SUMMARY OF CASSINI ACOUSTIC CRITERIA DEVELOPMENT USING TITAN IV FLIGHT DATA

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Abstract

The Cassini spacecraft is being developed by the Jet Propulsion Laboratory (JPL) for the National Aeronautics and Space Administration (NASA) to orbit and explore the planet Saturn, its rings and satellites. Cassini will be launched on a Titan IV and boosted out of earth orbit by a Centaur. This paper discusses the development of Cassini acoustic criteria using Titan IV flight data. The Titan IV flight acoustic measurements and the different flight data processing techniques employed by Martin Marietta and The Aerospace Corporation are described in Reference 1, as well as the methods employed by JPL for identifying and correcting for instrumentation system transients. Factors affecting the development of Cassini acoustic criteria using the corrected Titan IV flight data include the statistical methods used to account for spatial and flight-to-flight variations, the use of maximax spectra, data corrections for acoustic pressure increases near the payload fairing surfaces, and corrections for payload fill factor effects. Separate acoustic criteria were developed for the two different launch sites.

Introduction

All major JPL spacecraft have been previously flight-qualified to acoustic noise (e.g., Reference 2), and for good reason: acoustic noise internal to the payload fairing (PLF) is the sole cause of the most severe random vibration experienced by these spacecraft (Reference 3). The Cassini spacecraft will be no exception. This spacecraft, having a current configuration as shown in Figure 1, is to be launched on a Titan IV vehicle including two solid rocket motors (SRMs), with a Centaur upper stage. During the launch phase, Cassini and Centaur will be enclosed in a PLF. Fortunately, a substantial number of acoustic measurements have been or will be made on the Titan IV, including the PLF. This measurement program ended a twenty year hiatus since acoustic measurements were made last on Titan IIIs. As summarized in Table I, there have been a total of 34 PLF acoustic measurements on the first four flights, specifically 10 external and 24 internal to the PLF. The internal measurements are obviously the most applicable to the Cassini acoustic design and test criteria. However, if anomalies or excessive internal flight-to-flight variations were observed, the external measurements were used to help to identify the cause.

The first two flights (K-1 and K-4) were launched from LC-41 at the Cape Canaveral AFS/Eastern Test Range (ETR), whereas the second two (K-5 and K-8) were launched from SLC-4E at Vandenberg AFB/Western Test Range (WTR). The payloads for these flights, with and without upper stages, were different from Cassini/Centaur, which is to be launched from ETR. In addition, there are some important differences between the ETR and WTR launch pads and systems, which will be discussed later.

Acoustical Blankets

Blankets, comprised of 3 in. thick fiberglass enclosed in glass fabric, were installed on portions of the interior surfaces of the four PLFs. However, the amount of coverage varied from flight to flight, as described in Reference 1. The PLF used for Flight K-5 was 10 ft longer than the other three PLFs.

Microphone Installations and Locations

All of the microphones (mics) applicable to Cassini were attached to the PLF. Their locations and installations are described in Reference 1. Although it would be greatly preferable to locate the mics directly on the spacecraft, managers are often reluctant to pass instrumentation cables through two disconnects (one between the spacecraft and upper stage, and the other between the upper stage and launch vehicle) to reach the telemetry transmitter in the launch vehicle. The potential consequences of a PLF/launch vehicle disconnect failure would obviously be much less critical. Nineteen internal mics were attached to the PLF isogrid aluminum structure with diaphragms approximately 4 in. from the interior surface (between the isogrid stiffeners). Three K-4 and two K-8 internal microphones were installed on standoffs (or masts) approximately 20 in. from the PLF interior surface. These standoff measurements provided a unique opportunity to observe the internal noise field away from the PLF surface, where the noise is generally less severe and more representative of the acoustic environment seen by the payload. Thus it would be expected that the Cassini spacecraft would be exposed to a lesser noise field than that indicated by data from the internal PLF surface mics. Since PLF vibration, excited by external SRM exhaust-induced acoustic noise at liftoff, or flow-induced aerodynamic noise at transonic/max q, generates the internal noise (Reference 3), the noise emanating from the PLF surface is greater near the source (the direct field) than in the remaining space (the semi-reverberant field).

The internal mics, PCB Models 106M59 or 106M79, and external mics, PCB Model 106M80, were installed by McDonnell Douglas, the PLF supplier. These mics were not vibration-compensated, but were individually tested for vibration sensitivity. The remainder of the system was part of the Wideband Instrumentation System (WIS), supplied by Martin Marietta Corporation (MMC), developer of the Titan IV. Many other measurements throughout the vehicle, including vibration, were made via the WIS.

Acoustic Data Processing

All the acoustic signals were recorded on magnetic tape at either the ETR or WTR after telemetry reception. Tape dubs were subsequently made. Two organizations, MMC and The Aerospace Corporation (TAC), performed further data processing and analysis in a conscientious and straight-forward manner. As a result, it was unnecessary for JPL to reprocess or reanalyze the data. Nevertheless, some instrumentation problems were encountered, as discussed in Reference 1.

After resolving those instrumentation problems, it was then possible to concentrate on the acoustic data itself. JPL was fortunate to have four thorough data sources in the form of MMC flight test reports (References 4-7). Data from these reports showed that the most severe internal acoustic environment occurred during liftoff, rather than during transonic flight or max q, even though the maximum external environment occurred during transonic flight over portions of the PLF aft of the cone-cylinder junction (CCJ). Four possible causes of this apparent contradiction are discussed in Reference 1. There can be an important exception to the conclusion that liftoff internal acoustics is generally more severe. High narrowband noise has been observed near payload vents during transonic/max q, e.g., inside the Shuttle payload bay near 300Hz on some flights and inside a Commercial Titan PLF on two flights near 900Hz. However, no PLF vent noise was observed during the first four Titan IV flights, even though the mics were close enough to measure any vent noise existing. It is currently anticipated that vent noise need not be considered for the Cassini spacecraft.

Derivation of Maximax Spectra

To derive Cassini acoustic criteria, JPL was specifically interested in obtaining the maximum SPL in each 1/3 OB for all the internal PLF acoustic measurements. These various maxima do not occur at the same instant of time, but at various intervals during the liftoff event due to the nonstationary character of the external SRM-induced noise field. However, it is currently impractical to design or test a structure to short-duration time-varying (i.e., nonstationary) loading. To avoid underdesign or undertesting, the maximum SPLs were used to establish a maximax spectrum, to be applied simultaneously to the structure as a time-limited stationary loading.

The various maximum SPLs were obtained from References 4-7, using the procedure described in Reference 1. A study was performed on Titan IV and Shuttle liftoff internal PLF acoustic data to determine the optimum averaging times to be used for 1/3 OB analysis (Reference 8). It was concluded that the Titan IV optimum averaging times should be $T_o = 1.14$ sec for the OA SPL, and $T_{oi} = 4.88/f_i^{0.2}$ for 1/3 OB SPLs, where f_i is the applicable 1/3 OB center frequency. However, it was pointed out that the total rms error would be within 25% of the minimum if (a) $T_{av} = 1$ sec were used for the overall and 1/3 OB center frequencies greater than 250Hz, and (b) $T_{av} = 2$ sec for center frequencies equal to or less than 250Hz. Unfortunately, since the receipt of these results, there was insufficient time to reanalyze all the internal PLF acoustic data at and below 250Hz, as recommended. Thus all maximax spectra presented here were derived using the conventional T_{av} = 1 sec.

It has been previously observed that the internal acoustic environment is usually higher when the distance from the PLF to the payload surface is short. Based on measured Shuttle flight data, Reference 9 developed a graph for predicting 1/3 OB SPL increases for decreasing distances. Since the flight data had substantial scatter, a certain amount of conservatism was used in the prediction. Subsequently Reference 10 developed an improved graph for payloads on expendable launch vehicles, shown in Figure 2, based on statistical energy analysis, which removed the unnecessary conservatism and can therefore be used for either increasing or decreasing PLF-to-payload surface distances. During Flight K-5, Meas. 9705, 9706 and 9707 were located where the PLF-to-payload surface distances were 34, 40 and 25 in., respectively. During Flight K-8, Meas. 9715, 9716 and 9717 were located where the distance was 25 in. in all three cases. In order to remove these fill factor effects from subsequent acoustic criteria development, the 1/3 OB SPLs for these measurements were reduced using Figure 2. As a result, all 24 internal PLF acoustic spectra were then treated on an equal weight basis. The resulting maximax spectra are shown in Figures 3-8.

Selection of Acoustic Criteria

Comparison of data from Figures 3-6 shows that there is significant scatter in the maximax acoustic spectra from the 19 internal PLF surface measurements, caused by flight-to-flight as well as spatial variations. Under these circumstances, it is conventional to perform a statistical analysis of the data population, determine or assume a statistical distribution, and select a criteria based on a given probability and confidence of not exceeding the resulting criteria. JPL personnel decided to select the acoustic criteria based on the recommendations in Reference 11; namely, assume the 1/3 OB SPL population is normally distributed, determine the mean and standard deviation of the population, and compute the resulting criteria based on a 95% probability of not exceeding the criteria with 50% confidence.

This analysis may be expressed mathematically as $x_{cr} = \bar{x} + k\, s_x$, where x_{cr}, $\bar{x}$ and s_x are the criteria, mean value and standard deviation of the population, and k is the tolerance factor. The value of the tolerance factor is a function of the probability and confidence selected, and the number of samples. Table II from Reference 12 shows this factor as a function of the number of samples for a 95/50% tolerance statement. It should be noted that only Reference 12 provides values of k for a wide range of probabilities and tolerances, whereas other references have only a limited range available and do not include the 95/50% tolerance. Incidently, it has traditionally been found that the 95/50% criteria roughly approximates the data envelope when more than just a few measurements are made. The data and envelope of the 19 inverse fill factor-adjusted internal PLF surface maximax acoustic spectra are shown in Figure 9.

Figure 10 shows the mean and 95/50% criteria for the above 19 spectra, along with the envelope and the current Cassini flight acceptance (FA) criteria. Figure 10 is a correction of Figure 26 of Reference 1. The 95/50% criteria of Figure 26 was erroneously computed, which has been subsequently corrected in Figure 10. It is seen in Figure 10 that the envelope and 95/50% criteria exceed the current FA criteria at several 1/3 OB frequencies. Examination of maximax flight spectra shows that all the exceedances occurred during Flight K-8; specifically Measurements (Meas.) 9715FF and 9717FF at 25 Hz, Meas. 9716FF at 31.5 Hz, Meas. 9709 at 160 and 200 Hz, and Meas. 9705 between 125 and 315 Hz. There is considerable concern about these exceedances, especially the 4 dB at 200 Hz from Meas. 9705 of Flight K-8. This is especially troubling when Meas. 9705 from Flight K-8 is compared with a similar Meas. 9705 from Flight K-5, which shows that the K-8 spectrum exceeds the K-5 spectrum by 7 dB at 200 Hz. (These measurements are in similar, but not identical locations, as the K-5 PLF is 10 ft longer than the K-8 PLF.) In addition, there is a general concern about the significant flight-to-flight variations in the acoustic spectra, causing a re-evaluation of the assumption that the data should be treated as a single population.

Launch Pad Effects

It can be seen that the maximax spectra in Figures 3 and 4 from Flights K-1 and K-4, launched from the ETR, are significantly lower than the spectra in Figures 5 and 6 from Flights K-5 and K-8, launched from the WTR. If there are important differences between ETR and WTR launch pad configurations and conditions affecting the acoustic noise generated by the SRMs, this could have a beneficial effect on the Cassini acoustic criteria, since the spacecraft is to be launched from the ETR. For example, Figure 11 shows that the 95/50% criteria and envelope for the 8 internal PLF surface measurements from Flights K-1 and K-4 are less than the current Cassini FA criteria except for small exceedances at 2 and 4 kHz, whereas Figure 12 shows that the envelope and 95/50% criteria for the 11 corresponding measurements from Flights K-5 and K-8 substantially exceed the current Cassini criteria at 25 and 160-250Hz. Figures 11 and 12 are corrections of Figures 28 and 29 of Reference 1, with the 95/50% criteria now correctly computed. In addition, a comparison of overall pressure histories from ETR and WTR show a different character of the data, as illustrated in Figure 13 from Reference 8.

Examination of the ETR and WTR launch pads shows that there are many similarities and some differences, as discussed in Reference 1. In both cases, the SRM exhaust flows are directed into a single covered launch duct, having a length of approximately 135 ft and having approximately the same cross sectional areas. On Flight K-1, a significant low frequency overpressure (O/P) transient, which propagated up the vehicle at the speed of sound, was generated at SRM ignition. To attenuate this transient, O/P water suppression systems were installed at both facilities. As a result, the O/P was substantially reduced for the following three flights. Both systems were designed to achieve their maximum water flow rates from about T-1.5 to T+4 sec, with water valve shutoff at T+6 sec. Thus some effect on liftoff noise should have been observed. However, the maximum flow rates were considerably different: 50,000 gpm of water was applied to the SRM exhaust flows at the exhaust duct inlet at the ETR, whereas 60,000 gpm was applied at the inlet and an additional 25,000 gpm at the duct exit at the WTR. Thus, if water did attenuate liftoff acoustics prior to T+4 sec, as well as the O/P transient, then greater attenuation should have been achieved at the WTR. This hypothesis is in obvious contradiction to the observed acoustic increase at the WTR. One potential cause of the acoustical differences is reflections from the different types of Umbilical Towers used at ETR and WTR. More data will probably be required to ascertain the cause.

After T+3 sec, the increasing vehicle altitude above the launch pad is high enough for most of the diverging SRM exhaust flows to impact the top of the pad rather than enter the duct, so that water attenuation would no longer be effective. This is confirmed by the OA SPL history of Meas. 9705 from Flight K-5, but is in contradiction to the history of Meas. 9737 from Flight K-4, both of which are shown in Figure 13.

Status of Acoustic Criteria

JPL dynamics personnel recommend no change to the current Cassini acoustic criteria because of the usage of the ETR launch site. It should be noted that most of the spacecraft will be exposed to an acoustic environment less than that indicated in Figure 10, because the 19 internal measurements used for developing the 95/50% criteria were located adjacent to the PLF surface. The spectral differences between the average of the 6 measurements made at the PLF surface and that of the 3 measurements made at the 20 in. standoffs during Flight K-4 are shown in Figure 14. Similarly, the average differences between the 8 surface and 2 standoff measurements during Flight K-8 are shown in Figure 15. Applying these differences to the exceedances shown in Figures 11 and 12 indicate that the spacecraft will not be exposed to an acoustic environment greater than the current Cassini criteria.

For the current Cassini configuration, only one assembly is close enough to the PLF surface that an exceedance of the basic FA acoustic criteria is anticipated; specifically, the Huygens Probe (HP), now relocated to a PLF-to-HP distance of 34.1 in. The HP shown on the left side of Cassini in Figure 1, is a separate spacecraft designed to parachute and land on Titan, the largest Saturn satellite. Flight acceptance (FA) acoustic criteria were derived for the HP based on the direct application of the fill factor shown in Figure 2. The current Cassini FA criteria and the original and revised HP FA acoustic criteria are shown in Figure 16. A vibroacoustic analysis will be performed to determine the loading on the Cassini antenna, which separates the upper and lower portions of the payload cavity, as discussed in Reference 1. JPL sets design and qual test criteria at 4 dB above the FA criteria to compensate for acoustic test tolerances and to provide a margin for potential program changes. When acoustic testing is performed later in the program, it is anticipated that the HP will be tested separately to the slightly higher criteria. Consideration will also be given as to whether local "hot spot" horns will be required to excite an HP structural simulator to the slightly higher criteria during the spacecraft system acoustic test.

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Table I. Number of Titan IV Flight Measurements Used to Derive Cassini Acoustic Criteria

Launch Site	Flight	External	Internal		Fill Factor Affected
			PLF Surface	Standoff	
ETR	K-1	1	2	0	0
	K-4	4	6	3	0
WTR	K-5	0	3	0	3
	K-8	5	8	2	3

Table II. Statistical Tolerance Factors for Deriving Cassini 95/50% Acoustic Criteria Based on Number of Flight Measurements Analyzed (Reference 12)

Number	Tolerance Factor	Number	Tolerance Factor
2	2.339	16	1.678
3	1.939	17	1.676
4	1.830	18	1.674
5	1.779	19	1.673
6	1.750	20	1.671
7	1.732	21	1.670
8	1.719	22	1.669
9	1.709	23	1.668
10	1.702	24	1.667
11	1.693	25	1.666
12	1.691		
13	1.687	30	1.662
14	1.684	35	1.659
15	1.681	40	1.658
		45	1.656
		∞	1.64485

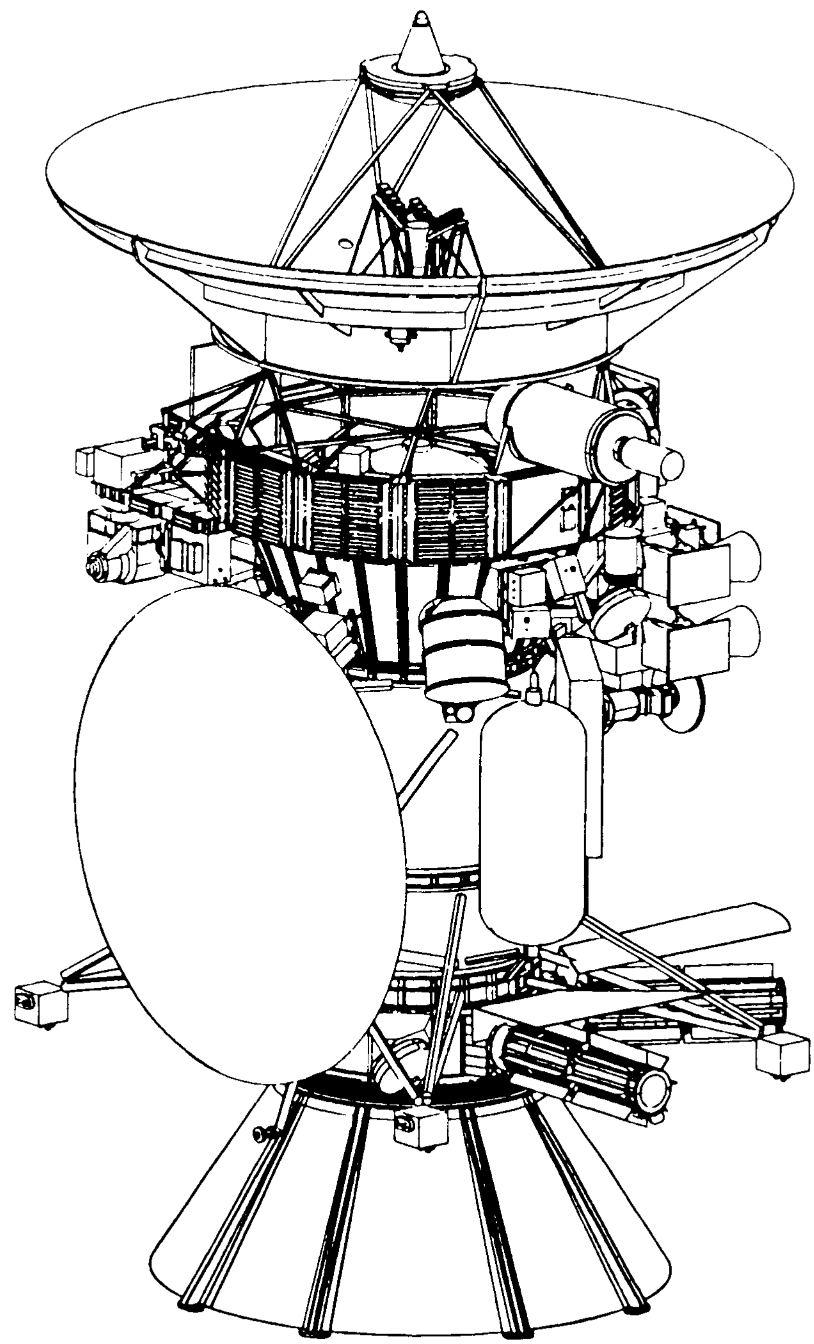


Fig. 1

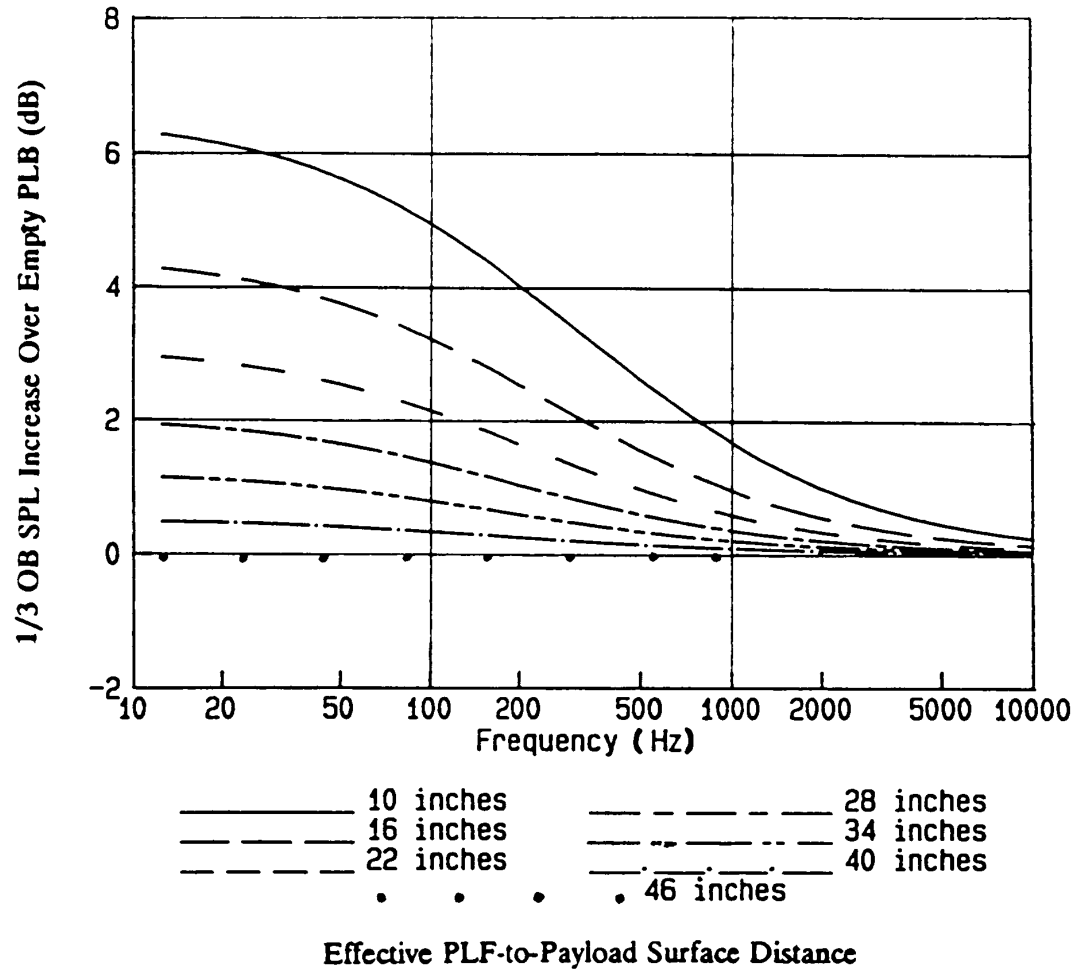

8
6
4
2
0
-2
1/3 OB SPL Increase Over Empty PLB (dB)
10
20
50
100
200
500
1000
2000
5000
10000
Frequency (Hz)
10 inches
16 inches
22 inches
28 inches
34 inches
40 inches
46 inches
Effective PLF-to-Payload Surface Distance

Fig. 2

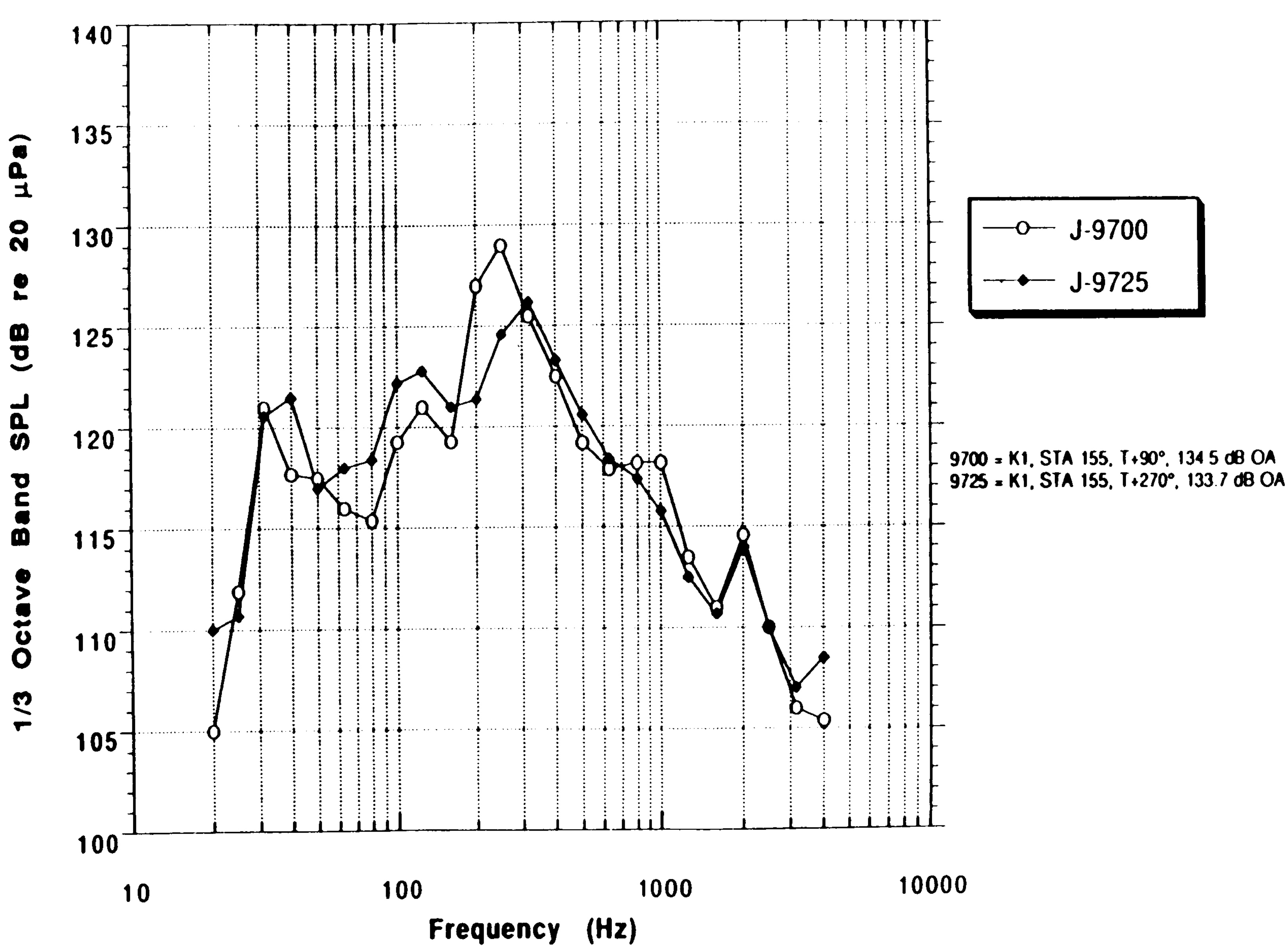

1/3 Octave Band SPL (dB re 20 μPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)
J-9700
J-9725
9700 = K1, STA 155, T+90°, 134.5 dB OA
9725 = K1, STA 155, T+270°, 133.7 dB OA

Fig. 3

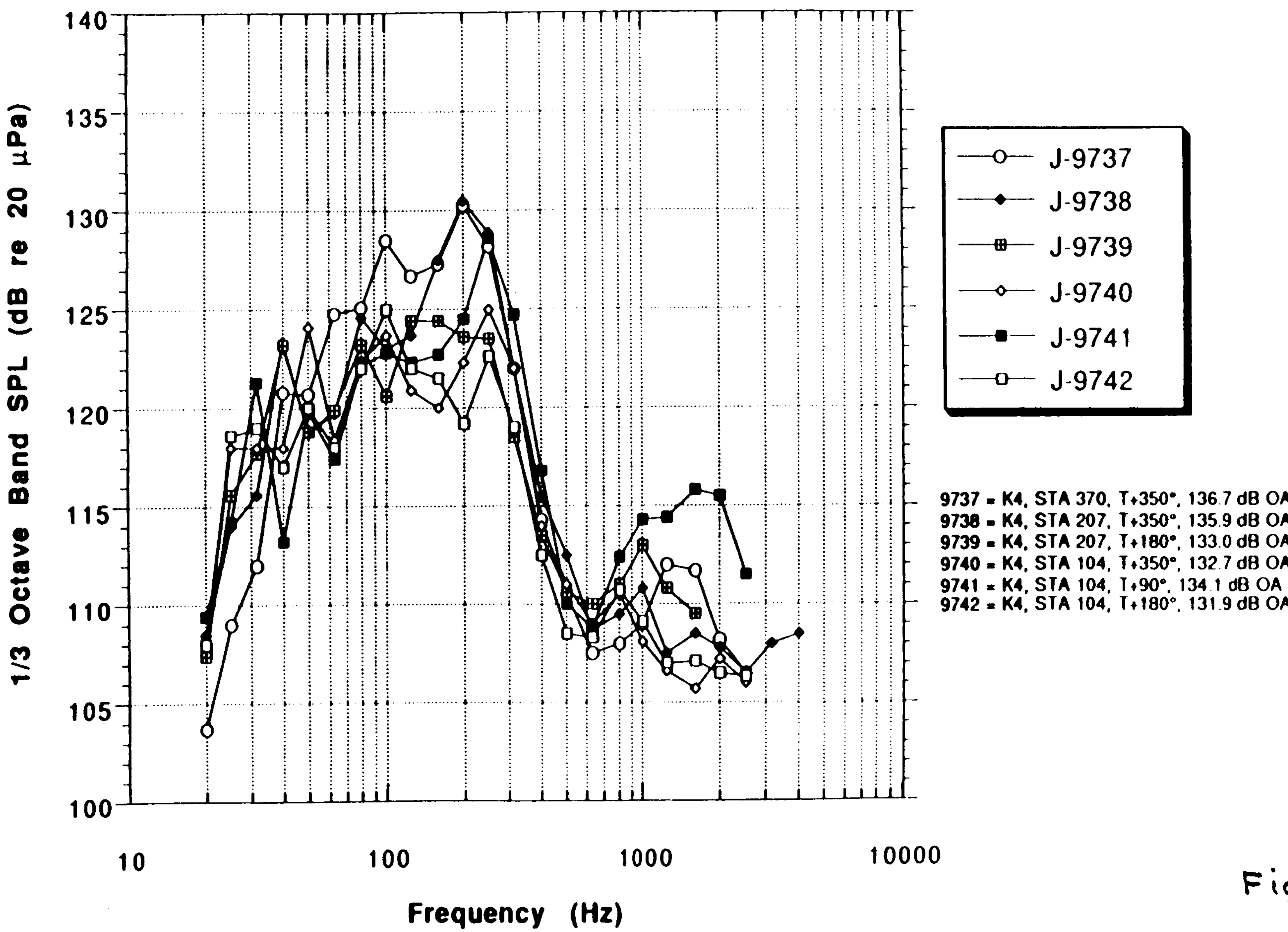
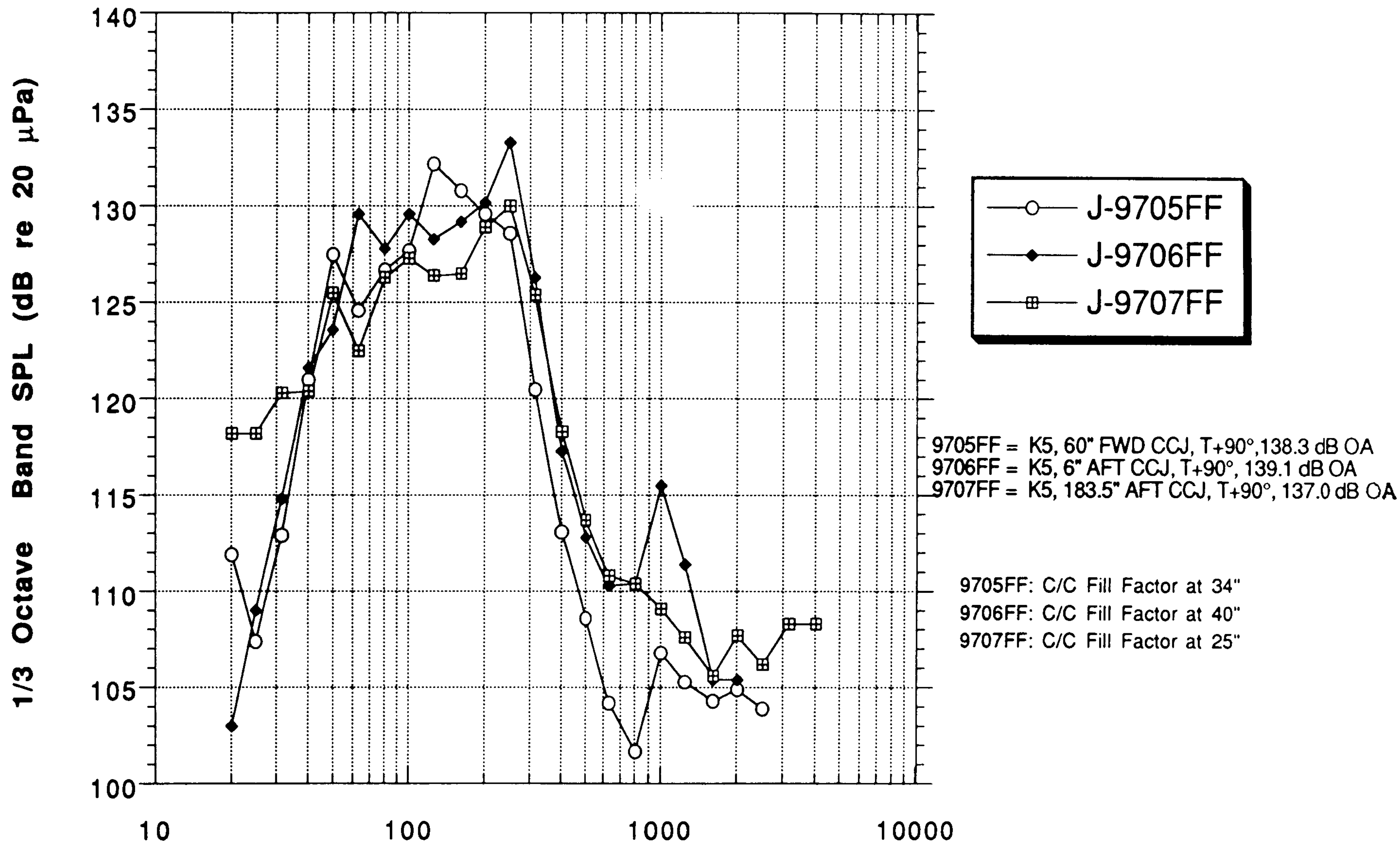
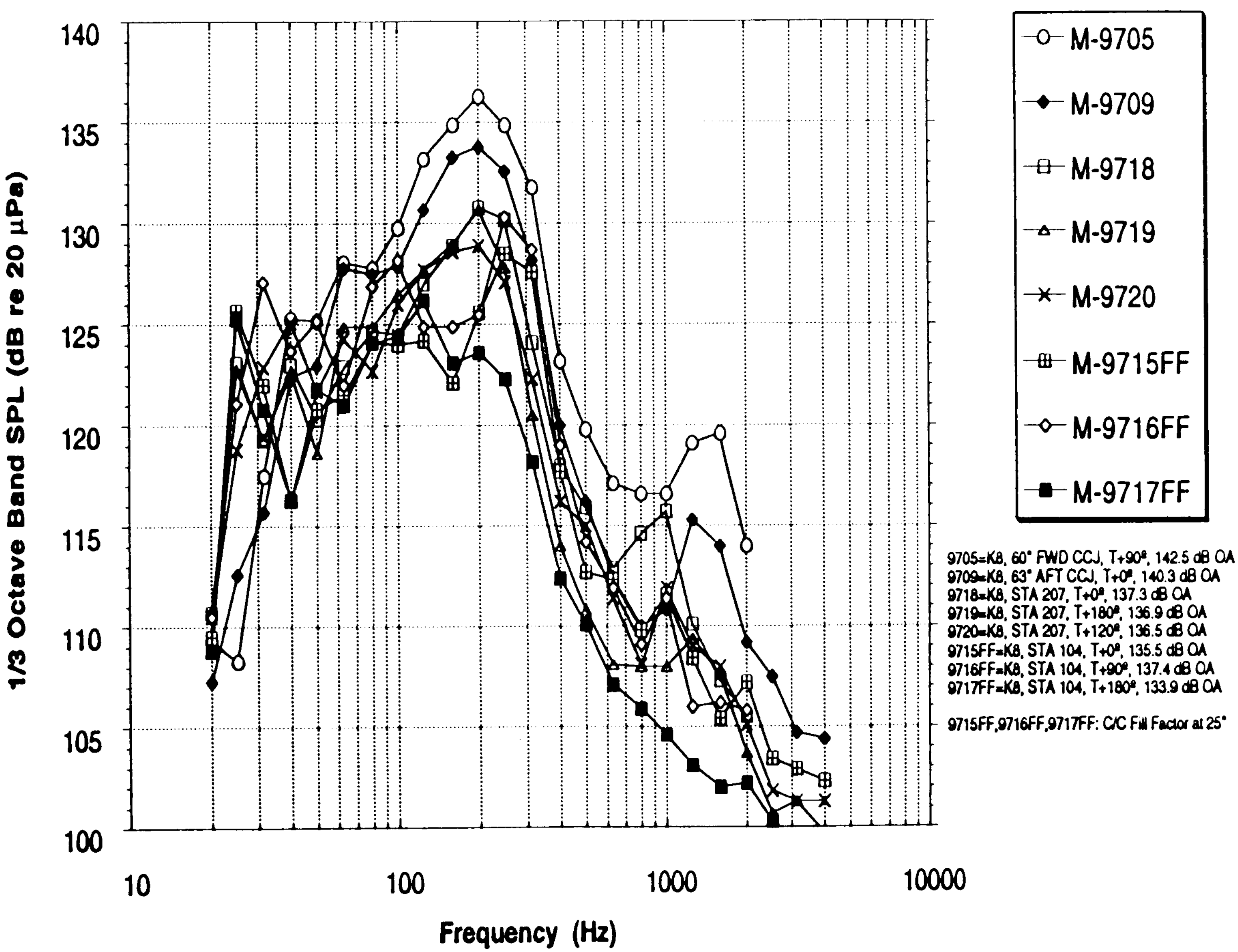

1/3 Octave Band SPL (dB re 20 μPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)
J-9737
J-9738
J-9739
J-9740
J-9741
J-9742
9737 = K4, STA 370, T+350°, 136.7 dB OA
9738 = K4, STA 207, T+350°, 135.9 dB OA
9739 = K4, STA 207, T+180°, 133.0 dB OA
9740 = K4, STA 104, T+350°, 132.7 dB OA
9741 = K4, STA 104, T+90°, 134.1 dB OA
9742 = K4, STA 104, T+180°, 131.9 dB OA

Fig. 4



J-9705FF
J-9706FF
J-9707FF
9705FF = K5, 60" FWD CCJ, T+90°,138.3 dB OA
9706FF = K5, 6" AFT CCJ, T+90°, 139.1 dB OA
9707FF = K5, 183.5" AFT CCJ, T+90°, 137.0 dB OA
9705FF: C/C Fill Factor at 34"
9706FF: C/C Fill Factor at 40"
9707FF: C/C Fill Factor at 25"
1/3 Octave Band SPL (dB re 20 μPa)
Frequency (Hz)
140
135
130
125
120
115
110
105
100
10
100
1000
10000

Fig. 5



140
135
130
125
120
115
110
105
100
1/3 Octave Band SPL (dB re 20 µPa)
10
100
1000
10000
Frequency (Hz)
M-9705
M-9709
M-9718
M-9719
M-9720
M-9715FF
M-9716FF
M-9717FF
9705=K8, 60° FWD CCJ, T+90°, 142.5 dB OA
9709=K8, 63° AFT CCJ, T+0°, 140.3 dB OA
9718=K8, STA 207, T+0°, 137.3 dB OA
9719=K8, STA 207, T+180°, 136.9 dB OA
9720=K8, STA 207, T+120°, 136.5 dB OA
9715FF=K8, STA 104, T+0°, 135.5 dB OA
9716FF=K8, STA 104, T+90°, 137.4 dB OA
9717FF=K8, STA 104, T+180°, 133.9 dB OA
9715FF,9716FF,9717FF: C/C Fill Factor at 25°

Fig. 6

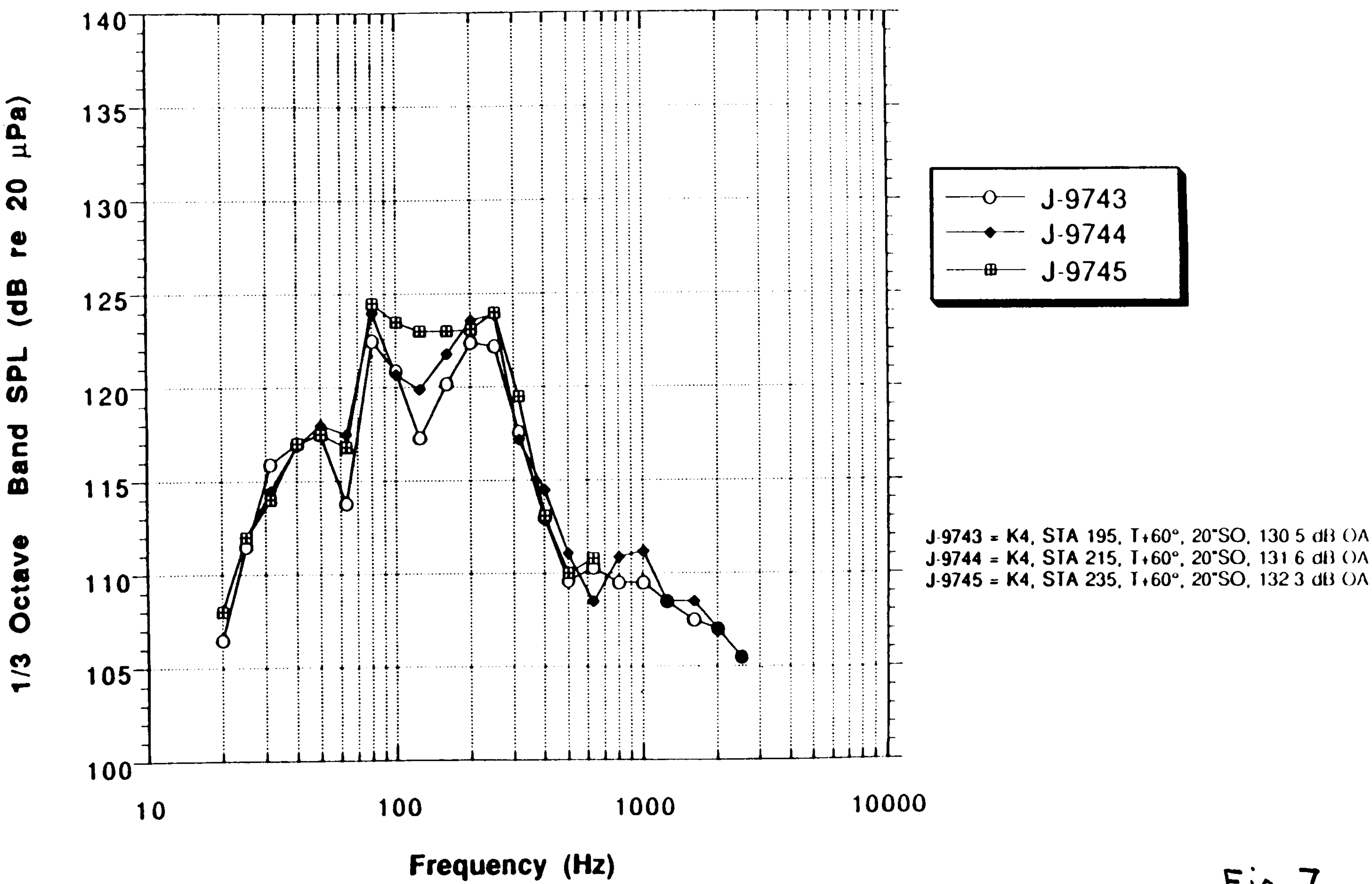
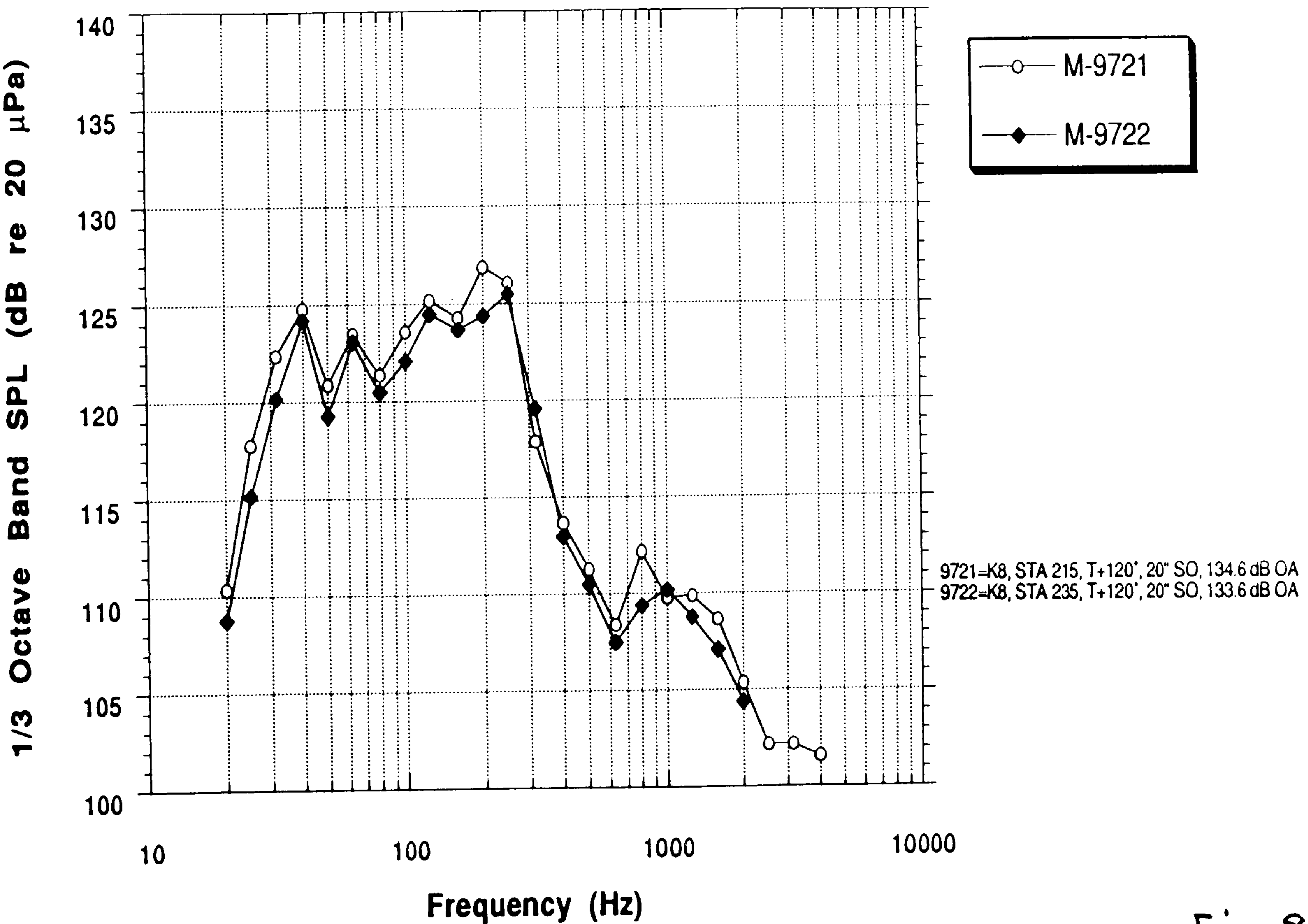
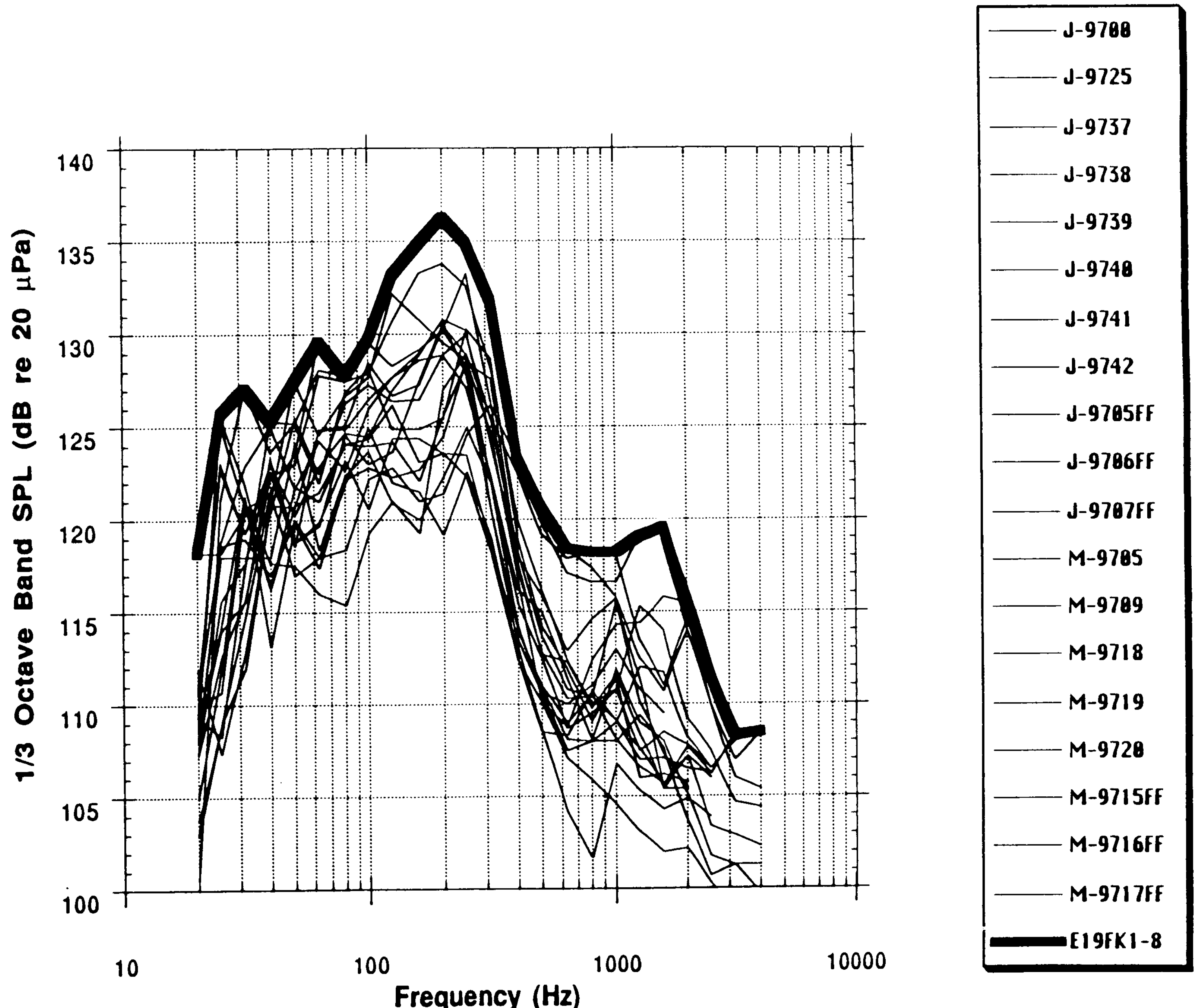

1/3 Octave Band SPL (dB re 20 μPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)
J-9743
J-9744
J-9745
J-9743 = K4, STA 195, T+60°, 20°SO, 130 5 dB OA
J-9744 = K4, STA 215, T+60°, 20°SO, 131 6 dB OA
J-9745 = K4, STA 235, T+60°, 20°SO, 132 3 dB OA

Fig. 7



M-9721
M-9722
9721=K8, STA 215, T+120°, 20" SO, 134.6 dB OA
9722=K8, STA 235, T+120°, 20" SO, 133.6 dB OA
1/3 Octave Band SPL (dB re 20 μPa)
Frequency (Hz)
140
135
130
125
120
115
110
105
100
10
100
1000
10000

Fig. 8



1/3 Octave Band SPL (dB re 20 µPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)
J-9700
J-9725
J-9737
J-9738
J-9739
J-9740
J-9741
J-9742
J-9705FF
J-9706FF
J-9707FF
M-9705
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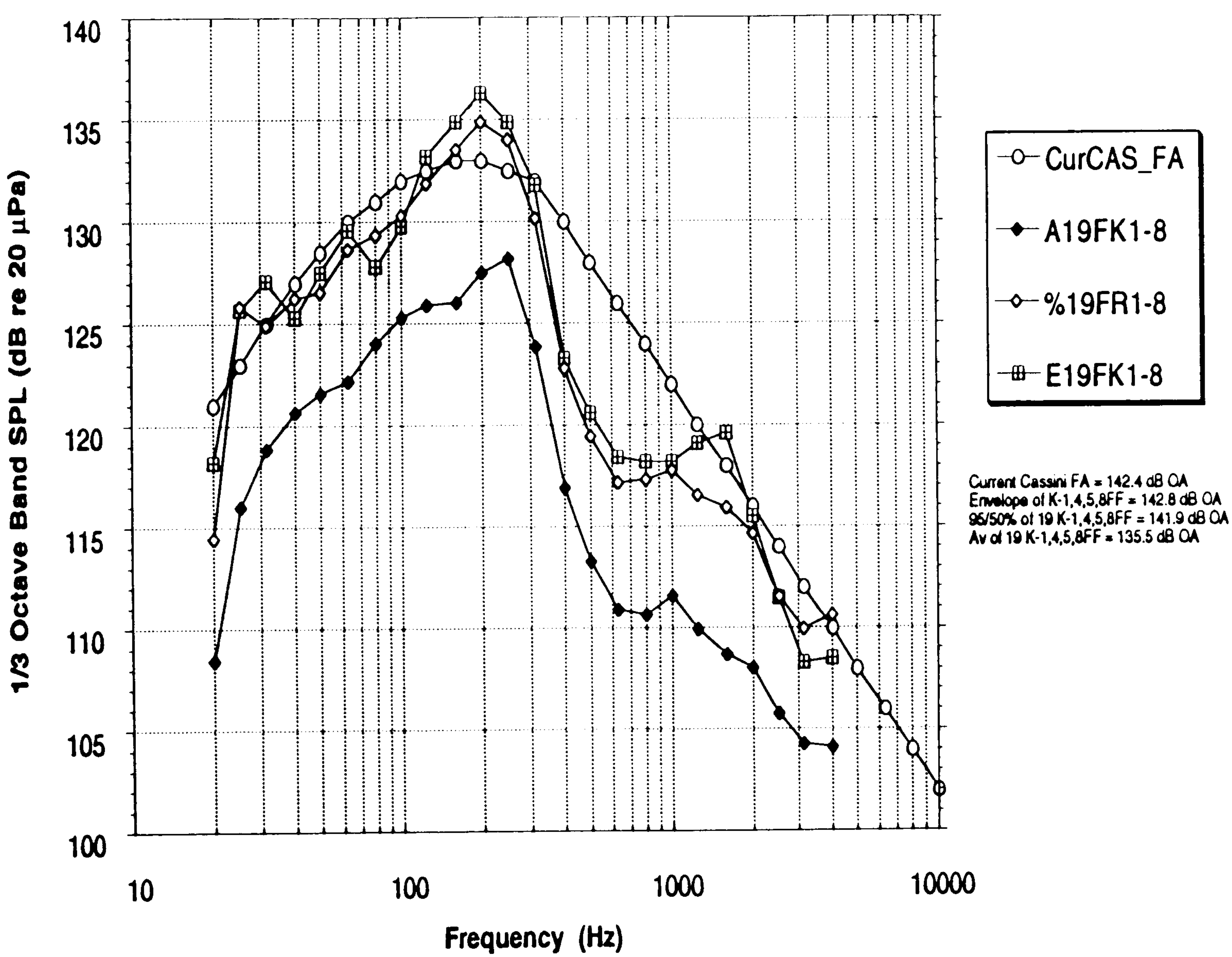
M-9720
M-9715FF
M-9716FF
M-9717FF
E19FK1-8

Fig. 9



140
135
130
125
120
115
110
105
100
1/3 Octave Band SPL (dB re 20 µPa)
10
100
1000
10000
Frequency (Hz)
CurCAS_FA
A19FK1-8
%19FR1-8
E19FK1-8
Current Cassini FA = 142.4 dB OA
Envelope of K-1,4,5,8FF = 142.8 dB OA
95/50% of 19 K-1,4,5,8FF = 141.9 dB OA
Av of 19 K-1,4,5,8FF = 135.5 dB OA

Fig. 10

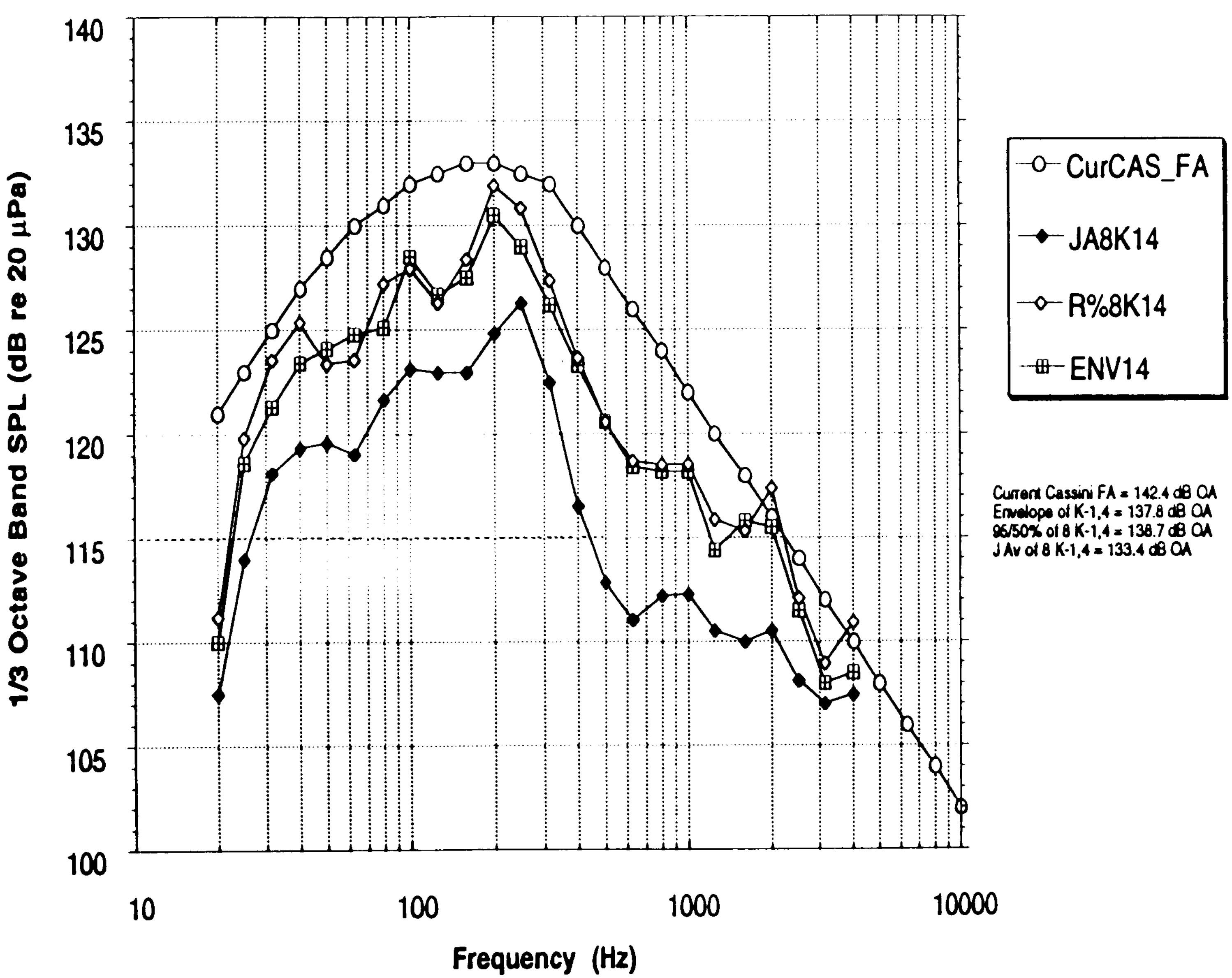
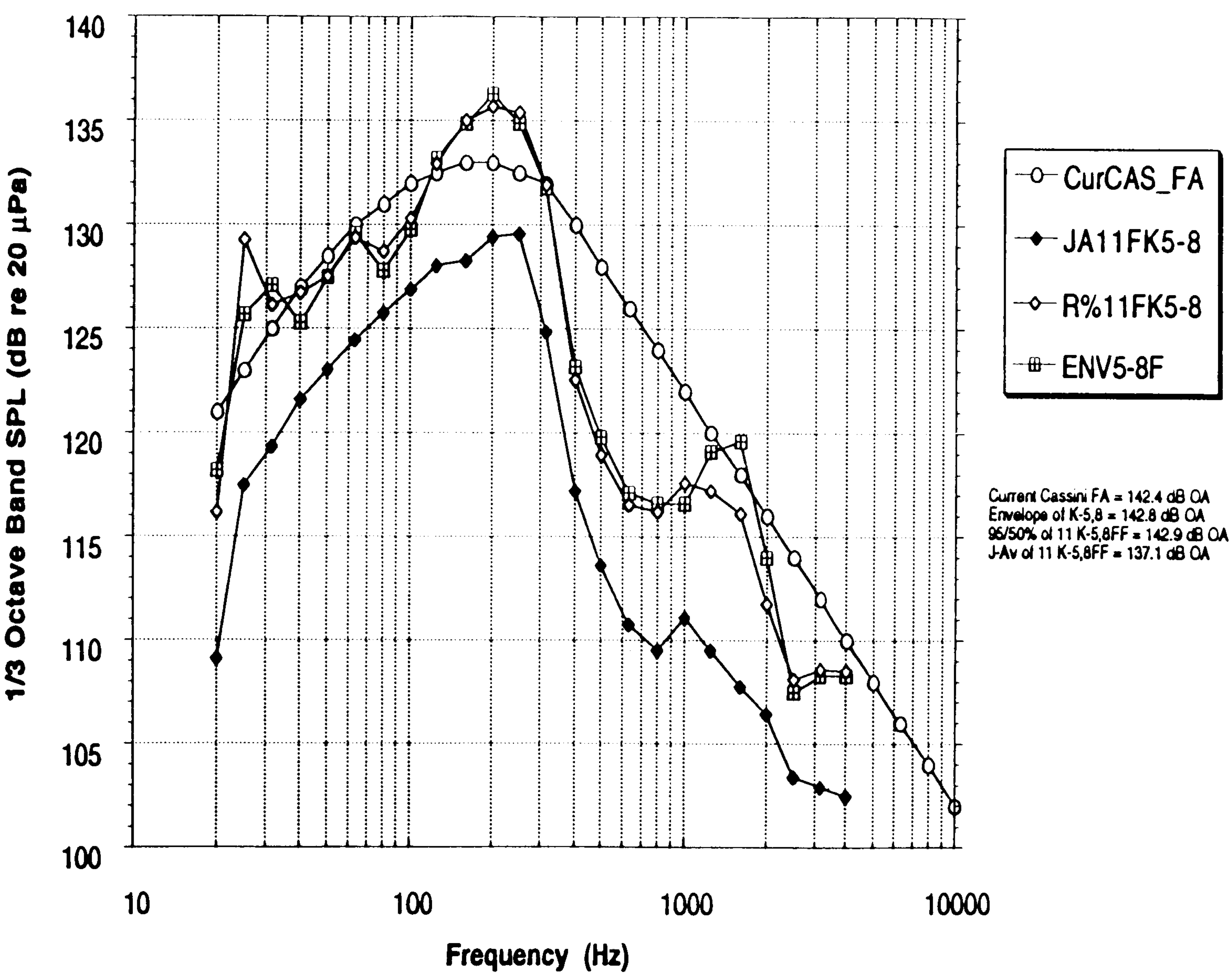

CurCAS_FA
JA8K14
R%8K14
ENV14
Current Cassini FA = 142.4 dB OA
Envelope of K-1,4 = 137.8 dB OA
95/50% of 8 K-1,4 = 138.7 dB OA
J Av of 8 K-1,4 = 133.4 dB OA
1/3 Octave Band SPL (dB re 20 μPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)

Fig. 11



1/3 Octave Band SPL (dB re 20 µPa)
140
135
130
125
120
115
110
105
100
10
100
1000
10000
Frequency (Hz)
CurCAS_FA
JA11FK5-8
R%11FK5-8
ENV5-8F
Current Cassini FA = 142.4 dB OA
Envelope of K-5,8 = 142.8 dB OA
95/50% of 11 K-5,8FF = 142.9 dB OA
J-Av of 11 K-5,8FF = 137.1 dB OA

Fig. 12

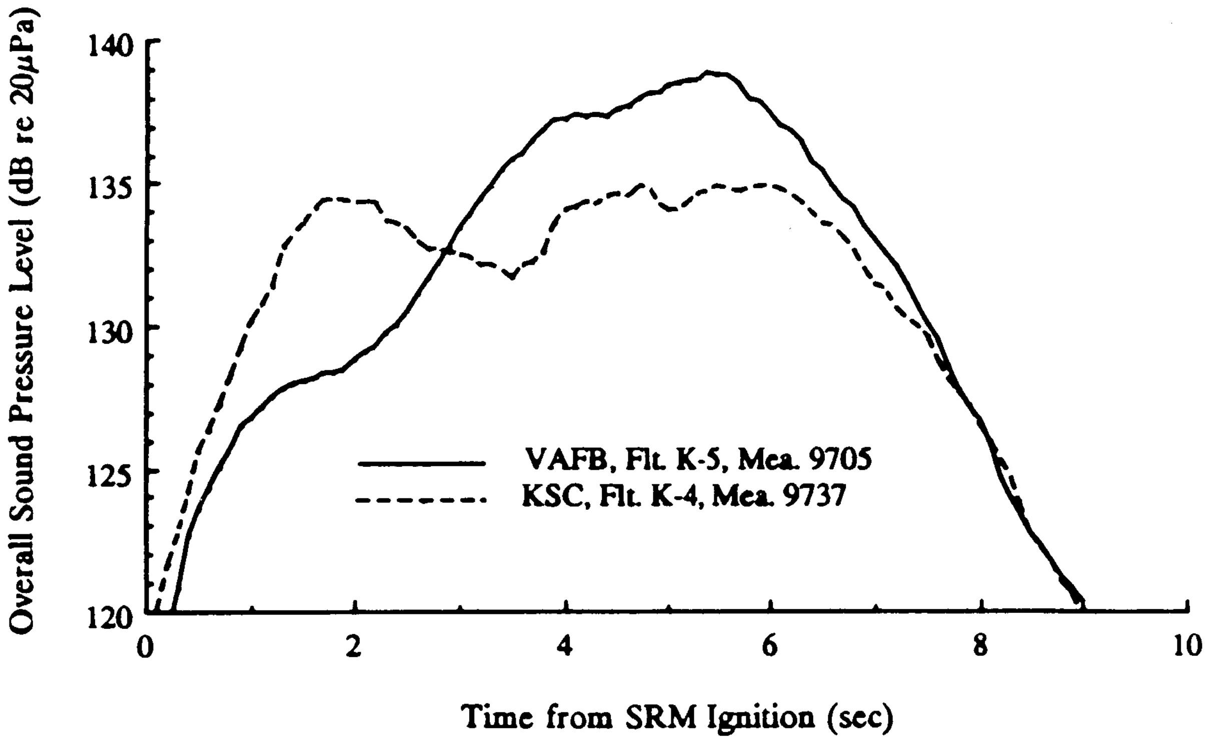

Overall Sound Pressure Level (dB re 20μPa)
140
135
130
125
120
0
2
4
6
8
10
VAFB, Flt. K-5, Mea. 9705
KSC, Flt. K-4, Mea. 9737
Time from SRM Ignition (sec)

Fig. 13

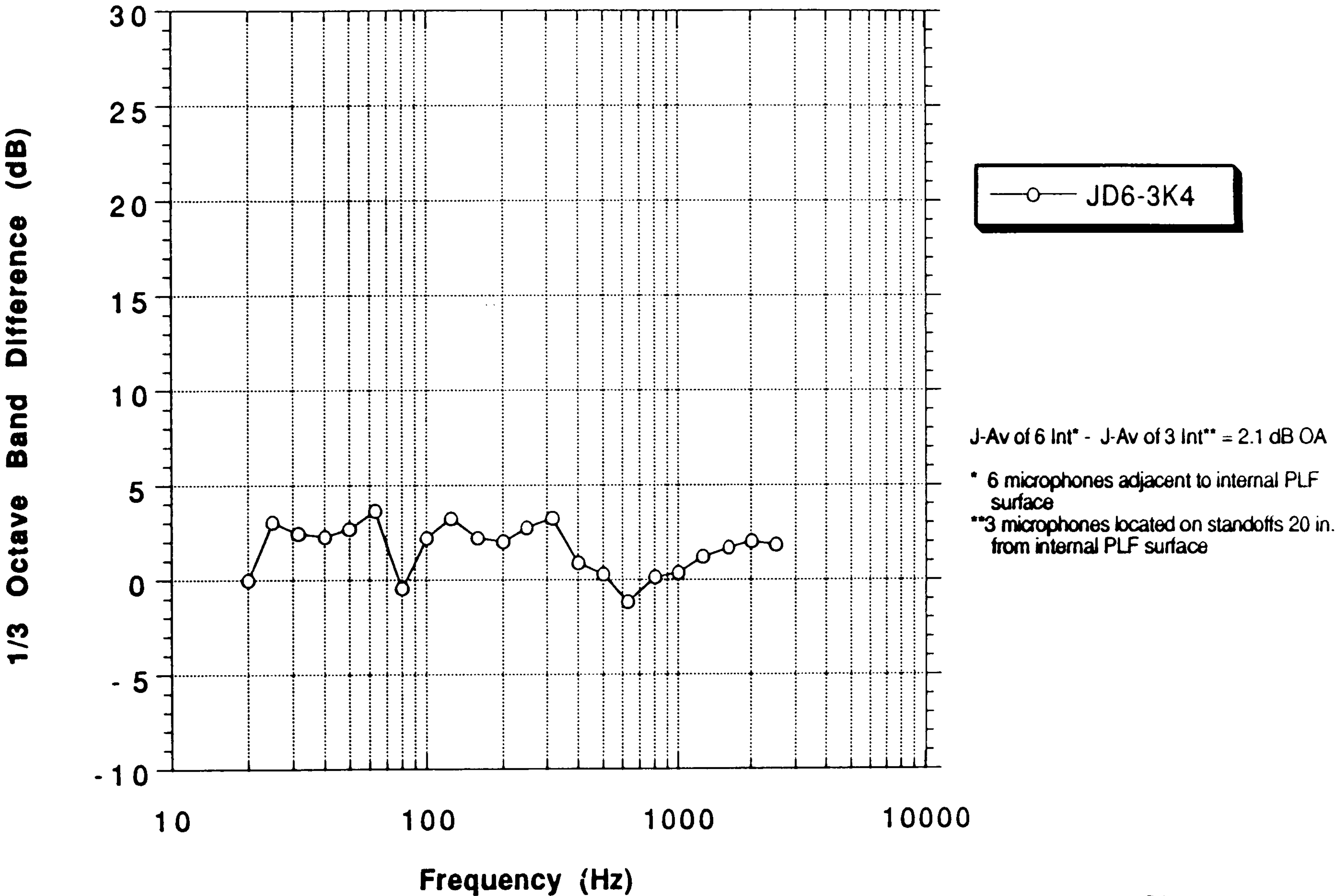

30
25
20
15
10
5
0
- 5
- 10
1/3 Octave Band Difference (dB)
10
100
1000
10000
Frequency (Hz)
JD6-3K4
J-Av of 6 Int* - J-Av of 3 Int** = 2.1 dB OA
* 6 microphones adjacent to internal PLF surface
**3 microphones located on standoffs 20 in. from internal PLF surface

Fig. 14

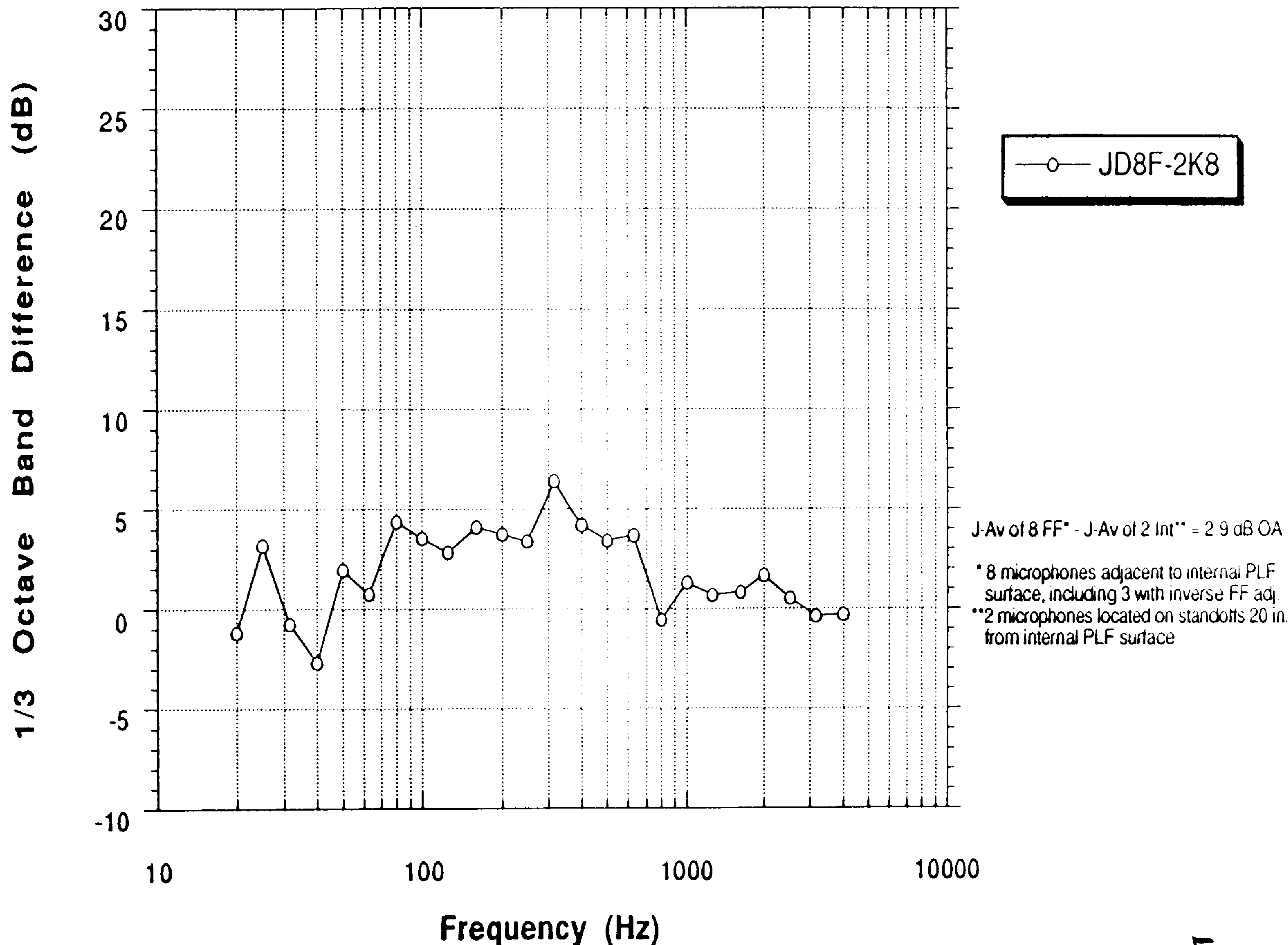

1/3 Octave Band Difference (dB)
30
25
20
15
10
5
0
-5
-10
10
100
1000
10000
Frequency (Hz)
JD8F-2K8
J-Av of 8 FF* - J-Av of 2 Int** = 2.9 dB OA
* 8 microphones adjacent to internal PLF surface, including 3 with inverse FF adj.
**2 microphones located on standoffs 20 in. from internal PLF surface

Fig. 15

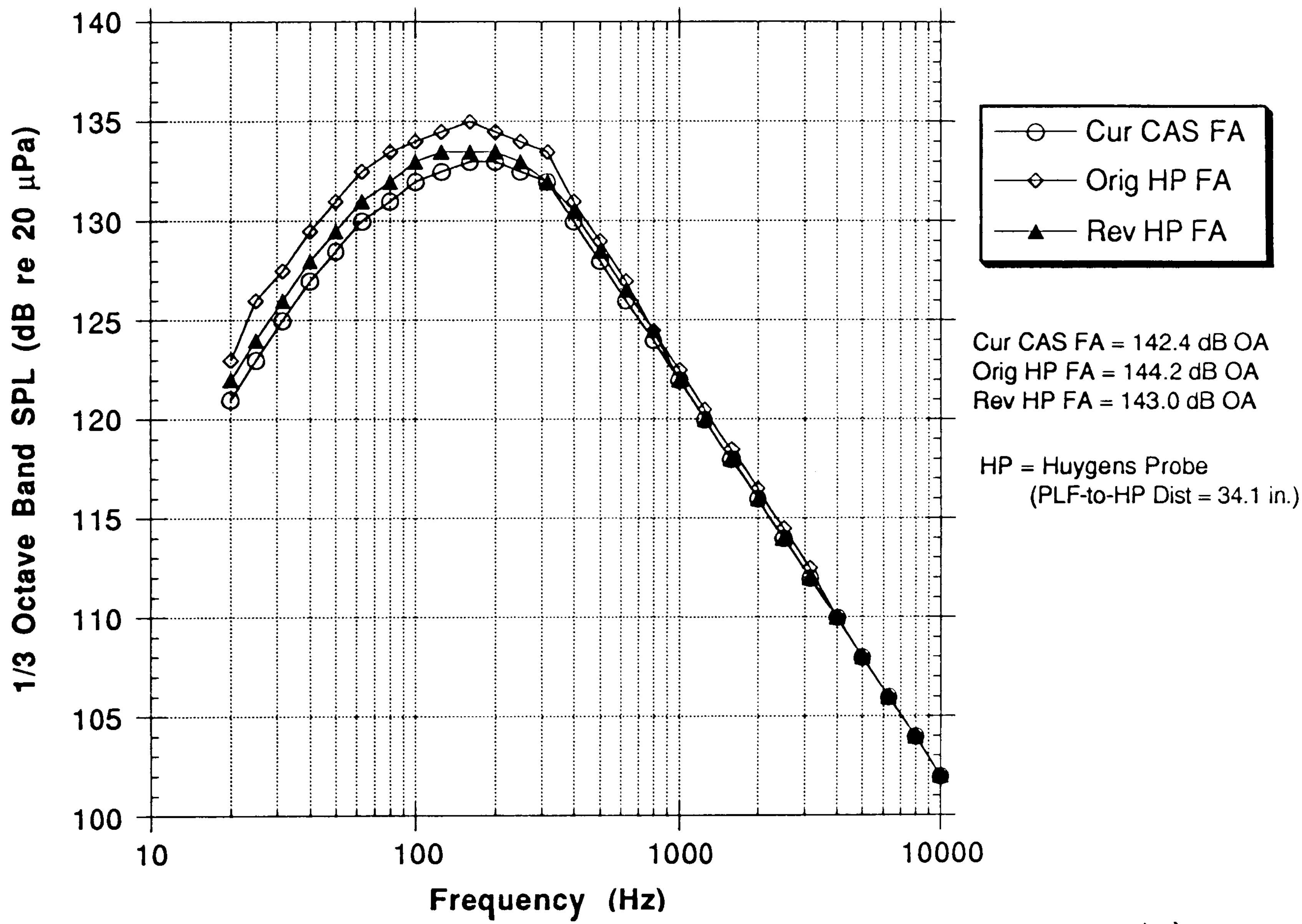

140
135
130
125
120
115
110
105
100
10
100
1000
10000
1/3 Octave Band SPL (dB re 20 µPa)
Frequency (Hz)
Cur CAS FA
Orig HP FA
Rev HP FA
Cur CAS FA = 142.4 dB OA
Orig HP FA = 144.2 dB OA
Rev HP FA = 143.0 dB OA
HP = Huygens Probe
(PLF-to-HP Dist = 34.1 in.)

Fig. 16