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DIESEL-POWERED HEAVY-DUTY REFRIGERATION UNIT NOISE

Thomas J. Retka

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FINAL REPORT

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16. Abstract

A series of noise measurements were performed on a diesel-powered heavy-duty refrigeration unit. Noise survey information collected included: (1) polar plots of the "A Weighted" noise levels of the unit under maximum and minimum load conditions; (2) a linear and "A" weighted acoustical time history of the refrigeration unit noise operating from start-up to load conditions representing both minimum (unloaded) and maximum (loaded) cooling capacity; (3) the determination of the unmuffled refrigeration unit engine exhaust noise level under maximum and minimum load conditions; (4) the determination of the noise contribution, under maximum load conditions, from the refrigeration unit engine exhaust and engine cooling system fan to the overall system noise.

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PREFACE

This report summarizes the contractual effort on U.S. Department of Transportation Contract DOT-TSC-532, a Baseline Study of the Parameters Affecting Diesel Engine Intake and Exhaust Silencer Designs. Amendments 1-3 of this contract, of which this report is concerned, involved the study of the noise of a diesel-powered heavy duty refrigeration unit. Contract efforts were basically performed during the months June - August 1974, with a report update being prepared during the months July - September 1975. The objective of the contract was to perform noise measurements on a diesel-powered heavy duty refrigeration unit.

Donaldson Company, Inc., in the performance of Contract DOT-TSC-532, relied on the assistance of a manufacturer of truck-trailer refrigeration units. We wish to extend thanks to Thermo King Corporation for its contribution to the performance of this program.

TABLE OF CONTENTS

		Page
Section 1	INTRODUCTION	1
Section 2	REFRIGERATION UNIT TESTED	1
2.1	Specifics of Unit Tested	1
2.2	Configuration of Unit for Tests	3
2.3	Noise Tests Performed	3
2.4	Instrumentation	8
Section 3	TEST RESULTS	8
3.1	Test Procedure	8
3.2	Results	8
3.2.1	Polar Plot of Refrigeration Unit Noise Levels	8
3.2.1.1	Refrigeration Unit Maximum Load Condition	11
3.2.1.2	Refrigeration Unit Minimum Load Condition	14
3.2.2	Acoustical Time History of Refrigeration Unit Load Cycle	19
3.2.3	Determination of Unmuffled Refrigeration Unit Engine Exhaust Noise Level	19
3.2.3.1	Unmuffled Refrigeration Unit Maximum Load Condition	19
3.2.3.2	Unmuffled Refrigeration Unit Minimum Load Condition	23
3.2.4	Contribution of The Refrigeration Unit Cooling System Fan to Overall Refrigeration Unit Noise	28
3.2.5	Contribution of The Refrigeration Unit Engine Exhaust Noise to The Overall System Noise	33
Section 4	SUMMARY	39
	APPENDIX	43

LIST OF FIGURES

Figure		Page
1	Cutaway View of Refrigeration Unit	2
2	Left Front View of Refrigeration Unit	4
3	Right Front View of Refrigeration Unit	5
4	Refrigeration Unit Configuration	6
5	Refrigeration Unit Mounted on Truck Trailer	7
6	Test Instrumentation for Noise Test of Refrigeration Unit	9
7	Polar Plot Microphone Locations	10
8	Polar Plot Noise Levels of the Refrigeration Unit at Maximum Load Conditions	12
9	Equal Loudness Contours of Refrigeration Unit for Maximum Load Condition	13
10	Refrigeration Unit Noise at Maximum Load - Position 2	15
11	Polar Plot Noise Levels of the Refrigeration Unit at Minimum Load Conditions	16
12	Equal Loudness Contours of Refrigeration Unit at Minimum Load Condition	17
13	Refrigeration Unit Noise at Minimum Load - Position 2	18
14	Plotted Time History of Refrigeration Unit - Linear Weighted	20
15	Plotted Time History of Refrigeration Unit - A-Weighted	21
16	Muffler Removed and Replaced by Equivalent-sized Pipe	22
17	Refrigeration Unit Muffler	22
18	Polar Plot Noise Levels of Unmuffled Refrigeration Unit Noise Levels at Maximum Load Conditions	24
19	Equal Loudness Contours of Unmuffled Refrigeration Unit (Maximum Load Condition)	25
20	Polar Plot Noise Levels of Unmuffled Refrigeration Unit Noise Levels at Minimum Load Conditions	26
21	Equal Loudness Contours of Unmuffled Refrigeration Unit (Minimum Load Condition)	27
22	Refrigeration Unit Noise at Maximum Load - Position 2	30
23	Refrigeration Unit Noise at Maximum Load Condition (Engine Cooling Fan Removed) - Position 2	31

LIST OF FIGURES (continued)

Figure		Page
24	A-Weighted Attenuation versus Frequency Plot (Cooling Fan Disconnected)	32
25	Octave Band Attenuation Provided by Cooling Fan Removed	33
26	Straight-Through Type Muffler in Series with Refrigeration Unit Muffler	34
27	Right-Angle Type Muffler in Series with Refrigeration Unit Muffler	34
28	Noise Levels of Refrigeration Unit at Maximum Load Condition Position 2	35
29	Position 2 Noise Levels of Refrigeration Unit at Maximum Load Condition (Additional In-Series Muffling)	36
30	Position 2 Noise Levels of Refrigeration Unit at Minimum Load Condition	37
31	Noise Levels of Refrigeration Unit at Minimum Load Condition (Additional In-Series Muffling) Position 2	38
32	Refrigeration Unit Noise at Maximum Load - Position 2	40
33	Refrigeration Unit Noise at Maximum Load (Additional In-Series Muffling)	41

1 INTRODUCTION

As part of the United States Department of Transportation (DOT) program to develop truck noise control technology (Contract DOT-TSC-532, Amendment 1), Donaldson Company, Inc., obtained acoustic noise data on a diesel-powered heavy-duty truck-trailer refrigeration unit.

2 REFRIGERATION UNIT TESTED

2.1 Specifics of Unit Tested

The refrigeration unit noise tested was a Thermo King diesel-powered heavy-duty truck-trailer unit Model Super NWD 30, serial no. 0442964099. Specifics on the refrigeration unit are:

Diesel Engine	Isuzu C 201, 4 cylinder
Horsepower	32 hp
Engine rpm	1350-1400 rpm Low speed operation 2200 rpm High speed operation
Cooling Capacity	Approximately 19,500 Btu/hr (0° F air to coil) Approximately 38,500 Btu/hr (35° F air to coil)
Cooling Range	-20° F to 80° F

The refrigeration unit mounts on the front of the trailer with the evaporator section extending into the trailer. It maintains the pre-set trailer temperature through refrigeration or heating as necessary. The unit is thermostatically controlled, operating at high or low speed to maintain the trailer temperature.

The evaporator section consists of an evaporator coil, fan, heat exchanger and expansion valve. The condenser section contains the engine, compressor, condenser coil, fan, alternator, generator and unit controls. Figure 1 presents a cutaway view of the refrigeration unit. The unit presented is identical to the unit tested with the exception that the exhaust muffler in the tested unit had a vertical-mounted muffler instead of the pitched horizontal muffler.

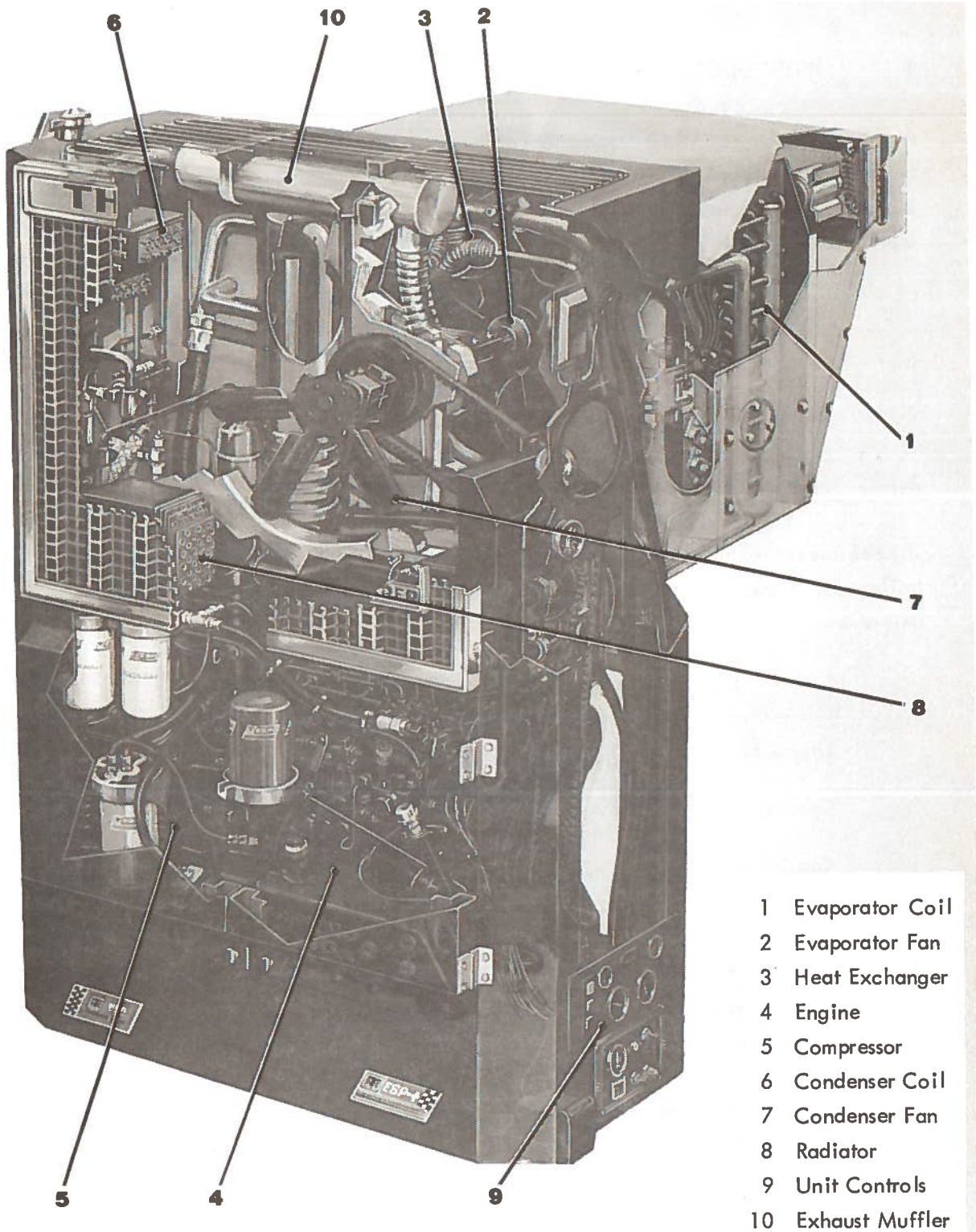


Figure 1. Cutaway View of Refrigeration Unit

The C 201 diesel engine supplies the power to run this unit. The C 201 is a 4 cylinder, vertical, in-line, 4 stroke cycle, overhead valve, liquid-cooled diesel engine. The compressor is a Thermo King Model 426 compressor which is a long stroke, 4 cylinder, "V" Type, reciprocating compressor. The fly wheel housing and direct drive coupling connect the engine to the compressor. Belts from the engine crankshaft pulley drive the condenser and evaporator fans, the water pump and the alternator.

Figures 2 and 3 present, respectively, left and right front views of the refrigeration unit. The diesel engine is situated behind the right and left front doors. Intake air is drawn through a precleaner and air cleaner on the right side of the refrigeration unit. Engine exhaust is ducted from the engine manifold, through a muffler situated within the refrigeration unit housing and out the top of the unit (rain cap). Air cooling louvers for engine cooling are located on both sides of the refrigeration unit. The diesel engine radiator cooling fan is located behind the grill on the front face of the refrigeration unit.

2.2 Configuration of Unit for Tests

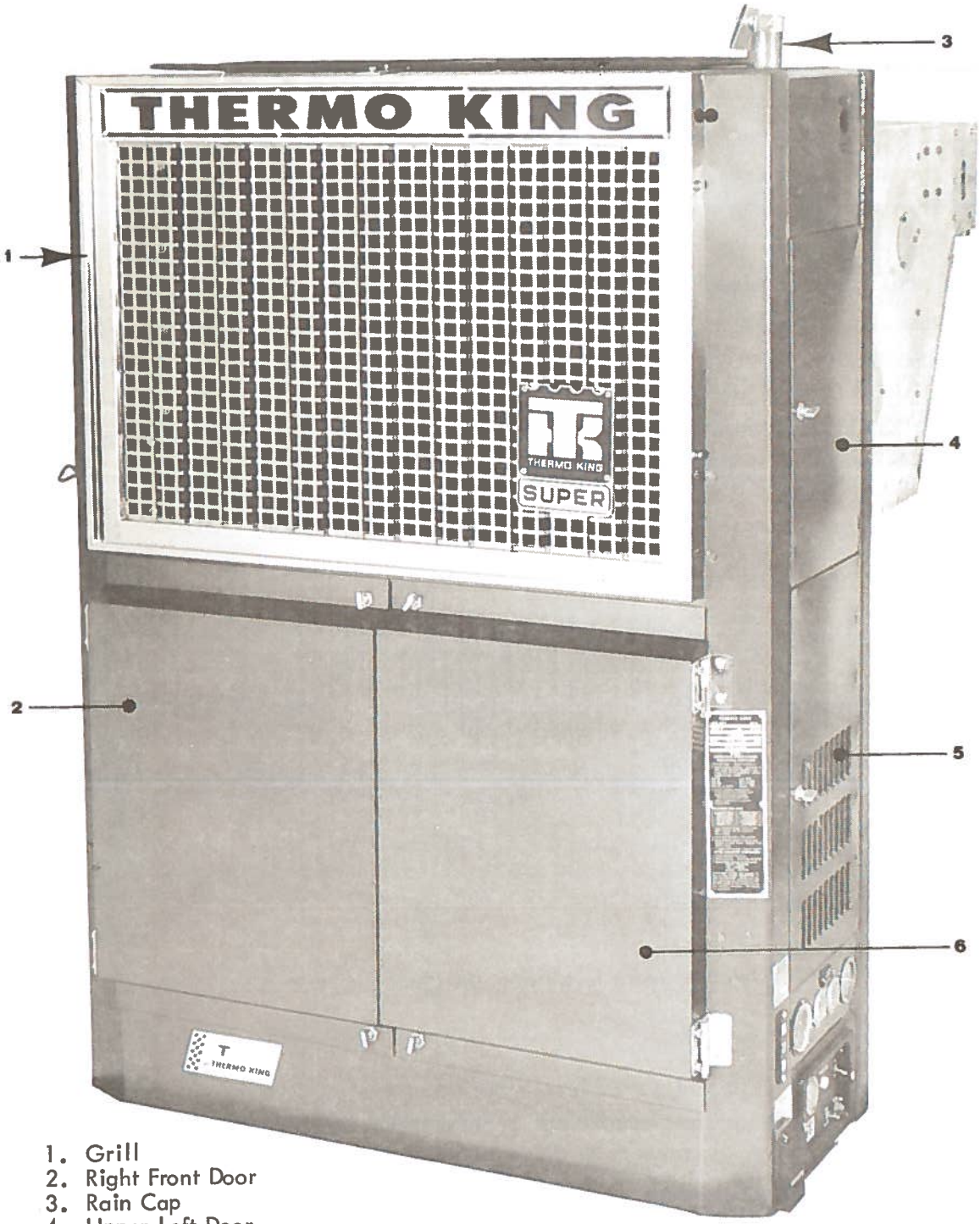
For the noise test of the refrigeration unit, the unit was mounted to the front of a 40 ft truck trailer. The position of the refrigeration unit relative to the semi-trailer is illustrated in Figure 4. Figure 5 shows the refrigeration unit mounted on the truck trailer at the Donaldson Company outdoor free-field acoustic noise test area.

2.3 Noise Tests Performed

The noise tests performed on the refrigeration unit included:

1) Polar plots of the "A" weighted noise levels from the device under maximum and minimum load conditions.

2) A "linear" and "A" weighted acoustical time history of the refrigeration unit noise operating from start-up to load conditions representing both minimum (unloaded) and maximum (loaded) cooling capacity.



1. Grill
2. Right Front Door
3. Rain Cap
4. Upper Left Door
5. Lower Left Door
6. Left Front Door

Figure 2. Left Front View of Refrigeration Unit

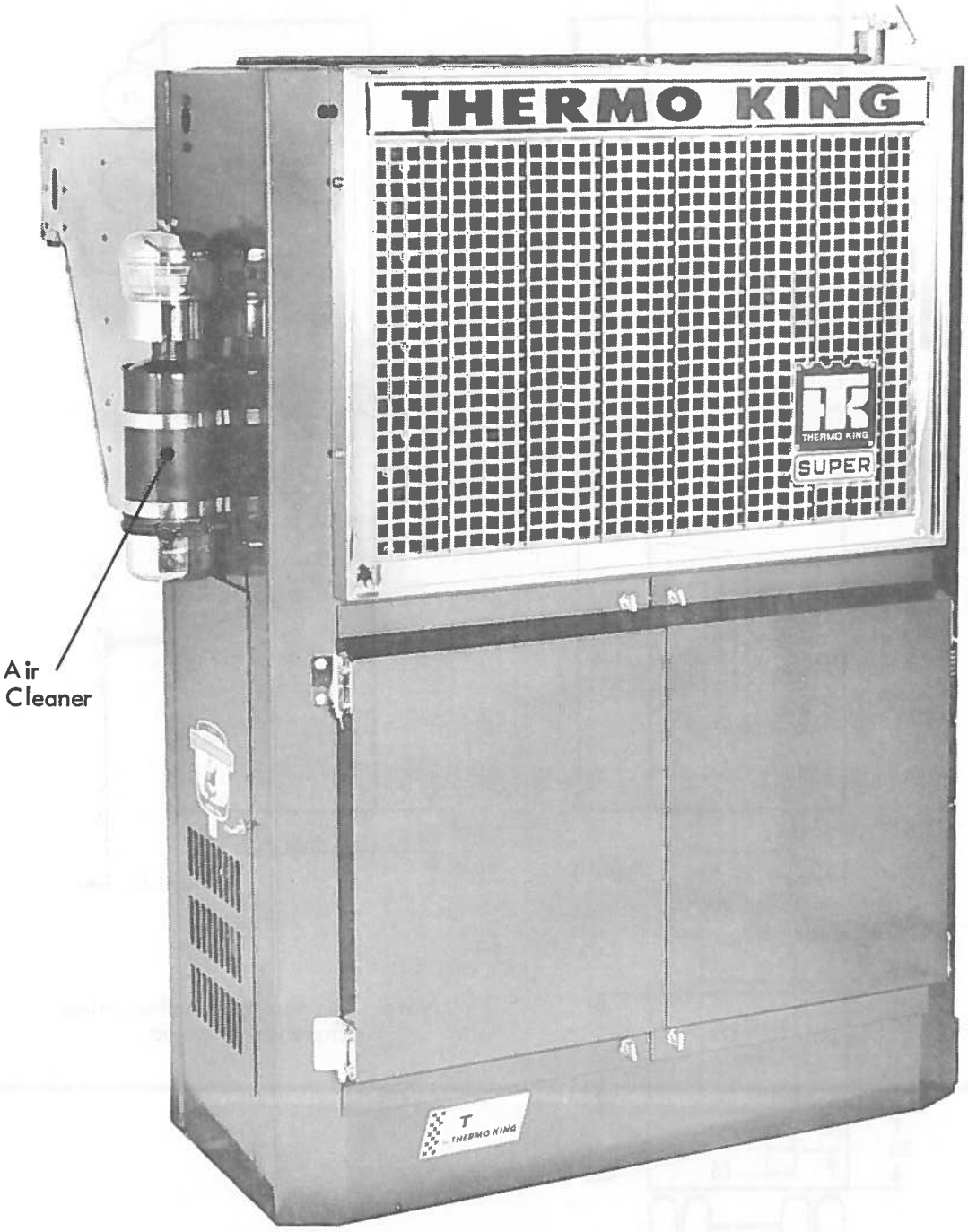
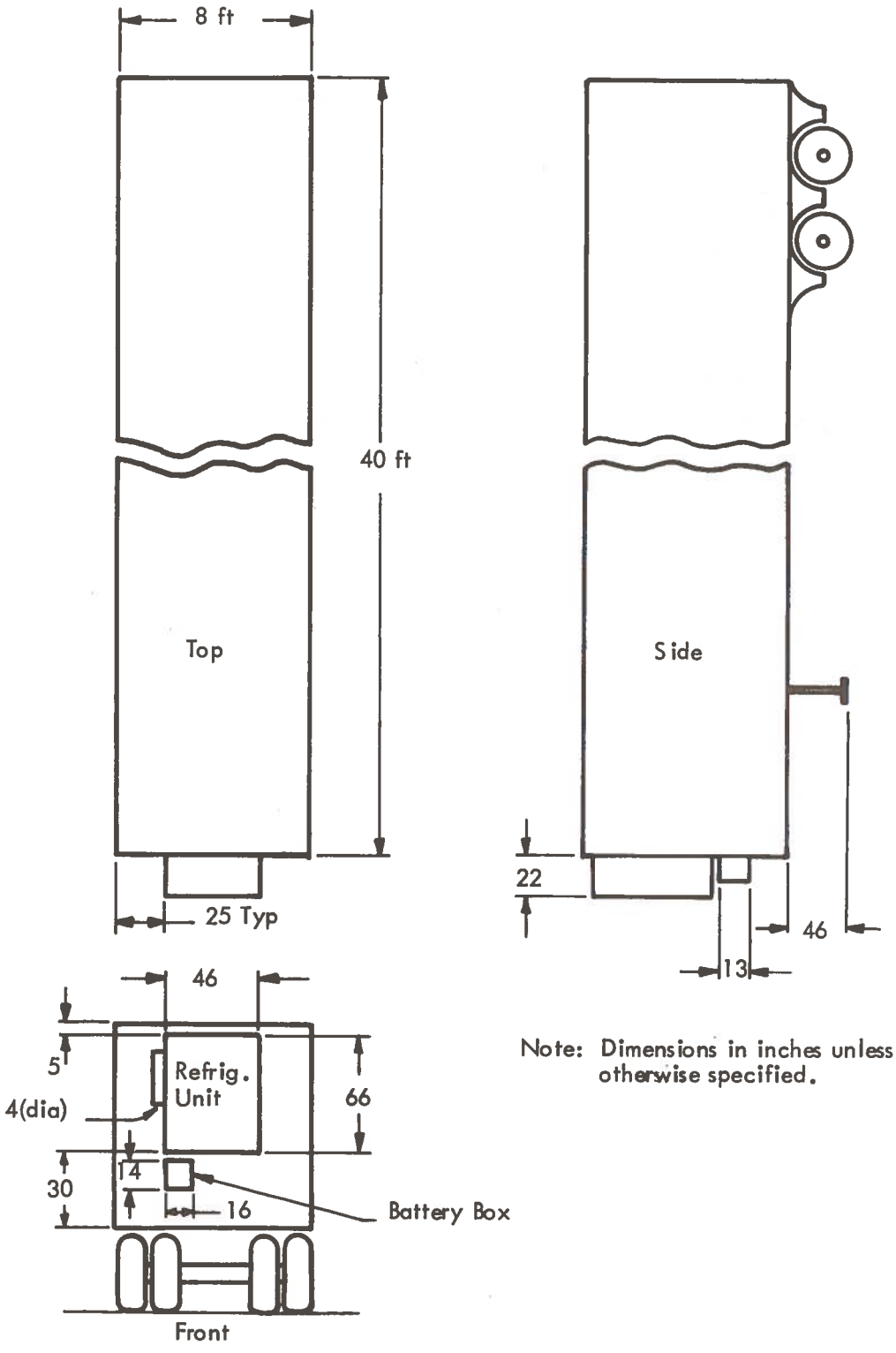
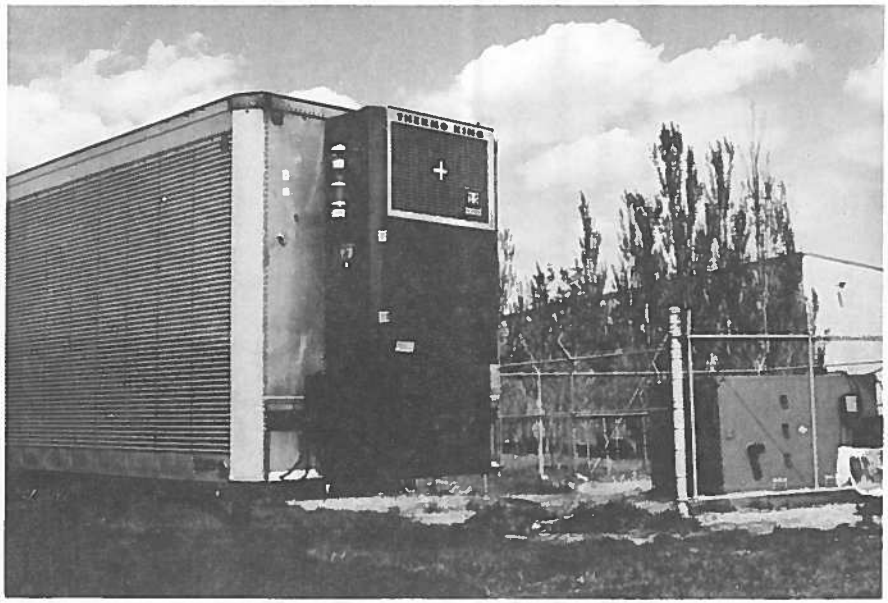


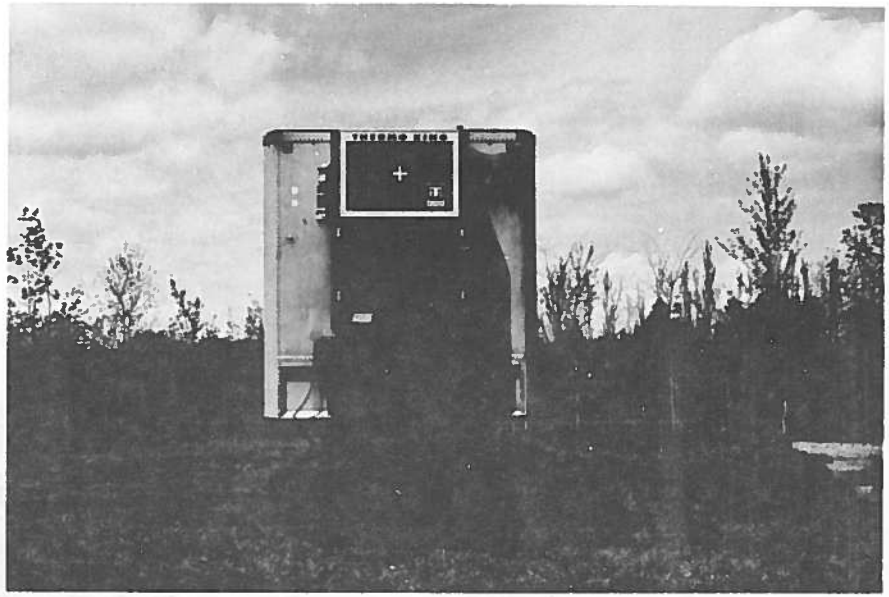
Figure 3. Right Front View of Refrigeration Unit



Note: Dimensions in inches unless otherwise specified.

Figure 4. Refrigeration Unit Configuration





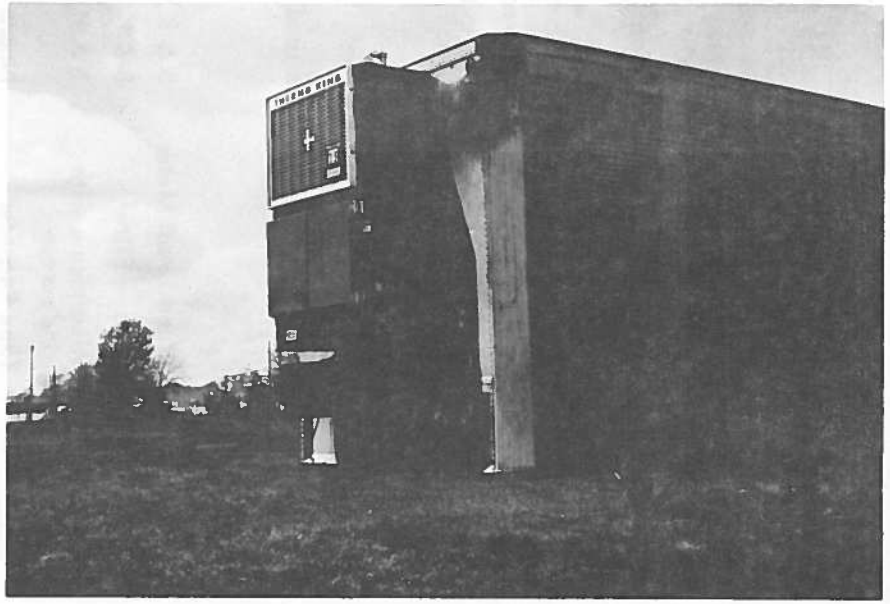


Figure 5. Refrigeration Unit Mounted on Truck Trailer

3) Determination of the unmuffled refrigeration unit engine exhaust noise level under maximum and minimum load conditions.

4) Determination of the noise contributions, under maximum load conditions, from refrigeration unit engine exhaust and engine cooling system fan to the overall system noise at the maximum noise point as indicated by the polar plot.

2.4 Instrumentation

The following instrumentation was used in the performance of noise tests of the refrigeration unit:

Sound Level Meter	B & K, Type 2203, Serial No.345473
Octave Filter	B & K, Type 1613, Serial No. 352841
Microphone with wind screen	B & K, Type 4145, 1 in., Serial No. 346201
Tape Recorder	Nagra IV-SJ, Serial No. 3624

Photographs of the instrumentation are presented in Figure 6.

3 TEST RESULTS

3.1 Test Procedure

Unless otherwise noted, the refrigeration unit noise measurements were made with the microphone located four (4) feet above grade level and at a distance of 50 ft from the center of the refrigeration unit cabinet face. All noise measurements were recorded on magnetic tape and octave plots of all measured levels were made.

3.2 Results

3.2.1 Polar Plot of Refrigeration Unit Noise Levels

Acoustic noise measurements were made at 11 positions on a circle at a 50 ft distance from the refrigeration unit cabinet face. Position designation is illustrated in Figure 7.

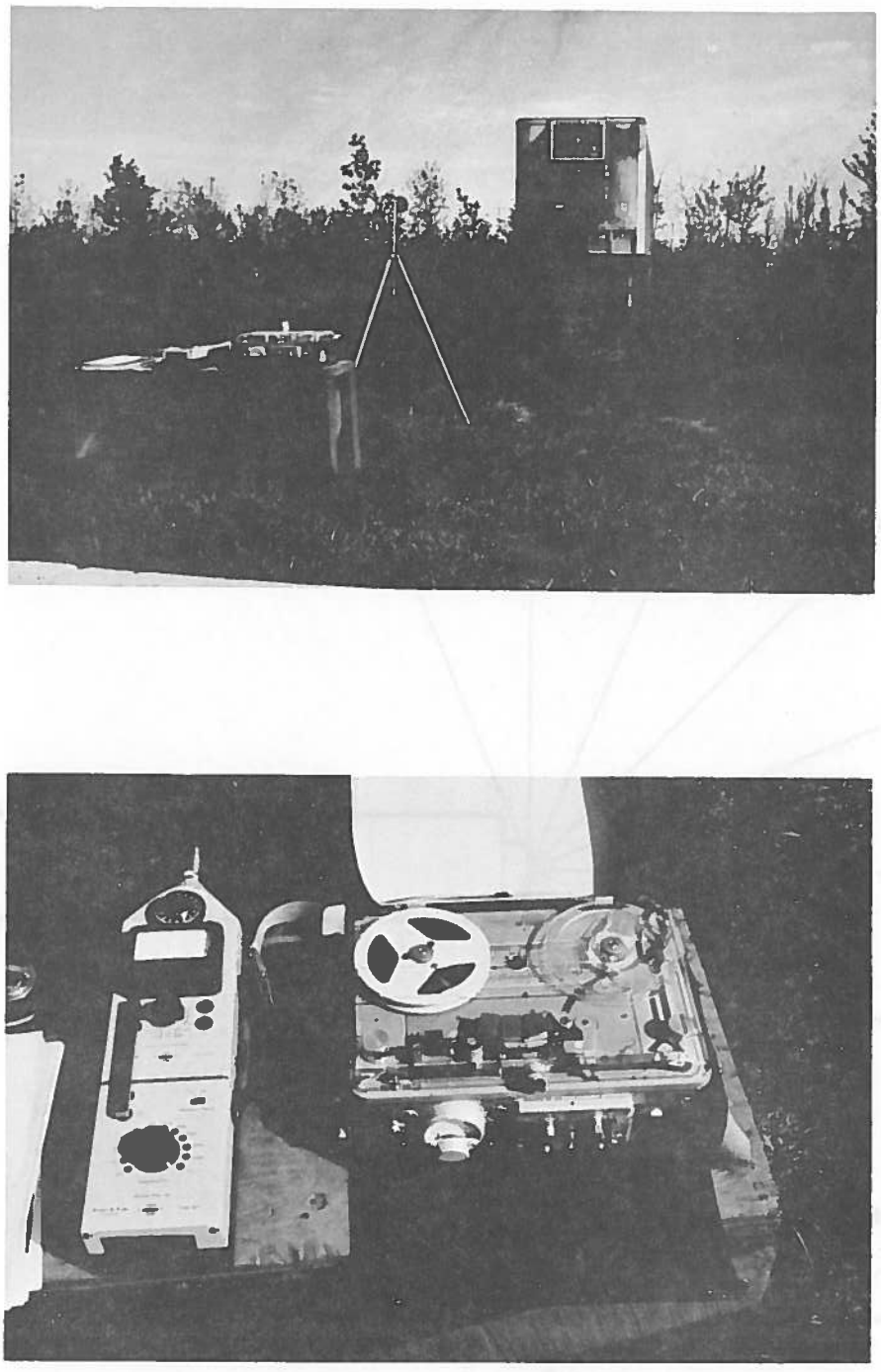


Figure 6. Test Instrumentation for Noise Test of Refrigeration Unit

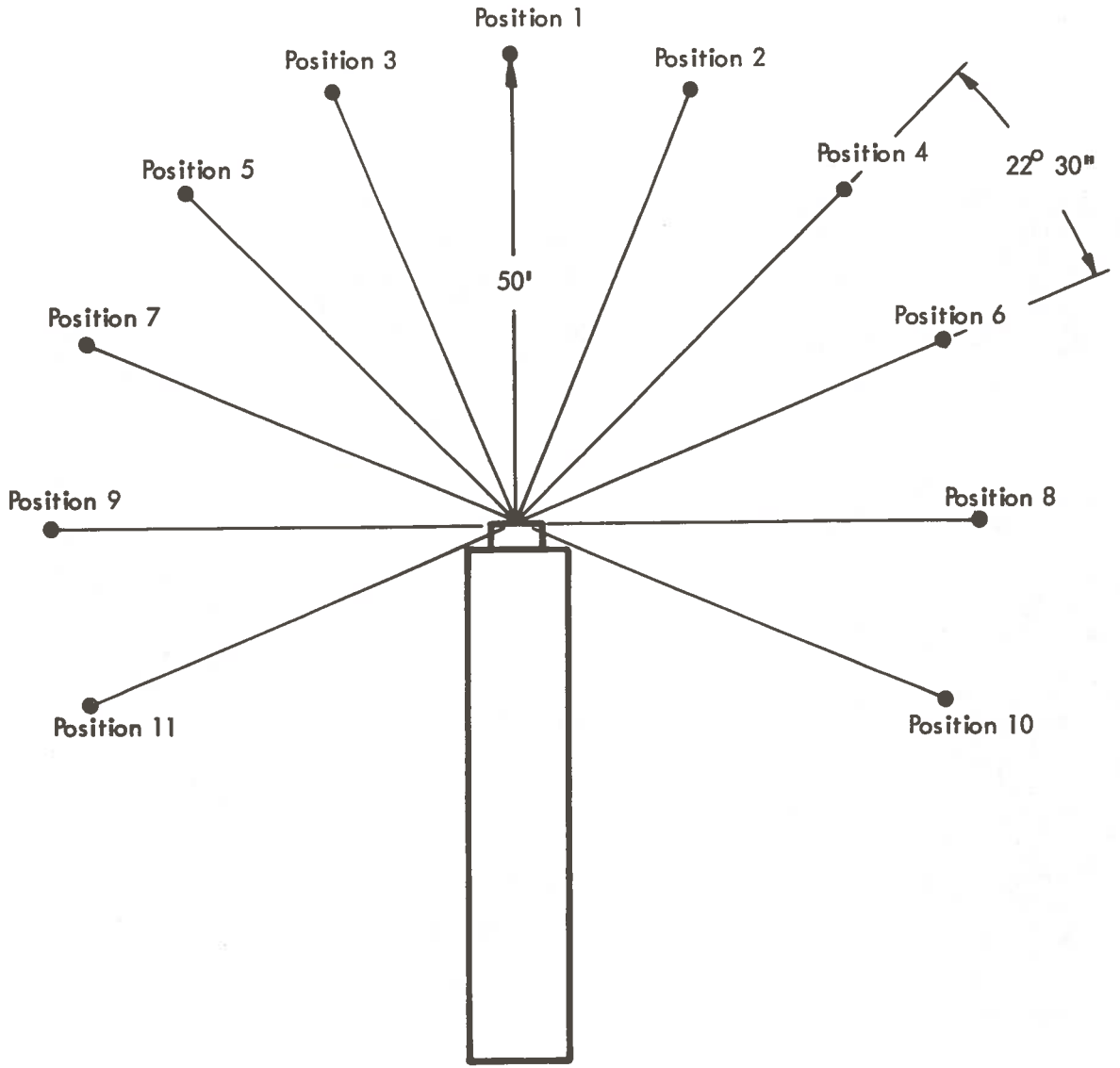


Figure 7. Polar Plot Microphone Locations

The refrigeration unit was in its normal configuration, which includes a muffler for the diesel engine.

3.2.1.1 Refrigeration Unit Maximum Load Condition (Maximum Cooling Demand)

The refrigeration unit was operated at a maximum load condition, by opening the trailer doors and setting the trailer compartment thermostat to -20° F. The ambient temperature was approximately 70° F. The refrigeration unit compressor suction pressure was 30 psig indicating maximum engine load. When operated at this maximum load the diesel engine operated at a high speed condition (2200 rpm).

The polar plot noise levels of the refrigeration unit at maximum load condition (high engine speed) are listed in Figure 8.

It should be noted that position 2 is the position of maximum noise intensity for the maximum load condition of the refrigeration unit. The refrigeration unit has two noise intensity lobes associated with it. The strongest lobe is located in the direction of position 2 and 4, and is located on the air inlet side of the refrigeration unit. The second lobe is located on the exhaust side of the unit (position 5).

Figure 9 presents the equal loudness contours (dB(A)) around the refrigeration unit under maximum load, illustrating the two intensity lobes. These equal loudness contours based on spherical propagation were calculated from the noise level data of Figure 8.

Reasons for the particular illustrated noise contour are as follows:

- At position 2, the diesel engine exhaust pipe, air intake system and diesel engine cooling fan, etc., present themselves as noise sources.

- At position 3 or 5, however, only the diesel engine exhaust pipe and diesel engine cooling fan present themselves as noise sources. The refrigeration unit cabinet acts as a barrier for air intake system noise at positions 3, 5, 7, 9 and 11.

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit operated at maximum load

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1		86	70.5	86.5	75	65	65	68.5	61	55	52
2		88.5	72	88	75	63.5	67	70	61	56.5	52
3		87	70	85.5	74	66	66	65.5	61	57.5	52
4		87	71.5	86.5	74	64.5	67.5	69	60	56	50.5
5		85	70.5	82	71	63	68	65	61	58	53
6		85	70	84.5	71.5	65	67.5	65	61	54.5	49
7		80	68	76.5	69.5	62	65.5	62.5	60.5	57	51
8		83.5	67.5	82.5	69.5	61	66	64	57	51	45
9		78	66	75.5	71	62	63.5	61	57	54	49.5
10		85	65.5	84	70	60.5	64	60.5	55	48	43
11		80	66	79.5	71	61	64	60	59.5	55	49

Figure 8. Polar Plot Noise Levels of Refrigeration Unit at Maximum Load Conditions

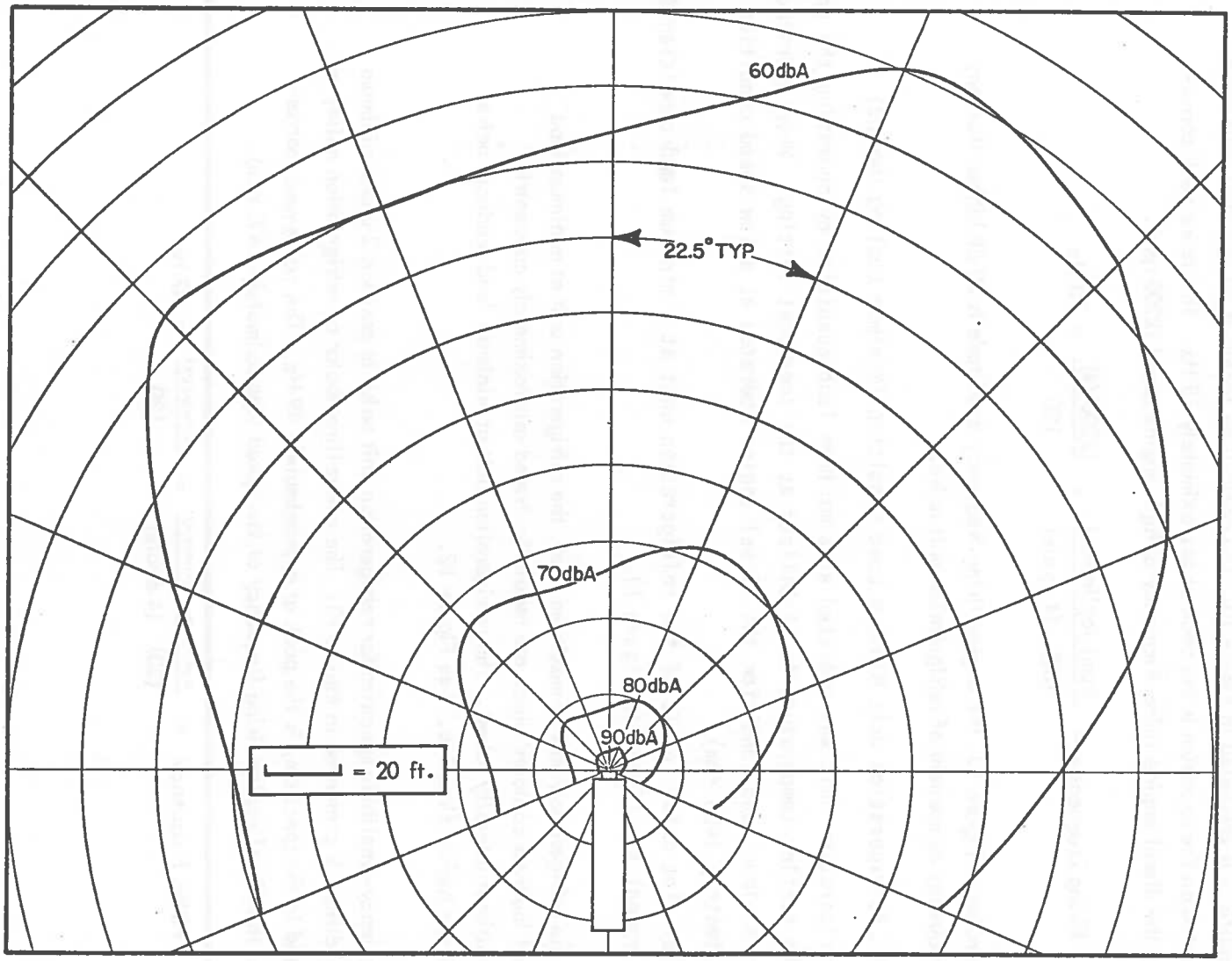


Figure 9. Equal Loudness Contours of Refrigeration Unit for Maximum Load Condition

The frequency-amplitude spectrum for refrigeration unit noise at position 2 under maximum load conditions is presented in Figure 10. The controlling factor of refrigeration unit noise as indicated on the spectrum is the peak at approximately 75 Hz. This noise peak corresponds to the diesel engine firing frequency at high engine speed (2200 rpm).

$$\text{Firing Frequency} = \frac{(\text{rpm})\ (\text{cylinders})}{(30)\quad (4\text{ cycle})} = \frac{(2200)(4)}{120} = 73\text{ Hz}$$

As illustrated in Figure 10, the engine firing frequency amplitude is 20 dB higher than any other frequency component of refrigeration unit noise.

3.2.1.2 Refrigeration Unit Minimum Load Condition (Minimum Cooling Demand)

The refrigeration unit was operated at a minimum laod condition by operating the unit when the trailer temperature is stabilized at the thermosat setting. When operated at this minimum load condition the diesel engine operated at a low speed condition (approximately 1400 rpm).

The polar plot noise levels of the refrigeration unit at a minimum load condition (low engine speed) are listed in Figure 11.

Unlike the refrigeration unit at maximum load, the refrigeration unit at minimum load has equal loudness contours which are regularly shaped (approximately concentric circles without intensity lobes). The refrigeration unit at minimum load produces noise which is not highly directive. See Figure 12.

The frequency-amplitude spectrum for refrigeration unit noise at position 2 under minimum load conditions is presented in Figure 13. The controlling factor of refrigeration noise, as illustrated in the spectrum, is the peak at approximately 49 Hz. This noise peak corresponds to the diesel engine firing frequency at low speed (approximately 1400 rpm).

$$\text{Firing Frequency} = \frac{(\text{rpm})\ (\text{cylinders})}{(30)\quad (4\text{ cycle})} = \frac{(1400)(4)}{120} = 47\text{ Hz}$$

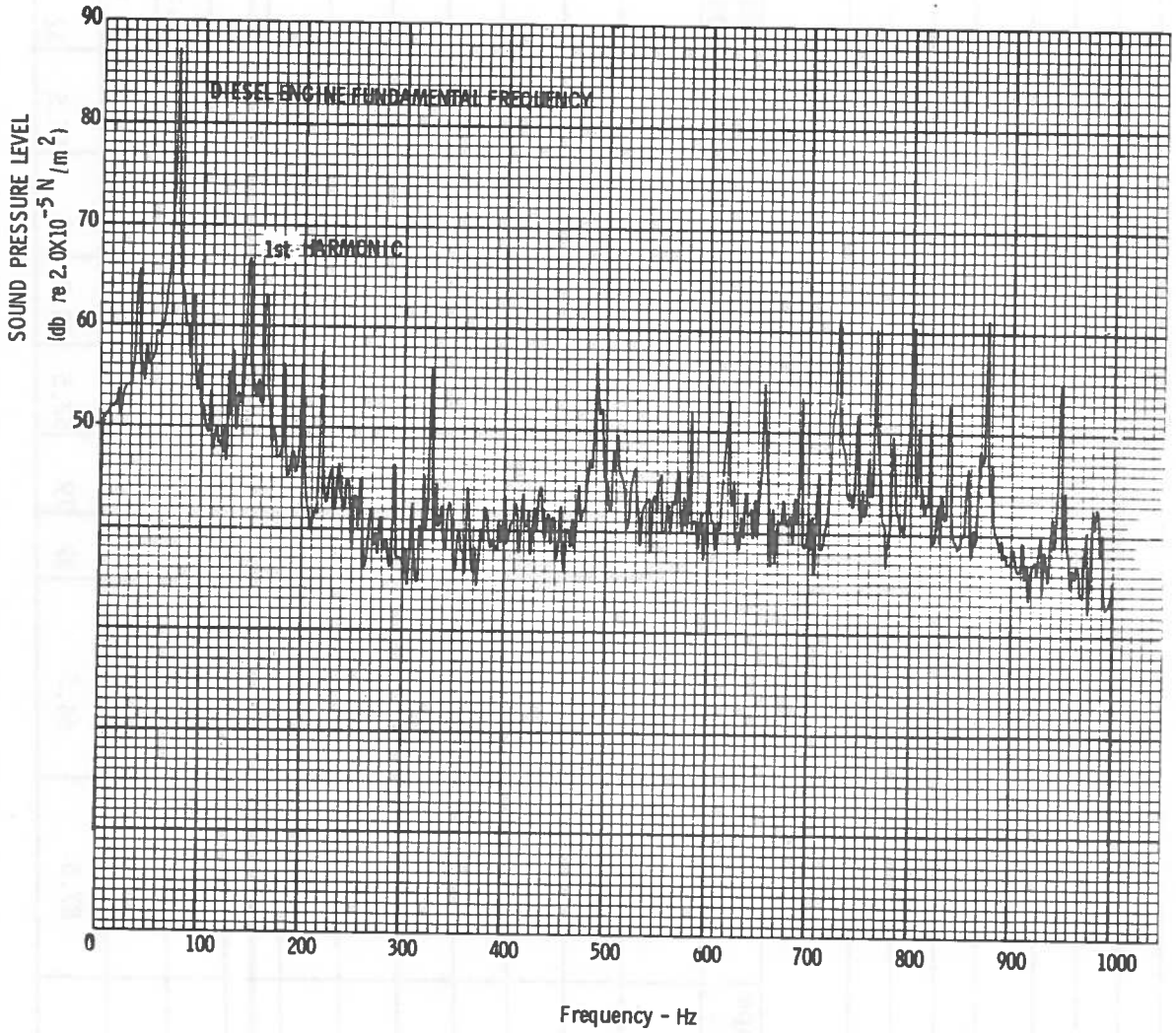


Figure 10. Refrigeration Unit Noise at Maximum Load-Position 2

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit operated at minimum load

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1		81	64.5	77	76.5	59	60	60	56	51	46
2		82	65	81	78	62	60	60.5	58	52	47.5
3		84	65	82	78.5	60	59.5	57.5	58	54	48
4		84.5	65	84	75.5	59	61	62	56.5	52	47
5		86	65.5	84	79	62	61	59	57.5	54	49
6		88	65.5	88	74.5	60	61	60	60.5	51	46
7		87.5	65	87	77.5	60	58	57.5	58	55	48.5
8		89	64.5	89	75	60.5	61	56.5	56.5	48	43
9		89	64	88.5	76	58	57	56.5	56	53.5	46
10		84	62	81	72.5	57	59.5	53	54	45.5	40
11		87.5	64.5	87	79	57.5	58.5	57	57.5	52	45

Figure 11. Polar Plot Noise Levels of the Refrigeration Unit at Minimum Load Conditions

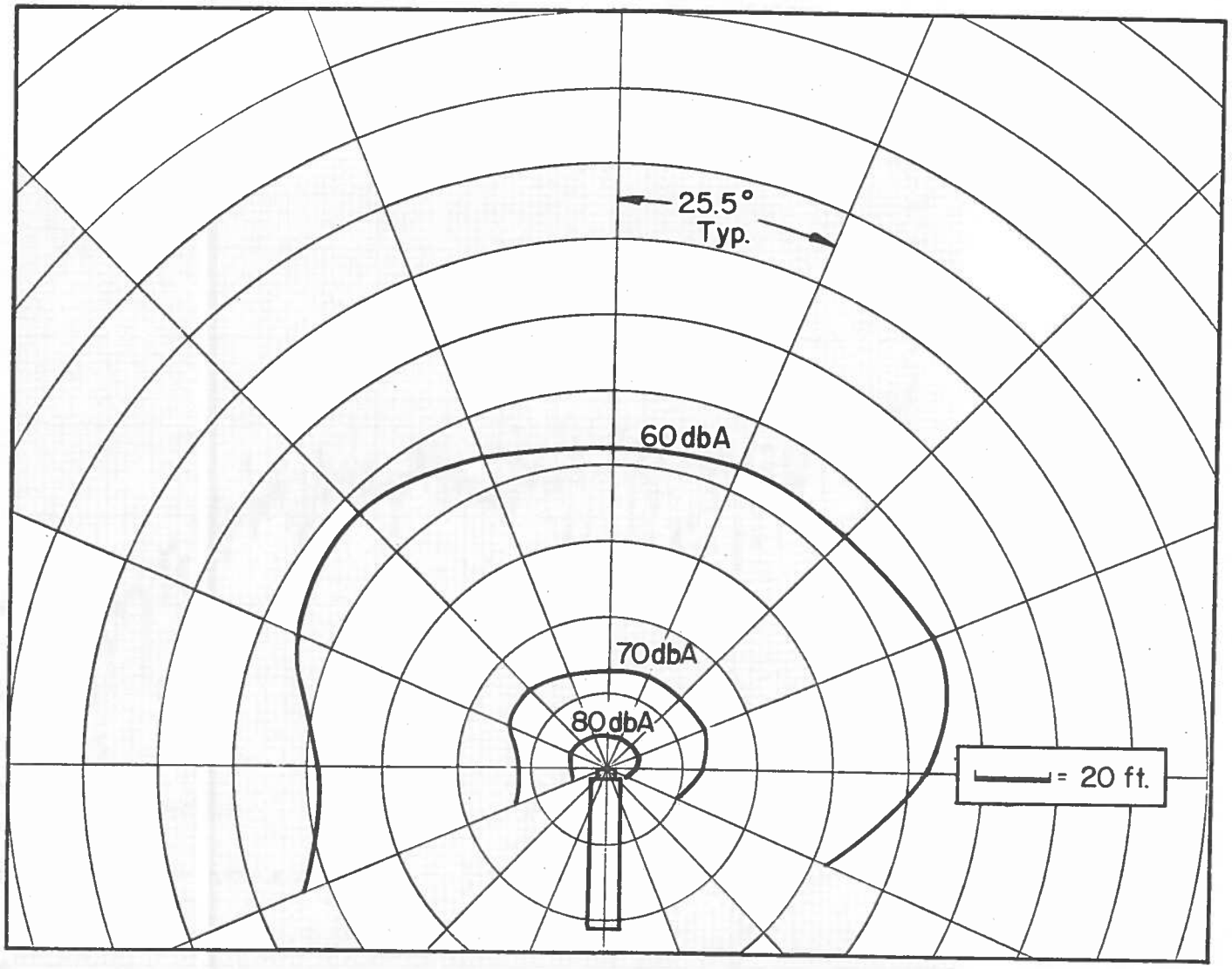


Figure 12. Equal Loudness Contours of Refrigeration Unit for Minimum Load Condition

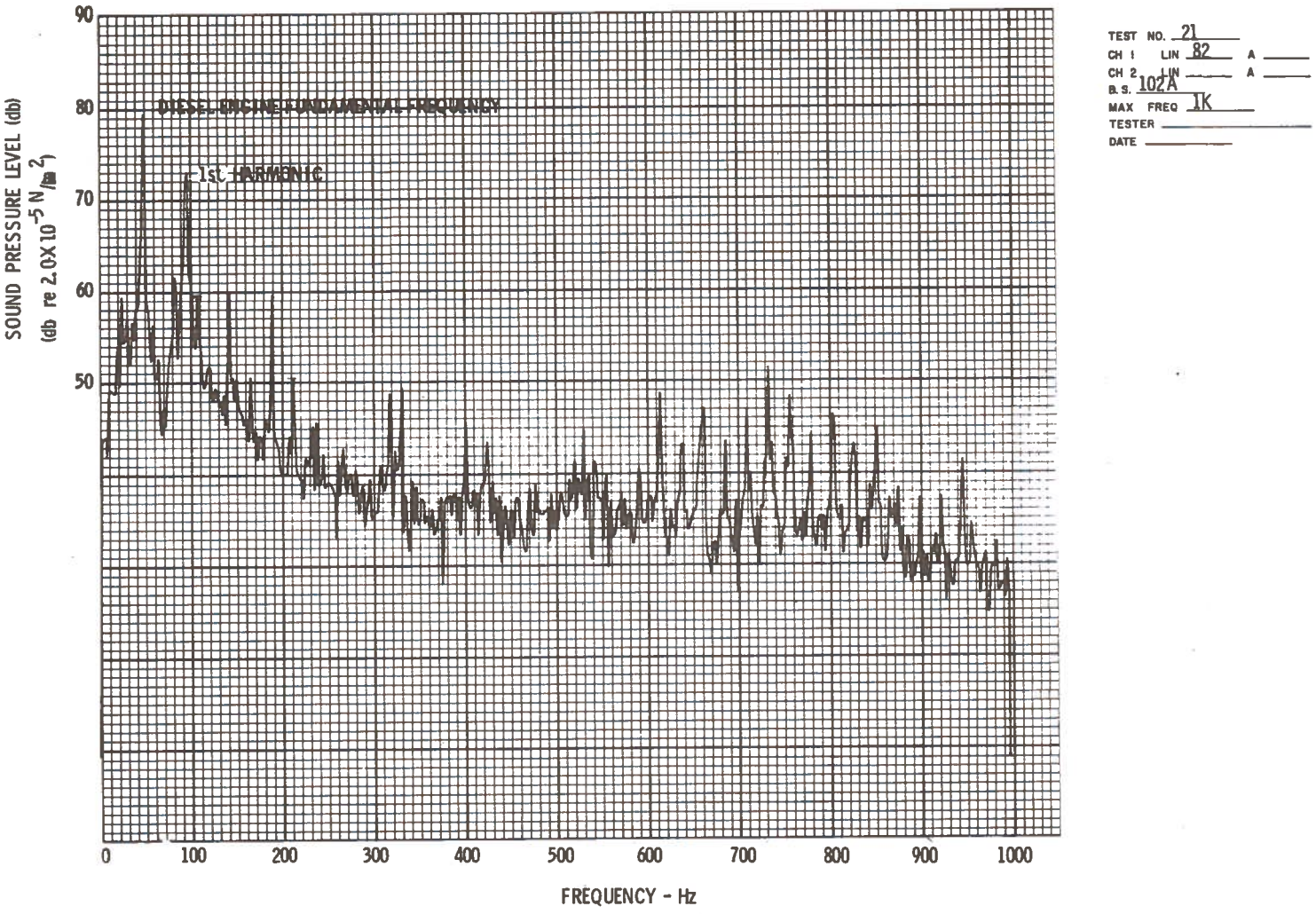


Figure 13. Refrigeration Unit Noise at Minimum Load - Position 2

3.2.2 Acoustical Time History of Refrigeration Unit Load Cycle

A tape recording of the refrigeration unit operating during a complete load cycle was made. The refrigeration unit was operated in the following cycle:

1) Refrigeration unit started
2) Refrigeration unit operated at maximum load (10 seconds minimum)
3) Refrigeration unit operated at minimum load (10 seconds minimum)
4) Refrigeration unit operated at maximum load (10 seconds minimum)
5) Refrigeration unit stopped.

The tape recording was made at microphone position 1 (50 ft from refrigeration unit cabinet face).

Figure 14 presents the plotted time history of the unit for a linear weighted tape recording.

The time history shows the 8.5 dB (lin) differential between the refrigeration unit maximum load condition and the minimum load condition. It also indicates that the refrigeration noise does not have a constant amplitude, varying $\pm$ .5 dB (lin) on the maximum load condition and $\pm$ 1 dB (lin) on minimum load condition.

Figure 15 presents the plotted time history of the unit for an A-weighted tape recording. The time history shows 6 to 7 dBA differential between the refrigeration unit maximum load condition and the minimum load condition.

3.2.3 Determination of Unmuffled Refrigeration Unit Engine Exhaust Noise Level

Acoustic noise measurements were made at 11 positions on a circle at a 50 ft distance from the refrigeration unit cabinet face. The refrigeration unit was in its normal configuration, except the diesel engine muffler had been removed. The muffler was replaced by an equivalent length of pipe. The photograph in Figure 16 shows the pipe installed in place of the muffler and Figure 17 shows the removed muffler.

3.2.3.1 Unmuffled Refrigeration Unit Maximum Load Condition

The unmuffled refrigeration unit was operated at a maximum load condition by opening the trailer doors and setting the trailer compartment thermostat to -20°F. The ambient temperature was approximately 70°F. The refrigeration unit compressor suction pressure was 30 psig indicating maximum engine load.

Refrigeration Unit
Acoustical Noise Time
History at Position 1
(50' from unit)

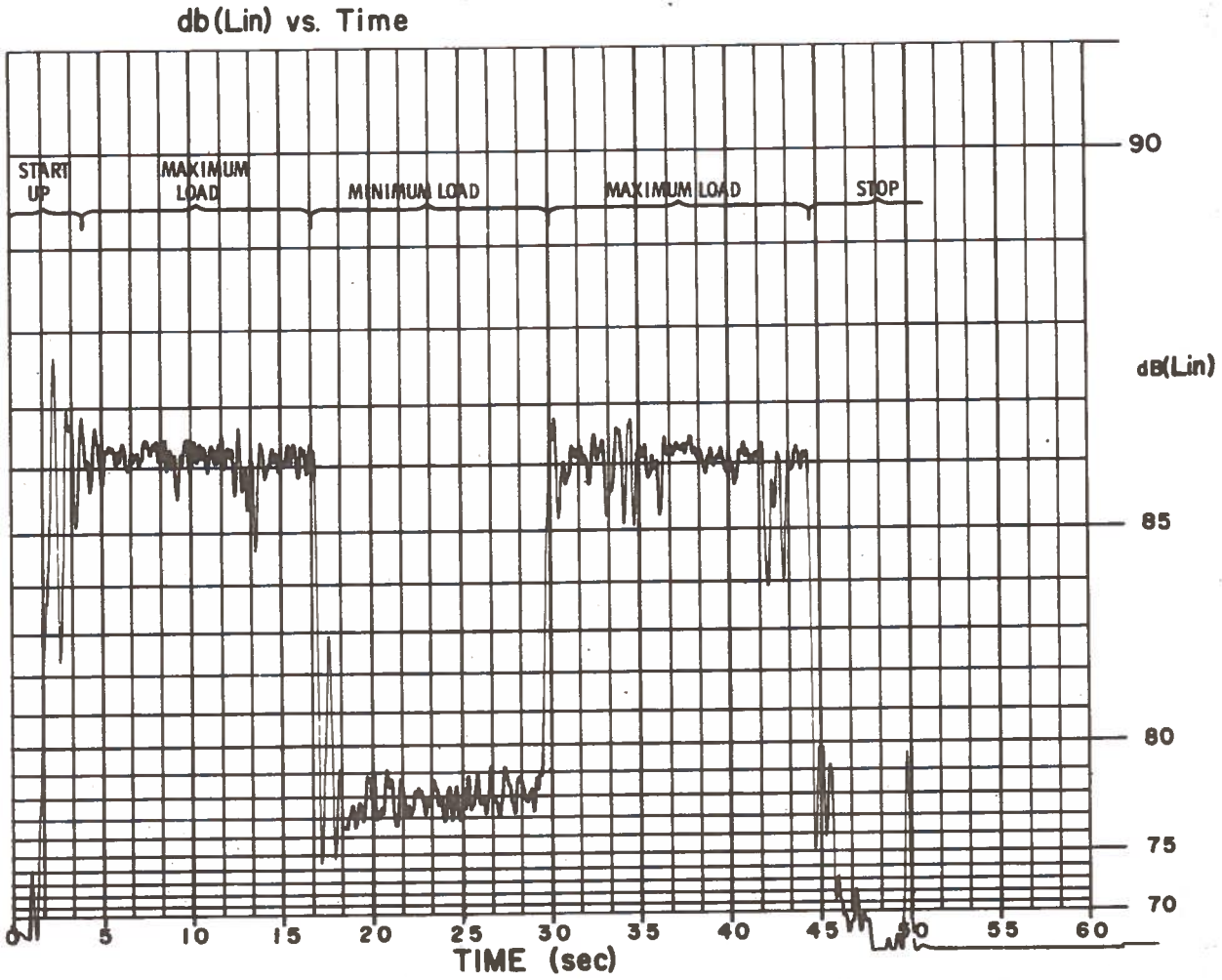


Figure 14. Plotted Time History of Refrigeration Unit - Linear Weighted

Refrigeration Unit
Acoustical Noise Time
History at Position 1
(50' from unit)

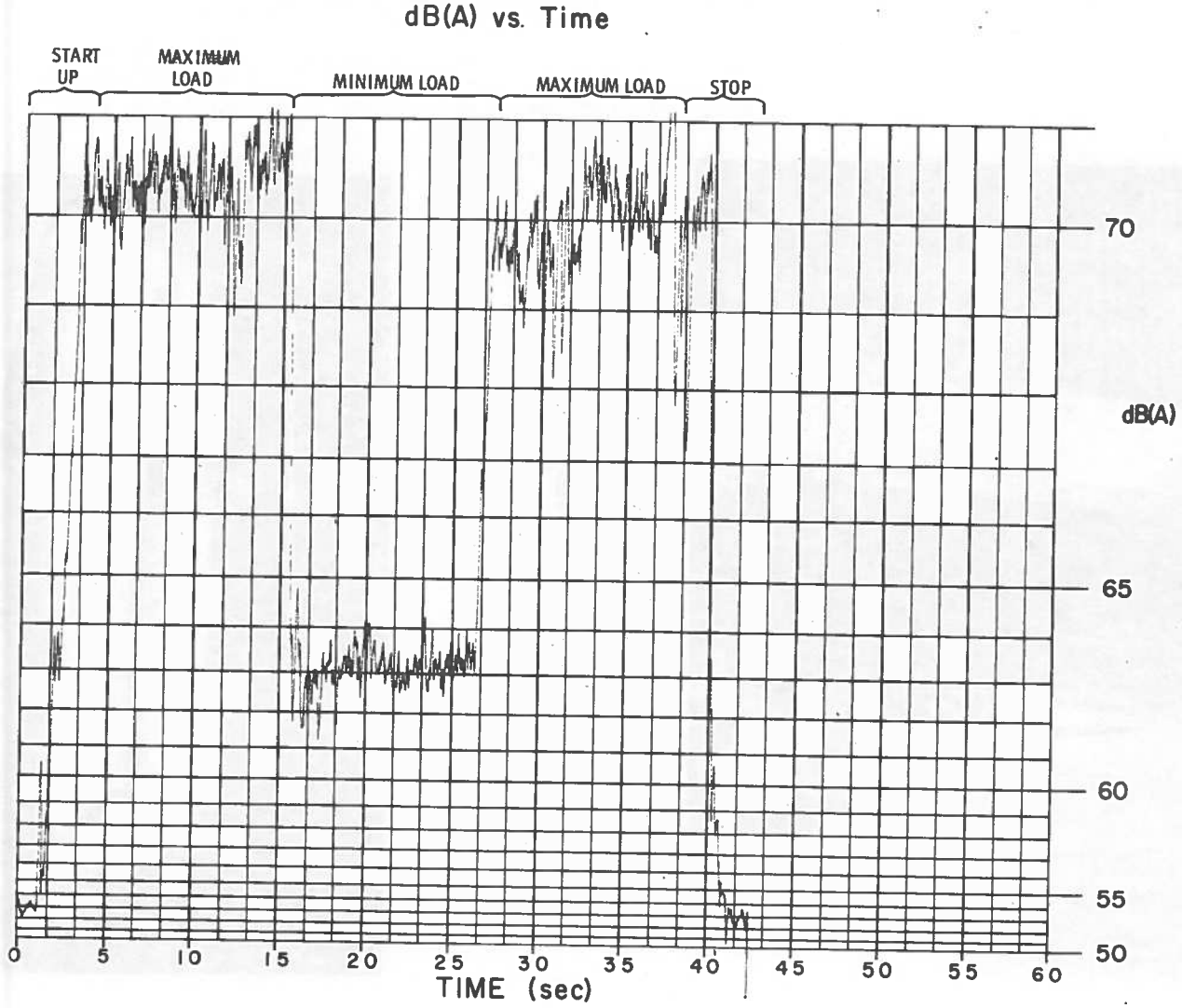


Figure 15. Plotted Time History of Refrigeration Unit – A-Weighted

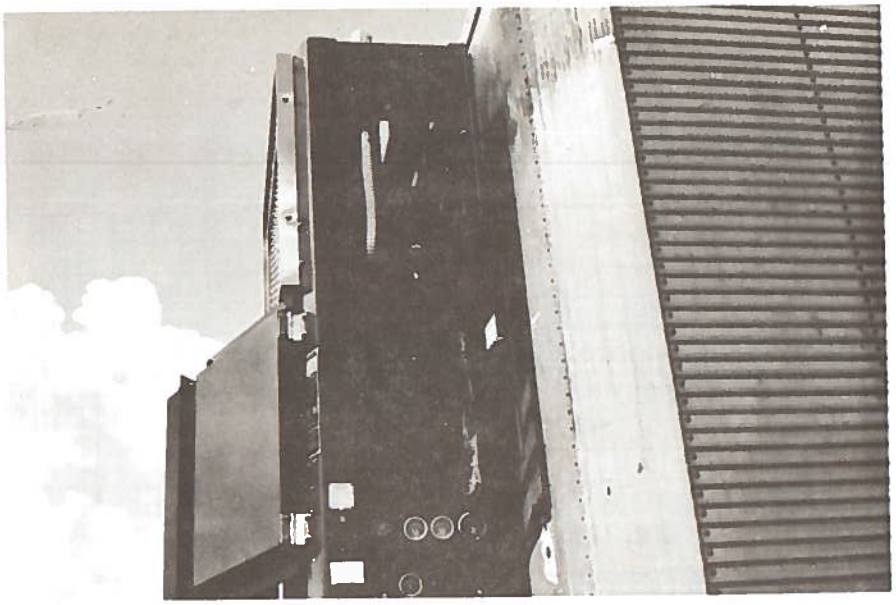


Figure 16. Muffler Removed and Replaced by Equivalent-sized Pipe

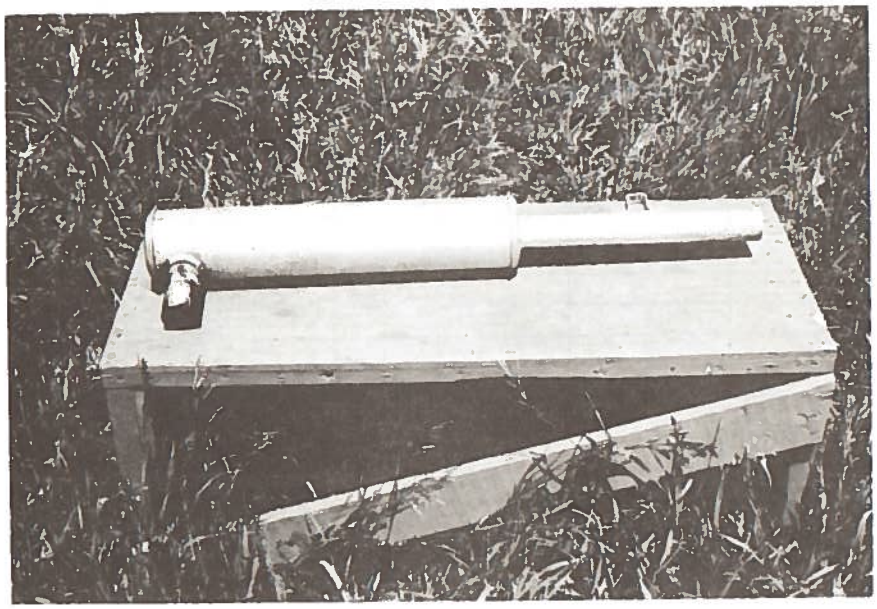


Figure 17. Refrigeration Unit Muffler

The polar plot noise levels of the unmuffled refrigeration unit at maximum load conditions are listed below in Figure 18.

Comparison of Figures 18 and 8 indicates that the inclusion of the muffler on the diesel engine of the refrigeration unit provides attenuation in all of the octave bands (125-8000 Hz). However, the muffler provides no attenuation in the 63 Hz octave band. Indeed, 2-3 dB of amplification were realized in the 63 Hz octave band with the muffler installed possibly because of the absence of attenuation produced by the equivalent length of straight pipe (unmuffled case). The net result is that with the muffler installed, the refrigeration unit produces lower dB(A) levels (6.5 dB(A) average for 11 positions) than the unmuffled case because of the frequency weighting of the "A" scale. "Linear" scale noise levels of the muffled refrigeration unit are generally 1 dB (lin) lower (average for 11 positions) than the unmuffled refrigeration unit.

Figure 19 shows that the unmuffled refrigeration unit noise contour is highly directive toward the exhaust outlet side of the refrigeration unit.

3.2.3.2 Unmuffled Refrigeration Unit Minimum Load Condition

The unmuffled refrigeration unit was operated at a minimum load condition by operating the unit when the trailer temperature is stabilized at the thermostat setting.

The polar plot noise levels of the unmuffled refrigeration unit at minimum load conditions are listed in Figure 20. Equal loudness contours for the unmuffled refrigeration unit at minimum load conditions are presented in Figure 21.

The same conclusions made for the maximum load unmuffled refrigeration unit noise levels are true for the minimum load unmuffled refrigeration unit noise levels.

1) The inclusion of the muffler on the diesel engine provides attenuation in all of the octave bands (125-8000 Hz).

2) Some amplification of noise in the 63 Hz octave band were produced because of the reduction of tail pipe attenuation in the low frequency region because of muffler installation.

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit in unmuffled condition

Refrigeration unit operated at maximum load

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1		86.5	76	84	81	70	73	69.5	69	66	56
2		86.5	75.5	84	81	69	71.5	71	67	65	56
3		86	77.5	82	81	73	70	70	71	69	59
4		87.5	75.5	85	82.5	73.5	69.5	71	68.5	65	56
5		84	77.5	76.5	80.5	70.5	71	71	73	70	59
6		86.5	74	84	80.5	73	72	67.5	66	62	51.5
7		83	77	73	79.5	72	74	71	72	67	58
8		84	71	82	76	70.5	68.5	64.5	63.5	56	46
9		83.5	77	71	81	72	74	70	70	68	54
10		84.5	69.5	83.5	76	67	68	64.5	60	54.5	44
11		85	78	77	79.5	71.5	67.5	70	72	69	56

Figure 18. Polar Plot Noise Levels of Unmuffled Refrigeration Unit Noise Levels at Maximum Load Conditions

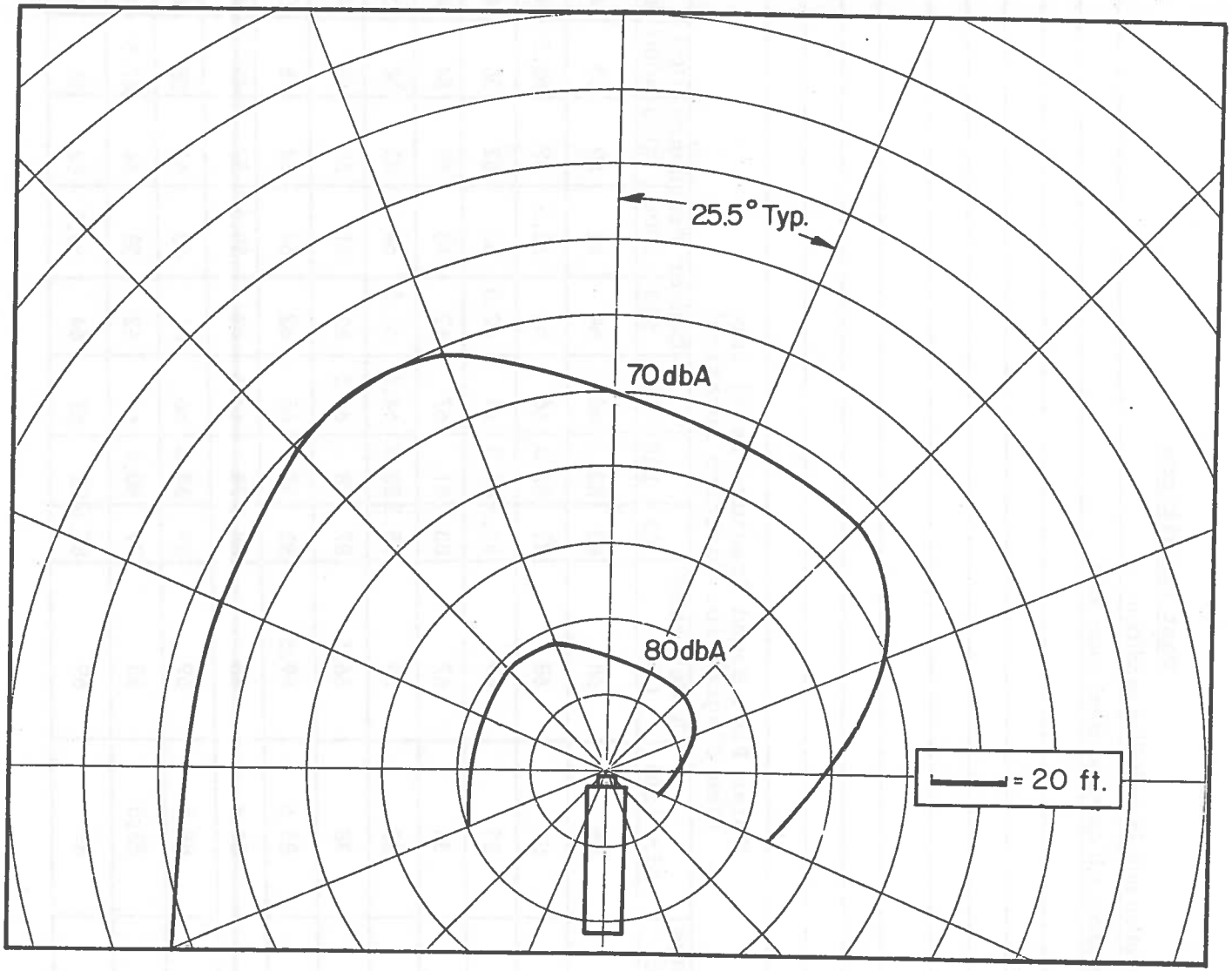


Figure 19. Equal Loudness Contours of Unmuffled Refrigeration Unit (Maximum Load Condition)

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit in unmuffled condition

Refrigeration unit operated at minimum load

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1		86	68	82	83	66	64	63	59	55	47
2		86	68	82	82.5	66	62	63.5	59	53.5	47.5
3		85	69	81.5	84.5	64	62.5	63	62	58	49
4		85	67	83	81	67	62	63	59	54	47
5		85	69	78.5	83.5	64.5	61.5	64	63	58	50
6		88	66.5	87	78	66.5	63	61	60	52	46
7		85.5	69.5	83	82	65	62	64	63	58	50
8		89.5	66	88.5	78	64.5	63	59.5	57	49	42
9		89.5	69	89	82.5	66	61	63	62	58	48
10		83.5	65	79	80.5	64	62	58	54	47.5	40
11		89	69	87.5	82	63	64	63.5	62	58	46

Figure 20. Polar Plot Noise Levels of Unmuffled Refrigeration Unit Noise Levels at Minimum Load Conditions

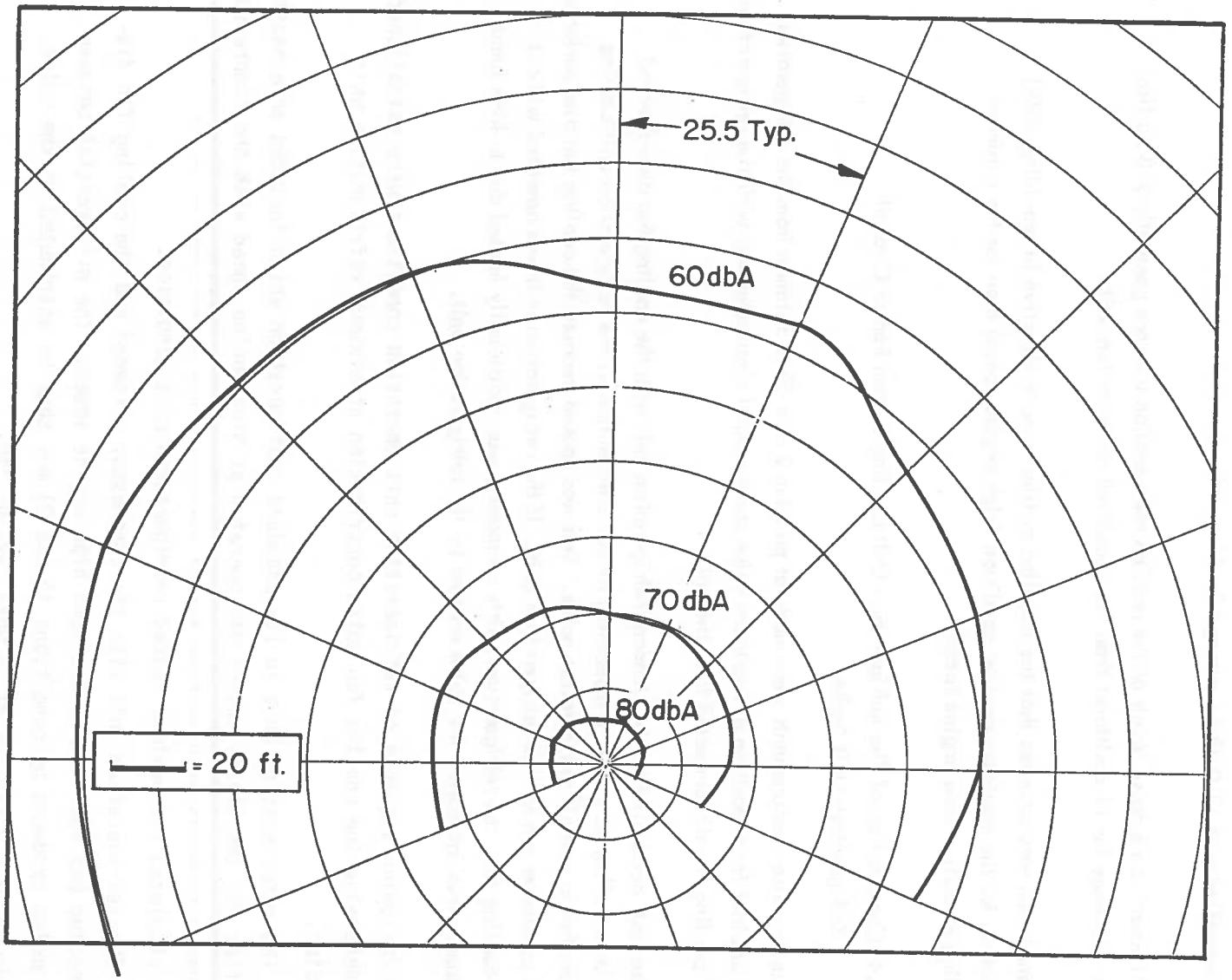


Figure 21. Equal Loudness Contours for the Unmuffled Refrigeration Unit (Minimum Load Condition)

3) With the muffler installed, the refrigeration unit produces lower dB(A) levels than the unmuffled case (3.0 dB(A) average for 11 positions).

4) "Linear" scale noise levels of the muffled refrigeration unit are generally 2-3 dB (lin) lower (average for 11 positions) than the unmuffled refrigeration unit.

A conclusion may be made that the installed muffler is more effective in providing dB(A) reduction for the maximum cooling condition (high engine speed) than for the minimum cooling condition (low engine speed).

3.2.4 Contribution of The Refrigeration Unit Cooling System Fan to Overall Refrigeration Unit Noise

Acoustic noise measurements were made at position 2 at a 50 ft distance from the refrigeration unit cabinet face (position of maximum noise under normal circumstances) with the refrigeration unit cooling fan disconnected from the unit.

Noise tests conducted on the standard refrigeration unit with the cooling fan disconnected would not allow an accurate assessment of the contribution of the refrigeration unit cooling system fan to overall refrigeration noise. This was caused because the cooling fan also performs as a condenser fan for the refrigeration unit. If the refrigeration unit was operated without the cooling fan, the refrigeration unit's compressor was additionally loaded due to high head pressure, thus increasing the noise emitted by the refrigeration unit.

The following sequence of refrigeration unit operating conditions were established to determine the cooling fan noise contribution at maximum refrigeration unit loading.

1) The refrigeration unit in its standard configuration which included an exhaust muffler for the diesel engine was operated at high engine speed with the compressor unloaded (compressor discharge valves closed). This established a new baseline and simulated the maximum loaded refrigeration unit condition.

2) The refrigeration unit with the compressor unloaded and the cooling fan disconnected was operated at the same high engine speed. The differential between the noise produced by conditions 1) and 2) may thus be attributed to the noise produced by the refrigeration unit cooling fan.

The cooling fan is a six blade, 24 in. diameter fan which rotates at the following speeds during refrigeration unit operation:

Diesel Engine Speed	Fan Speed
High (2200 rpm)	1620 rpm
Low (1350-1400 rpm)	1030 rpm

As such, the cooling fan would produce the following blade frequencies for the two refrigeration unit operating conditions:

Diesel Engine Speed	Blade Frequency
High (2200 rpm)	162 Hz
Low (1350-1400 rpm)	99-103 Hz

Figure 22 illustrates the frequency peak produced by the cooling fan blade passage of the refrigeration unit under maximum load condition (high speed). The blade frequency amplitude of the cooling fan is 25 dB lower than that of the refrigeration unit diesel engine fundamental.

Figure 23 illustrates the frequency spectrum of the maximum loaded refrigeration unit without the cooling fan operating. As expected, the blade passage frequencies (fundamental and 1st harmonic), were eliminated.

The elimination of the noise produced by the cooling fan provided the following reduction in the total noise of the refrigeration unit.

Attenuation Provided by Disconnection of Cooling Fan

.5 db Lin
4.0 db A

Figure 24 presents the A-weighted attenuation versus frequency plot (maximum frequency 5000 Hz) provided by the removal of the refrigeration unit cooling fan as a source of noise. The most significant attenuation occurs above 300 Hz which corresponds to the higher harmonics of the cooling fan.

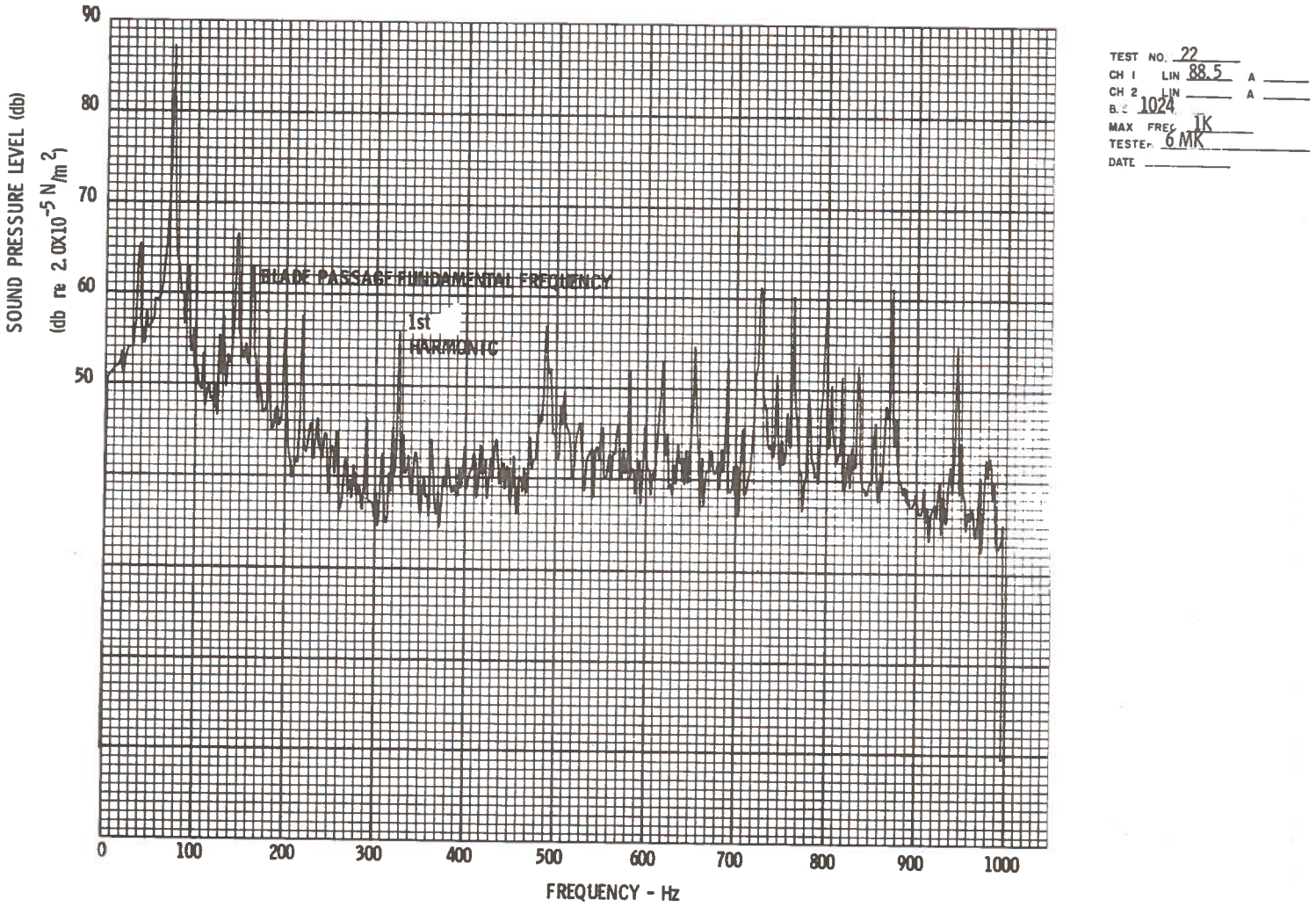


Figure 22. Refrigeration Unit Noise at Maximum Load - Position 2

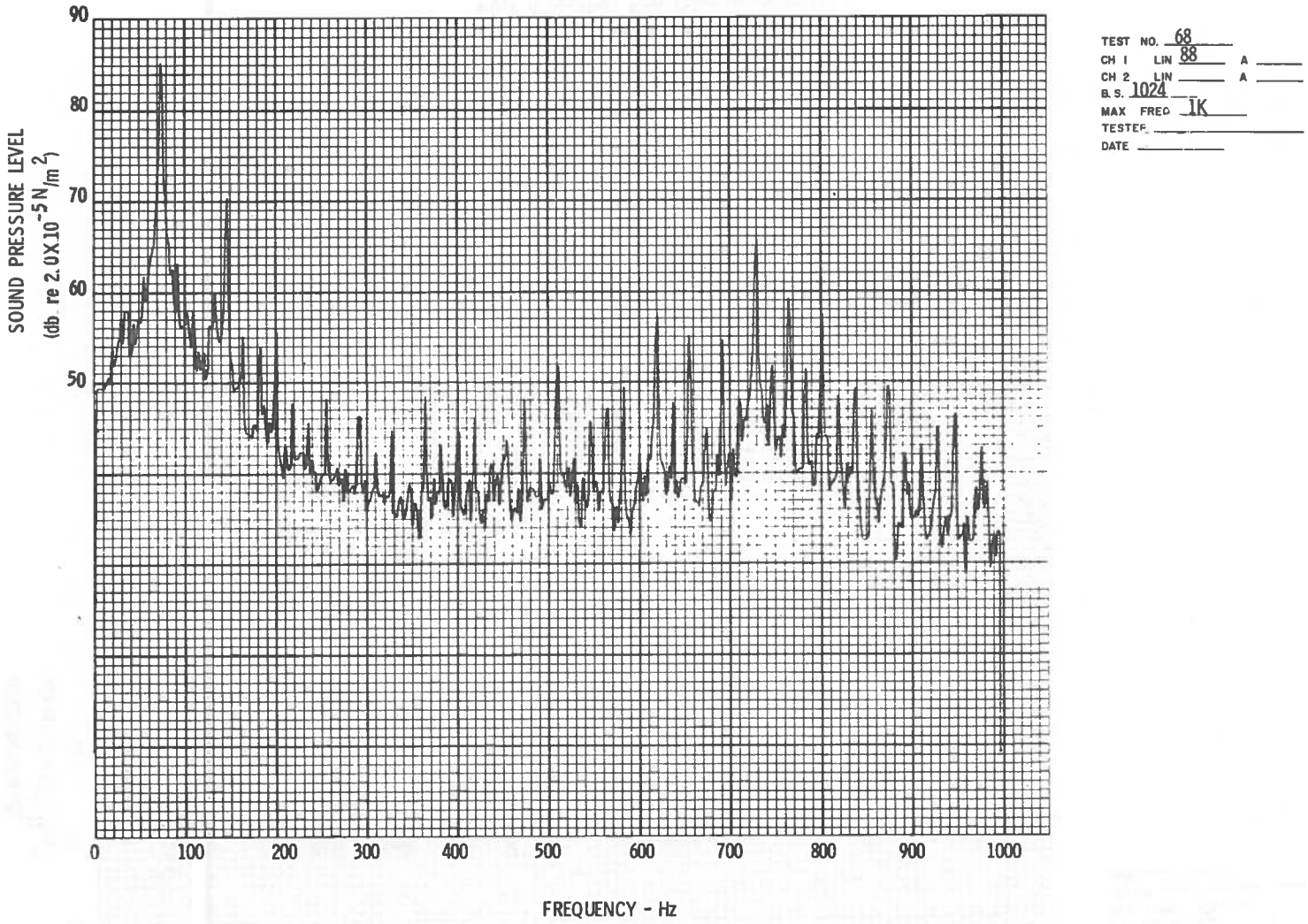


Figure 23. Refrigeration Unit Noise at Maximum Load Condition (Engine Cooling Fan Removed) - Position 2

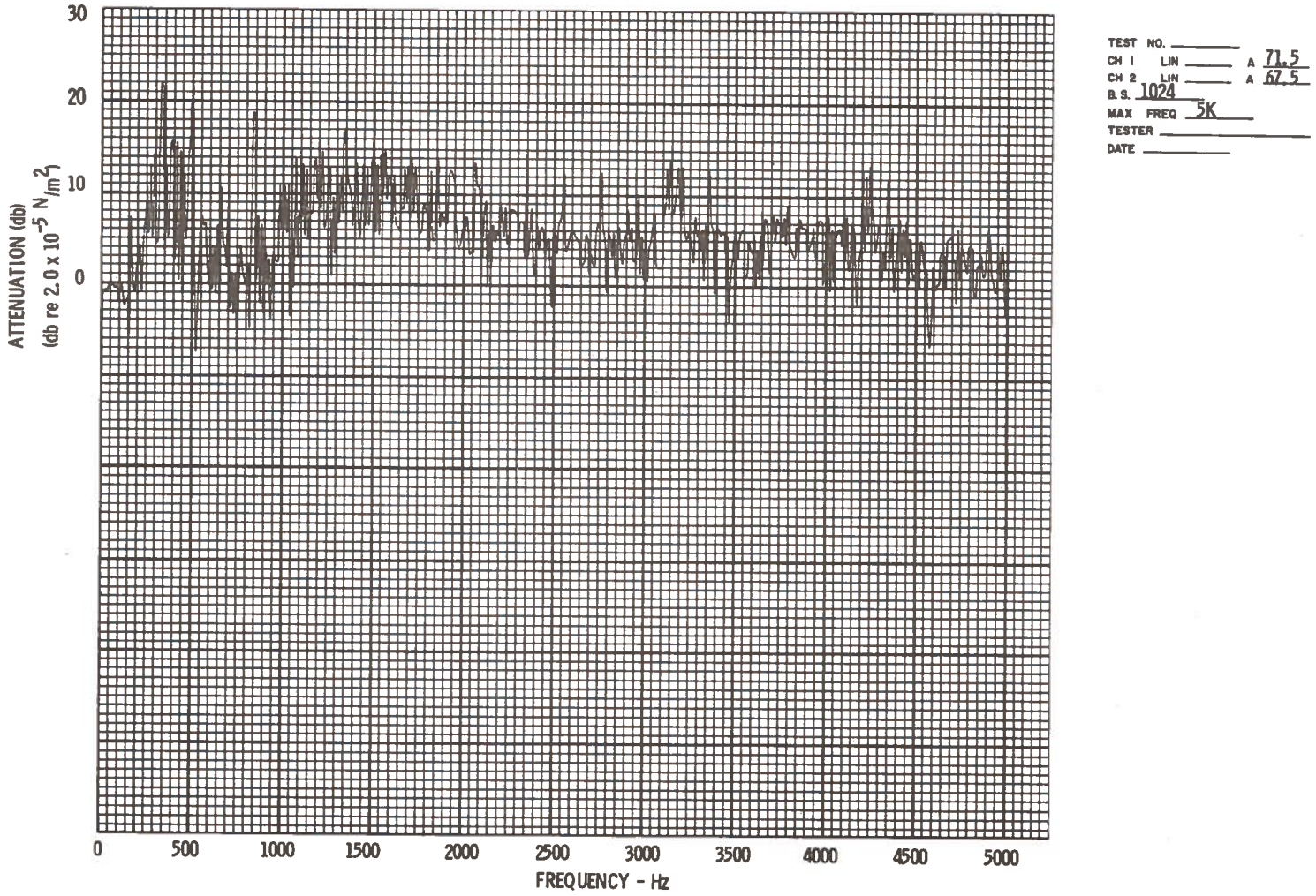


Figure 24. A-Weighted Attenuation versus Frequency Plot (Cooling Fan Disconnected)

Figure 25 below presents the octave band attenuation provided from the noise data for the simulated maximum loaded refrigeration unit with and without diesel engine cooling fan.

	Octave Band								
Center Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Attenuation	.5	.5	0	4.5	6	4	7	13	1

Figure 25. Octave Band Attenuation Provided by Cooling Fan Removed

3.2.5 Contribution of The Refrigeration Unit Engine Exhaust Noise to The Overall System Noise

In order to assess the contribution of diesel engine exhaust noise to the total refrigeration unit noise, attempts were made to reduce diesel engine exhaust noise through the use of multiple in-series mufflers.

The mufflers selected were not mufflers specifically designed for the refrigeration unit diesel engine, but rather off-the-shelf snowmobile and small engine mufflers which were easily adaptable to the existing muffler and its tail pipe and which would not produce excessive backpressures.

Figures 26 and 27 show the mufflers as installed in series with the existing muffler on the refrigeration unit.

The muffler which was most effective in reducing the perceived refrigeration unit noise was the right-angle type muffler, although the performance of the additional mufflers were within .5 dB of each other. The reason for the better performance of the right-angle muffler was because it directed the exhaust gases away from the front of the refrigeration unit.

Figures 28 and 29, 30 and 31 present a comparison of the existing noise levels of the refrigeration unit and those obtained with the additional in-series right-angle type muffler, respectively, for the maximum and minimum load conditions.

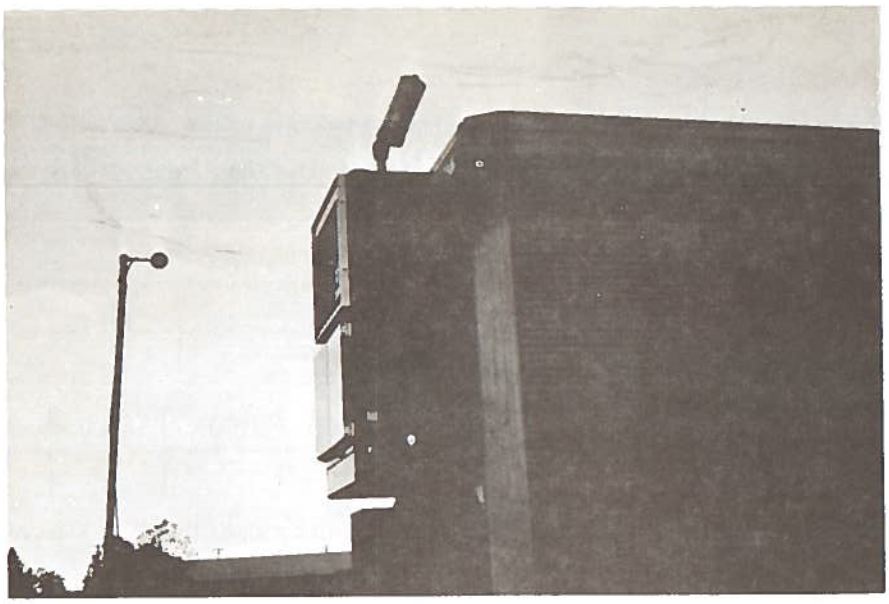


Figure 26. Straight-through Type Muffler in Series with Refrigeration Unit Muffler

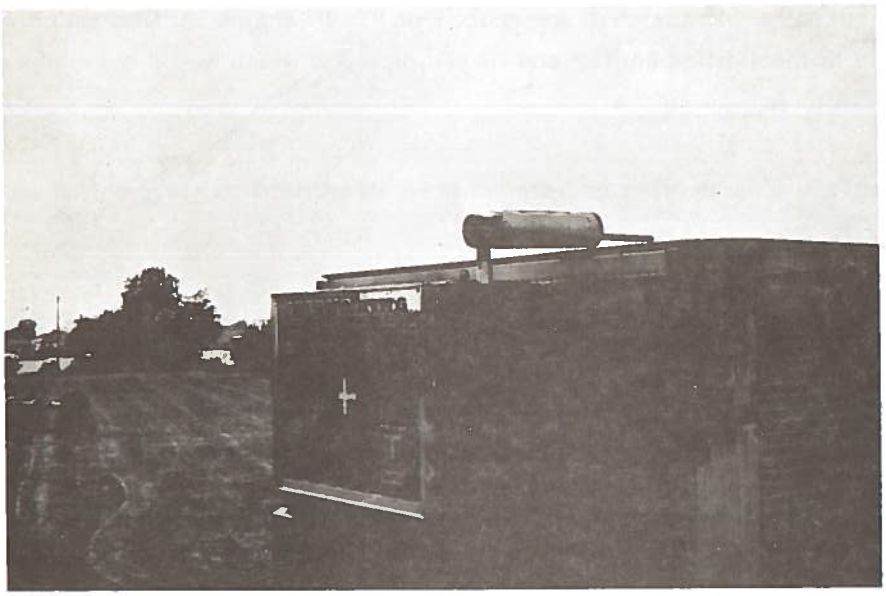


Figure 27. Right-angle Type Muffler in Series with Refrigeration Unit Muffler

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit maximum cooling

Position 2(50 ft from refrigeration unit)

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1											
2		88.5	72	88	75	63.5	67	70	61	56.5	52
3											
4											
5											
6											
7											
8											
9											
10											
11											

Figure 28. Noise Levels of Refrigeration Unit at Maximum Load Condition Position 2

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit maximum cooling

additional right-angle type muffler installed

Position 2(50 ft from refrigeration unit)

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1											
2		83	72	81.5	72	61	68.5	68.5	61	56	52
3											
4											
5											
6											
7											
8											
9											
10											
11											

Figure 29. Position 2 Noise Levels of Refrigeration Unit at Maximum Load Condition (Additional In-Series Muffling)

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit minimum cooling

Position 2(50 ft from refrigeration unit)

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1											
2		82	65	81	78	62	60	60.5	58	52	47.5
3											
4											
5											
6											
7											
8											
9											
10											
11											

Figure 30. Position 2 Noise Levels of Refrigeration Unit at Minimum Load Condition

Refrigeration Unit Information

Model Super NWD 30

Serial No. 0442964099

Power Diesel

Test Conditions

Refrigeration unit minimum cooling

Additional right-angle type muffler installed

Position 2(50 ft from refrigeration unit)

REMARKS

Polar Plot Sound Pressure Level (db)
(See Diagram for Position Location)

Pos. No.	Tape No.	Lin (dB)	A Weighted (dB)	Center Frequency (Hz) 63	125	250	500	1000	2000	4000	8000
1											
2		82	65	80	76.5	57	61	61	57	52	47
3											
4											
5											
6											
7											
8											
9											
10											
11											

Figure 31. Noise Levels of Refrigeration Unit at Minimum Load Condition (Additional In-Series Muffling) Position 2

For the maximum load condition, the additional in-series muffling provided 5.5 dB (lin) attenuation, but 0 dB(A) attenuation. The additional muffling provided reduction of the diesel engine fundamental frequency, as illustrated in Figures 32 and 33 (maximum load condition). No "A" weighted reduction in noise was accomplished because additional muffling lowered the diesel engine amplitude at the fundamental frequency (73 Hz at maximum load) in an octave band where 26 dB attenuation is obtained with the "A" weighted network. Thus, any diesel engine fundamental frequency amplitude reduction is masked in the "A" weighted network attenuation.

For the minimum load condition, the additional muffling provided no "linear weighted" attenuation or "A weighted" attenuation. Review of the octave bands (Figures 30 and 31) indicates that attenuation was obtained in the lower octave bands with the additional muffling. Reduction of the diesel engine fundamental frequency amplitude was obtained with the additional in-series type muffling.

4 SUMMARY

The heavy-duty diesel-powered refrigeration unit examined in this acoustic noise study exhibited the following characteristics:

1) The refrigeration unit produces a maximum acoustic noise level of 72 dB(A) at 50 ft distance on maximum load condition. This noise level was measured at 22.5° from the center of the refrigeration unit cabinet face on the air inlet side.

2) On minimum load condition, the refrigeration unit produces a maximum acoustic noise level of 65.5 dB(A) at a 50 ft distance.

3) The major noise contribution of the refrigeration unit is produced by diesel engine firing frequency.

Computations based on the A-weighted Frequency spectrum of the noise of the refrigeration unit in its standard configuration under maximum load (position 2) indicates the following hierarchy of noise sources:

Source	Level (dbA)	
Engine exhaust	68.5	Total Unit level = 72 dbA
Condenser fan	67.4	
Compressor, Evaporator	65.1	
Fan, Engine radiated, etc.		

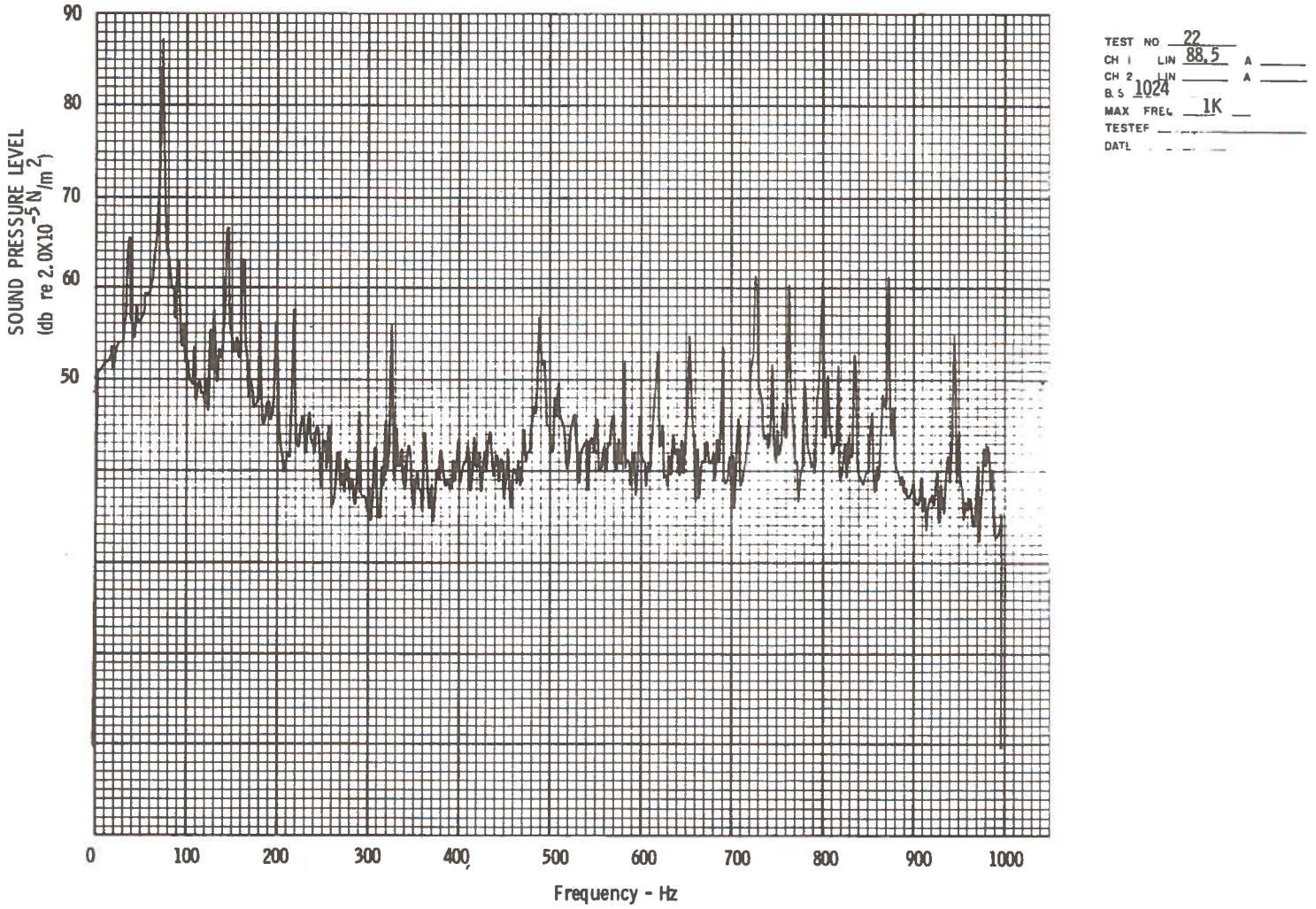


Figure 32. Refrigeration Unit Noise at Maximum Load - Position 2

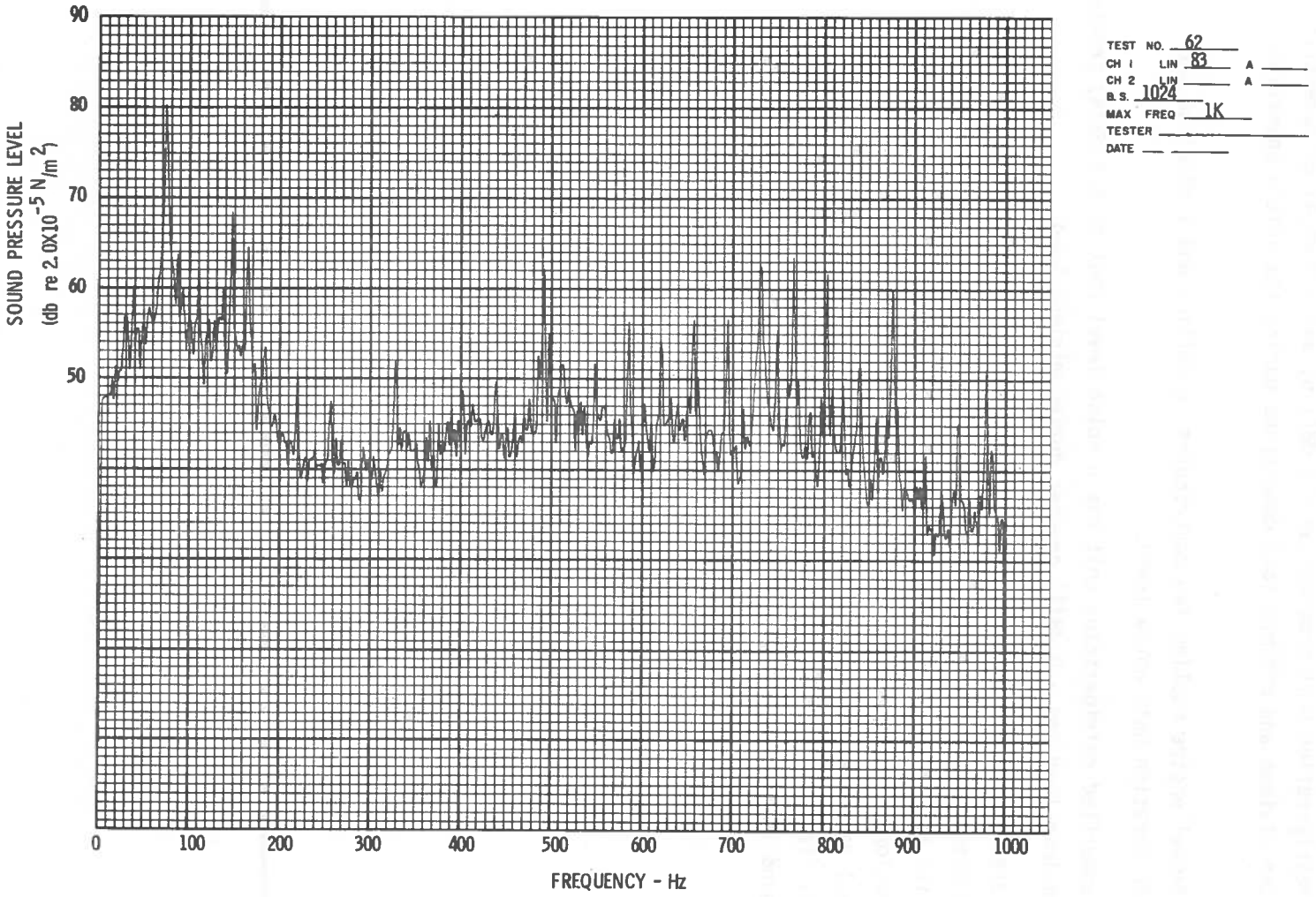


Figure 33. Refrigeration Unit Noise at Maximum Load (Additional In-Series Muffling)

4) The refrigeration unit produces an 8.5 dB(lin) and 7.0 dB(A) differential between the maximum and minimum load conditions during the unit's operating cycle.

5) The diesel engine cooling fan contributes .5 db(lin) and 4 dB(A) to the total refrigeration unit noise level.

6) The unmuffled refrigeration unit has a noise level that is 6.5 dB(A) greater during maximum load and 3.0 dB(A) greater during minimum load.

7) The diesel engine exhaust noise levels may be reduced with additional muffling which could reduce total refrigeration unit noise. A reduction of 5.5 dB(lin) on refrigeration unit maximum load was demonstrated. "A" scale refrigeration unit noise levels would not be lowered through the use of additional engine exhaust muffling. The engine fundamental has a low frequency (less than 100 Hz) and reduction of this would not improve "A" scale sound level, because of the nature of the "A" scale weighting network.

Appendix

A review of the work performed under this contract indicates that no innovation, discovery, improvement, or invention was made.