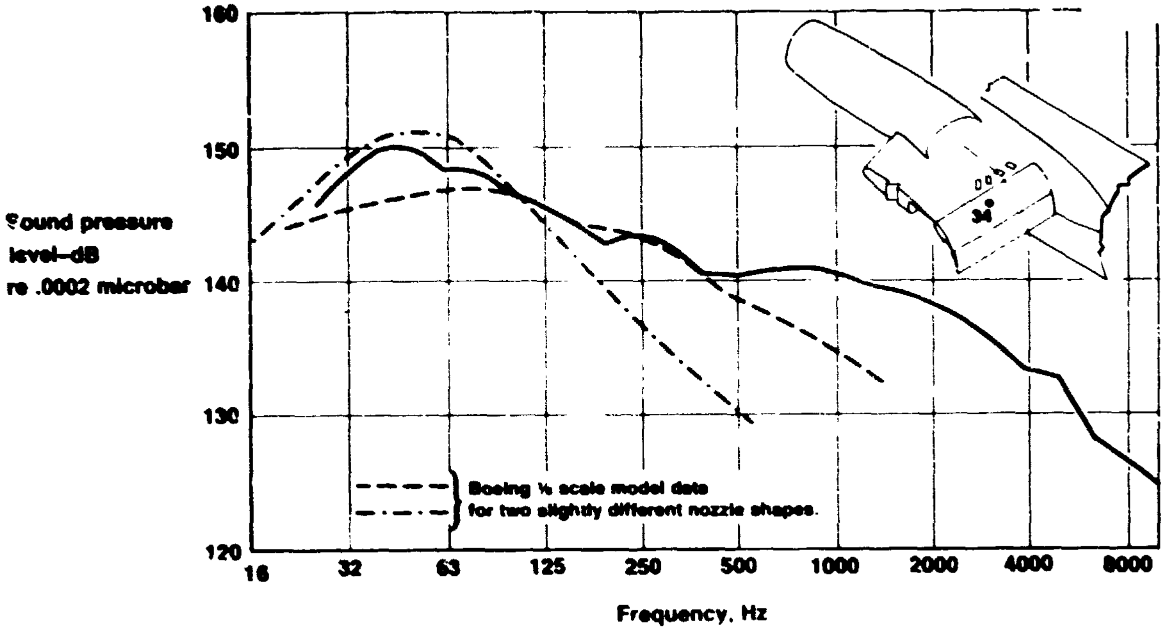

Figure 13.- Typical 1/3-octave band spectra.

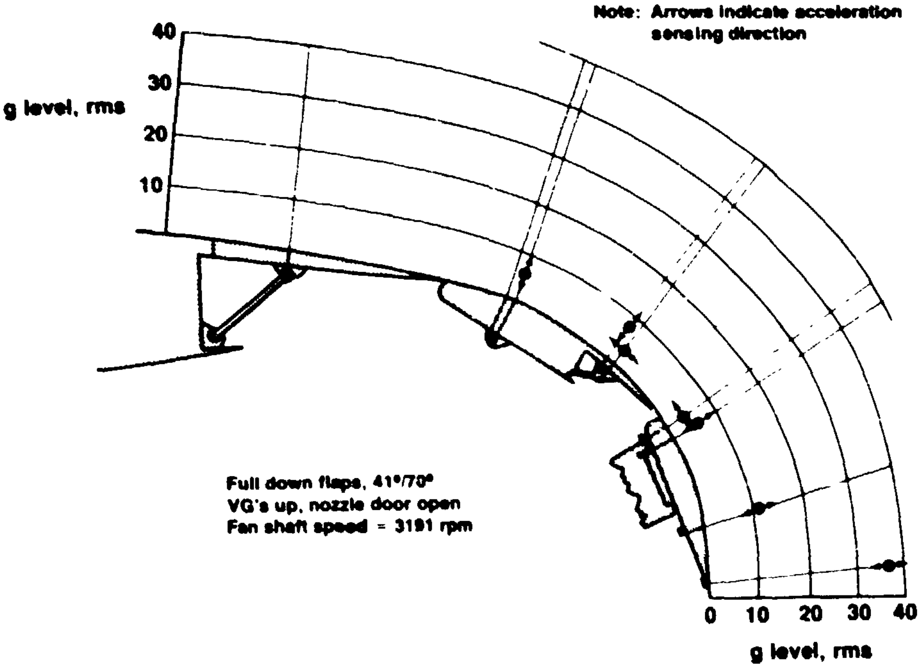

Figure 14.- Flap overall rms acceleration levels.

Frequency sweep results	
Noticeable responding frequencies Hz	Test engineer comments
25.4	–
55	–
62	–
90	–
128	Large resonance
151	–
181	Trailing edge
186	Small peak
196	Small peak
216	Fitting on trailing edge in resonance
278	Small peak
290	Very small
304	Very small
319	Stronger peak
351	Small peak
382	Large resonance

Representative modal pattern, aft flap at 128 Hz
(numbers indicate relative acceleration amplitude)

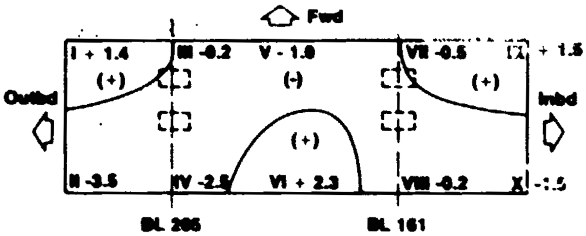

Figure 15.- Typical results of engine-off shake test.

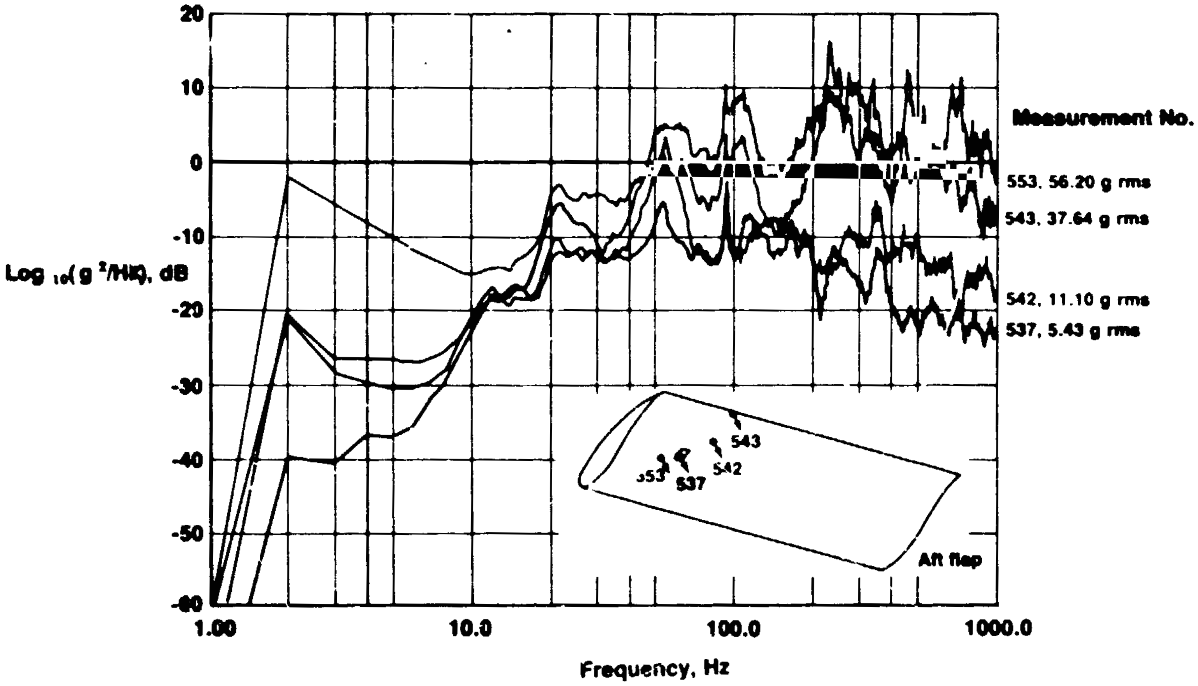

Figure 16.- Vertical acceleration spectra, flaps 41°/70°.

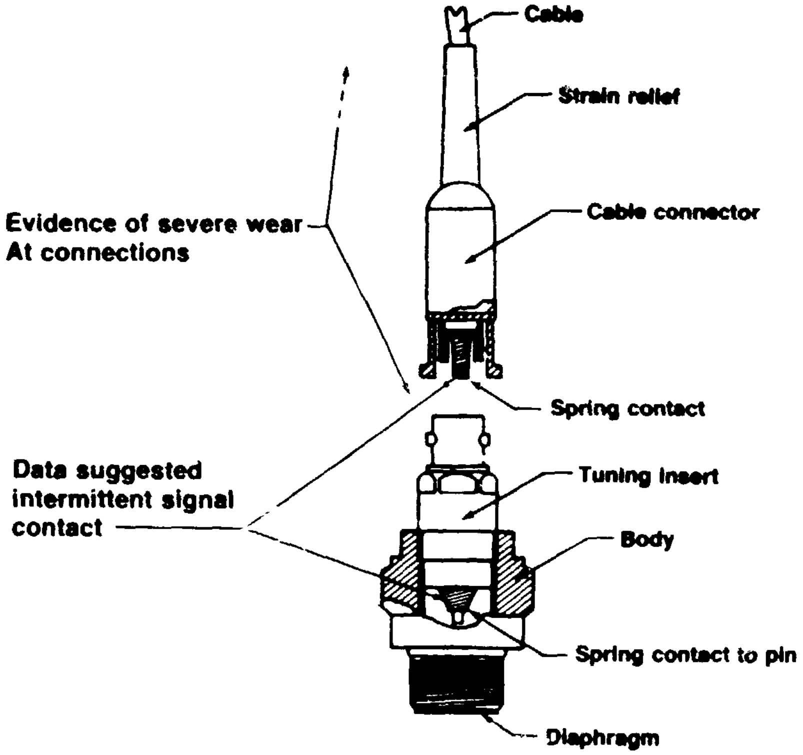

Figure 17.- Microphone description and problem areas.

- **Full-down flap turning angles of about 62° agreed well with Boeing model data**
- **Static pressure data confirmed force balance measurement trends; however agreement with model data was not satisfactory and further study is recommended**
- **Maximum (adjusted) flap temperature was 211.1° C and agreed well with model data**
- **Maximum (adjusted) surface acoustic levels of**
  - **-165 dB on the USB flaps and adjacent fairing**
  - **-155 dB on the fuselage and within the nacelle**

  agreed well with model data
- **Acoustic spectra showed activity at Strouhal no's of about 0.3 and 1.5 giving good agreement with model data**
- **Flap acceleration levels and spectra are interpretable in terms of the imposed acoustic pressure field and flap vibration modes established during engine-off shake tests**

Figure 18.- Conclusions based on preliminary analysis.