Florida State University Libraries

Electronic Theses, Treatises and Dissertations

The Graduate School

2016

Characterization and Validation of an Anechoic Facility for High-Temperature Jet Noise Studies

Joseph Michael Craft

FLORIDA STATE UNIVERSITY
COLLEGE OF ENGINEERING

CHARACTERIZATION AND VALIDATION OF AN ANECHOIC FACILITY FOR
HIGH-TEMPERATURE JET NOISE STUDIES

By
JOSEPH CRAFT

A Thesis submitted to the
Department of Mechanical Engineering
in partial fulfillment of the
requirements for the degree of
Master of Science

2016

Joseph Craft defended this thesis on November 11, 2016.
The members of the supervisory committee were:

Farrukh Alvi
Professor Directing Thesis

Rajan Kumar
Committee Member

Emmanuel Collins
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.

To my family. Thank you for always supporting me in all my endeavors.

ACKNOWLEDGMENTS

First and foremost, I praise my savior Jesus Christ for the opportunity to pursue a graduate degree and for its successful completion. I want to thank my advisor, Dr. Farrukh Alvi, for his dedicated mentorship throughout the years in both academic advising and research. I also want to thank the facility operators, Ted Worden and Puja Upadhyay, for their involvement in every experiment conducted; I couldn't have asked to be a part of a better team. Furthermore, I want to thank the numerous contributions made by fellow graduate students, Kade Aley and Malcolm Harmon, for their technical designs and experimentation assistance. The fabrications and design assistance by machinists Bobby Avant and Adam Piotrowski have played a pivotal role in the facility relocation and their contributions are greatly appreciated. Lastly, I want to thank my family and friends for their continuous motivation and support; I couldn't have done it without them.

TABLE OF CONTENTS

List of Tables	vii
List of Figures	xi
Abstract	xvi
1 Introduction	1
1.1 Motivation	1
1.2 Overview of Jet Behavior and Aeroacoustics	2
1.2.1 Relevant Parameters and Structural Characteristics	2
1.2.2 Sources and Jet Noise Behavior	5
1.3 Research Objective	7
2 Anechoic High-Temperature Jet Facility	9
2.1 Facility Overview	9
2.2 Air and Fuel Supply	11
2.2.1 Air Storage and Routing System	11
2.2.2 Fuel Storage and Routing System	11
2.3 Burner Room	14
2.3.1 Sudden Expansion (SUE) Burner	15
2.4 Anechoic Chamber	18
2.5 Control Room	19
2.5.1 Facility Operation	20
3 Experimental Setup	22
3.1 Characterization of an Anechoic Chamber	22
3.2 Jet Acoustics Characterization	25
3.3 Measurement Techniques, Instrumentation, and Processing	27
3.4 Error and Uncertainty	28
4 Results and Discussion	29
4.1 Anechoic Chamber Characterization	29
4.2 Jet Acoustics Validation	33
4.3 Rig Noise and Facility Operational Limits	44
4.3.1 Cold Jet Rig Noise Analysis	45
4.3.2 Heated Jet Rig Noise Analysis	48
4.3.3 Internal Rig Noise Investigation	51
5 Conclusions	55

Appendix	
A Acoustic Characterization Results	57
B Acoustic Data for Ideally Expanded Jets	68
C Acoustic Data for Off-Design Jets	94
References	155
Biographical Sketch	158

LIST OF TABLES

3.1	Relevant Nozzle Parameters	26
3.2	Test Conditions	26
4.1	Mach number and temperature limits of the CN-1in and CN-2in nozzles.	48
B.1	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.32$, $T_0=288.9$ K)	68
B.2	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=577$ K)	69
B.3	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=808.7$ K)	70
B.4	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=987$ K)	71
B.5	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=1099.8$ K)	72
B.6	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=1199.3$ K)	73
B.7	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.32$, $T_0=1312.6$ K)	74
B.8	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.53$, $T_0=288.4$ K)	75
B.9	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.53$, $T_0=599.3$ K)	76
B.10	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=802$ K)	77
B.11	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.51$, $T_0=975.9$ K)	78
B.12	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1088.7$ K)	79
B.13	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1208.7$ K)	80
B.14	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1314.8$ K)	81
B.15	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.82$, $T_0=284.2$ K)	82
B.16	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.8$, $T_0=814.8$ K)	83
B.17	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.79$, $T_0=1093.2$ K)	84
B.18	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.79$, $T_0=1207.6$ K)	85
B.19	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.78$, $T_0=1314.8$ K)	86
B.20	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.05$, $T_0=290.9$ K)	87
B.21	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.03$, $T_0=592.6$ K)	88

B.22	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.02$, $T_0=813.2$ K)	89
B.23	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=983.7$ K)	90
B.24	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1123.2$ K)	91
B.25	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1203.7$ K)	92
B.26	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1316.5$ K)	93
C.1	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.4$, $T_0=288.9$ K)	94
C.2	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.5$, $T_0=289.2$ K)	95
C.3	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.6$, $T_0=289.5$ K)	96
C.4	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.7$, $T_0=289.9$ K)	97
C.5	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.8$, $T_0=290$ K)	98
C.6	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.4$, $T_0=977.6$ K)	99
C.7	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.5$, $T_0=982.6$ K)	100
C.8	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.6$, $T_0=979.3$ K)	101
C.9	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.7$, $T_0=982.6$ K)	102
C.10	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.8$, $T_0=992$ K)	103
C.11	SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.51$, $T_0=1199.3$ K)	104
C.12	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.2$, $T_0=289$ K)	105
C.13	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.3$, $T_0=288.5$ K)	106
C.14	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=257.6$ K)	107
C.15	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=288.5$ K)	108
C.16	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=288.5$ K)	109
C.17	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.81$, $T_0=288.4$ K)	110
C.18	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.88$, $T_0=288.4$ K)	111
C.19	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=600.6$ K)	112
C.20	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=602.6$ K)	113
C.21	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=600.9$ K)	114

C.22	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=608.2$ K)	115
C.23	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.88$, $T_0=603.1$ K)	116
C.24	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.19$, $T_0=617.6$ K)	117
C.25	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.3$, $T_0=818.2$ K)	118
C.26	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=805.9$ K)	119
C.27	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=810.9$ K)	120
C.28	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=809.3$ K)	121
C.29	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=811.5$ K)	122
C.30	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.2$, $T_0=988.2$ K)	123
C.31	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.29$, $T_0=977$ K)	124
C.32	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=997$ K)	125
C.33	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=974.3$ K)	126
C.34	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=982$ K)	127
C.35	SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=977.6$ K)	128
C.36	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.3$, $T_0=287.7$ K)	129
C.37	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.4$, $T_0=286.7$ K)	130
C.38	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=286.1$ K)	131
C.39	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.6$, $T_0=285.7$ K)	132
C.40	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.7$, $T_0=285.1$ K)	133
C.41	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.9$, $T_0=288$ K)	134
C.42	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.0$, $T_0=289.1$ K)	135
C.43	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.1$, $T_0=289.5$ K)	136
C.44	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.72$, $T_0=589.3$ K)	137
C.45	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.3$, $T_0=815.4$ K)	138
C.46	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.4$, $T_0=810.9$ K)	139
C.47	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=816.5$ K)	140

C.48	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.6$, $T_0=819.8$ K)	141
C.49	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.7$, $T_0=813.7$ K)	142
C.50	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.9$, $T_0=807.6$ K)	143
C.51	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.0$, $T_0=823.2$ K)	144
C.52	SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=1208.2$ K)	145
C.53	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.2$, $T_0=289.7$ K)	146
C.54	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.3$, $T_0=289.8$ K)	147
C.55	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.4$, $T_0=289.8$ K)	148
C.56	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.5$, $T_0=289.9$ K)	149
C.57	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.6$, $T_0=289.9$ K)	150
C.58	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.7$, $T_0=290.7$ K)	151
C.59	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.8$, $T_0=290.9$ K)	152
C.60	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.9$, $T_0=290.8$ K)	153
C.61	SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.1$, $T_0=292.9$ K)	154

LIST OF FIGURES

1.1	Schlieren images of a $M_d = 1.5$ nozzle demonstrating the three jet expansion conditions a) over-expanded Mach 1.3 jet, b) fully expanded Mach 1.5 jet, c) under-expanded Mach 1.8 jet. The weak shock cells observed in the case of the ideally expanded jet is likely due to minor imperfections in the nozzle.	4
1.2	The two similarity spectra produced by Tam et al [26]. The dotted line is the spectra for fine-scale turbulent noise and solid line for large-scale turbulent noise.	6
2.1	CAD rendering and photographs of the High-Temperature Jet Facility layout including the anechoic chamber, fuel room, and burner room. The LabVIEW control program front panel and facility control rack with sensor displays are shown in the two bottom photographs.	10
2.2	Ethylene fuel manifold used to activate and monitor fuel flow prior and during heated jet operation [10].	13
2.3	Fuel room fuel system component layout [10].	13
2.4	Schematic of air supply control system.	14
2.5	Schematic of SUE burner component [10].	15
2.6	Operational limits of the SUE burner in the facility (provided by Kaiser Marquardt). [10].	16
2.7	Downstream components of the burner system [10].	17
2.8	CAD model of the anechoic chamber including relevant details such as the exhaust nozzle, the anechoic treatment on the walls and floor, and the main exhaust in black.	19
2.9	Labview Control Program.	21
3.1	Detailed CAD model of the anechoic chamber with the five required traverse directions.	23
3.2	Top view of the chamber CAD model showing the two additional directions.	24
4.1	Representative measured sound pressure level roll-off of the vertical direction (UP) compared to theoretical roll-off as calculated by the ISO standard. Blue dashed lines signify theoretical roll-off and red dashed lines represent the allowable tolerances.	30
4.2	Measured sound pressure level roll-off compared to theoretical roll-off for low frequency results (250 Hz to 500 Hz) to assess discrepancies. These two data sets are traversed downstream of the jet exit. a) DR traverse to the right, b) DL traverse to the left.	30

4.3	Measured sound pressure level roll-off comparison of low frequency results (250 Hz to 500 Hz). Each figure represents a traverse direction to the right of the jet exit. a) UR traverse to the right, b) UL traverse to the left.	31
4.4	Measured sound pressure level roll-off comparison of low frequency results (250 Hz to 500 Hz). Each figure represents a traverse direction to the right of the jet exit. a) HR traverse to the right, b) HL traverse to the left.	32
4.5	OASPL directionality for the ideally-expanded CD-1.3 nozzle at various temperatures and normalized to a distance of 100d.	35
4.6	OASPL directionality for the ideally-expanded CD-1.5 nozzle at various temperatures and normalized to a distance of 100d.	35
4.7	OASPL directionality for the ideally-expanded CD-1.8 nozzle at various temperatures and normalized to a distance of 100d.	36
4.8	OASPL directionality for the ideally-expanded CD-2.0 nozzle at various temperatures and normalized to a distance of 100d.	36
4.9	Representative acoustic spectra for ideally-expanded jets generated for the CD-1.5 nozzle and CD-2.0 nozzle. a) Mach 1.5 at 280 K, b) Mach 1.5 at 1311 K. c) Mach 2.0 at 280 K, d) Mach 2.0 at 1311 K. The spectra for peak radiation direction is shown in red.	37
4.10	OASPL directionality for imperfectly and ideally expanded jets (280 K). The ideally-expanded jet was generated through the CD-1.5 nozzle, and the under- and over-expanded jets through the CD-1.3 and CD-1.8 nozzles, respectively.	39
4.11	Narrow band spectra of the $M_j = 1.5$ jets at 280 K comparing ideal and off-design conditions at sideline and peak radiation angles.	39
4.12	OASPL directionality plot for imperfectly and ideally expanded jets (1200 K). The ideally-expanded jet was generated through the CD-1.5 nozzle, and the under- and over-expanded jets through the CD-1.3 and CD-1.8 nozzles, respectively.	40
4.13	Narrow band spectra of the $M_j = 1.5$ jets at 1200 K comparing ideal and off-design conditions at sideline and peak radiation angles.	41
4.14	Comparison between current and Greska's data. Difference in OASPL for imperfect expansion of CD-1.3, CD-1.5, and CD-1.8 nozzles at various temperatures.	42
4.15	Current Mach 2 OASPL data compared to Greska's data for multiple temperatures.	42
4.16	Third octave spectra comparison for ideally expanded Mach 2.0 jet at 290 K. The data is presented for the 90° and 150° orientations.	43

4.17	Third octave spectra comparison for ideally expanded Mach 2.0 jet at 1313 K. The data is presented for the 90° and 150° orientations.	44
4.18	OASPL and U_8 scaling law for CN-1 and CN-2 nozzles at various subsonic speeds and at 90° orientation.	45
4.19	OASPL and U_8 scaling law for CN-1in and CN-2in nozzles at various subsonic speeds and at 150° orientation.	46
4.20	SPL spectra for the CN-1in nozzle at perspective angle of 90°. The subsonic jet Mach number starts at $M_j = 0.5$ (red line), increases by 0.05 for each consecutive color, and ends with $M_j = 0.95$	46
4.21	SPL spectra for the CN-2in nozzle at perspective angle of 90° for converging nozzles at various subsonic speeds. M_j starts at $M_j = 0.5$ (red line) and increases by 0.05 for each consecutive color up to $M_j = 0.95$	47
4.22	OASPL and U_8 scaling law for the CN-2in nozzle at various temperatures and subsonic speeds and an orientation of 90°.	49
4.23	OASPL and U_8 scaling law for the CN-2in nozzle at various temperatures and subsonic speeds and an orientation of 150°.	49
4.24	SPL spectra for the CN-2in nozzle at perspective angle of 90° for converging nozzles at various subsonic speeds. M_j starts at $M_j = 0.5$ (red line), jumps to $M_j = 0.75$, and increases by 0.05 for each consecutive color up to $M_j = 0.95$	50
4.25	SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.22 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.95$, CN-2in nozzle at $M_j = 0.26$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.14$. . .	52
4.26	SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.17 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.75$, CN-2in nozzle at $M_j = 0.21$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.11$. . .	52
4.27	SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.11 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.5$, CN-2in nozzle at $M_j = 0.12$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.08$	53
A.1	The low frequency data (200 Hz - 630 Hz) traversed in the vertical (UP) direction. The data is measured sound pressure level roll-off compared to theoretical roll-off for the low frequency 3_{rd} octave bands. Blue dashed lines signify theoretical roll-off and red dashed lines represent the allowable tolerances.	57
A.2	The mid frequency data (800 Hz - 5 kHz) traversed in the vertical (UP) direction. . .	58
A.3	The high frequency data (6.3 kHz - 20 kHz) traversed in the vertical (UP) direction. .	58

A.4	The low frequency data (200 Hz - 630 Hz) traversed downstream and to the right (DR) direction.	59
A.5	The mid frequency data (800 Hz - 5 kHz) traversed downstream and to the right (DR) direction.	59
A.6	The high frequency data (6.3 kHz - 20 kHz) traversed downstream and to the right (DR) direction.	60
A.7	The low frequency data (200 Hz - 630 Hz) traversed downstream and to the left (DL) direction.	60
A.8	The mid frequency data (800 Hz - 5 kHz) traversed downstream and to the left (DL) direction.	61
A.9	The high frequency data (6.3 kHz - 20 kHz) traversed downstream and to the left (DL) direction.	61
A.10	The low frequency data (200 Hz - 630 Hz) traversed upstream and to the right (UR) direction.	62
A.11	The mid frequency data (800 Hz - 5 kHz) traversed upstream and to the right (UR) direction.	62
A.12	The high frequency data (6.3 kHz - 20 kHz) traversed upstream and to the right (UR) direction.	63
A.13	The low frequency data (200 Hz - 630 Hz) traversed upstream and to the left (UL) direction.	63
A.14	The mid frequency data (800 Hz - 5 kHz) traversed upstream and to the left (UL) direction.	64
A.15	The high frequency data (6.3 kHz - 20 kHz) traversed upstream and to the left (UL) direction.	64
A.16	The low frequency data (200 Hz - 630 Hz) traversed horizontally and to the right (HR) direction.	65
A.17	The mid frequency data (800 Hz - 5 kHz) traversed horizontally and to the right (HR) direction.	65
A.18	The high frequency data (6.3 kHz - 20 kHz) traversed horizontally and to the right (HR) direction.	66
A.19	The low frequency data (200 Hz - 630 Hz) traversed horizontally and to the left (HL) direction.	66

A.20	The mid frequency data (800 Hz - 5 kHz) traversed horizontally and to the left (HL) direction.	67
A.21	The high frequency data (6.3 kHz - 20 kHz) traversed horizontally and to the left (HL) direction.	67

ABSTRACT

In response to the increasing demand for jet noise studies performed at realistic conditions, the Florida Center For Advanced Aero-Propulsion at Florida State University has recently brought online an upgraded Anechoic High-Temperature Jet Facility. The function of this facility is to accurately simulate and characterize the aeroacoustic properties of exhaust from jet engines at realistic temperatures and flow speeds. The facility was previously located on the main campus of FSU but was relocated to the AME to unify FSU's aero-propulsion research facilities. The relocation process provided the opportunity to upgrade the facility's operational and diagnostic capabilities. This blow-down type facility is supplied by a 3500 kPa, 114 cubic meter compressed dry air system and a sudden-expansion ethylene burner that is capable of producing ideally expanded jets up to Mach 2.6 and stagnation temperatures up to 1500 K. The jet exhausts into a fully anechoic chamber which is equipped to acquire acoustic and flow measurements including the temperature and pressure of the jet. The facility is capable of operating under free jet as well as in various impinging jet configurations pertinent to sea- and land-based aircraft, such as the F-35B. During the relocation process, several improvements have been made including longer run times at higher temperatures and increased safety during operation. In this paper we demonstrate the facility's experimental capabilities and document jet aeroacoustic characteristics at various flow and temperature conditions. The anechoic chamber was characterized using ISO (3745:2003) guidelines and the lower cutoff frequency of the chamber was determined to be 315 Hz. Aeroacoustic properties of jets operating at subsonic conditions and supersonic Mach numbers ranging from 1.2 to 2.1 at temperatures of ~ 300 K to ~ 1300 K are documented. Where available, very good agreement was found when the present results were compared with data in the jet noise literature.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Throughout the past few decades, the aviation industry has experienced an increased demand for larger, faster, and more efficient military and commercial aircraft. Inherent to the development of more powerful jet engines is the corresponding increase in byproduct exhaust jet noise, which can create a hazard for aircraft operational personnel and a nuisance for the growing number of communities adjacently located to airports and military bases. In response to these noise concerns, researchers have developed and characterized several flow control techniques, both passive and active, aimed at attenuating aeroacoustic noise [11], [4], [12], [14], [29]. On the developmental level, full-scale testing of these control methods is not viable due to the cost and risks associated with full-scale experiments. This necessitates the availability of affordable and reliable small-scale facilities capable of simulating a wide-range of flow conditions to serve as test-beds for emerging flow control technologies. Proper characterization of jet noise and assessment of control methods can be achieved through means of a facility that can accurately simulate the high-speed and high-temperature jet engine exhaust conditions for various nozzle geometries and configurations. For comprehensive flow and acoustic characterization, the facility must be capable of accommodating non-intrusive instrumentation and measurement techniques for quantitative and qualitative flow and acoustic-field measurements.

The Florida Center for Advanced Aero-Propulsion's (FCAAP's) Anechoic High-Temperature Jet Facility (HotJet) is one of many aerospace-related facilities housed in Florida State University's newly developed multidisciplinary research building, the Aero-propulsion, Mechatronics, and Energy (AME) Center. The facility was previously located on FSU's main campus and is described in detail by Greska [10]. It was recently relocated to the AME to unify FSU's advanced aerospace research facilities which include a $12'' \times 12''$ polysonic wind tunnel, two high-speed heated jet facilities, a $30'' \times 30''$ hard-walled subsonic wind tunnel, a $4'' \times 3''$ supersonic pilot wind tunnel, a subsonic anechoic flow facility, and the Micro-Actuator Development (MAD) Laboratory. The

Anechoic High-Temperature Jet Facility is a blow-down jet facility capable of generating supersonic air jets at speeds up to Mach 2.6 (ideally-expanded) and temperatures up to 1500 K (2240 °F), making it one of the most unique and capable academic research facilities for the simulation of jet engine exhaust at realistic conditions. During the relocation, certain facility subsystems have been redesigned and upgraded for improved operational and diagnostic capabilities. The capabilities and performance of the updated test facility are documented in this paper in the context of jet noise research.

1.2 Overview of Jet Behavior and Aeroacoustics

The aeroacoustics of jet exhaust is an inherently challenging subject and is further complicated with elevated jet temperatures. Decades of research has provided volumes of comprehensive knowledge on both ambient temperature, “cold”, and heated jets for various exhaust nozzles types and orientations. The experiments conducted in this manuscript are all free jet types produced by axisymmetric nozzles at various conditions relevant to military jet exhaust. A brief review of jet structure, aeroacoustics, and terminology is provided below in order to provide a background relevant to the following research conducted.

1.2.1 Relevant Parameters and Structural Characteristics

During jet operation the most influential factors determining the characteristics of the flow include the internal geometry of the nozzle, the jet stagnation pressure, P_0 , and stagnation temperature, T_0 . While various geometries have been extensively studied, the axisymmetric nozzle is the simplest nozzle. This nozzle type is a single stream exhaust with an exit diameter, D , and either a converging or converging-diverging profile. These parameters influence the velocity of the jet and dictate flow behavior.

First addressing the definitions relevant to jet velocity, a jet can be classified as one of three different categories based on its velocity: subsonic, sonic, or supersonic. A subsonic flow is one that travels at a speed slower than ambient propagation of sound, a sonic flow travels at a speed equal to that of sound, and supersonic is a flow traveling faster than sound. This relationship between the flow velocity and sound velocity is defined by the jet Mach number, M_j . With the jet velocity labeled as U_j and the speed of sound, a , the Mach number is the ratio of the two

speeds as shown in Equation 1.1. As determined by this ratio, subsonic flows have Mach numbers of $M_j < 1$, sonic with $M_j = 1$, and supersonic flows with $M_j > 1$. To change or maintain a flow speed the nozzle pressure ratio, $NPR = P_0/P_e$, is manipulated. This ratio is the jet stagnation pressure over the jet exit pressure and the dependence of the Mach number on this ratio is shown in Equation 1.2. The other variable, γ , is the specific heat ratio and it fluctuates inversely with jet stagnation temperature.

$$M_j = \frac{U_j}{a} \quad (1.1)$$

$$M_j = \sqrt{\frac{2}{\gamma - 1} \left[\left(\frac{P_0}{P} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} \quad (1.2)$$

As shown in the equation, increasing NPR increases the Mach number and, assuming the ambient speed of sound stays constant, increases the jet velocity. However, flows of converging nozzles are limited to sonic speed at which the flow is choked. Disturbances in fluid flow, such as a pressure difference, is signaled through the fluid by a wave traveling at the speed of sound. At subsonic speeds, the fluid speed is slower than the speed of sound so the fluid adjusts accordingly. Once a sonic speed is reached for the flow, the fluid does not have time to react to disturbances such as pressure changes. Because the fluids disturbance waves are limited to the speed of sound, the flow cannot telegraph changes between stagnation pressure and the exit pressure. The flow is “choked” because increasing the stagnation pressure no longer increases mass flow rate and, consequently, flow velocity is no longer increased. Before the flow is choked, the calculation for mass flow rate is given by Equation 1.3 where A is the local area and R is the universal gas constant. Once the flow is choked, $M_j = 1$ and the calculation for mass flow rate is reduced to Equation 1.4. Because the converging nozzles can only create flows up to $M_j = 1$, subsonic tests are conducted using the converging nozzles while supersonic tests are conducted using the converging-diverging, or CD, nozzles.

$$\dot{M} = \frac{AP_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} M \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \quad (1.3)$$

$$\dot{M} = \frac{AP_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \quad (1.4)$$

Figure 1.1: Schlieren images of a $M_d = 1.5$ nozzle demonstrating the three jet expansion conditions a) over-expanded Mach 1.3 jet, b) fully expanded Mach 1.5 jet, c) under-expanded Mach 1.8 jet. The weak shock cells observed in the case of the ideally expanded jet is likely due to minor imperfections in the nozzle.

CD nozzles converge to a throat with a minimum diameter of D_t and then diverges to produce supersonic flow. At subsonic speeds, flow through this nozzle demonstrate similar behavior as in the converging nozzle. However, increasing the stagnation pressure will choke the flow at the minimum diameter, D_t , and further increasing the pressure will create a standing shock structure within the nozzle. Continuing to increase the NPR causes the shock to travel downstream to the jet exit until the shock bends out into the exhausted jet creating a complex interaction of “shock cells” between subsonic and supersonic sections of flow. The once perpendicular shock now deflects inward, because P_e is less than the ambient pressure, P_a . This inward deflection results

in an initially contracting jet and is commonly referred to as an over-expanded jet. Increasing the NPR will eventually create an exit pressure equal to ambient pressure resulting in a fully expanded jet with no shock cells. Increasing the NPR further will result in an underexpanded jet, where $P_e > P_a$. An under-expanded jet does form a shock-cell structure in the jet but for different reasons compared to an over-expanded. Now that the exit pressure is greater, expansion waves are formed at the nozzle lip and span out away from the jet center-line. Originally published by Day, [8], Figure 1.1 shows three schlieren images of the expansion types in order of over-, fully, and under-expanded jets from top to bottom. Each is created by the same nozzle designed for a Mach 1.5 jet. The design Mach number, M_d , is based off of when the flow is ideally (fully) expanded and the jet Mach number is equal to the design Mach number ($M_j = M_d$). In the figure below, the over-expanded case was created with a jet Mach number of $M_j = 1.3$ and the under-expanded with $M_j = 1.8$.

1.2.2 Sources and Jet Noise Behavior

The study of jet noise began with Sir James Lighthill and his two part publication, *On Sound Generated Aerodynamically* [17],[18]. This work introduces Lighthill's Acoustic Analogy of a free flow and the acoustic scaling law which demonstrates that acoustic power generated by a jet radiates proportionally with jet velocity raised to the eight power, U_j^8 . Roughly a decade later the scaling law was extended by Ffowcs-Williams [34] to show that the acoustic power of transonic and supersonic jets radiate proportionally to U_j^3 . As a result of these previous findings, a substantial amount of research has gone into studying jet structures, mixing interactions, and their acoustic contributions. The research of Brown & Roshko [6], Crow & Champagne [7], and Winant & Broward [35] revealed coherent structures created by the interactions between jets and the ambient flow in free shear flow and turbulent jets. These structures produce turbulent mixing noise, which is known to be the most dominant source of noise in the aft, downstream directions of shock-free turbulent jets. The two types of turbulent mixing noise are products of fine-scale structures and large-scale structures produced within the free shear layer of the jet [26]. Each demonstrating a unique behavior, the fine-scale turbulent noise dominates the sideline angles and the large-scale noise dominates the downstream. Tam et al. [26] used the jet acoustic data of the NASA Langley database to demonstrate that jet noise data can be fit to two universal similarity spectra as shown in Figure 1.2. The dotted line is the spectra for fine-scale turbulent noise and the solid is the

spectra for large-scale. These two spectra have been found to fit for most data regardless of jet Mach number and temperature ratio.

Figure 1.2: The two similarity spectra produced by Tam et al [26]. The dotted line is the spectra for fine-scale turbulent noise and solid line for large-scale turbulent noise.

The coherent large-scale turbulent structures have lengths on the scale of the jet diameter and emit Mach wave radiation when propagating supersonically with respect to the ambient fluid. Modeled by a wavy wall, the angle of the most intense radiation of the Mach waves is given by Equation 1.5. M_c is the convection Mach number which is the velocity of the large-structure over the ambient fluid speed of sound.

$$\mu = \sin^{-1}\left(\frac{1}{M_c}\right) \quad (1.5)$$

While coherent structures are the most dominant source in subsonic and fully expanded supersonic jets, the presence of shocks in over- and under-expanded jets introduce two more additional noise sources, screech and broadband shock associated noise (BBSN). Collectively known as shock associated noise, they both depend on jet Mach number and the total temperature ratio of the stagnation temperature over ambient air temperature ($TTR = T_0/T$). The source of BBSN is the interaction between the shock cells, created by imperfect expansion, and the inherent large coherent structures. The broad frequency range of the noise correlates to the broad frequency range of the

coherent structures. This noise dominates primarily at 90° and is demonstrated in the experimental results (Figures 4.10 and 4.11). The amplitude has been shown to directly relate to the spacing of the shock cell structure which is governed by observation angle, the degree of off-design operation, and nozzle profile. Another factor that influences BBSN amplitude and overall dominance is the TTR , but only to a limited extent. The affects of TTR reach their fullest potential at ratios close to 2 (Kuo et al. [16]).

Contrary to BBSN noise, screech tones are characterized by the presence of tones at discrete frequencies (and their harmonics). These tones are the product of an acoustic feedback loop created by the presence of a thick nozzle lip. Disturbances produced at the nozzle lip grow continuously as they travel downstream and interact with the shock cell structure. This interaction results in the production of acoustic waves that travel upstream and further stimulate disturbances at the nozzle exit [22]. While the screech tone persists at the same frequency for all angle orientations, it is again observed at 90° . While commonly present in cold jets, it is significantly reduced for high temperature jets and, therefore, not as prevalent in normal aircraft operation. The screech tones are also easily suppressed by disturbing the feedback loop. This is done through active and passive flow control with, for example, microjet injection or chevrons at the jet exit [2], [19], [15], [10] [23].

1.3 Research Objective

The initial approach to studying jet exhaust would be to operate a full scale jet engine, but this is by no means a practical option. The power and resources required would be far too costly and, due to its impracticality, this is rarely done. Two viable alternatives for experimentation include simulated jet exhausts using fluids of different properties and jet facility's capable of creating realistic conditions at a smaller scale. While it has been shown that mixtures of helium and air can simulate jet acoustics of high temperature exhausts the jet velocity and jet density cannot be matched simultaneously [9], [21]. McLaughlin et al. [20] demonstrated that small scale jets of helium/air mixtures could simulate heated jets within 1 dB proving the method. Despite its accuracy, the simulation can be rather expensive and a more practical approach would be to heat the air. By properly nondimensionalizing the jet parameters, a small scale exhaust is the most practical approach to studying the acoustics of high-temperature jet exhaust.

The high-temperature anechoic jet facility has recently been relocated from Florida State University's main campus and modified to accommodate aeroacoustic studies concerning modern military jet exhaust. In order to properly assess the facilities flow condition capabilities and ability to correctly model military jet exhaust, it is essential to recreate well studied jet conditions and determine the repeatability of the facility's results. Comparing to well documented results, this research will verify the facility performance and serve as baseline data for future research. Furthermore, the current experiments will attempt to evaluate and measure rig noise. Inherent to all jet facilities, rig noise has potential to severely contaminate acoustic results and it is important to evaluate it's nature and attempt to reduce contamination when possible.

CHAPTER 2

ANECHOIC HIGH-TEMPERATURE JET FACILITY

2.1 Facility Overview

The Anechoic High-Temperature Jet Facility (HotJet) is a blow-down type capable of generating high temperature and high pressure air flow comparable to the exhaust conditions of military aircraft. The facility was relocated in an effort to unify all of the Mechanical Engineering Department's aero-propulsion laboratories at the Aero-Propulsion, Mechatronics and Energy (AME) Center relocation presented itself as an opportunity to make much needed upgrades and modifications to the facility design and operation. The newly improved facility consists of major components that were utilized from the original facility and redesigned structural components and subsystems to improve control authority, precision of run conditions, and diagnostic capabilities. As mentioned previously the HotJet is capable of producing realistic jet exhaust conditions at various flow Mach numbers and stagnation temperatures. Figure 2.1 shows a CAD model of the facility layout including the fuel room, burner room, and the anechoic chamber. As shown, the fuel room houses the compressed ethylene cylinders used to attain high temperatures. All walls of the facility are 12 in-thick concrete, 2-hr fire-rated, and explosion proof to isolate any potential hazards as safety precautions for the operational personnel and nearby facilities. The facility can be used to study free jets exhausting to open atmosphere or impinging jets interacting with various structures. The CAD in the figure depicts an impinging jet configuration with the removable ground plane in the center of the anechoic chamber, which is used in impingement studies relevant to STOVL and VTOL aircraft Worden et al. [37], [38], [36]. Equipped with interchangeable nozzles, the facility has the ability to investigate various single and dual nozzle geometries. The succeeding sections will discuss each room in detail, including the updates made.

Figure 2.1: CAD rendering and photographs of the High-Temperature Jet Facility layout including the anechoic chamber, fuel room, and burner room. The LabVIEW control program front panel and facility control rack with sensor displays are shown in the two bottom photographs.

2.2 Air and Fuel Supply

2.2.1 Air Storage and Routing System

The redesign plan included a completely new air supply system for the HotJet facility with superior capabilities when compared to the previous facility. Three Gardner Denver model VH15H3N PET water cooled, 210 hp, compressors are used to charge the air storage tanks up to 3500 kPa (500 psi) at a rate of 560 CFM. This high pressure air is first passed through two desiccant dryers then three 600 gallon wet tanks used to filter out any harmful debris or oil and lastly the filtered dry air is stored in the storage tanks. With a combined volume of 114 m^3 (30,000 gallons), the dry air storage tanks provide enough air for numerous runs and/or extended run times without the need to recharge the tanks. Housed in an adjacently located building, the high pressure air from the dry storage tanks is routed underground to the burner room. The redesigned air supply piping has a pipe diameter of 3 inches (nominal) and only one pipe bend within the burner room. The advantage to these modifications is improved flow quality and reduced potential of internal rig noise contributions.

2.2.2 Fuel Storage and Routing System

Much of the fuel system designs and components in the current facility were salvaged from the original facility. Figure 2.2 and Figure 2.3 are originally from Greska’s research [10] and adequately depict the fuel piping systems in the Fuel Room and Burner Room, respectively. The only major change, which was incorporated into Figure 2.2, is the relief valve and piping routed to the scrubber. This is discussed further in the details of the system below.

The burner is a sudden expansion (SUE) burner that was intended to be fueled by propane. Propane has a maximum stagnation temperature of 1100 K, which is insufficient for studying heated jet exhaust relevant to modern military jets. Ethylene, C_2H_4 , proved to be a much better alternative with a stagnation temperature of 1700 K [10]. Eight cylinders are kept in the fuel room and, at full capacity, the cylinders provide fuel at 9650 kPa (1400 psi) to the system. With safety as the number one priority, the fuel system includes numerous valves, both manually and pneumatically operated, as well as a purge system designed into the fuel manifold in the isolated fuel room. During operation, the fuel is routed from the manifold, through the wall into the burner room where it connects to the SUE burner. The cylinders are used until they reach 3450 kPa (500

psi) and are exchanged for fresh cylinders. Because the fuel is at such high pressure in the cylinders, it experiences a large pressure drop throughout the piping system causing the stainless steel pipes to freeze and the fuel to potentially condense into liquid. This can cause issues in combustion as well as safety issues in regards to the structural integrity of the pipes. To address this concern, each cylinder is insulated by 900 W heating blankets and the fuel lines are wrapped in heat tape effectively preventing the fuel from condensing. To ensure the insulation blankets are working, the fuel pressure and temperature is monitored and regulated in the fuel manifold immediately downstream of the cylinders.

The fuel manifold and routing system, as shown in Figure 2.2, is designed to activate and regulate the fuel during heated jet operations. During heated jet operation, the fuel from the cylinders is immediately measured in regards to temperature and pressure and displayed in the control room. Over-pressurization of the fuel cylinders and manifold is a common and very dangerous threat to the safety of facility operators. The addition of the relief valve, previously mentioned, is a practical solution to preventing over-pressurization. In the event of the system reaching dangerously high pressures, the relief valve will activate and vent the fuel through the scrubber where it is processed by means of bioballs and water. This “scrubbing process” is an eco-friendly and safe way to discard fuel. Under normal operation, the fuel passes through a series of check valves before entering the burner room. Both manufactured by Whitey, the first is a manually operated ball valve and the second is a pneumatic fail close ball valve which is operated from the control room. Downstream, the dome regulator is also pneumatically operated from the control room allowing the facility operator to adjust the mass flow rate of the ethylene during ignition and monitoring combustion. The regulated flow is then routed from the fuel room into the burner room through the plumbing system shown in Figure 2.3. The fuel passes through another valve, this one being a solenoid valve and also controlled by the facility operators. Downstream of the valve, the conditions of the fuel are taken one more time with a flow meter, thermocouple, and pressure transducer before going into the main fuel control valve which is pneumatically operated and set previously before the jet is initiated. The fuel then passes through one last check valve, circulates in the circular manifold, or “halo”, and is injected into the SUE burner. During the ignition process, the ignition solenoid is activated in order to route fuel to the spark plug. Upon combustion, the ignitor solenoid is immediately deactivated and the flame is maintained by the constant flow of injected fuel.

Figure 2.2: Ethylene fuel manifold used to activate and monitor fuel flow prior and during heated jet operation [10].

Figure 2.3: Fuel room fuel system component layout [10].

When finished, the facility operators will then begin the shutdown process instated to properly and safely discontinue combustion and effectively purge the system lines of remaining fuel. The first step is to disable the main fuel solenoid and to engage the nitrogen solenoid valve, purging the lines of fuel. Referring to Figure 2.2, the lower pneumatic ball valve is deactivated while the pneumatic ball valve above is simultaneously activated. The nitrogen flow will effectively purge both the fuel room and burner room fuel line system. During the purge process the leftover fuel is

routed to the scrubber. Finally, the dome regulator is closed and the manually controlled Whitey valve is closed. Furthermore, if cylinders need to be changed or the manifold needs to be purged for any reason, the needle valve routes the remnant of fuel through the scrubber as well.

2.3 Burner Room

In the burner room, the high pressure air is controlled by a UniTorq M470DA DLS double-acting solenoid shut-off valve. The full layout of the system is shown in Figure 2.4. Controlled electronically the shut-off valve is designed to remain open in the event of a power failure. Downstream of this valve is a Leslie Aeroflow high performance control valves with a 1.5-inch valve stroke. This control valve is equipped with a Leslie Magnum Series piston actuator and a Siemens SIPART PS2 electro-pneumatic valve positioner. The facility operators control the positioner by means of the LabVIEW program from the control room PC. While the flow is regulated by the control valve setup, a pop-off valve was installed downstream (diverted by a T junction) to ensure that the air pressure does not reach dangerous levels.

Figure 2.4: Schematic of air supply control system.

This new control system is an upgrade from the previous dual air valve control system in the previous system. Operating with only one valve significantly reduces the potential for valve noise, a common source of rig noise, and reduces the variables to be considered when maintaining a desired air mass flow rate. The original dual valve system was intended to have the first valve create a large pressure drop and the second with a small pressure drop in an effort to increase precision. However, the conditions were harder to obtain and were not well maintained during operation. The single, larger valve proved to be the all around better choice by reducing the potential for rig noise and still providing adequate precision during operation.

2.3.1 Sudden Expansion (SUE) Burner

Downstream of the control valves, the supply air is routed to the 3 in.×6 in. SUE pipe burner, where the ethylene fuel is injected. The resulting air-fuel mixture is ignited to attain realistic jet exhaust temperatures. As discussed earlier in the fuel supply subsection, combustion is initiated by means of a spark plug and up to six fuel injection ports oriented azimuthally around the sudden-expansion portion of the burner. This burner and its components are illustrated in the Figure 2.5 schematic, a figure originally produced by Greska [10].

Figure 2.5: Schematic of SUE burner component [10].

The number of fuel injectors used is easily adjusted manually, prior to operation, in order to obtain specific heated jet temperatures. Upon ignition, the combustion is maintained by a stable supply of fuel/air to the flame front. The chosen injector orientation enhances the mixing and

creates a strong, uniform flame ideal for creating a constant temperature jet exhaust. The exhaust temperature is increased simply by increasing the fuel/air ratio and is restricted by the operational limits outlined by Figure 2.6. Originally provided by Kaiswer Marquardt, a combustion research and development company, and discussed in Greska's research [10], the figure illustrates the mass flow rate and pressure limits of the SUE burner for a given temperature. However, the limits of the SUE burner do not adequately account for the limits of the entire rig setup. Taking this into consideration, the actual facility limits are addressed in Chapter 4. Because the burner heats the air up to temperatures of 1700 K, a cooling system was incorporated in the steel walls to protect the integrity of the steel structure.

Figure 2.6: Operational limits of the SUE burner in the facility (provided by Kaiser Marquardt). [10].

The cooling system cycles 40 GPM of water through helical channels designed into the burner walls and creates a water jacket around the components exposed to excessive amounts of heat. These helical passages continue from the SUE burner into the downstream components as illustrated by Greska's diagram [10] in Figure 2.7. After passing through the helical passages, the used water is sent through a chiller (not shown) to bring it back to cold (ambient) temperatures. This cooled water is then sent back to the burner creating a closed loop cooling system. This is a much more conservative approach to the cooling system because the used water is not discarded as it was in the original facility. This superior cooling design is a much more environmentally conscience approach and sufficiently controls the burner temperature.

Figure 2.7: Downstream components of the burner system [10].

Immediately following the burner, and before the water-cooled extension, is the turbulator. The turbulator, made of Nistele 230, is 1.25 in. thick and reduces the flow down to a diameter of 3 in.

This component contains the combustion process within the burner and is intended to only let hot exhaust flow downstream. Because the combustion is not completely contained by the turbulator, the water-cooled extension follows immediately downstream of the turbulator. The long length of the extension compensates for any combustion instabilities. Along with the ceramic honeycomb, this extension straightens the flow and brings the exhaust back to stagnation conditions. Next, the conditions are then acquired in the measurement section by means of two C-type thermocouples and two pressure transducers. Following the measurement section is the extension section. A total length of 24 in., the section passes through the wall of the burner room into the anechoic chamber. The next component is the reducing section, also a total length of 24 in. With an initial inner diameter of 6 in., the reduction section reduces down to 3 in. at the exit of the section. Originally, the design intended to have nozzles with an inlet diameter of 3 in. but, due to manufacturer error, the nozzles have an inlet diameter of 2.7 in. A simple adapter was installed to attach the nozzles. Discussed further in the experimental setup chapter, the current inventory of nozzles consists of multiple converging and converging-diverging nozzles with design Mach numbers up to 2.0 and nozzle exit diameters in excess of 50mm (2in).

2.4 Anechoic Chamber

The jet exhausts into a fully anechoic chamber located adjacent to the burner room and shown below in Figure 2.8. The anechoic chamber is 5 m long, 5.7 m wide, and 4.3 m high, making it large enough for far-field acoustic measurements as well as flow visualization techniques, such as schlieren and shadowgraph. The chamber walls, floor, and ceiling are covered with flame-retardant 24 in. x 12 in. x 8 in. fiberglass wedges designed for a cutoff-frequency of 250 Hz. Designed and manufactured by Eckel the wedges are a custom design based off the original designs proposed by Beranek and Sleeper [3]. Because the floor is also covered in acoustic wedges, the chamber includes a raised steel grating floor to allow facility operators to walk freely without disturbing the floor wedges. With few exceptions, all surfaces are acoustically treated to ensure the anechoic characteristics of the room. The untreated components include the ceiling lighting and surveillance cameras (discussed in the succeeding subsection). Ambient conditions in the chamber are maintained on a completely isolated HVAC system with conditioned air inlet vents in the ceiling and two vertical exhaust stacks located in the upstream corners of the room. As illustrated in the figure, the jet is exhausted from

the chamber via a large acoustically-treated duct and ambient air for proper jet entrainment is provided via a 4 ft. x 4 ft. air inlet window. This HVAC system allows for extensively long runs without significant changes in chamber temperature. Additionally, the chamber requires a short recovery time allowing for multiple heated runs. While time averages have not been calculated, the ambient conditions did not exhibit unsafe levels or interfere with the experiments presented in this manuscript.

Figure 2.8: CAD model of the anechoic chamber including relevant details such as the exhaust nozzle, the anechoic treatment on the walls and floor, and the main exhaust in black.

2.5 Control Room

The entire facility operation and data acquisition is managed from the control room located adjacent to the burner room and anechoic chamber (not shown). Custom LabVIEW control programs

provide the means to regulate airflow and fuel flow and to monitor pertinent conditions in each room of the facility. Also, a 4-camera CCTV video monitoring system in the anechoic chamber and burner room allows visual inspection of each room. This centralization of controls permits easy monitoring and control of facility variables as well as an increased level of safety for facility personnel.

2.5.1 Facility Operation

Though it is not shown in the provided CAD diagram, an image of the operator controls is at the bottom right image of Figure 2.1. Starting with the facility activation and deactivation controls, the white control cabinet houses the switches for the supply air, fuel, heating blankets and wrappings, as well as the access to nitrogen for purging. Furthermore, this panel displays the chamber conditions including the room temperature, the ambient pressure, and ambient humidity. The ambient pressure is measured by a pressure transducer attached to an acoustic panel wedge and located immediately below the burner reducing section. The humidity sensor is attached to an acoustic wedge behind the microphone arc. While the microphone arc is described in the experimental setup section, it is worth noting that the humidity sensor is placed near the microphones to accurately incorporate the effects of humidity in the acoustic data. A total of eight thermocouples are dispersed in key locations throughout the anechoic chamber. The control panel cycles through each thermocouple displaying the given thermocouple reading. This ensures that the room is being adequately ventilated and maintains reasonable ambient conditions. Similarly, eight thermocouples are attached to the fuel tanks in the fuel room and are also cycled through and displayed one after the other.

Once the facility is activated by the control panel, the air and fuel flow rates are controlled by the custom LabVIEW control program, shown in Figure 2.9. On the program, the facility operator can control both the air and fuel flow by monitoring the percentages the respective control valves are open with 0% being closed and 100% being fully open. The program also displays the fuel temperature and pressure at multiple points and the air conditions as well. This ensures that the fuel lines are not getting too cold and condensing and that the supply air isn't reaching unsafe pressures. During the ignition process, the sequence is conducted by the virtual switches labeled "Nitrogen, Spark Plug, Ignition Fuel, and Main Fuel." The extinguishing and purging process is similar in that it utilizes the virtual switches in addition to the control cabinet controls. Throughout

the operation process the cooling water temperature is measured at multiple points to make sure that the water is effectively cooling the burner and not exceeding safe conditions. Furthermore, the jet conditions and ambient conditions are displayed so the jet operator knows the characteristics of the existing jet.

Figure 2.9: Labview Control Program.

This single PC operation is a significant advantage compared to the previous facility that required two PCs to operate both the air supply system and the burner. Using a single PC, only one facility operator is required to operate the jet conditions while the other monitors the safety of operation and assists in start up and shut down. Also, the second facility operator monitors the facility conditions as well as the facility video surveillance.

CHAPTER 3

EXPERIMENTAL SETUP

A number of references provide valuable information on the best practices in the design of jet noise facilities and the execution of jet noise experiments including Bridges and Brown [5], Ahuja [1], and Viswanathan [30]. There are several challenges associated with obtaining quality experimental data. Contaminating sources in jet noise measurements are commonly internal components, such as valves and combustors, and nearby reflective surfaces that affect the measured acoustics. Additionally, flow field properties can be contaminated by machining imperfections in the nozzle, inappropriate flow conditioning, or improper entrainment within the ambient environment. The characterization methodology employed by the current authors has been developed based on the experience and suggestions of the aforementioned references and other internal resources. Through execution of a substantial test matrix spanning a wide-range of flow conditions, an attempt has been made to validate the acoustic characteristics of jets generated in the facility and to shed light on facility operational limitations and potential rig noise sources. Because an extensive experimental database exists for this facility as it was formerly designed, comparison to the acoustic results of Greska [10] and the references therein have served as the primary means for jet acoustics validation. Greska's work features comparative results to multiple alternative jet noise rigs and theoretical jet noise models, thus providing a solid foundation to assess the new facility's acoustic performance. The authors acknowledge that this is by no means an end-all, be-all approach to validation due to the sensitivity of noise results to seemingly minute differences between jet facilities, but comparison to well-established historical data is a sensible step in the process.

3.1 Characterization of an Anechoic Chamber

The anechoic chamber was acoustically characterized by testing and documenting the frequency range at which the room could be considered anechoic. This process was conducted in accordance with the ISO (3745:2003) standard, which provides guidelines to determine the quality of the anechoic chamber by means of a radiating sound source and a microphone. The Inverse square

law is used to determine the theoretical roll-off of the sound pressure level (SPL) with increasing distance from the source. Utilizing a speaker placed in the center of the room, the sound source was triggered by a function generator to emit broadband noise with an acoustic frequency range of 200 Hz - 20 kHz. A lower limit of 200 Hz was chosen because the acoustic treatment installed is designed to have a frequency cutoff of 250 Hz. The highest frequency the speaker could reliably produce was 20 kHz, which is well beyond what is necessary for qualification. As defined by the standard, a single microphone was traversed in principal directions around the room to measure the SPL. In addition to the required directions, two more directions were chosen relevant to where jet noise measurements are typically made in aeroacoustic research.

Figure 3.1: Detailed CAD model of the anechoic chamber with the five required traverse directions.

The standard required the microphone to be traversed to the four upper corners of the room, and one additional direction as designated by the experimentalist. Figure 3.1 shows the four directions as well as the additional chosen vertical direction. Described by the key, each direction is designated by its traverse direction relative to the jet exit. For the traverse directed to the downstream corner to the right of the jet, the designation is DR. Furthermore, UR is for the traverse directed upstream and to the right, DL and UL for the directions downstream and upstream on the left side of the jet,

and UP for the vertical traverse. In addition to the required five directions, two more traverse paths were chosen based by their relevance to the microphone placements for jet acoustic measurements and are shown in Figure 3.2. In aeroacoustic experiments, microphone measurements are typically made at jet center line height and at a variable distance away from the jet exit. To characterize the anechoic properties for such measurements, the sound source was raised to jet centerline height and the microphone was traversed perpendicular to the right (HR) and to the left (HL) of the jet axis while maintaining the centerline height throughout. For each of the seven directions described, the first measurement was made at 0.5 m away from the noise source and in increments of 0.178 m thereafter until a wall or corner of the facility was reached. The specific starting point and separation distance between measurement points were outlined in the standard.

Figure 3.2: Top view of the chamber CAD model showing the two additional directions.

The SPL measurements were analyzed in third-octave frequency bands and compared to the SPL values predicted using the inverse square law. According to this law, the intensity of the SPL should drop proportionally with distance as the microphone travels away from the sound source towards the wall or the ceiling. Equation 3.1, from the ISO Standard [13], uses linear least square fit regression line to verify if the measured SPL levels do or do not demonstrate this trend.

$$L_p(r) = 20 \log \left(\frac{a}{r - r_0} \right) \text{ dB} \quad (3.1)$$

Variable r is the radius at the measurement location, a is the line regression variable, and r_0 is the collinear offset between the sound source acoustic center and the center of the measurement sphere. Since the acoustic source was centered in the chamber, it was assumed that the r_0 component is negligible. Furthermore, the linear regression variable is shown below

$$a = \frac{\left(\sum_{i=1}^N r_i \right)^2 - N \left(\sum_{i=1}^N r_i^2 \right)}{\sum_{i=1}^N r_i \sum_{i=1}^N q_i - N \sum_{i=1}^N r_i q_i} \quad (3.2)$$

where,

$$q_i = 10^{-0.05 L_{pi}} \quad (3.3)$$

Used to calculate the line regression variable a , q_i represents the acoustic pressure ratio between the reference sound pressure of air (20 μPa) and the measured sound pressure, L_{pi} is the SPL measurement at the given i th position, r_i is the radius at a that same (i th) position, and N is the total number of measurement positions for a given direction. Lastly, the error limits are specific to a respective 3rd octave center frequency and to be applied for each measured point; they are ± 1.5 dB for 630 Hz and below, ± 1.0 dB for 800 Hz to 5 kHz, and again ± 1.5 dB for frequencies thereafter.

3.2 Jet Acoustics Characterization

As mentioned previously, the extensive dataset provided by Greska [10] documents the acoustic characteristics of this facility as it was formerly designed. Therefore, the elaborate test matrix of those studies was replicated and extended here to validate the acoustic characteristics of the new facility. This test matrix is summarized in Table 3.2. A series of nozzles with design Mach numbers ranging from 1.0 to 2.0 were tested at various ideally-expanded and off-design conditions. The relevant parameters for the six axisymmetric nozzles, consisting of two converging nozzles and four converging-diverging nozzles, are listed in Table 3.1. All of these nozzles are made of Nistele 230, a nickel-based alloy capable of withstanding the elevated temperatures without significant thermal expansion.

Table 3.1: Relevant Nozzle Parameters

Nozzle	Nozzle Type	Design Mach #	Throat Diameter (mm)	Exit Diameter (mm)
NoN	Converging	—	N/A	68.6
CN-1in	Converging	—	N/A	25.4
CN-2in	Converging	—	N/A	50.8
CD-1.3	Converging-Diverging	1.3	33.1	34.3
CD-1.5	Converging-Diverging	1.5	33.1	36.2
CD-1.8	Converging-Diverging	1.8	33.1	40
CD-2.0	Converging-Diverging	2	33.1	43.9

Table 3.2: Test Conditions

Nozzle	Expansion Condition	Stagnation Temperature (K)	Jet Mach Number
NoN	N/A	289	0.08-0.14
CN-1in	N/A	289	0.5-0.95
CN-1in	N/A	289, 589, 811, 1313	0.5-0.95
CD-1.3	Ideal	289, 589, 811, 978, 1089, 1200, 1311	1.3
	Off-Design	289, 978	1.4-1.8
		1200	1.5
CD-1.5	Ideal	289, 600, 811, 978, 1089, 1200, 1311	1.5
	Off-Design	289, 600, 811, 978	1.2-1.9
CD-1.8	Ideal	289, 589, 811, 1089, 1200, 1311	1.8
	Off-Design	289	1.2-2.1
		811	1.2-1.9
		1200	1.5
CD-2.0	Ideal	289, 589, 811, 984, 1089, 1200, 1311	2
	Off-Design	289	1.2-2.1

The two converging nozzles were used in a preliminary investigation of potential rig noise sources, where the converging profiles of these nozzles were designed using a fifth-order polynomial. In addition to the converging nozzles, a few rig noise tests were conducted without a nozzle and are

labeled as NoN for “No Nozzle.” For the NoN tests, the exit diameter of the burner system adapter acts as the jet exit diameter. Even though it does not maintain the same converging profile, the adapter serves as a larger converging nozzle. Similar to the CN-1in and CN-2in converging nozzles, the converging-diverging (CD) nozzles also used a fifth-order polynomial to calculate the converging profile section. However, the diverging profile was designed using the Method of Characteristics. All of the CD nozzles have a throat diameter of 33.1 mm, and the exit diameter of each nozzle is dependent upon the area ratio required for ideal expansion at the design Mach number. It should be noted that the design Mach numbers of the nozzles are nominal values since the area ratio for ideal expansion varies slightly with temperature due to the change in specific heat ratio of air.

3.3 Measurement Techniques, Instrumentation, and Processing

Far-field acoustic measurements were performed using an array of microphones mounted on a circular arc at a radius of 102 inches, centered at the nozzle exit. The arc consisted of 8 microphones placed at every 10° increment between 80° and 150° as measured from the jet inlet axis (pilot forward). All of the microphones used in these experiments were B&K 4939 free-field condenser microphones equipped with model 2670 preamplifiers and powered by B&K model 2690 Nexus signal conditioning amplifiers. The filter on each Nexus was set to bandpass frequencies between 20 Hz and 100 kHz and the signals were additionally low-pass filtered at 50 kHz through Stanford Research Systems SR-640 filters. All data were acquired using a National InstrumentsTM PXI-6133 14-bit 16-channel simultaneously sampling system at a sampling frequency of 150 kHz for four seconds. Each microphone was calibrated in-situ prior to each run using a Brüel and Kjær Model 4220 pistonphone. MATLAB processing codes were used to calculate the statistics for the digitized raw data and to apply the necessary corrections. To calculate the frequency spectra, each time-domain signal was split into segments of 4096 points and a Hanning window was applied with 50% overlap, resulting in a frequency resolution of around 37 Hz. The frequency-domain signals were then converted to dB per unit frequency using a reference pressure of $20 \mu\text{Pa}$ and corrected using the manufacturer provided frequency response for normal incidence. Finally, the spectra were non-dimensionalized to dB per unit Strouhal frequency based on the characteristic frequency of the jet, $f_c = U_j d$, via Equation 3.4 such that the overall power in the signal was conserved. The OASPL were calculated by integrating each spectrum according to Equation 3.5.

$$PSD(St) = PSD(f) + 10\log_{10} \frac{U_j}{d} \quad (3.4)$$

$$OASPL = 10\log_{10} \left(\Delta \sum 10^{\frac{PSD(St)}{10}} \right) \quad (3.5)$$

As previously mentioned, the stagnation conditions of the jet were measured in the test section just upstream of the nozzle. The stagnation pressure of the jet was measured using a pair of Omega steady pressure transducers (PX01C1-300AI) and the stagnation temperature was measured using two C-type thermocouples. The ambient conditions, such as pressure, temperature, and relative humidity were monitored and recorded using several sensors strategically positioned at various locations in the anechoic chamber. The ambient pressure was measured near the nozzle exit using an Omega Dyne steady pressure transducer (PX02K1-16AI). The ambient temperature and humidity conditions in the chamber were measured near the 90° microphone location using a K-type thermocouple and a relative humidity transmitter (HX92BC), respectively.

3.4 Error and Uncertainty

While there was a limited amount of error from the instrumentation, the most significant source of error had to do with maintaining appropriate jet flow conditions. Addressing the instrumentation first, the OASPL uncertainty in the microphones is ± 0.5 dB, the thermocouples were within ± 2.2 K, and the pressure transducers were within ± 3.1 kPa. In reference to the facility operation error, the NPR fluctuated as much as ± 0.02 from desired value and the stagnation temperatures uncertainty was within ± 25 K from the desired value. Both the NPR and temperature of the jet are controlled by the facility operator. Regarding the jet validation experiments discussed in Chapter 4, measurements were taken three times for each desired set of jet conditions. Of the three acquisitions, the most accurate case, in respect to the desired conditions, was used for analysis.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Anechoic Chamber Characterization

Following standard practice outlined in Section 3.1, the acoustic measurements for chamber characterization was analyzed using 3^{rd} octave bands to accurately determine the cutoff frequency at which the chamber could still be considered anechoic. Figure 4.1 shows representative results for the vertical traverse direction as the microphone was traversed directly above the source towards the ceiling. Each plot shows the SPL measured (y-axis) at a given distance from the source (x-axis) for a specified 3^{rd} octave band. For discussion purposes, only a few frequency bands were selected and the rest of data can be found in Appendix A. The theoretical far-field roll off calculated using inverse square law is depicted by the dotted blue line and the dotted red lines indicate the allowable tolerance within ± 1.5 decibels, as discussed in Section 3.1. The lower center frequency of 250 Hz was chosen for analysis as this is the design limit of the anechoic wedges used. The plot for the center frequency of 250 Hz clearly shows that the measured SPL stays within the error bounds up until the microphone traverses a total distance of roughly two meters. This contamination is suspected to be from the air ducts and the chamber lights on the ceiling due to their highly reflective sheet metal and glass surfaces. Acoustically treating these surfaces would result in covering the lights and HVAC intakes and are therefore left untreated. Reviewing the next consecutive frequency band, the measured SPL appears to fall at or within the limits of the theoretical bounds for 315 Hz. The anechoic treatment becomes increasingly effective at higher frequencies because it is relatively easier to dampen high frequency sound waves. This is clearly shown by the data conforming to the theoretical (free field) roll off in the 400 Hz and 500 Hz bins. Following this trend, the rest of the data up to 20 kHz follows the slope of the inverse square law with no noticeable high frequency reflections. The data collected from the other directions were very similar in nature to the results of the vertically traversed case presented in Figure 4.1. For all directions, the measured SPL followed the theoretical roll-off within the error bounds for each frequency.

Figure 4.1: Representative measured sound pressure level roll-off of the vertical direction (UP) compared to theoretical roll-off as calculated by the ISO standard. Blue dashed lines signify theoretical roll-off and red dashed lines represent the allowable tolerances.

Figure 4.2: Measured sound pressure level roll-off compared to theoretical roll-off for low frequency results (250 Hz to 500 Hz) to assess discrepancies. These two data sets are traversed downstream of the jet exit. a) DR traverse to the right, b) DL traverse to the left.

Similar to what was seen for the vertical direction, the only significant deviations existed at the lower frequency bands and mitigated at the mid and higher frequencies. While the rest of the directions were tested in the same manner, Figure 4.2 through Figure 4.3 show only the low frequency bins to access the frequency cutoff of the chamber. Appendix A shows the 3rd octave analysis in detail for each traverse direction. Starting with the downstream traverse directions, the data for the microphone measurements made downstream to the right of the jet exit (DR) and downstream to the left (DL) are shown in Figure 4.2a and Figure 4.2b. The direction details are discussed in Section 3.1. As previously mentioned the results compare very well to the vertically traversed microphone data points. While significant deviations exist at 250 Hz for each downstream direction, they fall back on, or within, the error bounds at 315 Hz and become negligible thereafter. Moreover, for the DR direction, a slight hump is observed for the 315 Hz band roughly 2 meters from the source. While this hump is not significant at DL, similar deviation from the theoretical roll off is shown by the UP direction.

Figure 4.3: Measured sound pressure level roll-off comparison of low frequency results (250 Hz to 500 Hz). Each figure represents a traverse direction to the right of the jet exit. a) UR traverse to the right, b) UL traverse to the left.

Looking at the other two corner directions required by the standard, Figure 4.3a and Figure 4.3b present the SPL roll-off for the upstream directions. UR designates the microphone traversed upstream to the right of the jet exit while UL designates upstream to the left. As expected,

the cutoff frequency is again 315 Hz for these directions with slight humps existing around 2 meters. While all five directions are traversed to the ceiling at different angles, four out of five show the same slight hump at 2 meters between 250-315 Hz and small disturbances at 400 Hz. The deviations become more and more insignificant with increasing frequency, suggesting that the observed reflections are from the ceiling components.

Figure 4.4: Measured sound pressure level roll-off comparison of low frequency results (250 Hz to 500 Hz). Each figure represents a traverse direction to the right of the jet exit. a) HR traverse to the right, b) HL traverse to the left.

Mentioned in the previous chapter, the two additional directions chosen were the horizontal direction with the microphone traversed to the right hand wall (HR), and the horizontal direction traversed to the left (HL) and are shown below in Figure 4.4a and Figure 4.4b respectively. While the data was collected and processed in the same manner as the other directions, it should be noted that the distance from the source center to each wall is significantly shorter in comparison. Although both directions are anechoic at 315 Hz and remain so at the higher frequencies, the HR direction (Figure 4.4a) actually shows a cutoff frequency of 250 Hz while the HL direction (Figure 4.4b) maintains the expected 315 Hz cutoff. The observed acoustic differences between HR and HL is likely due to the variation in wall layout. Each wall has unique HVAC components, sensor equipment, and different acoustic treatments used to cover them. All details considered, the nature of the discrepancies are similar to those shown by the rest of the tested directions with

humps occurring just after 2 meters. The deviations in the horizontal directions are not as broad or significant and are likely due to the HVAC and sensor components.

From the presented results it is clear that the largest deviations were observed at 250 Hz when the microphone was in close proximity to the chamber ceiling or the walls. Considering the cutoff frequency of the wedges (250 Hz) and the presence of unavoidable reflecting surfaces close to the ceilings and walls, these errors were anticipated a priori. After analyzing the results for all the pertinent directions, it is reasonable to conclude that the chamber has a lower cut-off frequency of 315 Hz and has been verified to be anechoic up to 20 kHz. This range of frequencies is sufficient for accurately studying jet aeroacoustics. Furthermore, the additional directions tested verify that the anechoic characteristics of the chosen microphone locations for the jet validation experiments are consistent with the ISO standard results.

4.2 Jet Acoustics Validation

The four CD nozzles listed in Table 3.1 were used to produce jets at various Mach numbers and temperatures, summarized in Table 3.2, allowing noise measurements for both ideally expanded as well as shock containing jets. The process of acoustic validation involved comparing the acquired far-field results to the well-established jet noise metrics published in the literature. This section starts with the presentation of the jet directivity and select spectra for ideally expanded supersonic jets at various jet conditions. Following this, representative results for jets operated at off-design (over- and under-expanded) conditions are presented. Finally, these results are compared to the noise data in the literature and the observed discrepancies, if any, are addressed.

Figure 4.5 through 4.8 present far-field OASPL directionality for the ideally expanded jets produced by four CD nozzles at various stagnation temperatures. The OASPL measurements presented below reveal trends that are typical of high speed turbulent jets and show key components of turbulent mixing noise described by Tam et al. [27]. The upstream or sideline angles (80-110 degrees) exhibit comparatively low levels of radiated noise, followed by a gradual increase in noise intensity in the downstream direction. These angles are argued to be dominated by the omnidirectional noise due to small scale turbulence in the jet. Furthermore, the noise levels at lower polar angles (80-110 degrees) are observed to increase with jet Mach number as well as temperature ratio; however, for higher stagnation temperatures ($T_o > 811$ K) the increase in noise level with

temperature is not as significant. The downstream polar angles exhibit significantly higher OASPL values and the noise levels peak between 120° to 150° depending on the jet temperature. It is generally accepted that the dominant component of turbulent mixing noise is radiated by large scale coherent structures in the jet. This highly directional noise typically governs the aft angle directivity where the peak noise radiation direction shifts upstream with increasing jet temperature [24],[33]. Figure 4.5 through Figure 4.8 exhibit similar behavior where all the ideally expanded cases clearly demonstrate a peak shift towards upstream polar angles with increased stagnation temperature. Moreover, the OASPL distributions show a relatively rapid increase in noise levels with jet temperature for cold and mildly heated jets, whereas small increase in OASPL is noted for higher jet temperatures. These observations made in the current study are in agreement with the trends discussed by Tam et al. [27], [26], [25], Seiner et al. [24] and others.

Next, we look at narrow band acoustic spectra at select polar angles to examine the contribution of different frequency ranges in the overall sound radiation. Figures 4.9a through 4.9d present narrowband acoustic spectra for the ideally expanded Mach 1.5 and 2.0 jets at cold (280 K) and heated (1311 K) conditions. The acoustic spectra for the lower polar angles appear flat over a broad range of frequencies. This behavior is typical of the noise radiated in the sideline and upstream directions. For the downstream angles, highly directional noise due to large scale coherent structures dominates the acoustic spectra. These structures are known to be primarily responsible for radiation at lower frequencies, where the spectra corresponding to the downstream angles typically contain a broad peak approximately at $St \approx 0.1 - 0.25$ [25]. Moreover, this peak shifts to lower frequencies with increasing downstream angle, as also clearly exhibited by spectral plots in Figure 4.11 and Figure 4.13. For the cold Mach 1.5 jet, the peak frequency for the peak noise radiation direction (150°) is observed to occur at $St \approx 0.18$. It is evident that the elevated temperature shows a more pronounced shift in peak frequency with increasing observation angle. In addition to the elevated noise levels, the peak noise radiation angle for the heated Mach 1.5 jet exhibits a prominent low frequency peak at $St \approx 0.12$. Acoustic spectra for the Mach 2 jets show similar trends compared to the Mach 1.5 jet with overall higher noise levels. It is evident that the elevated temperature shows a more pronounced shift in peak frequency with increasing observation angle. These results show good agreement with the results of Seiner et al.[24] for a Mach 2 jet at high temperatures.

Figure 4.5: OASPL directionality for the ideally-expanded CD-1.3 nozzle at various temperatures and normalized to a distance of 100d.

Figure 4.6: OASPL directionality for the ideally-expanded CD-1.5 nozzle at various temperatures and normalized to a distance of 100d.

Figure 4.7: OASPL directionality for the ideally-expanded CD-1.8 nozzle at various temperatures and normalized to a distance of 100d.

Figure 4.8: OASPL directionality for the ideally-expanded CD-2.0 nozzle at various temperatures and normalized to a distance of 100d.

Figure 4.9: Representative acoustic spectra for ideally-expanded jets generated for the CD-1.5 nozzle and CD-2.0 nozzle. a) Mach 1.5 at 280 K, b) Mach 1.5 at 1311 K. c) Mach 2.0 at 280 K, d) Mach 2.0 at 1311 K. The spectra for peak radiation direction is shown in red.

In addition to validating the jet at ideal conditions, acoustic measurements were also carried out to investigate the jet performance at off-design (under- and over-expanded) conditions. Imperfectly expanded jets are characterized by the presence of shock cell structures in the jet plume. Turbulent structures in the jet shear layer interact with these shock cells producing two additional noise components, screech and broadband shock associated noise (BBSN). Screech is identified as a tone occurring in the acoustic spectra at discrete frequencies, whereas BBSN usually appears as a broadband hump with well-defined peak frequency [28],[31]. The four CD nozzles listed in Table 3.1 were used to generate imperfectly expanded jets at the various Mach numbers and temperatures listed in Table 3.2. To facilitate comparison, these flow and temperature conditions were chosen to match with the conditions presented in Table 4.1 and Table 4.4 in Greska’s work [10].

Figure 4.10 shows representative cold (280 K) OASPL directionality for a $M_j = 1.5$ jet at over- and under-expanded conditions compared to the corresponding ideally-expanded jet and scaled to 100d. In this figure, the ideally-expanded jet was generated through the CD-1.5 nozzle, and the under- and over-expanded jets were generated through the CD-1.3 and CD-1.8 nozzles, respectively. By directly comparing the imperfectly expanded conditions to the ideally expanded jet, the shock associated noise contributions can be identified. OASPL distribution for the cold case shows that the sideline noise levels for the under- and over-expanded jets are significantly higher compared to the ideally expanded case. These imperfectly expanded jets exhibit comparatively elevated noise levels for all polar angles up to 130° . For further downstream angles, including the peak radiation direction, the OASPL levels approach the ideally expanded values. This is consistent with the idea that the effect of screech and BBSN are more prominent at sideline angles, whereas the downstream angles are mostly dominated by turbulent mixing noise due to large scale structures [25].

Figure 4.11 shows the corresponding narrowband acoustic spectra for the sideline (90°) and the respective peak radiation angles for the cases shown in Figure 4.10. These angles are chosen to demonstrate the acoustic behavior of shock containing jets at the two extremes of the directivity curve. In addition to the overall elevated noise levels, the imperfectly expanded jets at 280 K show significant peaks resulting from screech and BBSN. On the other hand, the effect of shock associated noise is not as prominent for downstream polar angles, where the spectra for 150° are only minimally affected by the presence of shocks.

Figure 4.10: OASPL directionality for imperfectly and ideally expanded jets (280 K). The ideally-expanded jet was generated through the CD-1.5 nozzle, and the under- and over-expanded jets through the CD-1.3 and CD-1.8 nozzles, respectively.

Figure 4.11: Narrow band spectra of the $M_j = 1.5$ jets at 280 K comparing ideal and off-design conditions at sideline and peak radiation angles.

As opposed to the cold case, the effect of screech and BBSN is significantly less for elevated jet temperatures. Shown in Figure 4.12 is the heated case data, also scaled to 100d just as was done for the ambient temperature jets. In this figure, the OASPL distribution exhibits only slightly elevated levels for the under- and over-expanded cases at lower polar angles. Naturally, the sideline angle shows a little more deviation compared to the downstream angles, but the magnitude of the discrepancy is far less than the cold cases. This is also evident in the acoustic spectra (Figure 4.13), where screech is not present and the effect of BBSN is very small for the 90° angle. This is consistent with the observations in the literature where the changes in shock cell structures, and hence the increase in shock associated noise, is not as significant at higher temperatures [10], [31].

Figure 4.12: OASPL directionality plot for imperfectly and ideally expanded jets (1200 K). The ideally-expanded jet was generated through the CD-1.5 nozzle, and the under- and over-expanded jets through the CD-1.3 and CD-1.8 nozzles, respectively.

Following the investigation of jet characteristics for each nozzle at various Mach numbers and temperature conditions, a direct comparison of the acquired measurements was made to the data obtained by Greska in the old facility. Figure 4.14 summarizes the effects of shock-associated noise for various off-design jet conditions and temperatures for three of the nozzles: CD-1.3, CD-1.5, and CD-1.8. The differences in OASPL values between the off-design and ideal cases, Δ OASPL, are

presented as a function of P_e/P_a , where P_e and P_a correspond to the jet exit and ambient pressure conditions, respectively. The heated case presented for the CD-1.3 nozzle was run at 978 K. For CD-1.5 and CD-1.8 nozzles, the heated cases presented are for a stagnation temperature of 811 K. These directivity measurements overlaid on Greska's findings (shown as open symbols) not only demonstrate the contribution of shock associated noise to the OASPL but also directly compare and validate the performance of the current facility against the old one.

Figure 4.13: Narrow band spectra of the $M_j = 1.5$ jets at 1200 K comparing ideal and off-design conditions at sideline and peak radiation angles.

The plot clearly shows that the effect of shock noise is more prominent in cold jets. The most notable example is the substantial increase in OASPL for under-expanded cold jets compared to their heated counterparts. Moreover, the presence of screech tones in the spectra of Mach 1.3 and 1.5 under-expanded cases have resulted in their higher OASPL values compared to Mach 1.8 jet. For the heated cases, the under-expanded conditions of different nozzles collapse together further supporting the idea that for a large increase in jet temperature the effect of shock associated noise does not change significantly. With a few exceptions owing to the differences in operating conditions, the current data matches Greska's results within 1 dB validating the performance of the current facility for off-design jet conditions.

Figure 4.14: Comparison between current and Greska's data. Difference in OASPL for imperfect expansion of CD-1.3, CD-1.5, and CD-1.8 nozzles at various temperatures.

Figure 4.15: Current Mach 2 OASPL data compared to Greska's data for multiple temperatures.

For the ideally expanded conditions, Figure 4.15 compares current directivity data for the CD-2.0 nozzle with Greska's measurements for various stagnation temperatures. It is apparent that

the largest discrepancy is observed for the cold case where the current OASPL levels are slightly higher for all observation angles. This is possibly due to slight differences in jet temperatures and a higher sensitivity of cold jets to changes in temperature, also discussed in the context of Figure 4.5 through 4.8. On the other hand, the OASPL values for the heated jets show overall excellent agreement with Greska's results for all jet temperatures. There are no significant deviations from Greska's values due to slight changes in jet temperatures demonstrating the weak temperature dependence. For a more direct comparison of the data presented in Figure 4.15, representative third octave spectra for 90° and the corresponding peak radiation angles for cold and heated cases are presented in Figure 4.16 and Figure 4.17. Again, all the data have been scaled to 100d.

Figure 4.16: Third octave spectra comparison for ideally expanded Mach 2.0 jet at 290 K. The data is presented for the 90° and 150° orientations.

As expected, the current SPL data for the cold case exhibits slightly higher levels compared to Greska for nearly all Strouhal numbers at both 90° and 150° (see Figure 4.16). Figure 4.17, on the other hand, shows very good agreement for the heated case at both sideline as well as peak radiation direction (130°). All the results discussed in this section clearly demonstrate that the current acoustic measurements show overall good agreement with the spectral and directivity trends observed in the literature.

Figure 4.17: Third octave spectra comparison for ideally expanded Mach 2.0 jet at 1313 K. The data is presented for the 90° and 150° orientations.

4.3 Rig Noise and Facility Operational Limits

Extraneous noise generated by mechanical components within a facility’s piping system or ambient environment, termed rig noise, is inherent in all small-scale jet facilities. Air flow through valves, pipe bends, flow conditioners, and other in-line components, as well as exhaust duct fans and ambient air inlets, all have an acoustic contribution to the measured noise. For heated flow facilities like the current facility, additional rig noise can be generated by the combustion process and fuel injection components. Ideally, the acoustic contribution of all rig noise sources would be known and modeled over all possible flow conditions, such that the noise could either be mitigated or appropriately removed from acquired jet noise data. Bridges and Brown [5] discuss a method of insertion loss, where certain components are sequentially removed from the rig, as a means of characterizing the noise of each component. Unfortunately, due to the complexities of the piping system, the primary components of the facility have not been characterized in such a way. Rather, the rig noise generated by all in-line components is essentially lumped together, and semi-independent components, such as the exhaust duct and the combustor, are of course easily distinguishable. This section serves to briefly demonstrate some components of rig noise that have

been documented in the facility and to provide some insight as to limitations on the flow conditions for which accurate jet noise measurements can be obtained.

4.3.1 Cold Jet Rig Noise Analysis

Although this facility has not been specifically designed for subsonic jet noise studies, an elementary procedure for determining the significance of total rig noise contribution relative to the jet noise is to verify that the OASPL follows the generally-recognized U^8 scaling law for subsonic jets first discussed by Lighthill[17]. Representative results for ambient temperature jets operated from Mach 0.5 to 0.95, and generated through the two converging nozzles specified in Table 3.1, are shown in Figure 4.18 and Figure 4.19 for the $\theta = 90^\circ$ and $\theta = 150^\circ$ microphones.

Figure 4.18: OASPL and U^8 scaling law for CN-1 and CN-2 nozzles at various subsonic speeds and at 90° orientation.

At the 150° microphone, the OASPL scales perfectly with jet velocity down to $M_j=0.6$ for the 1-inch nozzle and down to $M_j=0.7$ for the 2-inch nozzle, below which the effects of rig noise cause deviation from the ideal roll-off. Since the dominant jet noise components propagate primarily in the downstream direction, the effect of rig noise is much more noticeable in the $\theta = 90^\circ$ direction. Here, the 2-inch nozzle shows significant deviation from the ideal line, but the 1-inch nozzle adequately rolls off for higher subsonic Mach numbers.

Figure 4.19: OASPL and U_8 scaling law for CN-1in and CN-2in nozzles at various subsonic speeds and at 150° orientation.

Figure 4.20: SPL spectra for the CN-1in nozzle at perspective angle of 90° . The subsonic jet Mach number starts at $M_j = 0.5$ (red line), increases by 0.05 for each consecutive color, and ends with $M_j = 0.95$.

Figure 4.21: SPL spectra for the CN-2in nozzle at perspective angle of 90° for converging nozzles at various subsonic speeds. M_j starts at $M_j = 0.5$ (red line) and increases by 0.05 for each consecutive color up to $M_j = 0.95$.

Through analysis of the corresponding spectra in Figure 4.20 and Figure 4.21 (only $\theta = 90^\circ$ is shown), specific components of rig noise can be identified. The rig noise is observed to feature both broadband and discrete content. In Figure 4.20, distinct double peaks can be seen near 1.15 kHz and 1.25 kHz at the lower mass flow rates through the 1-inch nozzle (ranging from 100 to 200 g/s). It seems that this noise is most prominent at low mass flow rates and begins to saturate at higher mass flow rates for the 1-inch nozzle, although its influence is still observed in the spectra due to the inherently low sound pressure levels generated by the jet. The double peaks are also seen at low Mach numbers for the 2-inch nozzle (Figure 4.21), signifying the noise may also be slightly dependent on the nozzle back pressure. Discrete noise near 1.8 kHz and 2.4 kHz behaves similarly. Two distinguishable broadband contributions are observed as well. Low frequency broadband spanning the 600 Hz to 800 Hz range is apparent at only the lowest flow rate through the 1-inch nozzle and seems to disappear or negligibly affect the data at all higher flow rates. Much more prominent is the broadband noise centered about 4.2 kHz and spanning the range 3-6 kHz for lower Mach numbers, especially in the 2-inch nozzle (Figure 4.21). As the Mach number is increased, the noise produced by the jet causes this rig noise to gradually influence a narrower span of frequencies,

but the noise still significantly alters the acquired jet noise data at nearly all Mach numbers for the 2-inch nozzle. This explains the considerable deviation from the U^8 scaling law.

4.3.2 Heated Jet Rig Noise Analysis

Following the ambient temperature cases, the converging nozzles were operated at various temperatures with the intent to demonstrate facility capabilities with subsonic flows (Table 4.1) and investigate additional rig noise due to combustion. Operating the CN-1in nozzle, various jet conditions were attempted but could not be maintained below $M_j = 0.9$ and $T_0 = 950$ K. The CN-1in nozzle has the smallest nozzle diameter and therefore operates at a much lower mass flow rate compared to the others. Moreover, the fuel flow rate was minimized but still maintained a high-temperature flow. This facility cannot practically operate subsonic high-temperature jets with this nozzle as it is not designed for such low fuel and air flow rates. However, the CN-2in provided much better results operating at various flow speeds with a large temperature range. As shown in Table 4.1, the facility can operate heated subsonic jets with a Mach number range of $M_j = 0.5$ -0.9 and temperatures of 589 K to 1313 K. Outside this range of jet conditions, the flow either cannot maintain combustion for lower airflow rates or the required fuel flow rates become too high for safe operation at high airflow rates. However, the facility can operate safely within the given condition range. In addition to testing the facility limits, further investigation was conducted in order to assess the quality of the subsonic jet characteristics.

Table 4.1: Mach number and temperature limits of the CN-1in and CN-2in nozzles.

Nozzle	Jet Mach Number	Stagnation Temperature (K)
CN-1in	—	—
	0.9	950
CN-2in	0.9	589 - 1313
	0.5	589 - 1313

Figure 4.22: OASPL and U_8 scaling law for the CN-2in nozzle at various temperatures and subsonic speeds and an orientation of 90° .

Figure 4.23: OASPL and U_8 scaling law for the CN-2in nozzle at various temperatures and subsonic speeds and an orientation of 150° .

For high-temperature subsonic jet operation, the flow is expected to continue to follow the U^8 scaling law as explained by Tam [32]. However, the combustion process is a very common source of rig noise and could greatly impact acoustic measurements. Figure 4.22 and Figure 4.23 show how the CN-2in nozzle cases compare to the proposed scaling law at sideline and downstream angles. Two different temperatures are plotted at the sideline and downstream angles; 811 K and the 289 K cases previously discussed. Starting with Figure 4.22, the heated Mach number cases shows a significant amount of rig noise at the sideline. However, they are not as affected by rig noise as shown by the slightly better agreement with the U^8 slope. At the downstream angle (Figure 4.23), the plot line of the high-temperature jets is much less affected by rig noise compared to the ambient plot line. Despite the falling off at $M_j=0.7$ for the ambient jets, the heated jets show little discrepancy compared to the scaling law at each subsonic speed.

Figure 4.24: SPL spectra for the CN-2in nozzle at perspective angle of 90° for converging nozzles at various subsonic speeds. M_j starts at $M_j = 0.5$ (red line), jumps to $M_j = 0.75$, and increases by 0.05 for each consecutive color up to $M_j = 0.95$.

Figure 4.24 shows the spectra for the CN-2in nozzle operated at $T_0 = 811$ K for various subsonic speeds. Compared to its ambient condition counterpart, this dataset is significantly less contaminated by rig noise. The rig noise still exists, it is simply saturated by the overall increase in SPL.

As discussed in the previous section, this is expected with heated jets increasing jet velocity. While most of the rig noise is saturated, there is a persistent broadband hump that occurs at roughly 1.5 kHz. Similar to the other results, the peak decreases in amplitude with increasing Mach number. The comparatively small rig noise contamination in the spectra verifies the significant reduction in deviations from the U^8 scaling law. Overall, the increasingly heated cases show improved performance but the jet still falls away from the scaling law at roughly the same jet Mach number demonstrated in the 90° angle.

4.3.3 Internal Rig Noise Investigation

A detailed investigation of internal rig noise can be done through insertion loss tests. This testing includes changing one component at a time to identify the various rig noise sources. The main priority of this research is to demonstrate the facility capabilities, so changing internal components was not an ideal approach. Instead, the internal rig noise was lumped together and identified by running the jet exhaust with various nozzle diameters at the same mass flow rate. Additionally, each test is a cold case run so there are no rig noise contributions due to combustion. The acoustic behavior for each nozzle will demonstrate relatively unique rig noise characteristics. However, it can be assumed that there were no internal changes by maintaining a constant mass flow rate for each case. Moreover, any consistent peaks or broadband content that is seen in multiple nozzle cases can be reasonably attributed to internal rig noise sources. Using the CN-1in nozzle, CN-2in nozzle, and running the facility without a nozzle, each nozzle was run at the same mass flow rate and compared in an attempt to identify internal rig noise sources. This comparison was done three times for three different mass flow rates. Figures 4.25 through 4.27 show the SPL spectra results for the three different mass flow rate tests at the sideline angle. Only the sideline is presented since this is where rig noise is most clearly evident. The first figure shown is the SPL spectra results for each nozzle at a mass flow rate of $\dot{m} = 0.22 \frac{kg}{s}$. This mass flow rate creates a flow of $M_j = 0.95$ in the CN-1in nozzle and is therefore the maximum mass flow rate possible for comparison purposes. As expected at the given Mach number, the CN-1in spectra is seemingly unaffected by any rig noise sources in the data. However, the rig noise is much more clearly seen for the CN-2in and the no nozzle, NoN, spectra. Between the two data sets, there is broadband overlap at a frequency range of roughly 1.56 kHz to 3.2 kHz. These overlapping frequencies of the same mass flow rate and different nozzle diameters can reasonably be assumed to be internal rig noise.

Figure 4.25: SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.22 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.95$, CN-2in nozzle at $M_j = 0.26$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.14$.

Figure 4.26: SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.17 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.75$, CN-2in nozzle at $M_j = 0.21$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.11$.

Figure 4.26 show the SPL spectra for the same jet nozzle diameters operated at $0.17 \frac{kg}{s}$, a smaller valve stroke percentage than the previous. While the CN-1in spectra remains mostly unaffected by rig noise, the two other low speed spectra still show significant rig noise contributions. However, there isn't good overlap to demonstrate rig noise at this mass flow rate. The only possible recognizable sign of valve noise exists around 1.85 kHz, but not at the other frequencies. While this could be due to a lack of resonance for the valve stroke position, it could also be a result of the error in mass flow rates. At such low mass flow rates, the facility is being run at jet speeds far below it's intended design.

Figure 4.27: SPL spectra for three different exit diameters, each with a mass flow rate of $\dot{m} = 0.11 \frac{kg}{s}$. The CN-1in nozzle is operated at $M_j = 0.5$, CN-2in nozzle at $M_j = 0.12$, and the last spectra corresponds to the jet running without a nozzle at $M_j = 0.08$.

As discussed previously, the CN-1in jet acoustics will be contaminated by rig noise for jet Mach numbers below $M_j = 0.6$ and this is demonstrated by the $M_j = 0.5$ jet in Figure 4.27. At this low Mach number, the rig noise clearly contaminates the jet. In addition, the results show a greater range of overlapping rig noise frequencies, including the frequencies first identified in Figure 4.25. The overlap between the NoN and CN-2in spectra begins with a sharp peak around 1.22 kHz and continues on to 3.2 kHz.

Based off these rig noise tests, it is clear that the internal rig noise is a large component of the rig noise contamination produced at low speeds. Furthermore, the noise maintains a relatively consistent at a frequency range of 1.56 kHz to 3.2 kHz. While insertion loss testing can further clarify the rig noise characteristics, enough has been done to assure that quality acoustic measurements can be made within the outlined limits of the subsonic nozzles.

CHAPTER 5

CONCLUSIONS

The anechoic high-temperature jet facility validation process was executed by exhaustive characterization of the anechoic chamber and jet acoustics validation at various flow and temperature conditions. The anechoic chamber was characterized using guidelines published in ISO (3745-2003). In addition to what is suggested in the standard, the current anechoic chamber was validated for two additional pertinent directions. The rigorous evaluation of the anechoic chamber data concluded with a conservative cutoff frequency estimate of 315 Hz throughout.

The demonstration of the aeroacoustic capabilities of the facility at various flow and temperature conditions were performed using six interchangeable nozzles spanning Mach number ranges from subsonic to Mach 2, and stagnation temperatures around 1300 K. In addition to ideally-expanded jets, the facility performance was also documented for off-design conditions at various temperatures. Where prior results were available in literature, they agree well with the current data and demonstrate the expected acoustic trends as well as characteristics generally proposed by the jet-propulsion community. Additionally, investigation of rig noise sources was executed by operating the two converging nozzles, CN-1in and CN-2in, and some cases with no nozzle, NoN, at various subsonic Mach numbers and temperatures. The analysis revealed that the CN-1in nozzle can be operated down to $M_j=0.6$ and the CN-2in nozzle down to $M_j=0.7$ before rig noise sources start to contaminate the acoustic measurements. For heated jet cases, the CN-1in nozzle could not be characterized due to its mass flow rate limitations. However, the CN-2in nozzle proved to be capable of maintaining combustion at temperatures ranging from 589 K to 1313 K. The last set of rig noise experiments was done in an effort to characterize internal rig noise. Based off the analysis, this rig noise contaminates comparatively low speed, subsonic flows. It may also be part of the reason why the CN-2in nozzle is limited to $M_j = 0.7$ for subsonic studies.

Considering the characterization and validation performed for the facility, the results show the facility to be well equipped and fit for supersonic high-temperature acoustic experiments and subsonic measurements within the given Mach number and temperature restrictions. In terms of

related future work, the Mach number and temperature capabilities of the facility can be documented in better detail using point-wise velocity measurements and qualitative schlieren imaging. Furthermore, continued research on the unknown rig noise sources and contamination at subsonic speeds can be investigated through insertion loss tests.

APPENDIX A

ACOUSTIC CHARACTERIZATION RESULTS

Figure A.1: The low frequency data (200 Hz - 630 Hz) traversed in the vertical (UP) direction. The data is measured sound pressure level roll-off compared to theoretical roll-off for the low frequency 3_{rd} octave bands. Blue dashed lines signify theoretical roll-off and red dashed lines represent the allowable tolerances.

Figure A.2: The mid frequency data (800 Hz - 5 kHz) traversed in the vertical (UP) direction.

Figure A.3: The high frequency data (6.3 kHz - 20 kHz) traversed in the vertical (UP) direction.

Figure A.4: The low frequency data (200 Hz - 630 Hz) traversed downstream and to the right (DR) direction.

Figure A.5: The mid frequency data (800 Hz - 5 kHz) traversed downstream and to the right (DR) direction.

Figure A.6: The high frequency data (6.3 kHz - 20 kHz) traversed downstream and to the right (DR) direction.

Figure A.7: The low frequency data (200 Hz - 630 Hz) traversed downstream and to the left (DL) direction.

Figure A.8: The mid frequency data (800 Hz - 5 kHz) traversed downstream and to the left (DL) direction.

Figure A.9: The high frequency data (6.3 kHz - 20 kHz) traversed downstream and to the left (DL) direction.

Figure A.10: The low frequency data (200 Hz - 630 Hz) traversed upstream and to the right (UR) direction.

Figure A.11: The mid frequency data (800 Hz - 5 kHz) traversed upstream and to the right (UR) direction.

Figure A.12: The high frequency data (6.3 kHz - 20 kHz) traversed upstream and to the right (UR) direction.

Figure A.13: The low frequency data (200 Hz - 630 Hz) traversed upstream and to the left (UL) direction.

Figure A.14: The mid frequency data (800 Hz - 5 kHz) traversed upstream and to the left (UL) direction.

Figure A.15: The high frequency data (6.3 kHz - 20 kHz) traversed upstream and to the left (UL) direction.

Figure A.16: The low frequency data (200 Hz - 630 Hz) traversed horizontally and to the right (HR) direction.

Figure A.17: The mid frequency data (800 Hz - 5 kHz) traversed horizontally and to the right (HR) direction.

Figure A.18: The high frequency data (6.3 kHz - 20 kHz) traversed horizontally and to the right (HR) direction.

Figure A.19: The low frequency data (200 Hz - 630 Hz) traversed horizontally and to the left (HL) direction.

Figure A.20: The mid frequency data (800 Hz - 5 kHz) traversed horizontally and to the left (HL) direction.

Figure A.21: The high frequency data (6.3 kHz - 20 kHz) traversed horizontally and to the left (HL) direction.

APPENDIX B

ACOUSTIC DATA FOR IDEALLY EXPANDED JETS

Table B.1: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.32$, $T_0=288.9$ K)

NPR = 2.83, Stagnation Temperature = 60.3 °F, Chamber Temperature = 71.1 °F
Relative Humidity = 34.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	72.91832	73.04525	73.20458	73.46119	72.54068	73.73738	76.49642	82.59072
250	72.92226	73.89531	73.55567	75.55016	74.86966	76.07569	78.92746	84.2908
315	73.3269	74.50629	76.16179	77.27341	76.42036	78.8461	80.23568	86.49993
400	75.26222	77.56923	78.15454	78.37357	78.86784	80.57056	83.74392	89.38823
500	77.30425	78.54012	79.1485	79.77035	80.10618	82.08667	86.05837	92.1841
630	79.52078	80.34599	80.92898	82.17198	82.76403	85.36042	90.03628	95.82928
800	81.45235	83.14179	84.32166	84.85386	85.6561	88.02311	93.48879	98.98959
1000	82.8419	84.69878	85.20373	86.51353	86.99917	90.89521	95.70609	102.0908
1250	84.56937	86.09074	88.51472	89.60333	90.43544	94.4006	99.90246	105.2496
1600	86.25939	87.98069	89.42416	90.87755	91.60692	95.05171	100.9015	106.587
2000	87.22041	89.19932	90.44555	91.54795	92.65075	96.31344	102.2111	107.7114
2500	88.53076	90.29205	90.84931	92.28121	93.86611	97.12477	102.9607	107.9342
3150	89.66323	91.22553	92.69727	93.67491	95.14886	98.156	102.9903	107.4946
4000	90.04944	91.77123	92.58488	94.1696	95.75203	98.576	102.5408	106.4034
5000	90.53182	91.92052	92.76871	94.34643	95.86789	98.61284	101.5617	104.0494
6300	93.41598	92.94777	93.19954	94.71581	96.0033	98.77408	100.589	101.7206
8000	97.73353	96.57713	94.28859	95.24907	96.34845	98.69063	99.5833	99.77168
10000	98.49175	98.56826	96.42471	95.86731	96.25189	98.2121	98.66939	97.80386
12500	97.97893	98.51752	97.11429	97.17998	96.56902	97.81758	97.67476	96.2165
16000	97.1277	97.41752	96.47176	97.68497	96.80857	97.33632	96.59731	94.59442
20000	96.30281	96.91307	95.48292	97.22382	96.956	97.03138	95.57765	92.84918
25000	95.2458	95.73713	94.80026	96.21828	96.1783	96.19603	94.43122	91.35297
31500	93.52186	94.01128	93.4932	94.71644	94.358	94.20908	92.37439	89.33357
40000	92.27981	92.80172	93.22354	93.26739	92.89701	92.3358	90.23205	87.33226
OASPL	111.1208	111.5003	110.8563	111.6911	112.0656	113.9929	116.8534	120.6749

Table B.2: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=577$ K)

NPR = 2.78, Stagnation Temperature = 579 °F, Chamber Temperature = 86.8 °F
Relative Humidity = 51.1 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.44835	73.23188	73.94469	74.56822	74.95321	77.73401	81.63768	87.21734
250	73.54273	73.08031	75.31471	76.84374	77.74998	80.84926	85.1819	89.61647
315	76.16498	77.20046	78.82805	80.07005	81.08436	84.51215	86.24527	92.76405
400	78.25339	80.66537	81.43002	81.92854	83.63884	86.15803	91.41298	95.02001
500	80.47566	82.3134	82.59497	83.166	84.30824	89.05179	93.27744	98.64843
630	82.77263	83.81284	84.16972	85.22891	87.73884	92.7726	97.30509	101.9694
800	83.70962	85.71247	87.28411	88.2065	90.90492	96.04507	101.5292	105.8059
1000	85.9211	87.59129	88.49802	89.88028	92.43046	99.0336	103.8203	108.4097
1250	87.9378	88.96511	90.62808	92.35844	96.15192	102.2119	107.6136	110.9203
1600	89.50528	91.25184	92.62609	94.76539	98.07728	105.2984	110.109	112.6781
2000	91.15999	92.71553	94.29772	96.67614	100.5368	108.0577	112.5009	113.9587
2500	93.14003	94.74525	96.17449	98.40828	102.7698	110.0151	114.1749	114.5491
3150	95.14431	96.82537	98.16321	99.75718	104.2728	111.7032	115.1152	115.3784
4000	95.30259	97.60789	98.87593	101.1943	105.2009	112.4974	115.6603	116.2631
5000	95.76644	97.67137	99.45759	102.1176	105.902	112.5252	115.9806	116.4893
6300	96.0452	98.31977	100.0608	102.9295	106.1918	111.9003	115.6715	115.9691
8000	96.22832	98.29137	99.82516	103.1826	106.4871	110.7792	114.6672	114.7138
10000	96.95967	98.57829	99.87218	103.347	106.1786	109.3718	113.5734	113.3434
12500	97.71706	99.19766	99.72322	103.348	105.6421	108.2835	112.3487	112.2095
16000	97.23709	98.83195	99.32875	103.0473	104.6694	106.7524	110.7702	110.6939
20000	96.62047	98.18109	98.65999	102.3885	103.6433	105.3336	109.0795	109.1191
25000	95.74243	97.15213	97.59446	101.2058	102.3023	103.5958	107.3209	107.4004
31500	93.86016	95.03799	95.85952	98.96167	99.87024	101.0972	104.7734	105.2228
40000	92.26221	93.42324	94.99807	96.77435	97.57619	98.8762	102.3279	103.1702
OASPL	111.9405	113.6413	114.813	117.7538	120.5694	125.7246	129.5439	130.1721

Table B.3: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=808.7$ K)

NPR = 2.75, Stagnation Temperature = 996 °F, Chamber Temperature = 71.1 °F
Relative Humidity = 27.7 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.92074	74.72338	75.97998	76.95842	77.66364	79.96815	83.40441	87.99808
250	75.40188	75.59849	76.81393	78.54306	79.94841	83.5567	87.16325	91.26767
315	78.00759	79.02412	80.64634	81.82984	82.93971	87.07274	88.94173	94.89374
400	80.58679	82.50894	83.18455	83.59628	85.75809	88.86219	93.86215	97.47633
500	82.78324	84.15431	84.33171	85.15253	87.34368	92.21488	96.26721	101.1145
630	85.04769	85.95573	86.44139	87.32443	90.77104	96.15705	100.3691	104.5431
800	86.75835	88.24042	89.36574	90.79487	95.05772	100.2487	105.0305	108.6707
1000	88.8577	90.11596	90.80363	93.17932	97.1208	103.2567	107.2279	110.9636
1250	90.80553	92.28979	93.60064	95.0434	100.8222	106.673	110.9317	113.0071
1600	92.49649	94.46454	95.66037	98.58247	103.6865	110.523	113.6766	114.7377
2000	94.69526	95.83776	97.63006	100.6588	106.6591	113.4871	115.794	115.6758
2500	96.42561	97.95759	99.64489	102.5213	109.0916	115.7736	117.126	116.5433
3150	98.08635	100.2751	101.8676	104.2865	111.1466	117.581	118.0912	117.8299
4000	99.04759	101.2965	102.9987	105.859	112.2237	118.447	118.8205	118.9654
5000	99.86499	101.6708	103.7445	106.7694	112.6493	118.7765	119.5042	119.3806
6300	100.1071	102.5552	104.4158	107.833	112.6693	118.6302	119.7076	118.9393
8000	100.1079	102.587	104.5255	108.1463	112.1899	117.765	118.735	117.5469
10000	100.0215	102.6132	104.4479	108.3886	111.441	116.5248	117.2083	115.7638
12500	100.2871	102.7096	104.2297	108.2985	110.538	115.1813	115.8046	114.2539
16000	99.76231	102.1297	103.4593	107.6558	109.1876	113.5466	114.4915	112.5033
20000	99.06589	101.3664	102.5956	106.8275	107.9825	112.0449	113.0445	110.8619
25000	98.18395	100.208	101.5524	105.5785	106.6447	110.5486	111.7254	109.2036
31500	96.49806	98.3753	99.99226	103.5097	104.567	108.4743	109.8415	107.2452
40000	95.38924	97.22373	99.52475	101.9339	102.9495	107.0982	108.2261	105.8965
OASPL	115.1	117.2967	119.0054	122.4412	126.384	132.0934	133.1183	132.6497

Table B.4: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=987$ K)

NPR = 2.73, Stagnation Temperature = 1317 °F, Chamber Temperature = 73 °F
Relative Humidity = 51.4 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.84818	77.27659	78.23562	79.49317	80.86276	82.91298	85.91754	89.74951
250	76.26194	77.54611	78.84777	80.00551	81.07297	84.68082	88.32174	92.20422
315	78.24601	80.57535	82.27724	82.529	84.45298	88.18142	90.27829	96.28283
400	81.77504	83.13155	84.46339	85.08284	87.56155	90.31196	95.05837	98.50629
500	83.42026	85.42279	85.31059	86.47274	88.41902	93.65859	97.45025	102.1786
630	85.78254	87.00036	87.1356	88.37496	91.92738	97.92728	101.9947	105.7695
800	87.03126	88.61036	90.15183	91.72353	96.39001	101.7373	106.3858	109.4686
1000	89.02843	90.53416	91.17475	93.75102	98.0725	104.7008	108.6265	111.5293
1250	90.98617	92.45919	93.55881	95.61228	101.6872	107.5149	111.7462	113.2723
1600	92.64095	95.06309	96.06555	99.17409	104.8602	111.2881	114.4122	114.5523
2000	94.91486	96.24669	97.59151	100.8256	107.4371	113.6348	116.2106	115.2858
2500	96.90647	98.16649	99.89775	102.9027	110.3066	115.8835	117.3845	115.825
3150	98.48251	100.2781	101.9716	104.8438	112.7687	118.0184	118.1454	116.5888
4000	99.10289	101.1033	103.1265	106.4126	114.2729	119.0209	118.8007	117.435
5000	100.1656	102.0093	103.9108	107.4471	115.0363	119.6324	119.5486	117.4652
6300	100.6675	102.9372	104.8397	108.5232	115.3674	119.9161	119.3328	116.1563
8000	100.7667	103.1062	105.1569	109.1314	114.8598	119.5639	118.0274	114.4957
10000	100.6333	103.2652	105.1035	109.3143	113.9141	118.3947	116.3436	112.8827
12500	100.7702	103.48	104.9005	109.4529	112.682	117.001	115.0119	111.2561
16000	100.3844	103.0372	104.1628	108.9525	111.3015	115.4728	113.4598	109.6131
20000	99.34793	102.1068	103.3254	107.9496	110.1383	114.0931	111.9007	107.7078
25000	98.24383	100.7233	102.027	106.4552	108.7227	112.4637	110.4025	105.7803
31500	96.19035	98.54481	100.1555	104.1694	106.5663	110.4517	108.2873	103.4476
40000	94.72345	97.12206	99.329	102.3875	104.9437	109.0779	106.6041	101.9261
OASPL	115.4347	117.7276	119.4121	123.2954	128.5533	133.2513	132.8972	131.0053

Table B.5: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=1099.8$ K)

NPR = 2.73, Stagnation Temperature = 1520 °F, Chamber Temperature = 94.9 °F
Relative Humidity = 44.1 %, $\gamma = 1.33$

3rd Octave 3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	76.75386	79.14857	80.60877	81.9761	83.57724	85.33945	87.59518	90.89774
250	75.70737	77.25889	78.33244	80	81.90299	85.15813	88.17251	91.89632
315	79.03858	81.02544	82.66315	83.31506	85.79159	89.05311	91.18492	96.84789
400	82.43357	83.85966	84.88194	85.61315	87.73087	91.53382	95.92559	98.98723
500	84.41981	85.84222	85.97667	87.58326	89.92535	95.18382	98.53378	103.1593
630	86.63263	87.29552	87.66252	89.15888	93.14215	98.5415	102.3151	106.0193
800	88.08671	89.42359	90.61258	92.56231	97.43207	102.4485	106.7344	109.6929
1000	90.34008	91.86997	92.63537	95.00584	99.58466	105.4418	109.1197	111.9342
1250	92.22091	93.93688	95.16243	97.18269	103.6881	108.93	112.4852	113.5924
1600	93.76974	96.15306	97.02672	100.5429	106.6617	112.5782	114.8908	114.6747
2000	95.48226	97.39641	98.94018	102.6942	109.2608	115.0347	116.121	114.8389
2500	97.57928	99.37539	101.2584	104.9734	112.328	117.2832	117.0675	115.6333
3150	99.46972	101.2918	103.2894	107.0756	114.7841	119.0667	117.9648	116.7712
4000	100.114	102.5232	104.5771	108.6348	116.405	120.0378	118.5917	117.3377
5000	101.1282	103.5337	105.5132	109.6189	117.7592	120.5777	119.0044	117.071
6300	101.8774	104.4922	106.7741	110.7196	118.1247	120.6781	118.684	116.1127
8000	102.275	104.9955	106.9217	111.1701	117.8532	120.297	117.3263	115.1471
10000	102.2908	105.1692	107.2215	111.311	116.7072	119.2603	115.8894	113.8023
12500	102.5401	105.3584	107.1876	111.33	115.5215	117.8575	114.6788	112.3937
16000	102.1354	104.8951	106.6114	110.7767	113.9275	116.4959	113.3653	110.8521
20000	101.2836	104.1552	105.8513	109.9353	112.6681	115.122	111.9598	109.2711
25000	100.1697	102.9372	104.7411	108.5444	111.1044	113.6282	110.4827	107.4901
31500	98.12585	100.6923	102.876	106.2529	108.8338	111.6612	108.3418	105.2704
40000	96.60782	99.0173	101.8935	104.2919	107.0963	110.3042	106.5465	103.5111
OASPL	116.8854	119.4645	121.4489	125.323	131.1171	134.2245	132.6144	131.2035

Table B.6: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.31$, $T_0=1199.3$ K)

NPR = 2.72, Stagnation Temperature = 1699 °F, Chamber Temperature = 88.9 °F
Relative Humidity = 56.9 %, $\gamma = 1.31$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	76.66334	78.23846	78.89363	79.6244	80.45922	83.45805	86.85139	90.33133
250	77.48525	78.42158	79.79219	81.60092	82.64617	85.77081	89.23394	93.2722
315	79.63058	81.75237	83.47113	84.2094	86.37502	89.20903	91.99634	97.63351
400	83.07142	84.69668	84.9105	86.2944	88.73621	92.49194	96.77438	99.56359
500	85.07954	86.62963	86.74499	87.66945	90.33422	95.83655	99.29969	103.9109
630	86.89545	88.09414	88.58606	89.88365	93.65825	99.26041	102.9893	106.5875
800	88.56391	90.12299	91.42524	93.28089	98.10589	103.3415	107.5314	110.2877
1000	90.5435	92.3746	93.34863	95.9082	100.3147	106.2625	109.6739	112.1878
1250	92.60689	94.25476	95.7056	97.94686	104.231	109.887	113.0306	113.8946
1600	94.23972	96.58532	97.5799	101.3385	107.2514	113.3555	115.45	115.019
2000	96.13619	97.90057	99.47913	103.4676	110.1381	115.8264	116.5978	115.3583
2500	98.03983	99.86918	101.7944	105.5568	112.9657	117.8871	117.4582	116.1058
3150	99.56312	101.6353	103.8612	107.7062	115.6049	119.3309	118.1143	117.2133
4000	100.4478	102.651	105.1761	109.5733	117.2659	120.1057	119.1162	117.9297
5000	101.5249	103.7899	106.3476	110.5974	118.6691	120.4731	119.7282	117.5609
6300	102.347	104.9399	107.5945	111.8076	119.2258	120.7145	119.0366	116.3387
8000	102.8048	105.3889	108.1127	112.4215	119.1877	120.1963	117.6919	115.53
10000	102.7438	105.718	108.409	112.696	118.4277	118.8144	116.3341	113.9678
12500	103.0824	106.0616	108.4039	112.6394	117.2336	117.4836	115.1082	112.3566
16000	102.7395	105.7941	108.0297	112.1324	115.5522	116.0725	113.6843	110.5359
20000	101.9948	105.1501	107.2678	111.2259	114.2762	114.7522	112.3551	108.7979
25000	100.9483	103.86	106.1248	109.8253	112.9276	113.3592	110.7908	107.0328
31500	98.86186	101.6586	104.3447	107.6096	110.9482	111.4206	108.6553	104.7481
40000	97.21146	100.0124	103.3903	105.5972	109.3213	110.0668	106.8978	102.9527
OASPL	117.393	120.0824	122.5444	126.4922	132.3907	134.2272	133.0623	131.5312

Table B.7: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.32$, $T_0=1312.6$ K)

NPR = 2.74, Stagnation Temperature = 1903 °F, Chamber Temperature = 97.3 °F
Relative Humidity = 48.7 %, $\gamma = 1.3$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.86771	77.93514	79.15573	79.55385	80.2835	83.54659	86.86737	90.38764
250	76.69495	78.36143	80.61673	81.93492	82.6411	86.18537	89.85677	93.71023
315	79.7747	82.12916	83.37623	84.58554	87.63653	89.75196	92.67663	98.16726
400	83.2912	84.56763	85.35803	86.67312	89.20685	92.52753	96.66685	99.63572
500	85.6455	86.43737	86.87045	88.1752	90.54396	95.63371	99.11156	103.9262
630	87.00332	88.17311	88.74451	90.26945	93.76109	99.38983	103.2794	107.0424
800	88.73333	90.15977	91.96304	94.06788	98.44196	103.3097	107.5278	110.6178
1000	90.36864	92.4714	93.94888	96.33173	100.6737	106.5676	109.9908	112.6897
1250	92.33157	95.07022	96.11442	98.65094	104.3006	109.5298	112.7274	113.7957
1600	93.97259	96.46517	98.19736	102.3757	107.793	113.428	115.2595	114.7818
2000	95.88895	97.96386	100.0407	104.225	110.6763	115.8518	116.3739	114.652
2500	97.921	99.76825	101.7599	106.2818	113.3873	117.7134	117.0084	115.2369
3150	99.70812	101.6101	103.8199	108.369	116.0165	119.2626	117.2691	115.4697
4000	100.4645	103.0403	105.3132	110.254	117.7556	119.8094	117.5409	115.3476
5000	101.6737	104.0812	106.3658	111.6776	118.9799	120.2216	117.6464	114.594
6300	102.4541	105.2744	107.8893	112.9251	119.5353	120.2437	116.9312	113.5735
8000	103.1334	105.7965	108.3723	113.4241	119.4854	119.6039	115.7234	112.8972
10000	103.1172	106.1438	108.6327	113.4604	118.5865	118.3071	114.3627	111.4424
12500	103.4134	106.4582	108.6066	113.3564	117.4723	116.9164	113.1013	110.0459
16000	103.072	106.1472	107.9902	112.6254	115.9743	115.6151	111.7278	108.5718
20000	102.2298	105.3967	107.2133	111.8021	114.8416	114.1647	110.1657	106.7525
25000	101.0772	104.1313	106.0224	110.3892	113.337	112.7473	108.4675	104.7108
31500	98.99695	101.7857	104.0555	108.1322	111.3323	110.6406	106.0488	102.2593
40000	97.27935	100.0662	103.1205	106.3226	109.8964	109.2686	104.0786	100.4439
OASPL	117.5907	120.3696	122.6288	127.2645	132.7296	133.8768	131.6988	129.9478

Table B.8: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.53$, $T_0=288.4$ K)

NPR = 3.82, Stagnation Temperature = 59.5 °F, Chamber Temperature = 70 °F
Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	78.67068	75.22809	75.9639	76.71642	76.98706	77.46604	80.43036	86.38757
250	78.36678	75.5935	76.13126	77.86054	78.42201	78.99865	82.83099	87.96999
315	78.74719	78.69555	79.89991	81.36409	80.75274	82.7933	84.5183	90.44684
400	80.49057	81.67804	82.17015	82.56022	83.92799	85.25822	88.92244	94.05032
500	82.25203	82.98232	83.24449	84.51445	84.80888	86.07166	90.45803	96.60704
630	84.2698	84.48946	85.03963	86.36409	87.12693	89.30769	93.88958	100.0109
800	85.38267	86.79721	88.1167	89.36507	90.26778	92.03241	98.06991	103.685
1000	87.19079	88.37063	88.82582	90.57326	90.83237	93.9603	99.73826	106.3711
1250	88.23208	88.94622	90.74282	92.26031	93.50815	97.17123	103.6543	109.2856
1600	90.24831	91.4732	92.52494	94.32221	95.25328	98.78793	105.2002	111.034
2000	91.07861	92.691	93.62995	95.28708	96.5079	100.5305	107.2707	112.421
2500	92.19358	93.89043	94.3751	95.95125	97.99965	101.6978	108.5729	113.0273
3150	93.80162	94.93276	96.48585	97.43616	99.1133	102.866	109.0242	113.4686
4000	93.81947	95.165	95.94108	97.83065	99.65798	103.2246	108.4904	113.3496
5000	94.50998	95.1898	96.11817	98.30044	99.97545	103.4568	107.5538	112.4288
6300	96.24097	96.28692	96.57095	98.49917	100.3257	103.6052	106.4343	111.078
8000	96.86513	97.3004	97.04317	98.83413	100.5914	103.53	105.369	109.4724
10000	97.34669	97.7192	97.61407	99.31574	100.5982	103.105	104.3246	107.733
12500	99.55886	98.44075	97.50363	99.65175	100.6479	102.5926	103.1963	105.8363
16000	99.19463	99.55806	97.70848	99.48667	100.1241	101.6676	101.9036	103.8006
20000	97.93664	98.75433	98.03522	99.6088	99.59159	100.7732	100.5986	101.7991
25000	96.59222	97.23287	96.94662	99.23054	99.02117	99.47659	98.99948	99.81157
31500	94.36949	94.9295	95.12858	97.18856	97.49848	97.32133	96.53685	97.24622
40000	92.44777	93.13857	94.27226	95.21705	95.59547	95.36941	93.94394	94.64179
OASPL	112.514	112.9818	113.0004	114.6969	115.7682	118.3671	122.2664	126.8311

Table B.9: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.53$, $T_0=599.3$ K)

NPR = 3.82, Stagnation Temperature = 619 °F, Chamber Temperature = 70 °F
 Relative Humidity = 62.5 %, $\gamma = 1.3$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	77.48141	78.3891	78.81181	79.33906	79.58607	82.05424	86.15028	90.5774
250	77.85048	78.25395	79.913	81.45677	82.21326	84.90705	89.19736	93.78178
315	79.60491	81.63949	84.03286	84.20998	85.31175	88.89897	90.80619	97.46531
400	82.76895	84.59875	86.15963	86.29201	88.06739	90.43292	95.76649	100.152
500	85.49149	86.99031	86.92264	88.07883	88.8947	94.00819	98.63415	104.1117
630	87.35934	87.75105	88.51973	88.91412	91.33748	97.24214	102.4825	107.3318
800	87.80497	89.65637	91.21239	91.88861	95.18787	101.0508	106.8568	111.3149
1000	89.88834	91.48325	92.18773	93.96256	96.97541	103.7598	108.6823	113.4227
1250	91.66972	92.7963	94.93349	96.49073	100.37	107.1808	112.852	115.9615
1600	93.66338	95.22707	97.19092	99.20547	103.0973	110.9358	115.423	117.5216
2000	95.41245	96.70332	98.57574	100.7043	105.1359	113.4147	117.5119	118.3151
2500	97.4155	98.84253	100.4119	102.3267	107.2784	115.587	118.8353	118.9982
3150	99.56064	100.7792	102.4352	103.8334	109.0194	117.475	119.8157	119.943
4000	99.53432	101.1873	103.1021	105.2979	110.0318	118.512	120.5239	120.3034
5000	100.103	101.5991	103.4716	106.2136	110.8999	118.9807	120.6673	119.6502
6300	100.6587	102.3811	104.0925	106.9725	111.438	118.5689	120.215	118.1094
8000	100.9543	102.7971	104.2046	107.6645	111.5652	117.8751	119.1358	116.5346
10000	101.3315	103.3224	104.4274	108.0729	111.5025	116.9934	117.9579	115.2528
12500	102.1165	103.8563	104.5008	108.3115	111.0996	116.0681	116.9772	114.3525
16000	102.647	103.9037	104.2197	108.1189	110.162	114.7672	115.7757	112.9716
20000	102.1618	103.8553	103.8819	107.6412	109.2636	113.431	114.6023	111.439
25000	101.0358	102.9541	103.1968	106.7074	108.1565	111.8472	113.129	109.8407
31500	98.96481	100.7739	101.6833	104.6897	106.0597	109.7423	111.1442	107.7054
40000	97.2532	99.23	100.899	102.9069	104.151	108.1212	109.2656	105.8874
OASPL	116.6786	118.3553	119.4973	122.4898	125.8002	132.3724	134.3589	133.7323

Table B.10: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=802$ K)

NPR = 3.7, Stagnation Temperature = 984 °F, Chamber Temperature = 71.8 °F
Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	79.7184	77.49617	78.96036	80.12929	80.5258	83.31533	87.57738	92.38042
250	79.37727	78.75921	80.51982	82.30344	83.42096	86.45187	90.53546	95.0536
315	81.22927	82.28841	84.50912	85.07954	86.82469	90.46105	92.75812	98.88933
400	84.07282	85.7629	86.90505	87.14276	89.67412	92.43543	97.45167	101.4315
500	86.37365	88.23338	88.08712	89.09643	90.92365	96.02692	100.4159	105.3398
630	88.55849	89.60297	90.29981	90.81739	94.31993	100.1045	104.5759	108.6784
800	90.13287	91.82666	92.78383	94.29749	98.47072	104.1184	108.9144	112.2632
1000	92.27451	93.91737	94.57638	96.83121	101.1189	107.7242	111.5893	114.7224
1250	94.0961	95.88571	97.17665	98.89421	105.1515	111.2251	115.2954	116.5454
1600	96.2108	98.11273	99.60068	102.5081	108.2605	115.0547	117.7206	117.7858
2000	98.355	99.71234	101.3834	104.4128	111.3075	118.0265	119.4977	118.3678
2500	100.2432	101.6395	103.3235	106.3154	114.2721	120.245	120.5022	119.4125
3150	102.2136	103.5872	105.7955	108.4961	116.572	121.8992	121.3292	120.5775
4000	102.8755	104.7341	106.8245	110.0607	117.8103	122.9856	122.2047	121.4557
5000	103.9192	105.6025	107.8621	111.0813	118.4451	123.3924	122.8878	121.2043
6300	104.42	106.4696	108.7098	112.0206	118.4368	123.3679	122.3726	120.0294
8000	104.8709	107.002	109.0133	112.5931	117.8981	122.6272	120.9428	118.9164
10000	105.0235	107.2541	109.1475	112.7715	116.9584	121.3978	119.6941	117.3615
12500	105.5009	107.5134	109.093	112.7649	115.8989	120.117	118.5471	115.8284
16000	105.3176	107.2861	108.4358	112.2075	114.5239	118.776	117.1441	114.1806
20000	104.8675	106.7965	107.7387	111.425	113.3749	117.5183	116.0303	112.562
25000	103.7843	105.6806	106.6939	110.0536	112.0689	116.2335	114.6595	110.8919
31500	101.781	103.6599	104.9805	107.8512	110.0189	114.3653	112.7152	108.8423
40000	100.1531	102.1199	104.1563	106.0547	108.3457	113.1291	111.0978	107.3767
OASPL	119.847	121.7813	123.503	126.7805	131.8826	136.8494	136.2013	134.847

Table B.11: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.51$, $T_0=975.9$ K)

NPR = 3.65, Stagnation Temperature = 1297 °F, Chamber Temperature = 61.8 °F
 Relative Humidity = 69.3 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.93965	85.13827	86.85807	88.92343	91.4152	93.26164	95.44754	99.40219
250	79.70178	79.10597	81.101	82.86535	84.54434	88.08878	91.65382	95.7074
315	81.92016	83.34985	84.99775	85.93414	87.8557	91.3045	93.5781	99.60039
400	85.32023	86.96048	87.74801	88.5944	90.64792	93.68635	99.00647	102.4585
500	87.43797	88.78286	88.43659	90.06869	91.83624	97.43512	101.4246	106.37
630	88.9283	90.17748	90.19878	91.78386	95.38405	101.2952	105.3431	109.3682
800	90.44234	91.87454	93.23273	95.20897	99.87667	105.4033	109.9164	113.0921
1000	92.79993	94.23908	94.88843	97.68136	102.0005	108.4876	112.1997	115.1419
1250	94.50244	96.51355	97.70225	99.45285	105.7553	111.6761	115.4463	116.5602
1600	96.36166	98.74085	99.83047	103.273	108.98	115.5335	117.6382	117.3569
2000	98.52183	100.2873	101.5247	105.3026	111.9413	118.0349	118.8079	117.5091
2500	100.6165	102.1214	103.7532	107.541	115.0363	120.3712	119.6894	118.3166
3150	102.107	104.0133	105.9218	109.7063	117.5046	121.7476	120.396	119.1179
4000	103.227	105.1646	107.38	111.5017	119.1417	122.6978	121.1562	119.4031
5000	104.5407	106.1555	108.4809	112.8094	120.4257	123.1763	121.4337	118.6348
6300	105.123	107.2717	109.7532	113.8769	120.8855	123.3198	120.4865	117.8619
8000	105.6571	107.8346	110.4265	114.3867	120.7516	122.6669	119.4473	117.326
10000	105.7562	108.0989	110.7237	114.5073	119.8175	121.1822	118.2648	116.047
12500	106.1894	108.5348	110.7046	114.4019	118.4733	119.9814	117.211	114.567
16000	106.0124	108.246	110.1424	113.657	117.0227	118.6998	115.8206	113.0459
20000	105.6049	107.6221	109.3413	112.7953	115.8021	117.4649	114.5362	111.2445
25000	104.7056	106.5535	108.132	111.3227	114.467	116.037	113.0812	109.3944
31500	102.8847	104.4448	106.2024	108.9979	112.4217	114.076	110.9678	107.2278
40000	101.3911	102.9992	105.2873	107.146	110.8405	112.7996	109.2498	105.7626
OASPL	120.1062	122.5394	124.7265	128.1629	133.8184	136.3923	134.5392	132.7973

Table B.12: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1088.7$ K)

NPR = 3.65, Stagnation Temperature = 1500 °F, Chamber Temperature = 91.3 °F
Relative Humidity = 65.8 %, $\gamma = 1.33$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.11802	79.83024	81.64366	82.42578	83.67939	86.32046	89.58928	93.52559
250	79.95493	80.05453	82.46747	83.31985	84.82928	88.9068	92.53896	96.59362
315	81.48251	83.75814	85.50715	86.0477	88.29902	91.4526	94.09673	100.2117
400	85.424	86.97074	88.54503	89.33844	91.38762	94.85934	99.65999	102.9431
500	87.32886	88.59966	89.3754	90.4227	92.51822	98.04821	101.8392	106.9238
630	88.96722	89.67596	91.06357	91.92292	95.88882	101.8272	106.005	109.9779
800	89.87449	91.60306	93.44196	95.237	100.2499	105.5322	109.9743	113.1858
1000	92.10865	94.17361	95.37258	97.68365	102.2191	108.6434	112.1891	115.0836
1250	93.87476	95.85262	97.52983	99.60637	106.0608	111.897	115.3187	116.325
1600	95.46317	98.02791	99.49391	102.988	109.1389	115.4917	117.593	117.1547
2000	98.0875	99.23083	101.1527	104.874	111.8068	117.8713	118.6723	117.2621
2500	99.77276	100.9004	103.2689	107.2479	114.8528	119.8303	119.3318	117.7746
3150	101.0326	102.7902	105.0263	109.2194	117.3779	121.3078	119.8906	118.067
4000	102.1813	104.1024	106.6558	111.2057	119.1554	122.1211	120.3806	118.0122
5000	103.3406	105.1448	107.6627	112.5291	120.6095	122.573	120.3676	117.1632
6300	104.2876	106.5932	109.2436	113.8669	121.4163	122.6631	119.4897	116.3683
8000	104.9133	107.1902	109.8262	114.611	121.7923	122.1995	118.7568	115.9547
10000	105.1427	107.7463	110.2325	114.9666	121.3317	121.007	117.7315	114.8583
12500	105.6252	108.2336	110.4888	115.1486	120.4088	119.7983	116.8919	113.6841
16000	105.6469	108.1489	110.1138	114.5827	118.9317	118.5481	115.584	112.3132
20000	105.2394	107.5912	109.4112	113.6953	117.7985	117.3378	114.295	110.4871
25000	104.4005	106.6129	108.354	112.3768	116.528	116.0695	112.9075	108.8256
31500	102.5285	104.479	106.5264	110.1336	114.6358	114.1802	110.8024	106.5571
40000	100.9957	102.9567	105.6464	108.3248	113.1311	112.8171	108.9622	104.9477
OASPL	119.9023	122.135	124.4162	128.7258	134.9928	136.3616	134.5307	132.7071

Table B.13: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1208.7$ K)

NPR = 3.65, Stagnation Temperature = 1716 °F, Chamber Temperature = 94.2 °F
Relative Humidity = 65.8 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.51905	81.07345	82.18381	82.31135	82.4998	86.06984	90.02472	94.19407
250	80.44713	80.81576	82.95267	84.39615	85.65104	89.32637	93.17495	97.47273
315	82.14517	84.41298	86.12109	86.4515	88.97426	92.01248	95.02679	101.1109
400	86.0657	87.89466	88.67641	89.63715	92.2555	95.67425	100.6835	103.7038
500	88.18979	89.67945	89.87803	91.11389	93.66609	99.52798	103.1829	108.0743
630	89.77584	91.06384	91.78439	93.0569	97.04458	103.3575	107.3653	111.0695
800	91.39026	92.8391	94.39278	96.74101	102.1416	107.6773	111.6787	114.3655
1000	93.65914	95.04996	96.23976	99.06859	104.207	110.8109	113.9181	116.2755
1250	94.95157	97.27133	98.82105	101.051	107.9466	113.7401	116.5171	116.9519
1600	96.68165	99.01369	100.7714	104.8554	111.2269	117.2981	118.3395	117.4144
2000	99.24869	100.605	102.5939	106.9355	114.3122	119.8393	119.3114	117.793
2500	101.0567	102.5015	104.5552	109.2128	117.1347	121.4331	119.9367	118.4334
3150	102.4705	104.259	106.6064	111.4223	119.4605	122.6675	120.415	118.6438
4000	103.6705	105.4515	108.0916	113.3243	121.0807	123.347	120.7748	118.1168
5000	104.8741	106.5324	109.1892	114.5322	122.2451	123.6547	120.1849	116.918
6300	105.627	107.8703	110.7468	115.7187	122.7579	123.4006	119.256	116.3342
8000	106.1742	108.44	111.4099	116.1475	122.6111	122.2121	118.4029	115.5967
10000	106.4709	108.8593	111.6713	116.1995	121.7807	120.7692	117.2043	114.5491
12500	106.8468	109.3017	111.8817	116.0698	120.5917	119.5786	116.0851	113.3136
16000	106.6205	109.1196	111.444	115.24	119.1401	118.24	114.8845	111.7565
20000	106.1092	108.593	110.6092	114.347	118.0176	116.9437	113.4793	109.9692
25000	105.131	107.5184	109.4494	112.8916	116.6906	115.66	111.9967	108.1904
31500	103.1751	105.3905	107.6447	110.6571	114.7595	113.6872	109.8149	105.8169
40000	101.7262	103.8773	106.8113	109.0391	113.4191	112.4922	107.9331	104.3135
OASPL	121.0348	123.2459	125.7942	130.0142	136.0131	137.0948	134.699	132.9995

Table B.14: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.52$, $T_0=1314.8$ K)

NPR = 3.65, Stagnation Temperature = 1907 °F, Chamber Temperature = 96.8 °F
Relative Humidity = 73.2 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.23666	81.20443	82.37809	82.51798	83.67013	87.21748	90.82246	94.82788
250	80.47311	81.58545	83.82146	84.84625	86.16233	89.78088	93.5959	97.87191
315	83.2239	85.78386	87.43038	88.22697	90.78562	93.33585	96.76478	102.7301
400	86.47093	88.33537	89.38724	90.56271	92.59176	96.3462	100.9677	104.3655
500	88.91985	89.93613	90.32277	91.64616	94.34736	100.1471	103.8845	108.7487
630	90.44104	91.70563	91.92202	93.49572	97.8836	104.0868	108.207	111.8699
800	92.04307	93.66769	95.26677	97.28247	102.6403	108.3071	112.5106	115.2675
1000	93.8508	95.77717	96.66821	99.85427	104.8261	111.3547	114.591	116.9092
1250	94.98092	97.94715	99.48456	101.5882	108.7648	114.5674	117.0785	117.3301
1600	97.15463	99.60901	101.6206	105.6579	112.0701	118.168	119.1215	118.0423
2000	99.33622	101.6054	103.2368	107.9356	114.8587	120.3831	119.8044	117.9756
2500	100.9624	103.0642	105.2234	110.2042	117.7727	122.1631	120.3064	118.6506
3150	102.4945	104.5656	107.2774	112.3856	120.0698	123.2181	120.6934	118.7469
4000	103.5315	105.8148	108.9987	114.3982	121.7607	123.9966	121.0238	117.913
5000	104.6358	106.985	110.1514	115.8359	123.0733	124.265	120.2191	116.5738
6300	105.5496	108.191	111.6681	117.0335	123.5037	123.5805	118.818	115.778
8000	106.1709	108.8129	112.2931	117.3162	123.1883	122.0803	117.9382	114.8797
10000	106.5213	109.1826	112.5853	117.3195	122.231	120.8646	116.4936	113.5041
12500	106.9754	109.6045	112.7329	116.907	120.9551	119.8323	115.3748	112.1865
16000	106.6787	109.2796	112.1751	116.1572	119.6132	118.5616	113.9864	110.8996
20000	106.1996	108.6401	111.5575	115.2202	118.5105	117.3527	112.5331	108.8831
25000	105.308	107.4668	110.3918	113.9042	117.3362	115.9688	110.9554	106.8375
31500	103.3795	105.4334	108.6348	111.7738	115.4426	114.0672	108.7638	104.3022
40000	101.8738	104.1211	107.8762	110.2535	114.2816	112.9495	107.1875	102.724
OASPL	121.0778	123.5463	126.695	131.0966	136.6305	137.5229	134.785	133.028

Table B.15: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.82$, $T_0=284.2$ K)

NPR = 5.91, Stagnation Temperature = 51.9 °F, Chamber Temperature = 68.5 °F
Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.52115	80.97476	82.19229	82.7826	83.26506	83.93796	86.79031	92.2071
250	81.41292	81.13875	83.16301	84.73598	85.30569	85.4932	88.928	95.14715
315	84.0134	85.24644	87.33106	88.21401	87.86729	90.40597	90.92491	97.36472
400	86.8481	88.44038	89.47459	89.52146	90.83474	91.72128	94.71518	101.1813
500	88.87593	90.15555	89.98604	90.68955	91.18834	92.18421	96.04096	103.6469
630	90.49225	90.60229	91.15619	92.16138	93.17026	95.03475	99.75984	107.2893
800	91.03944	92.55682	93.58991	94.74747	95.83451	97.60858	103.6194	110.8426
1000	92.89656	94.32536	94.70148	95.92034	96.48821	99.74414	105.3441	113.2189
1250	93.81151	94.8524	96.40075	97.56308	98.96463	102.6533	109.3387	115.8954
1600	95.57884	96.85515	98.02826	99.53186	99.9973	104.0263	111.1465	117.666
2000	96.37013	98.13512	99.00183	100.2724	101.0888	105.3186	113.2295	119.0398
2500	97.37095	99.03763	99.95417	101.1899	102.7436	106.6133	114.5419	119.4136
3150	98.94987	100.3125	101.7218	102.1599	103.7009	107.3397	115.34	120.027
4000	99.92432	100.5232	101.5075	102.8665	104.2895	107.9602	115.4548	120.2959
5000	101.2691	101.8452	101.9052	103.2761	104.7881	108.118	114.8107	120.0447
6300	101.2186	102.8033	103.2617	103.7093	105.2412	108.4698	114.1335	119.2393
8000	101.1877	102.4814	103.153	104.4585	105.5128	108.4017	113.1136	118.1155
10000	101.4929	102.8318	102.7197	104.6168	105.9794	108.0993	112.2133	116.5917
12500	101.6483	103.011	102.734	104.5877	105.8906	107.7073	111.2836	115.2415
16000	101.3754	102.7562	102.4271	104.5262	105.1607	107.0192	110.1237	113.75
20000	100.9431	102.4558	101.9297	104.2586	104.5121	105.9954	108.9681	112.4389
25000	99.88701	101.4602	101.2525	103.4945	103.7507	104.5896	107.4953	110.9935
31500	97.67224	99.35966	99.73375	101.7061	101.9087	102.3363	105.0479	108.919
40000	95.73631	97.53064	98.84004	99.69126	99.87476	100.2111	102.4033	106.7032
OASPL	116.5146	117.8462	118.2388	119.6803	120.6857	123.3109	129.1555	134.2292

Table B.16: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.8$, $T_0=814.8$ K)

NPR = 5.66, Stagnation Temperature = 1007 °F, Chamber Temperature = 68.5 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.57097	83.01529	84.43771	85.30117	85.39601	87.62094	92.06753	96.99977
250	82.64328	83.32053	85.94505	87.47427	88.26771	91.35639	95.51003	100.2968
315	85.52246	87.78571	89.79472	90.2106	92.08523	94.79773	97.05363	104.807
400	89.40824	90.94372	92.17643	93.12676	94.83936	96.76789	102.4962	106.6929
500	91.69632	93.04881	92.86628	93.49809	94.85195	99.70312	104.4418	110.7762
630	92.84	93.46909	93.69936	94.28512	97.04356	103.3211	108.8081	114.3266
800	93.40812	94.88886	96.64807	97.7998	100.9466	107.007	113.0471	117.5959
1000	95.65247	97.51048	98.50889	100.2333	102.7095	110.0869	115.3946	119.6117
1250	96.83501	99.39728	100.3688	101.6354	106.8351	113.8785	118.9609	121.1134
1600	98.61517	100.1775	102.3878	104.6057	109.1452	117.4163	121.2702	121.806
2000	100.9971	102.4902	103.5618	106.1371	111.6093	119.9591	122.6444	121.8426
2500	102.5151	103.8224	105.0676	107.5428	114.2434	122.1417	123.41	121.9955
3150	103.9886	105.2374	106.7053	109.1975	116.5463	124.0327	123.8301	122.0058
4000	104.5235	106.2247	107.8691	110.8037	118.2178	125.0716	123.6463	120.8982
5000	105.615	106.9812	108.8124	112.1234	119.3864	125.4065	122.8244	119.7813
6300	106.7536	108.1488	110.0199	113.4468	120.1969	125.3125	121.603	118.7048
8000	107.3213	108.794	110.6736	114.1467	120.4567	124.4192	120.6609	117.9769
10000	107.7195	109.5623	111.1576	114.7681	120.1171	123.1064	119.5438	116.6097
12500	108.3856	110.0803	111.5112	115.085	119.4678	122.0391	118.531	115.3949
16000	108.1445	109.9353	111.1748	114.7355	118.3078	120.9283	117.2504	113.9569
20000	107.4832	109.4097	110.5591	114.1831	117.329	119.6926	116.048	112.0719
25000	106.5097	108.3969	109.5432	112.8836	116.1385	118.3833	114.6048	110.3695
31500	104.5514	106.2984	107.9462	110.737	114.1323	116.4123	112.5365	108.1556
40000	102.8385	104.6889	107.0052	108.7707	112.389	114.956	110.5441	106.4377
OASPL	122.3586	124.0441	125.6179	128.7754	134.0331	138.8214	137.4937	136.27

Table B.17: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.79$, $T_0=1093.2$ K)

NPR = 5.52, Stagnation Temperature = 1508 °F, Chamber Temperature = 98.2 °F
Relative Humidity = 48.7 %, $\gamma = 1.33$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	88.84802	89.06186	90.544	91.39727	94.97882	98.4587	102.1226	106.2237
250	83.85174	84.92184	86.89072	88.22368	89.36464	93.23013	97.09216	101.9227
315	86.03224	88.89645	90.66982	91.01648	93.38478	95.90592	99.79428	106.3514
400	90.42429	92.28778	93.10696	94.32651	96.12995	99.82492	104.4094	108.1744
500	93.3183	94.30239	94.68857	95.38404	97.04892	102.6002	106.9225	112.7366
630	94.12059	95.32425	95.47876	96.73362	100.3255	106.4448	111.2546	115.816
800	94.84891	96.76259	98.44513	100.2824	104.8825	110.7526	115.76	119.0756
1000	96.46153	99.06098	100.2419	101.8445	106.6928	113.7994	117.9766	120.6936
1250	98.24191	101.3901	102.7452	104.2793	110.2185	116.533	120.396	121.4914
1600	99.83742	102.5172	104.3357	107.2961	113.3196	120.2168	122.5319	121.9399
2000	101.7708	104.1708	105.7559	108.9651	116.0119	122.4669	123.4451	122.2172
2500	103.4227	105.7688	107.61	110.8861	118.74	124.2023	123.9788	122.3986
3150	104.785	107.1824	109.1822	112.8916	121.0121	125.4648	124.2814	122.1097
4000	105.7881	108.436	110.657	114.6116	122.6013	125.8913	123.7027	121.2319
5000	106.7962	109.5297	111.7452	115.8005	123.615	125.8264	122.9294	119.9318
6300	107.9081	110.8663	113.2705	117.1628	124.2048	125.0202	122.0244	119.0237
8000	108.746	111.6403	114.0251	117.6099	124.4046	123.9947	121.2816	118.4625
10000	109.2579	112.299	114.4841	117.9351	123.9385	122.9796	120.2216	117.1883
12500	109.8247	112.6753	114.5157	117.658	122.9527	121.7789	119.097	115.9209
16000	109.6361	112.4179	114.0194	116.8797	121.2751	120.3872	117.8351	114.6219
20000	108.9972	111.8124	113.106	115.8845	120.0583	119.0644	116.4641	112.8658
25000	108.0636	110.6562	111.9365	114.5007	118.73	117.7278	114.9986	111.0674
31500	106.0907	108.5257	110.1067	112.1488	116.8634	115.8725	112.9407	108.8218
40000	104.62	107.0458	109.3159	110.4357	115.5752	114.6561	111.2522	107.2905
OASPL	123.7589	126.5017	128.4455	131.5743	137.8156	139.3902	138.1425	136.7474

Table B.18: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.79$, $T_0=1207.6$ K)

NPR = 5.52, Stagnation Temperature = 1714 °F, Chamber Temperature = 99.4 °F
Relative Humidity = 45.3 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	85.11063	85.4909	86.51024	85.94873	86.40587	90.20273	94.25129	99.1653
250	83.80466	85.46639	87.60028	88.71814	89.30512	92.99944	97.20159	101.9401
315	86.73158	89.47295	91.17309	92.04493	93.92071	95.52269	100.057	106.6938
400	90.77203	92.7326	93.98045	94.77062	96.31752	99.91349	104.8706	108.6612
500	93.84859	94.63992	94.99124	95.77539	97.30562	102.8432	107.1272	112.9907
630	94.39848	95.26759	95.73048	97.18831	100.2371	106.5573	111.5396	116.1165
800	95.25519	97.07063	98.60466	100.2991	105.0958	110.7203	115.7561	119.1168
1000	96.80307	99.33272	100.4891	102.3066	106.9078	113.9211	118.3134	120.9229
1250	98.37077	101.5839	102.8084	104.6274	110.4954	116.7978	120.499	121.3832
1600	100.2729	102.7547	104.8143	107.7746	113.6504	120.301	122.6747	121.9098
2000	102.2152	104.2114	105.9737	109.5131	116.6663	122.5773	123.5905	122.0215
2500	103.8966	105.9763	108.0592	111.6708	119.4413	124.4544	123.9703	121.9244
3150	105.3552	107.3373	109.572	113.7287	121.8413	125.8408	124.0214	121.385
4000	106.3856	108.8767	111.1243	115.6186	123.5802	126.2623	123.5409	120.4414
5000	107.6341	109.9464	112.3879	117.1813	124.7841	126.0455	122.6555	119.3742
6300	108.9232	111.3336	114.0094	118.4821	125.4754	125.155	121.8544	118.6022
8000	109.6417	111.9601	114.6091	119.0802	125.5675	124.0096	121.0415	117.8383
10000	110.2402	112.4651	115.0216	119.1848	124.8114	122.9934	120.0239	116.5774
12500	110.6442	112.8968	115.0824	118.936	123.4938	121.8042	118.795	115.4193
16000	110.3958	112.5456	114.3226	118.1259	122.0088	120.4625	117.603	113.9944
20000	109.7192	111.8349	113.3608	117.2189	120.9788	119.2075	116.2164	112.2406
25000	108.7393	110.6644	112.0977	115.7568	119.7926	117.8917	114.72	110.3622
31500	106.8239	108.5003	110.1737	113.6241	117.9182	115.9797	112.726	108.17
40000	105.3432	107.0425	109.3971	112.06	116.6784	114.7166	111.0021	106.5752
OASPL	124.5396	126.6942	128.8621	132.8357	138.78	139.5934	138.0527	136.4533

Table B.19: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.78$, $T_0=1314.8$ K)

NPR = 5.52, Stagnation Temperature = 1907 °F, Chamber Temperature = 104.9 °F
Relative Humidity = 40.1 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	85.29116	85.05561	86.09223	85.89385	86.79769	90.69048	94.24738	98.68381
250	85.54832	86.11701	87.74607	89.06055	90.36447	94.32928	98.09835	102.7588
315	87.15392	89.5017	91.25979	91.92384	94.32938	96.21585	100.8972	107.0114
400	90.70579	92.88312	93.76766	94.74257	96.57871	100.5853	105.1587	108.8262
500	93.81816	94.67199	95.03436	96.06332	98.37527	104.0606	107.9752	113.4408
630	94.17849	95.90138	96.07626	97.66889	101.5543	107.6634	112.2977	116.4271
800	95.54624	97.3435	99.15102	101.3069	106.451	111.8834	116.5122	119.3871
1000	97.06326	99.60381	101.157	103.2634	108.5254	115.0874	118.8713	120.9595
1250	99.07603	102.308	103.5399	105.9026	112.1706	118.0897	120.8866	121.3802
1600	101.1431	103.7488	105.7247	109.3937	115.6853	121.7168	122.6548	121.5413
2000	102.6077	105.1395	106.9007	111.2407	118.2888	123.5002	122.9969	121.6775
2500	104.8026	107.0619	108.9988	113.6373	121.2533	125.117	123.5582	121.7368
3150	106.3936	108.3588	110.8723	115.9124	123.532	126.1971	123.6874	121.5137
4000	107.4143	109.8094	112.3191	118.2587	125.2276	126.5744	122.9544	120.5083
5000	108.4922	111.1392	113.6888	119.6814	126.3376	126.1663	122.1354	119.5902
6300	109.7761	112.5444	115.1814	120.8383	126.9909	125.0994	121.2423	118.8226
8000	110.6197	113.345	115.8272	121.2149	126.6833	124.081	120.4635	118.1804
10000	110.9097	113.7793	115.8251	120.9293	125.4572	122.9932	119.3549	116.8933
12500	111.3319	114.2097	115.7692	120.3005	124.0635	121.7484	118.1212	115.7818
16000	111.0234	113.8971	114.9319	119.2183	122.6888	120.4237	116.8297	114.3862
20000	110.3796	113.1185	113.9237	118.0968	121.5802	119.0938	115.4047	112.4199
25000	109.3289	111.9439	112.5318	116.5931	120.3217	117.729	113.9334	110.5026
31500	107.313	109.7421	110.617	114.4688	118.4553	115.8313	111.8999	108.2096
40000	105.9731	108.3886	109.9352	113.0533	117.4217	114.7318	110.3928	106.9075
OASPL	125.261	127.944	129.7383	134.5581	139.9677	139.9046	137.7073	136.4844

Table B.20: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.05$, $T_0=290.9$ K)

NPR = 8.46, Stagnation Temperature = 63.9 °F, Chamber Temperature = 71.7 °F
Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.19565	83.79801	84.99471	86.2902	87.40623	87.84322	90.4208	96.40988
250	82.23296	84.30622	86.48104	88.70543	89.11431	90.01952	93.79921	99.60935
315	87.13971	89.39475	91.35647	92.37011	92.68279	94.8574	94.90037	102.8251
400	91.07213	93.05388	94.44057	94.18992	95.32832	96.00286	99.80826	105.2262
500	93.45307	94.65546	94.263	95.127	95.39739	96.68394	100.9225	108.8941
630	94.73983	95.14171	95.11902	95.73389	97.01963	99.14988	104.3963	112.3618
800	94.49172	96.13768	97.56777	98.50603	99.60012	101.863	108.337	116.1208
1000	96.69089	98.28825	98.71689	99.74953	100.2076	103.6167	109.8772	118.2763
1250	97.48078	98.58809	100.0497	101.2779	102.9195	106.6842	114.1117	120.9579
1600	98.90565	100.4848	101.2206	103.0224	103.9117	108.1239	115.9348	122.4721
2000	99.90834	101.5903	102.4104	103.908	104.9632	109.7967	118.3115	123.5394
2500	101.1331	102.8215	103.4186	105.0549	106.2487	110.8563	119.8249	123.8672
3150	103.7363	104.2514	105.22	106.0202	107.3254	111.759	120.8475	124.2419
4000	105.1276	106.0549	105.7183	106.6917	108.0494	112.2108	121.2839	123.884
5000	105.192	106.8031	107.1413	107.4415	108.7528	112.6311	121.4419	122.8286
6300	105.5735	106.8213	107.4913	108.6774	109.4045	112.9084	121.1748	120.9066
8000	105.9014	107.2658	107.1228	108.8995	110.037	112.7763	120.5743	119.3696
10000	105.7192	107.4688	107.3538	108.8863	110.2944	112.5915	119.6593	118.1325
12500	105.6547	107.3579	107.2738	109.1736	110.1204	112.0786	118.4646	116.6167
16000	104.7597	106.7058	106.8302	109.105	109.305	111.2086	117.1632	114.9736
20000	103.7983	105.9656	106.3228	108.9146	108.8753	110.4089	115.9441	113.5952
25000	102.8197	105.0055	105.5929	108.31	108.2779	109.3225	114.6602	112.1903
31500	101.0447	103.1745	104.3922	106.7474	106.8806	107.6802	112.6845	110.3457
40000	99.81588	101.9481	104.1066	105.2827	105.38	106.2587	110.7094	108.5518
OASPL	120.5345	122.1219	122.6102	124.1391	124.9203	127.7727	135.435	137.7096

Table B.21: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.03$, $T_0=592.6$ K)

NPR = 8.16, Stagnation Temperature = 607 °F, Chamber Temperature = 85.4 °F
 Relative Humidity = 64.7 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	84.30839	86.36566	87.43033	88.56003	92.2407	90.28798	93.94991	100.4851
250	83.25424	85.89798	87.91627	89.66762	91.60202	93.0542	96.65331	102.5812
315	87.62445	90.90101	93.06726	93.57276	93.07069	97.31445	99.00916	107.7612
400	92.54432	94.21328	95.30228	96.15983	94.31643	99.13482	104.7762	109.1839
500	95.31246	96.50532	96.49312	96.89772	93.2855	101.3191	106.5571	113.6049
630	95.73536	96.20178	96.49254	97.25786	94.1017	104.3802	110.6963	116.9621
800	95.38602	96.91834	98.4892	100.0122	97.21543	107.9833	115.0658	120.6045
1000	98.22822	99.92184	100.6663	102.2514	98.63136	110.8542	117.4458	122.6419
1250	99.55634	101.6796	102.4158	103.8922	101.7259	114.0469	120.6073	124.2173
1600	100.1493	102.3299	104.2027	105.825	103.6959	117.4743	123.2711	125.0436
2000	102.6114	104.0016	105.1859	107.1859	105.2981	120.1378	124.6382	125.0143
2500	103.9622	105.9082	106.6447	108.8524	107.5611	122.2828	125.7559	124.8338
3150	105.5786	106.7743	108.0898	109.8977	109.1805	124.0968	126.2833	124.2667
4000	106.2436	107.831	109.045	111.2191	110.3189	125.4348	125.9221	122.9313
5000	107.2595	108.5362	109.5844	112.1792	111.2249	126.0361	124.7895	121.6228
6300	108.4064	109.8435	110.7251	113.5519	111.9216	126.0035	123.5448	120.5485
8000	109.1246	110.6495	111.3294	114.2209	112.1323	125.2352	122.3785	119.6082
10000	109.2823	111.1059	111.7356	114.7057	111.7904	123.95	121.2389	118.1767
12500	109.2723	111.3697	111.7932	115.0854	111.3214	122.7149	120.1587	116.7072
16000	108.8025	110.9815	111.3943	114.7954	110.1767	121.5373	118.9399	115.1883
20000	107.8899	110.269	110.6673	114.1003	109.1963	120.3487	117.7841	113.6125
25000	106.6694	109.0123	109.6163	112.987	108.0404	119.0576	116.4721	112.0093
31500	104.5614	106.7885	107.8878	110.8276	106.0491	117.1829	114.4302	109.8832
40000	103.0364	105.1703	107.1169	109.0986	104.29	115.8458	112.575	108.1966
OASPL	123.5207	125.3893	126.2123	128.98	126.1361	139.3754	139.5439	138.8316

Table B.22: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.02$, $T_0=813.2$ K)

NPR = 8.03, Stagnation Temperature = 1004 °F, Chamber Temperature = 99.5 °F
Relative Humidity = 64.7 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	86.36365	87.70056	88.91266	89.4912	89.79967	91.74745	95.77213	101.5399
250	85.54907	88.50895	90.53127	91.72863	91.68268	94.76353	98.83408	104.4652
315	88.27697	91.5363	93.23482	94.25183	96.227	97.82421	101.0662	109.0476
400	93.13239	95.54144	96.64689	97.54097	98.24205	101.1221	106.038	110.4739
500	96.35085	97.36516	97.6834	98.2312	98.57357	103.3431	107.7914	115.0536
630	96.70332	97.2458	97.87661	98.3998	100.436	106.2221	112.214	118.3665
800	96.49717	98.09401	100.251	101.6248	104.4647	110.5	116.7148	121.5006
1000	98.64877	100.4782	101.8172	103.2345	105.9054	113.4098	119.0714	123.3385
1250	100.0617	102.6795	103.9663	105.6897	109.3731	116.7275	122.2239	124.7337
1600	101.1345	103.5061	105.7345	107.8498	111.8831	120.4301	124.6335	125.1988
2000	103.5887	105.426	106.8654	109.2671	114.2841	122.8649	125.7333	125.1587
2500	104.9693	107.3101	108.3552	111.0259	116.9646	124.9288	126.5847	125.0275
3150	106.4379	108.061	109.8184	112.339	118.9264	126.6142	126.8172	124.217
4000	107.1165	109.1342	110.8621	113.9759	120.6203	127.4355	125.924	123.2264
5000	108.0412	110.0031	111.7814	115.0971	121.7336	127.4601	124.9012	122.015
6300	109.3134	111.3727	113.102	116.4183	122.4565	126.5298	124.0427	120.8286
8000	110.1348	112.3285	113.9198	117.1086	122.7143	125.3955	122.9534	119.9574
10000	110.5127	112.7578	114.2669	117.4777	122.4722	124.1455	121.8891	118.5233
12500	110.6093	113.0955	114.3639	117.5953	121.7453	122.9082	120.7616	117.2562
16000	110.0938	112.6822	113.8273	117.1385	120.4202	121.6827	119.5263	115.7392
20000	109.2566	112.0088	113.131	116.267	119.3393	120.4668	118.317	114.1325
25000	108.0062	110.7106	111.9095	114.7979	118.1037	119.1589	116.9282	112.4753
31500	105.9368	108.4864	110.0683	112.6901	116.0965	117.311	114.9114	110.3624
40000	104.4364	107.0159	109.2883	111.006	114.753	116.1404	113.2825	108.9311
OASPL	124.6495	126.978	128.4974	131.4122	136.3393	140.6227	140.2332	139.2042

Table B.23: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=983.7$ K)

NPR = 7.85, Stagnation Temperature = 1311 °F, Chamber Temperature = 112 °F
Relative Humidity = 57.8 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	88.26963	88.59952	89.62997	89.33562	90.08828	93.18281	96.94836	102.3553
250	86.768	89.19605	90.09736	91.84276	92.81852	96.0427	100.0842	105.6663
315	89.51263	92.68426	94.32036	95.56228	97.57389	98.76362	103.2486	110.2194
400	94.25012	96.51029	97.55309	98.97196	99.49509	103.4769	107.9132	112.1996
500	97.32844	98.51384	98.67532	99.02301	100.0422	104.905	109.9002	116.6199
630	97.25316	98.49169	99.09083	99.88802	102.0081	108.2187	114.1766	119.6945
800	97.40969	99.15213	101.2466	102.7532	106.461	112.4248	118.4459	122.5341
1000	99.48673	101.4838	103.1474	104.8218	108.3642	115.3132	120.7515	124.3037
1250	100.6241	103.0461	105.179	106.7072	111.6408	118.5212	122.966	124.7566
1600	102.5142	104.807	107.2625	109.5135	114.9279	122.327	125.6168	125.4818
2000	104.3949	106.0328	108.385	111.0221	117.4195	124.2515	126.2404	125.4247
2500	105.9211	107.9338	109.9817	113.0138	119.9639	126.2132	127.0868	125.2015
3150	107.1251	109.2865	111.5066	114.941	122.3388	127.5381	126.9248	124.4086
4000	108.1455	110.3542	112.8732	116.4233	123.9665	128.0574	126.0253	123.4277
5000	109.1606	111.3744	114.0849	117.6126	125.2177	127.5388	125.2095	122.1635
6300	110.4828	112.9444	115.3876	119.0209	125.8742	126.5514	124.1809	121.2822
8000	111.4043	113.8069	116.0555	119.6504	125.9011	125.4842	123.2861	120.3096
10000	111.6035	114.2447	116.207	119.6971	124.8902	124.2898	122.0931	118.949
12500	111.831	114.554	116.2644	119.4574	123.6087	123.1019	120.7962	117.5943
16000	111.5554	114.0738	115.5895	118.6273	122.1559	121.7535	119.5163	116.2005
20000	110.7124	113.1979	114.5722	117.6539	120.9719	120.5492	118.1138	114.3974
25000	109.5067	111.8414	113.1681	116.1015	119.7518	119.1563	116.6945	112.537
31500	107.4595	109.6224	111.2259	113.8605	117.8359	117.3218	114.7201	110.411
40000	106.0801	108.1212	110.4737	112.3077	116.7445	116.2733	113.2083	109.1469
OASPL	125.877	128.2844	130.276	133.4003	139.072	141.1757	140.6315	139.5858

Table B.24: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1123.2$ K)

NPR = 7.82, Stagnation Temperature = 1562 °F, Chamber Temperature = 93.1 °F
Relative Humidity = 57.8 %, $\gamma = 1.33$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	87.45055	88.50373	89.80732	89.34667	89.64525	93.03348	97.4346	102.8939
250	86.71232	89.28112	90.13119	91.90642	92.59561	95.94735	100.2845	105.8414
315	89.04153	92.22651	93.9594	95.1101	97.10282	98.16898	102.8194	110.0365
400	93.94668	96.56125	97.34338	98.90381	99.38093	103.0502	107.182	111.5741
500	96.70839	98.2925	98.50634	98.98997	99.84971	105.1062	109.8066	116.6782
630	97.16369	98.51745	99.06777	99.86109	102.4466	108.2088	114.0589	119.4185
800	97.29586	99.54858	101.2634	102.9517	106.5954	112.5685	118.4171	122.4814
1000	98.60784	101.2069	102.8246	104.7844	108.6547	115.7243	120.7902	124.0368
1250	100.3471	103.2641	105.0702	107.206	111.6338	118.5494	123.0914	124.9344
1600	102.5124	104.665	106.9701	109.7246	115.0669	122.4112	125.5244	125.5216
2000	104.4416	106.4825	107.8888	111.1365	117.5556	124.6561	126.1383	125.2192
2500	105.7882	107.959	109.9069	113.2495	120.0615	126.1853	126.7407	124.8301
3150	107.2971	108.9698	111.4875	114.8543	122.5006	127.6849	126.6601	124.0713
4000	108.1398	110.2385	112.6863	116.68	124.3192	128.0806	125.8256	122.8468
5000	109.2837	111.3965	113.9571	117.9421	125.6038	127.6653	124.753	121.4711
6300	110.5847	112.7648	115.3065	119.3613	126.2426	126.6541	123.7581	120.499
8000	111.4392	113.6471	115.9641	120.0151	126.1241	125.5954	122.9545	119.5779
10000	111.8048	114.1598	116.2807	120.1743	124.9741	124.3838	121.8584	118.2421
12500	112.1376	114.4349	116.3844	119.898	123.7383	123.2567	120.591	116.8648
16000	111.8056	114.1088	115.7533	119.0985	122.4208	121.8051	119.3098	115.3212
20000	111.0489	113.3223	114.7517	118.023	121.2426	120.5898	117.8985	113.4933
25000	109.9279	111.9697	113.3227	116.4742	119.89	119.2843	116.4328	111.6515
31500	107.8787	109.6803	111.3321	114.2876	118.041	117.5001	114.4263	109.3644
40000	106.4576	108.2421	110.6215	112.7546	116.988	116.5269	113.0155	108.1637
OASPL	126.0734	128.2422	130.2747	133.7711	139.3349	141.2685	140.4043	139.2979

Table B.25: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1203.7$ K)

NPR = 7.82, Stagnation Temperature = 1707 °F, Chamber Temperature = 101.8 °F
Relative Humidity = 69.6 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	88.06238	88.59334	89.61362	89.20296	90.01836	93.31825	97.37626	102.4358
250	87.23522	89.92631	90.56962	92.01665	92.81706	96.2186	100.6164	106.3007
315	89.15411	92.07337	93.99163	95.68394	97.58727	98.46349	103.6967	110.3927
400	93.94378	96.52137	97.9112	99.37116	99.52201	103.3833	107.9789	112.3737
500	96.77857	98.28595	98.85519	99.19541	100.4666	105.7521	110.5568	116.8605
630	97.28777	98.36061	99.07629	100.0085	102.5148	108.9221	114.8351	119.8215
800	97.27924	99.27746	101.4654	103.0175	106.5523	112.7917	119.0135	122.7722
1000	98.60216	101.5854	103.0349	105.0604	108.7696	115.9308	121.449	124.1488
1250	100.5181	103.6741	105.2804	107.4311	111.9962	118.8838	123.8708	124.982
1600	102.5105	104.816	107.3706	110.1701	115.4481	122.4379	126.1161	125.4754
2000	104.5154	106.9335	108.5045	111.8233	117.9307	124.6286	126.9442	125.2351
2500	106.1295	108.4848	110.1661	113.8317	120.6653	126.5007	127.8001	124.8193
3150	107.5139	109.7123	111.7657	115.9271	123.2214	127.7841	127.6648	123.9652
4000	108.3498	111.063	113.1431	117.7102	124.8315	128.1058	126.9719	122.9732
5000	109.3708	112.2375	114.2207	119.0689	126.1287	127.7512	126.0402	121.7067
6300	110.6944	113.7513	115.6184	120.3926	126.7562	126.714	125.0272	120.7713
8000	111.4524	114.3808	116.3553	121.0165	126.3826	125.6975	124.0943	119.8414
10000	111.7902	114.8769	116.6907	121.2092	125.1634	124.4963	123.0628	118.5825
12500	111.9554	115.2486	116.6619	120.8927	123.8535	123.372	121.902	117.473
16000	111.6062	114.7934	115.9365	120.0675	122.3924	122.0714	120.6676	115.9687
20000	110.808	113.9706	114.9938	119.1407	121.4535	120.8323	119.3881	114.2434
25000	109.658	112.6607	113.6751	117.7003	120.1489	119.4638	118.0038	112.5182
31500	107.4931	110.3253	111.7805	115.5647	118.3306	117.6362	115.9522	110.3058
40000	106.0729	108.916	111.0413	114.0563	117.2213	116.5438	114.4406	109.0877
OASPL	125.994	128.9705	130.6129	134.8242	139.6733	141.3872	141.4362	139.4182

Table B.26: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.01$, $T_0=1316.5$ K)

NPR = 7.73, Stagnation Temperature = 1910 °F, Chamber Temperature = 100.4 °F
Relative Humidity = 43 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	89.01174	89.12871	90.07453	89.24062	90.02963	93.983	97.99138	103.1081
250	87.16087	89.60414	90.08992	91.90774	93.33553	96.65202	100.7974	106.2222
315	89.54233	92.53363	94.31944	95.50234	97.50728	98.8306	104.069	110.5859
400	94.6171	96.93895	97.52733	99.1234	99.81039	103.9937	108.3383	112.4474
500	96.93474	98.36313	98.37323	99.37853	100.701	105.6297	110.7226	116.8428
630	97.51643	98.51518	99.38718	100.1749	103.0269	109.2919	114.8196	119.7743
800	97.5638	99.86294	101.6901	103.434	107.9027	114.0666	119.4438	122.895
1000	99.25401	101.6561	103.5567	105.5802	109.7582	116.7844	121.3738	124.0395
1250	100.925	104.1643	105.5193	107.8901	112.9877	119.8503	123.5707	124.6197
1600	102.942	105.3106	107.4934	110.5821	116.1709	123.1423	125.8796	125.3642
2000	105.0632	107.0169	108.8514	111.8804	119.186	125.3433	126.5138	125.0888
2500	106.5607	108.8537	110.7413	114.114	121.9316	127.2955	127.0681	124.6527
3150	107.6262	109.9665	112.1218	115.9852	124.0452	128.4365	126.7703	123.8817
4000	108.7286	111.2567	113.6382	117.8859	125.9196	128.5962	126.0047	122.92
5000	109.7813	112.4898	114.8108	119.1468	127.0435	128.0747	125.2358	121.6941
6300	111.1673	113.8075	116.2498	120.3887	127.5378	127.1968	124.1703	120.7167
8000	111.9348	114.8246	116.9543	120.8148	127.0866	126.201	123.4177	119.8085
10000	112.3481	115.3192	117.0929	120.8208	125.8086	125.0683	122.3455	118.6004
12500	112.631	115.5799	117.0391	120.5069	124.4242	123.9565	121.1526	117.5135
16000	112.3115	115.2793	116.3098	119.3886	123.0353	122.5622	120.1034	116.232
20000	111.6057	114.5256	115.254	118.3922	121.8489	121.3333	118.8068	114.4328
25000	110.3148	113.2068	113.8934	116.9406	120.66	119.9748	117.4129	112.6061
31500	108.2564	110.9139	111.9855	114.7475	118.7687	118.1476	115.4632	110.4727
40000	106.7372	109.4345	111.1423	113.265	117.6455	116.9614	113.9221	109.2014
OASPL	126.5632	129.3478	131.0266	134.5194	140.4674	141.9461	140.8256	139.3264

APPENDIX C

ACOUSTIC DATA FOR OFF-DESIGN JETS

Table C.1: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.4$, $T_0=288.9$ K)

NPR = 3.17, Stagnation Temperature = 60.3 °F, Chamber Temperature = 59.6 °F
Relative Humidity = 69.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.57914	75.71598	74.92641	74.85038	73.8115	74.75447	77.93493	83.43976
250	73.77065	75.20126	75.20845	77.00157	76.56061	76.74053	79.95344	85.65706
315	74.97086	76.93904	77.99681	79.43629	78.36832	80.6379	82.85029	88.2926
400	77.11004	79.91373	80.71826	81.06295	81.47266	83.08833	86.89648	92.32198
500	79.79254	80.99412	81.46922	82.45772	82.67223	84.07783	88.30191	94.77037
630	81.75597	82.8569	83.59433	84.62095	84.64583	86.99193	91.94693	98.18477
800	83.0512	84.89975	86.16925	86.79011	87.69851	89.92894	95.70666	101.417
1000	84.74894	86.35332	87.01201	88.41478	88.65415	92.15026	97.73306	104.3956
1250	86.2673	87.76207	90.07621	91.22773	92.25072	95.73232	101.8808	107.5697
1600	88.49623	90.53294	91.62039	92.94227	93.76972	97.134	103.5522	109.3469
2000	89.95621	91.74097	92.88191	94.0053	95.19633	98.79514	105.4941	110.8952
2500	90.87798	92.90106	93.31875	94.61794	96.30695	99.83408	106.2359	111.0614
3150	92.11968	93.69208	94.95742	95.82824	97.40201	100.7832	105.9182	110.4676
4000	92.56454	94.41921	94.88418	96.28103	97.95142	101.3761	105.2393	109.6213
5000	97.1873	95.80522	95.50374	96.72533	98.05398	101.2266	104.1276	108.489
6300	105.4992	102.6333	98.22771	98.02669	98.74961	101.2751	103.0169	105.4988
8000	109.0615	108.6661	103.6269	100.7014	100.1736	101.6123	102.0364	103.6917
10000	106.468	107.8404	105.9832	103.7302	101.215	101.5461	101.1459	101.8658
12500	104.1724	105.6415	105.1228	105.5646	103.7731	102.4677	100.714	100.5043
16000	103.1481	103.8463	102.8151	104.8396	104.7143	103.5614	100.5389	99.38662
20000	102.0429	102.9937	101.5747	103.1332	104.1118	104.05	100.2067	98.05795
25000	100.8435	101.8159	100.6227	101.8971	102.1554	102.7991	99.50181	96.70242
31500	98.9927	99.90097	99.28774	100.1197	99.62817	99.77418	97.30729	94.58538
40000	97.75975	98.66216	99.04541	98.64073	98.11008	97.49649	94.74911	92.46705
OASPL	118.8522	119.1701	117.3618	117.3707	117.0961	117.9011	119.7976	123.853

Table C.2: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.5$, $T_0=289.2$ K)

NPR = 3.66, Stagnation Temperature = 60.9 °F, Chamber Temperature = 71.1 °F
Relative Humidity = 34.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	79.09866	74.66354	76.2226	76.89151	76.63707	77.94694	82.62733	88.9591
250	79.00928	74.23009	76.27004	78.23984	78.94824	79.40281	84.53391	89.11205
315	78.41395	78.44515	79.96053	81.00929	80.39573	82.98612	85.5649	91.36202
400	80.12374	81.78461	82.34502	82.47208	83.07404	85.26721	88.78576	94.39546
500	82.31503	83.52527	83.82047	84.57996	84.646	86.5744	91.17364	97.09484
630	84.55038	85.65949	86.75446	87.27775	87.67546	90.2672	94.90513	100.6586
800	86.61012	88.43398	89.60623	90.21957	90.83718	93.24448	99.09221	104.2825
1000	87.85263	90.08227	90.87842	92.43081	92.46441	96.07333	101.2314	107.191
1250	89.98762	92.07739	93.97665	94.95914	95.97264	99.91013	106.2917	111.1142
1600	92.36839	94.48352	95.72837	97.30258	97.86967	102.0877	108.678	113.2935
2000	93.66795	95.80277	96.96898	98.28633	99.39834	104.2824	110.878	114.7707
2500	94.74838	96.7292	97.68203	98.93608	100.6262	104.9509	111.0308	113.9877
3150	95.90789	98.57241	99.59141	99.91714	101.7092	105.6922	110.6934	113.0531
4000	98.04232	101.419	101.4279	100.6444	102.5202	106.9699	111.3823	113.2136
5000	104.7242	101.9668	100.2103	100.8994	102.2222	105.5391	108.253	110.3794
6300	111.0327	111.2844	108.0679	103.0713	103.2327	105.7598	107.1016	108.9833
8000	111.4915	115.1087	113.5633	106.6121	104.9673	106.0121	106.1651	107.6367
10000	107.1561	107.4906	108.2319	109.12	106.5571	105.5569	104.9616	106.1179
12500	106.483	106.9551	105.7491	107.8933	108.5912	106.4317	104.4303	104.7413
16000	104.8737	106.5669	105.3053	106.1012	107.8279	107.1947	104.0587	103.343
20000	103.8823	104.8118	103.8901	105.428	105.9577	106.8125	103.7047	101.6833
25000	102.5875	103.5303	102.8563	104.2417	104.0247	104.647	102.743	100.0531
31500	100.7609	101.6349	101.3616	102.5063	102.0185	101.8744	100.4604	98.02837
40000	99.53034	100.3767	100.9949	100.9585	100.3042	100.0282	97.98584	96.23779
OASPL	121.7284	123.4067	122.1822	120.7329	120.7428	121.8791	124.4566	127.1672

Table C.3: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.6$, $T_0=289.5$ K)

NPR = 4.24, Stagnation Temperature = 61.4 °F, Chamber Temperature = 71.1 °F
 Relative Humidity = 34.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.45338	76.8031	77.82591	78.29936	78.52276	79.31177	81.80143	87.13058
250	79.65292	77.28081	78.90616	80.41051	80.49932	80.38117	83.98834	89.92482
315	80.46471	80.96556	82.70011	83.61864	83.09766	85.25743	86.26703	92.75978
400	81.93129	83.63663	84.57085	84.69765	85.43842	87.10488	90.32275	96.07688
500	84.72312	85.69681	86.1855	86.95777	86.88094	88.45018	92.87307	99.9414
630	86.37916	87.35016	88.00546	88.8346	89.59452	91.70269	96.95889	103.6522
800	87.88935	89.36212	91.00262	91.83848	92.87959	94.63985	100.8526	107.1261
1000	89.51604	91.02499	91.72296	93.41642	93.61951	96.72946	103.0514	110.4803
1250	90.7741	92.09648	94.24336	95.11711	96.11455	99.813	107.0651	113.4859
1600	93.07749	94.5813	95.90056	97.49918	98.11456	101.9652	109.3181	115.5974
2000	93.63278	95.53887	96.73235	98.33212	99.31877	103.5667	111.24	116.965
2500	94.7607	96.75555	97.48939	98.95499	100.7733	104.4456	111.7224	116.8719
3150	99.12107	100.0521	101.4528	102.0602	102.0955	106.5155	112.9516	116.5654
4000	103.14	100.4217	99.72444	100.5589	102.0058	105.4897	110.7067	116.3421
5000	111.8859	107.7127	102.7804	102.0001	102.7504	105.5079	109.5113	114.8113
6300	114.8591	116.8472	111.8284	105.5366	104.6229	106.3442	108.4671	113.6371
8000	110.3376	113.1928	113.5744	110.4932	106.8943	107.1336	107.7931	112.4955
10000	109.3025	109.2767	110.5862	112.8682	110.552	108.0784	107.1796	110.9916
12500	108.7572	109.9552	107.852	110.5956	113.1306	109.8734	107.2141	109.7533
16000	107.6446	108.3367	107.8287	108.6592	111.6944	111.2699	107.2081	108.1331
20000	106.5784	107.633	106.3686	108.3897	109.0337	111.3291	107.01	106.3746
25000	105.5453	106.4	105.4771	107.0831	107.7087	108.9001	106.0735	104.9413
31500	103.7819	104.5976	104.1211	105.3947	105.8637	105.7578	103.7288	103.125
40000	102.5705	103.472	103.8626	103.9212	104.0158	104.222	101.2613	101.2867
OASPL	124.4202	125.3853	123.7887	123.6008	123.8833	124.0633	125.7331	130.4182

Table C.4: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.7$, $T_0=289.9$ K)

NPR = 4.93, Stagnation Temperature = 62.2 °F, Chamber Temperature = 71.1 °F
Relative Humidity = 34.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.53494	78.76978	79.3569	79.76942	80.45052	81.02042	83.85132	90.90539
250	80.51368	78.21111	80.13085	81.79728	82.25065	82.48962	86.12845	92.80256
315	82.11411	82.6215	84.54669	85.31053	85.18759	87.58476	88.22567	95.28238
400	84.56858	85.82347	87.12827	87.21738	87.84838	89.02672	92.60727	98.62563
500	86.51921	87.47255	87.58789	88.60573	88.53124	89.82185	94.39601	101.7046
630	88.33973	88.74999	89.02813	89.72711	90.59288	92.84015	97.8085	105.2489
800	88.86603	90.77706	91.699	92.6892	93.84503	95.46517	101.8213	109.0514
1000	91.14863	92.91986	92.74314	94.27317	94.83473	97.61588	103.6541	112.1729
1250	92.29653	92.90745	94.85105	96.04726	97.41384	100.7545	107.4997	115.0861
1600	93.91898	95.1838	96.59208	98.22399	98.70762	102.371	109.4184	117.1851
2000	94.74069	96.34021	97.58691	98.67705	99.4463	103.4562	111.2092	118.3759
2500	95.9628	97.73353	98.56108	99.94421	101.3802	104.7343	111.9469	118.8326
3150	100.4219	100.046	100.7954	100.7347	102.2679	105.3397	111.8038	118.7221
4000	109.6043	104.5167	101.8659	101.8388	102.8332	105.735	111.183	118.626
5000	116.2567	113.8796	106.9728	104.3307	104.2614	106.3453	110.1194	117.858
6300	114.3142	117.3988	114.7172	108.6844	106.6917	107.6229	109.573	116.828
8000	110.4484	113.0103	115.4981	114.2496	109.9783	109.2127	109.1554	115.7466
10000	110.9476	110.8092	110.4924	114.818	114.0406	110.7973	109.1101	114.1983
12500	109.8899	111.5672	109.7507	111.1093	116.1612	112.709	109.4669	112.6143
16000	109.0538	110.1995	109.5144	110.3396	113.3585	113.8424	109.5459	110.9194
20000	108.1278	109.4682	108.2561	110.1328	110.8333	113.5188	109.3595	109.3893
25000	107.0494	108.4236	107.3708	108.8828	110.2736	110.987	108.1842	108.0537
31500	105.3529	106.5492	106.1627	107.3127	108.192	108.0692	105.8111	106.02
40000	104.2433	105.4631	105.9945	105.8904	106.5393	106.6523	103.63	104.0923
OASPL	126.1051	126.8603	125.7014	125.6196	126.3439	126.0277	126.4632	132.6735

Table C.5: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.8$, $T_0=290$ K)

NPR = 5.74, Stagnation Temperature = 62.4 °F, Chamber Temperature = 71.1 °F
 Relative Humidity = 34.6 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.86454	80.28613	81.0853	81.81971	82.55455	83.39187	85.84465	90.73866
250	81.17381	79.95509	81.58216	83.26709	84.13546	85.06755	88.2085	93.66561
315	83.16309	84.392	86.3072	86.51639	86.76296	89.34638	89.78273	96.92348
400	86.6822	87.77879	88.64337	88.92553	89.80113	91.08188	94.45417	100.6856
500	88.25915	89.58927	89.37956	90.36338	90.26236	91.78468	95.89024	103.5088
630	89.98148	90.21443	90.58643	91.50035	92.37394	94.57742	99.73622	107.2843
800	90.58591	92.46407	93.38333	94.4441	95.6054	97.04876	103.6965	111.207
1000	92.357	93.77497	94.37979	95.64699	96.10095	99.13017	105.0896	113.5488
1250	93.40627	94.21814	96.394	97.27622	98.37753	101.9992	108.8467	116.3655
1600	95.03368	96.59021	98.08921	99.39371	99.77883	103.803	110.7294	118.1726
2000	96.04603	97.76388	98.86208	99.97985	100.9146	104.9567	112.4234	119.3481
2500	97.4543	99.13818	99.90135	101.0538	102.5725	106.0621	112.9995	119.6874
3150	102.1141	101.1592	101.8683	101.8977	103.2867	106.7421	112.9269	119.9037
4000	111.807	106.7781	103.2448	102.9791	103.8145	107.0839	112.2632	119.7089
5000	115.1974	115.2779	109.0642	105.2142	105.0366	107.6654	111.277	119.2963
6300	112.1137	115.0186	115.4321	110.108	107.2272	108.3964	110.8174	118.6117
8000	109.8975	110.8698	113.3361	114.68	110.486	109.6688	110.6015	117.3783
10000	109.9179	110.5257	109.3268	113.221	114.0616	111.0323	110.4153	115.9187
12500	109.2108	110.1527	109.6417	110.4235	114.9742	112.6464	110.5837	114.3386
16000	108.5105	109.418	108.7604	110.2726	112.3387	113.2671	110.4777	112.8002
20000	107.7532	108.6909	107.9758	109.7622	110.1353	112.3067	109.9415	111.3821
25000	106.7506	107.7226	107.1916	108.7705	109.4224	110.1496	108.7696	109.9253
31500	105.1349	105.9517	106.0012	107.2229	107.6719	107.7313	106.7089	107.9995
40000	103.9484	104.9239	105.8369	105.9137	106.0123	106.1121	104.8395	106.264
OASPL	125.4338	126.044	125.3928	125.466	125.8984	125.9552	127.5962	133.9747

Table C.6: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.4$, $T_0=977.6$ K)

NPR = 3.1, Stagnation Temperature = 1300 °F, Chamber Temperature = 73 °F
Relative Humidity = 51.4 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.48028	85.65218	87.51168	89.31899	91.35937	92.91464	95.1194	98.81896
250	77.35345	79.40925	80.53786	81.60284	83.29237	87.02574	90.22391	94.21458
315	79.42812	81.99892	83.36969	83.66311	85.86239	89.06946	91.23945	97.34963
400	82.68644	84.7402	85.99286	86.52966	88.48486	91.485	96.50407	99.95041
500	84.90949	87.07302	86.60054	88.12329	89.53436	94.8339	98.68034	104.0832
630	86.74097	88.03575	88.39191	89.57196	92.74985	98.27378	102.7356	107.1612
800	87.76921	89.60939	91.28518	92.64843	96.88432	102.3181	107.0674	110.7429
1000	90.22345	91.86461	92.74121	95.03965	98.84243	105.3644	109.4421	112.9615
1250	91.83111	93.88046	94.93857	96.48335	102.6873	108.6405	112.7953	114.7423
1600	93.49749	95.42333	96.86378	99.78245	105.316	112.1766	115.3057	115.9936
2000	95.76228	97.20097	98.63513	101.6207	108.1199	115.04	117.0787	116.2942
2500	97.6448	98.50742	100.3573	103.5935	110.997	117.4685	118.2464	116.8856
3150	99.03509	100.5462	102.6259	105.571	113.1671	119.1847	118.8109	117.4485
4000	99.86948	101.6088	103.5698	107.1237	114.5308	120.1343	119.4711	117.7765
5000	100.9244	102.71	104.5429	108.3171	115.6881	120.9347	120.7015	117.8423
6300	101.6441	103.4865	105.4538	109.3194	116.198	121.0359	119.1972	115.5184
8000	102.6749	103.7387	105.8176	109.8502	115.8913	120.7745	117.7323	114.4679
10000	105.3799	104.7539	106.1033	110.2855	115.2149	119.8515	116.4185	113.0861
12500	106.5993	106.4198	106.2562	110.4918	114.1868	118.6398	115.1781	111.5056
16000	104.97	106.7086	106.3236	110.1674	112.9115	117.2041	113.6822	109.7845
20000	103.1213	104.9802	105.9825	109.6606	111.7963	115.8141	112.1653	107.8756
25000	101.8538	103.1467	104.5836	108.5753	110.4113	114.3259	110.598	105.9931
31500	99.54354	100.9549	102.5886	106.5157	108.3793	112.2497	108.4331	103.7781
40000	97.98219	99.57007	101.9103	104.7115	106.9192	111.0075	106.7584	102.3844
OASPL	118.5045	119.5442	120.7812	124.4711	129.5451	134.6093	133.4034	131.6436

Table C.7: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.5$, $T_0=982.6$ K)

NPR = 3.58, Stagnation Temperature = 1309 °F, Chamber Temperature = 75 °F
Relative Humidity = 41.1 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.29733	86.39002	88.59087	90.92247	93.05436	94.36093	96.33464	100.0563
250	79.52637	80.57337	82.42282	83.53693	84.79499	88.0317	91.36617	95.46549
315	80.9469	83.53102	85.20022	85.64526	87.92079	90.70206	93.02858	99.47023
400	84.92804	86.2066	87.52093	88.2732	90.42148	93.45957	98.49284	102.0516
500	86.97646	88.46938	88.49507	89.73621	91.42797	96.67966	100.7373	106.0971
630	88.28318	89.33124	89.86687	91.12992	94.57977	100.0919	104.6193	108.8799
800	89.65989	91.04486	92.51206	94.6014	99.20242	104.1311	108.8681	112.5079
1000	91.55286	93.53189	94.32119	96.88307	100.7215	107.1235	111.2705	114.6743
1250	93.3005	95.68439	96.86834	98.35828	104.4361	110.3878	114.7383	116.614
1600	94.98692	97.15237	98.81381	101.7339	107.509	114.1811	117.1202	117.4034
2000	97.64226	98.96759	100.3146	103.7273	110.2479	116.736	118.4613	117.5255
2500	99.46391	100.5201	102.082	105.7829	112.9794	118.816	119.4348	118.1384
3150	100.6632	102.4216	104.3582	107.4949	115.4574	120.6936	120.0352	118.6553
4000	101.4787	103.3707	105.5833	109.3427	116.7756	121.7995	120.8728	118.8168
5000	103.1063	105.049	106.6598	110.4014	117.9303	123.2251	123.0063	119.4269
6300	104.5429	105.5376	107.5085	111.4425	118.4768	122.1101	119.2858	116.3345
8000	108.5046	106.8818	108.3169	112.245	118.3728	121.9381	118.1444	115.7378
10000	111.9963	109.9006	109.1476	112.7982	117.696	120.7367	117.2815	114.5364
12500	110.2451	111.9351	110.3014	113.235	116.7064	119.6864	116.1376	113.3276
16000	108.0674	110.4022	110.9483	113.2594	115.3187	118.2845	114.8562	111.8836
20000	107.0451	108.3659	109.7938	113.1942	114.2139	116.9946	113.4925	110.1089
25000	105.613	107.1457	108.0557	112.1453	112.89	115.5973	111.9115	108.3129
31500	103.5161	104.924	106.2643	109.7575	110.8885	113.6483	109.7889	106.1065
40000	101.9338	103.4309	105.465	107.8174	109.2104	112.2857	107.9814	104.5384
OASPL	122.5905	123.2846	123.9411	127.2011	131.8914	136.0172	134.7232	133.0458

Table C.8: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.6$, $T_0=979.3$ K)

NPR = 4.14, Stagnation Temperature = 1303 °F, Chamber Temperature = 75 °F
 Relative Humidity = 41.1 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	86.61231	88.6944	89.76655	90.81265	92.9278	94.8064	97.21954	101.0497
250	80.25337	81.42022	83.21989	84.35069	85.20958	88.49643	92.50503	97.23166
315	82.35416	85.2651	86.99253	87.40372	89.61077	92.07127	94.97074	101.7184
400	86.12406	87.90685	89.15148	90.19194	91.74657	94.6667	100.0354	103.6651
500	89.26133	90.10291	90.33187	91.50025	92.67379	97.90455	102.3894	108.0024
630	90.51269	91.42489	91.65401	92.89269	95.67196	101.6024	106.6986	111.392
800	91.15063	92.64867	94.67572	96.34258	100.0607	105.6816	111.0508	114.9601
1000	93.3271	95.16742	96.10926	98.28164	101.7118	108.6645	113.3808	116.94
1250	94.9505	97.4349	98.39482	99.60555	105.3625	111.6912	116.4148	118.3378
1600	96.24881	98.66919	100.4959	103.3311	108.2793	115.6197	119.1695	119.3322
2000	98.85611	100.7118	101.8512	104.863	110.988	118.0296	120.7151	119.4012
2500	100.5223	102.0339	103.7225	106.8439	113.6799	120.2226	121.6224	119.923
3150	101.9501	103.6626	105.6835	108.6724	116.21	122.4025	122.1068	119.9798
4000	104.5136	106.5055	108.1169	110.6305	117.5434	125.8146	126.1637	121.5074
5000	104.6378	105.8448	107.543	111.1718	118.5013	123.7647	122.1871	118.1093
6300	108.605	107.6533	108.8106	112.4594	119.3039	123.42	120.3609	116.9112
8000	115.6935	110.713	109.9226	113.4111	119.4976	122.6629	119.8226	116.1116
10000	114.0562	114.5402	111.2053	113.907	119.0575	121.2983	118.4204	114.3993
12500	110.9024	114.5274	113.0386	114.4596	118.2528	120.0777	117.184	113.0052
16000	110.1984	111.4813	113.1743	114.636	117.1083	118.7484	115.7424	111.3464
20000	109.1851	110.5211	111.2383	114.4404	116.0327	117.4737	114.4224	109.3089
25000	107.9003	109.3075	109.6509	113.354	114.7994	116.0944	112.9745	107.3887
31500	105.8143	106.9693	107.9481	110.9158	112.6766	114.1261	110.8976	105.0108
40000	104.3551	105.5899	107.1733	109.1018	111.2616	112.9058	109.325	103.461
OASPL	125.5722	125.866	125.8276	128.3953	133.0612	137.3738	136.6709	134.2732

Table C.9: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.7$, $T_0=982.6$ K)

NPR = 4.83, Stagnation Temperature = 1309 °F, Chamber Temperature = 68.1 °F
 Relative Humidity = 69.3 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	91.55229	94.19853	95.55162	97.01212	99.04052	100.8067	103.3836	107.1687
250	82.68083	83.58255	84.91211	86.60771	87.85567	90.77349	94.33924	99.03254
315	84.34444	87.3106	88.90492	89.31232	91.38048	94.13188	96.91499	103.5106
400	88.5454	90.31104	92.04196	93.122	94.12987	97.54186	102.6129	106.0974
500	91.27376	92.41936	92.38007	92.97509	94.53598	99.54979	103.9936	110.0051
630	92.12933	92.92636	93.33235	94.09383	97.00945	103.32	108.5813	113.4073
800	92.0853	94.06549	95.87717	97.574	101.2692	107.0045	112.5656	116.5469
1000	94.76737	96.45858	97.4995	99.58077	103.0761	110.2828	115.0609	118.5641
1250	96.17218	98.45378	99.90757	101.3256	106.5803	113.3542	118.3034	120.0093
1600	97.40049	99.59674	101.8704	104.4539	109.2555	117.0788	120.638	120.6987
2000	100.3159	101.7599	102.8814	106.1936	112.1975	120.0385	122.3903	121.0619
2500	101.7848	102.9884	104.7181	107.7832	114.834	122.1445	123.1862	121.2151
3150	103.353	104.739	106.4762	109.4793	116.9022	123.9598	123.9166	121.24
4000	104.673	106.481	108.1035	111.1138	118.4475	125.6081	124.8063	120.3682
5000	106.8924	107.2818	108.6055	112.0333	119.6198	125.1421	122.6147	118.6021
6300	112.2493	109.9257	110.2878	113.536	120.4169	125.0294	121.3514	117.7078
8000	116.2895	113.8849	111.8742	114.4232	120.6109	123.9103	120.3951	116.8386
10000	113.9343	117.1387	113.9807	115.4455	120.4652	122.6143	119.1666	115.4333
12500	111.9002	115.0628	115.8882	116.3815	119.9247	121.5379	118.0489	114.0491
16000	111.7059	112.997	114.9826	116.8824	118.8977	120.2399	116.9318	112.6866
20000	110.713	112.8879	113.0526	116.7019	117.9814	119.0234	115.5715	110.8404
25000	109.5478	111.4507	112.0673	115.5127	116.7742	117.7013	114.1435	109.1588
31500	107.4998	109.3102	110.4191	113.1622	114.73	115.7695	112.045	106.8387
40000	105.9412	107.8311	109.567	111.2678	113.1019	114.3055	110.2206	105.1876
OASPL	126.6627	127.7881	127.8685	130.0924	134.4035	138.5904	137.4111	135.3058

Table C.10: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.8$, $T_0=992$ K)

NPR = 5.62, Stagnation Temperature = 1326 °F, Chamber Temperature = 68.1 °F
Relative Humidity = 69.3 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	96.58179	97.23609	97.20847	98.6406	101.6831	103.2836	104.8076	107.7251
250	83.85838	85.1543	87.33023	88.95787	89.79505	92.48986	96.21715	101.3035
315	85.74411	88.58777	90.20085	91.21087	93.4701	95.43906	98.98717	105.9668
400	90.27916	92.05839	93.26344	95.06219	95.33291	99.81285	104.1689	107.5965
500	92.29825	93.38943	93.71937	94.68933	96.05315	101.4109	105.4652	111.6656
630	93.25137	94.32045	94.91761	95.79047	98.67424	104.9509	110.0533	115.1502
800	93.69101	95.58279	97.61948	98.9978	103.1902	109.0764	114.4374	118.4122
1000	95.63018	97.92479	99.33184	101.2535	104.8261	112.2277	116.8075	120.2048
1250	97.26749	100.4224	101.7539	102.9445	108.5655	115.1913	119.4657	121.304
1600	99.12828	101.2924	103.5681	106.0137	111.5036	119.037	121.971	121.9414
2000	100.9293	103.5632	104.8091	107.3239	113.9406	121.2978	123.0664	122.0797
2500	103.0676	104.7907	106.3286	109.3733	116.7868	123.4891	124.0496	122.4674
3150	104.6846	106.1865	108.0051	110.8976	118.7079	125.0979	124.5478	122.0001
4000	105.4932	107.5887	109.314	112.6109	119.869	125.7094	123.9094	120.6405
5000	108.2704	108.697	110.0597	113.8371	121.0635	126.0836	122.5099	119.2851
6300	113.7271	111.4971	111.7174	115.1693	121.8864	125.6386	121.3412	118.409
8000	115.1805	115.7382	113.0503	115.9432	122.2927	124.2944	120.5265	117.5803
10000	112.8501	116.7353	114.9985	116.737	122.1206	122.8587	119.1552	116.2625
12500	112.0766	114.5025	116.2877	117.3759	121.5559	121.8621	118.0302	114.8918
16000	111.5175	113.4646	114.73	117.5235	120.2726	120.4299	116.7633	113.2827
20000	110.5556	112.9319	113.5607	116.8575	119.1697	119.1992	115.3597	111.3208
25000	109.5198	111.5739	112.2816	115.3449	117.8571	117.895	113.7873	109.5485
31500	107.5861	109.3833	110.5168	112.948	115.8244	115.9916	111.7202	107.311
40000	106.0575	107.915	109.7135	111.2767	114.3759	114.6636	109.9902	105.8989
OASPL	126.569	128.1797	128.4878	130.9373	135.9352	139.2842	137.7203	136.3395

Table C.11: SPL and OASPL for the Mach 1.3 Nozzle ($M_j=1.51$, $T_0=1199.3$ K)

NPR = 3.63, Stagnation Temperature = 1699 °F, Chamber Temperature = 94.4 °F
Relative Humidity = 50.2 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.69227	81.89493	82.71426	83.18986	84.20637	86.86326	90.19014	94.16732
250	79.33014	80.79107	82.71071	83.51663	84.62701	88.59369	92.31332	96.29189
315	82.38433	85.02683	86.38308	86.77357	89.14852	91.80052	94.97508	101.1294
400	85.51072	87.44128	88.17458	89.58052	91.33779	94.76207	99.57077	102.7128
500	88.04982	89.40671	89.7974	90.48355	92.58686	98.33571	102.1721	107.3382
630	89.45422	90.35767	91.07546	92.28458	95.85553	101.7805	106.015	110.1891
800	90.74214	92.55677	93.98233	95.77896	100.2647	105.7046	110.2401	113.5618
1000	92.6458	95.08289	95.93973	97.79783	102.3358	108.9851	112.8531	115.6269
1250	94.31045	97.28558	98.30495	100.015	105.9549	112.014	115.6463	116.7927
1600	96.13947	98.71517	100.144	103.085	109.1278	115.9571	118.0174	117.3166
2000	98.2541	100.2445	101.7123	105.1392	111.9863	118.2861	118.8209	117.3341
2500	100.0418	102.0778	103.7649	107.2323	114.9713	120.5358	119.6876	117.7612
3150	101.4686	103.6091	105.591	109.2129	117.4798	122.0047	120.0664	117.8272
4000	102.3569	104.8306	106.9339	110.9233	119.2692	122.8101	120.3848	117.2463
5000	103.836	106.0266	108.1379	112.1626	120.4153	123.58	120.4471	116.3471
6300	104.7698	107.2555	109.6719	113.3696	121.2087	122.8009	118.7244	115.1926
8000	107.2415	108.2015	110.2732	113.9271	121.2676	121.8327	117.8501	114.7171
10000	110.515	109.8818	110.8984	114.1413	120.4769	120.3392	116.6421	113.3623
12500	110.3901	111.8353	111.5217	114.1915	119.4779	119.2468	115.5705	112.0813
16000	108.3784	111.4603	111.7324	113.7409	118.0079	117.8749	114.3611	110.9169
20000	107.3241	109.7965	111.3106	113.2333	116.916	116.5795	112.9859	109.2694
25000	106.0587	108.4087	109.958	112.086	115.6608	115.222	111.4748	107.3985
31500	104.0817	106.2692	108.0266	109.9824	113.6507	113.2342	109.3173	104.8617
40000	102.5427	104.7031	107.1694	108.1137	112.1549	111.8044	107.3228	102.888
OASPL	122.4191	124.1565	125.4668	128.1936	134.4994	136.5064	134.295	132.3336

Table C.12: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.2$, $T_0=289$ K)

NPR = 2.43, Stagnation Temperature = 60.5 °F, Chamber Temperature = 70 °F
 Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	68.9666	70.01488	70.25689	70.66269	70.84915	71.8429	74.93124	79.82733
250	70.28128	70.85319	70.41051	72.12243	72.60745	73.79199	76.4661	81.36639
315	69.96736	71.77232	72.81838	74.13865	73.29022	75.67905	77.96418	82.72096
400	72.6864	74.78754	75.25074	75.72371	75.78284	78.42132	81.77572	86.21387
500	74.49377	75.90232	75.88327	77.19038	77.73683	79.77705	83.92313	88.78317
630	76.91677	77.65378	78.31519	79.3645	80.31165	83.28678	87.5827	92.05386
800	79.24261	80.44178	81.07189	82.06142	83.27529	85.88599	91.09193	95.35977
1000	80.15874	81.7797	82.15217	83.7614	84.43549	88.17473	92.75447	97.86793
1250	81.99131	83.41771	85.1725	86.64538	87.835	91.58987	96.53314	100.7406
1600	84.1002	85.5316	86.44501	88.0805	89.27866	92.4379	97.56731	101.938
2000	85.11566	86.72739	87.46056	89.17896	90.66502	93.75956	98.45027	102.6196
2500	86.37989	87.51794	88.3016	89.99509	91.56433	94.60212	99.04932	102.6885
3150	87.62586	88.59008	89.63906	91.20928	93.06383	95.79221	98.99219	101.5391
4000	88.19441	89.43831	90.10956	92.30285	93.88953	96.35041	98.77418	99.60981
5000	89.24947	90.11098	90.39361	92.37868	94.08633	96.51974	98.28998	98.0121
6300	95.8278	96.00215	91.54247	94.63939	94.79506	97.3911	98.44022	98.87992
8000	92.62916	91.38606	90.94552	92.96795	94.56173	96.55304	96.80794	95.68775
10000	97.75838	95.71116	92.72817	93.53218	94.53131	96.24201	96.106	94.32066
12500	96.69759	97.35453	95.29602	94.86753	94.68043	95.95681	95.2944	93.29078
16000	94.08604	94.09112	93.44498	95.53011	95.11057	95.64966	94.50523	91.95193
20000	93.21689	92.81749	91.7186	94.58496	95.04205	95.28083	93.62389	90.40069
25000	91.68777	91.60251	90.36269	92.88853	93.98178	93.88455	92.36242	89.05495
31500	89.8165	89.26306	88.49611	90.5483	91.41336	91.38239	89.4428	86.42962
40000	88.40685	87.87655	87.69061	88.50033	88.79041	88.83373	86.42358	83.41154
OASPL	109.0503	108.8861	107.613	109.23	110.0192	111.8244	113.6292	115.7096

Table C.13: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.3$, $T_0=288.5$ K)

NPR = 2.78, Stagnation Temperature = 59.6 °F, Chamber Temperature = 70 °F
 Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	69.82032	72.50554	71.88606	72.56069	72.36038	73.1115	76.38951	81.23587
250	72.92572	73.72345	73.27204	74.89898	75.3474	76.53482	79.22008	84.35052
315	73.21632	75.21232	75.67659	76.85144	76.0917	78.44948	80.6006	85.781
400	75.30773	77.66744	77.78497	77.96597	78.76861	81.2045	84.49507	89.32171
500	78.02151	78.91223	79.32965	80.64398	80.89578	82.60743	86.45622	91.23278
630	80.19395	81.37552	82.03985	83.0182	83.76534	86.08533	90.30729	94.6633
800	82.97788	84.27713	85.12078	86.11545	87.15406	89.54277	94.34986	98.32146
1000	83.70441	85.38483	85.88747	87.62226	88.36945	92.30962	96.58692	101.0927
1250	86.25043	87.99208	89.44796	90.77966	91.9342	96.20301	101.4141	104.911
1600	88.48707	90.03286	91.19215	92.87861	93.66206	97.91422	103.5619	107.2085
2000	89.97031	91.58964	92.56975	94.29671	95.52915	100.7684	107.1409	110.5887
2500	91.63065	92.88019	93.68621	95.07339	96.64077	101.2602	107.2243	109.9661
3150	92.509	93.75547	94.76463	96.39043	98.02238	101.6255	105.2903	106.7522
4000	100.9382	98.54378	96.18803	97.71397	100.1613	105.2982	104.8201	105.6319
5000	97.05152	96.08553	95.59856	97.17714	99.2759	103.1018	103.901	103.5767
6300	99.39506	98.13209	96.90632	97.84619	99.41381	102.1837	103.054	102.1924
8000	109.4567	112.2556	108.8545	103.4135	100.9202	102.7847	102.4497	101.3277
10000	106.4323	108.0968	105.1749	102.5753	101.0917	102.1264	101.4954	100.0119
12500	104.9246	104.559	103.1829	103.8348	103.047	102.4895	100.9691	99.0527
16000	102.8706	103.4189	101.8348	103.1067	103.0937	102.6307	100.5887	98.00422
20000	101.2332	101.83	100.7274	102.0847	102.3749	102.2321	100.2672	96.89612
25000	99.64034	99.99138	98.88319	100.6911	100.9273	100.4154	98.94704	95.71652
31500	97.25957	97.55673	97.04992	98.25543	98.41311	97.85754	95.93187	93.15947
40000	95.35235	95.75335	95.99689	96.1275	95.90326	95.51038	92.97465	90.28777
OASPL	118.5615	120.0264	117.6381	116.5691	116.5105	118.3204	119.9559	121.612

Table C.14: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=257.6$ K)

NPR = 3.18, Stagnation Temperature = 59.4 °F, Chamber Temperature = 70 °F
Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	73.30635	74.75896	73.67284	74.23127	73.96476	75.40834	78.20246	82.20287
250	75.79476	76.47934	75.32888	76.99383	77.14723	78.72736	81.46309	85.15477
315	75.48323	77.0589	77.54456	79.06032	78.00426	80.22238	82.21607	86.69787
400	77.31296	79.87225	80.1673	80.5563	81.37223	83.4608	86.89095	91.35248
500	80.15475	80.91461	81.70519	83.06121	83.4197	85.33606	89.08838	94.06149
630	82.20704	83.48206	84.32851	85.51597	85.89143	88.4411	93.09914	97.75705
800	84.57253	85.74762	86.97675	88.15201	89.0373	91.25956	96.94002	101.3799
1000	85.54138	87.24856	87.80887	89.52854	90.03012	93.62927	98.778	104.2698
1250	87.52329	88.96093	90.4764	91.95122	93.04971	96.79392	103.121	107.6623
1600	90.2233	91.50819	92.38157	94.21301	95.18422	99.00312	105.5833	110.037
2000	91.15453	92.427	93.52778	95.45081	96.48212	100.997	107.7127	111.7704
2500	92.09679	93.45921	94.30097	96.11143	97.63372	101.8706	108.0559	111.3194
3150	93.27261	94.47715	95.71128	97.18073	98.98456	102.7385	107.6074	110.2387
4000	94.95092	97.74643	98.46344	99.08053	100.4381	103.615	107.2214	110.1003
5000	96.46226	95.66115	95.76597	97.74954	99.4903	102.9137	105.8388	107.4678
6300	102.2103	100.7236	98.35948	98.64604	99.91884	102.7878	104.6813	105.8328
8000	106.8859	108.8104	106.2699	100.7658	100.7166	103.0175	103.7091	104.2133
10000	101.8796	102.4515	102.0741	102.5339	101.2651	102.3083	102.5601	102.4638
12500	101.1977	100.8978	100.4157	102.9487	102.5755	102.4927	101.764	100.8923
16000	100.4209	100.5767	99.04689	101.4405	102.5145	102.6183	100.9831	99.34345
20000	99.04658	99.33772	98.27426	100.486	101.244	102.0474	100.2212	97.65681
25000	97.89349	97.91639	96.96249	99.2702	99.46279	100.1776	98.94544	96.10841
31500	95.82594	95.6979	95.30028	97.1874	97.16174	97.21132	96.2367	93.74279
40000	94.21831	94.1247	94.48706	95.29505	95.05931	94.85681	93.28515	90.94921
OASPL	116.097	116.8862	115.6462	115.8742	116.3292	118.3195	121.352	124.0775

Table C.15: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=288.5$ K)

NPR = 4.22, Stagnation Temperature = 59.6 °F, Chamber Temperature = 70 °F
 Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	79.45123	76.44305	76.76689	77.62776	78.38029	79.22973	81.88549	86.62542
250	78.31164	76.87334	77.71503	79.50687	80.20601	81.03845	83.93002	88.7478
315	79.46774	80.12573	81.51959	82.5532	81.93566	84.44533	85.57879	91.72793
400	82.01619	83.03327	83.84491	84.38272	84.94187	86.51734	90.35024	95.54438
500	83.73959	84.76103	84.61219	86.09742	86.64377	87.86653	91.90557	98.42173
630	85.80939	85.9948	86.70211	88.0483	88.77432	90.63001	95.81978	102.0855
800	87.19146	88.49217	89.68485	90.88602	91.95481	93.57577	99.73878	105.7949
1000	88.83803	90.13186	90.33016	91.85064	92.47338	95.68903	101.3094	108.1044
1250	89.83494	90.56481	92.50258	93.887	95.17691	98.664	105.1648	111.0404
1600	91.5441	92.80561	93.85545	95.83676	96.84243	100.3227	107.1835	112.8655
2000	92.48889	94.01583	94.99377	96.66626	97.70845	101.8049	109.0951	114.4079
2500	93.72098	95.32689	95.80936	97.44364	99.23492	103.2129	110.1143	114.5944
3150	95.3439	96.38202	97.62036	98.81304	100.2939	103.9022	110.4928	115.1045
4000	96.82226	96.93272	97.36852	99.21533	100.7785	104.4601	110.1794	115.5092
5000	103.2942	99.44198	97.97834	99.68915	101.269	104.6571	109.0742	114.6064
6300	106.7331	105.2919	101.0843	100.9877	101.8322	104.9003	108.1737	113.5566
8000	105.596	106.7631	105.1696	103.2985	102.7412	105.0422	107.1217	112.0762
10000	103.6446	104.8192	105.1529	105.9605	104.2904	105.0963	106.264	110.846
12500	103.825	103.6495	102.8272	105.8354	106.439	105.6502	105.5434	109.2542
16000	102.3828	103.2807	101.8036	104.1412	106.1628	106.1366	104.6629	107.3496
20000	101.3383	102.0847	101.3298	103.3297	104.5039	106.0257	103.8335	105.5306
25000	99.86459	100.629	100.0267	102.4154	102.6348	104.177	102.4645	103.63
31500	97.60903	98.23792	98.18445	100.2371	100.6307	100.8829	99.7554	101.1662
40000	95.73577	96.54152	97.32717	98.23556	98.51789	98.49891	96.90366	98.77871
OASPL	118.0353	118.1506	117.2623	118.4516	119.0279	120.6908	124.0736	128.9676

Table C.16: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=288.5$ K)

NPR = 4.94, Stagnation Temperature = 59.7 °F, Chamber Temperature = 70 °F
 Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.81278	78.28503	78.68142	79.00832	80.11568	81.51962	84.81946	88.80383
250	79.93063	78.38519	80.2226	82.21998	82.72991	83.03145	86.70867	91.89976
315	81.22912	81.92783	84.3769	86.04945	85.09153	86.9654	88.24975	94.54877
400	84.35956	85.36325	86.43815	87.2475	87.93698	88.96232	92.82069	98.10681
500	86.40034	87.43579	87.14096	88.49322	89.10479	90.12682	93.98323	101.2005
630	87.89804	87.79408	88.52352	89.43204	91.0606	92.69852	97.83372	104.4644
800	88.72039	90.08617	91.48553	92.66197	93.93797	95.38864	101.4522	107.9402
1000	90.92954	91.64469	92.1292	93.92035	94.74339	97.68541	103.7898	111.0723
1250	92.06384	92.51762	94.35943	95.30315	97.03612	100.8091	107.7173	114.1175
1600	93.61922	94.74307	95.91232	97.8084	98.42626	102.3606	109.3947	115.8693
2000	94.63905	96.02101	96.84227	98.53204	99.59419	103.686	111.3832	117.355
2500	95.67748	97.15594	97.51256	99.42776	101.0793	104.7917	112.423	117.8764
3150	98.59107	98.61952	99.8791	100.7526	102.1228	105.5694	112.7519	118.3077
4000	105.4929	101.1155	99.97518	101.2039	102.6155	106.1899	112.4911	118.8065
5000	112.4998	108.8942	102.9992	102.7614	103.5887	106.7226	111.5957	118.2976
6300	112.1473	113.378	109.7285	105.8792	105.0344	107.5129	110.5779	117.5467
8000	108.6238	110.9393	112.0072	110.6404	107.6717	108.3561	109.827	116.402
10000	107.7258	107.6991	108.7462	112.2521	111.0394	109.3739	109.2694	115.0053
12500	107.1972	107.8719	106.4411	109.6319	113.25	111.044	109.1342	113.5329
16000	106.3499	106.9039	106.2082	107.9697	111.4553	112.1156	108.9132	111.7894
20000	105.2876	105.9822	105.1136	107.5775	108.8098	111.8213	108.4393	110.1616
25000	103.9362	104.6072	104.056	106.1515	107.1282	109.334	107.0658	108.5739
31500	101.7646	102.3756	102.3147	104.0755	104.801	105.8776	104.4426	106.3863
40000	99.97649	100.649	101.5064	102.2274	102.6107	103.7191	101.7748	104.2203
OASPL	123.1271	123.232	122.2052	123.0418	123.8823	124.7146	126.7738	132.4974

Table C.17: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.81$, $T_0=288.4$ K)

NPR = 5.78, Stagnation Temperature = 59.4 °F, Chamber Temperature = 70 °F
Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.18467	79.41486	80.40762	81.38362	82.25205	83.08988	85.92081	90.40125
250	80.77944	80.29774	82.82867	84.81798	84.86174	85.20602	88.87722	93.84622
315	83.24739	85.07477	86.80256	87.49124	87.16333	89.79625	90.2235	96.76872
400	86.80203	88.05414	89.06062	89.59104	90.8951	91.76194	94.93258	100.5602
500	88.80329	89.58758	89.40196	90.76437	91.37232	92.53325	96.32757	103.3206
630	90.76616	90.70001	90.39615	91.93867	93.797	95.53262	100.2508	107.2551
800	91.0689	92.08494	93.54105	94.88661	96.4537	98.11598	104.225	111.0721
1000	93.25054	94.12833	94.291	96.13111	97.07044	100.1694	105.8398	113.7534
1250	94.25621	94.34957	96.51308	97.96219	99.27519	102.8954	109.8185	116.7289
1600	95.63905	96.55054	97.62757	99.82757	100.4694	104.1269	111.5009	118.4875
2000	96.42596	97.78876	98.63199	100.2508	101.4202	105.4302	113.2276	119.8251
2500	98.11812	99.16236	99.83984	101.9697	103.1568	106.4509	114.2861	120.621
3150	103.5709	101.399	101.5139	102.3684	104	106.9189	114.2527	120.8377
4000	112.9593	107.5936	103.5306	103.7094	104.5761	107.4726	114.0048	120.9421
5000	115.8557	115.825	109.5536	106.3898	106.1948	108.37	113.248	120.6391
6300	111.7823	115.0692	115.6499	111.1737	108.5958	109.5237	112.6518	119.9516
8000	110.0533	110.5814	113.2898	115.5693	112.0767	111.0129	112.1998	118.4267
10000	110.0937	110.8967	109.0824	113.887	115.9207	112.5559	112.0195	116.7775
12500	109.3611	110.2965	109.8121	111.0757	116.6773	114.1827	112.0262	115.2191
16000	108.4222	109.4528	108.5599	111.1322	113.5049	114.935	111.7765	113.6842
20000	107.4129	108.3214	107.6155	110.0787	111.3254	114.0266	111.1218	112.1392
25000	106.1469	107.0051	106.4482	108.7951	110.3683	111.3962	109.6188	110.5977
31500	103.9655	104.7769	104.675	106.722	107.8734	108.6253	107.0799	108.5028
40000	102.2689	103.1418	103.9522	104.8248	105.8713	106.6763	104.6929	106.3901
OASPL	125.6831	126.1137	125.2717	126.0558	127.2281	127.2	128.8753	134.8383

Table C.18: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.88$, $T_0=288.4$ K)

NPR = 6.45, Stagnation Temperature = 59.4 °F, Chamber Temperature = 70 °F
Relative Humidity = 60.3 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.35261	81.63548	82.18251	83.52441	84.36011	84.64057	87.83489	93.08825
250	80.66569	81.56397	83.58014	85.82084	86.13725	86.5722	90.63581	96.02955
315	84.29397	86.39898	88.377	89.18024	88.82456	91.49736	92.16329	98.51559
400	88.45238	89.528	90.49199	91.25176	92.37076	93.12276	96.66223	102.1752
500	90.677	91.43814	90.85119	92.49868	92.83671	94.27527	97.8544	105.0219
630	91.95804	91.60761	91.75268	92.82583	94.84437	96.63462	101.7267	108.8153
800	92.01698	93.7282	94.61043	96.04286	97.86615	99.51436	105.443	112.7409
1000	94.86866	95.54812	95.74182	97.15692	98.35669	101.4705	107.3768	115.5159
1250	95.60723	95.703	97.38987	98.84678	100.568	103.9284	111.2321	118.2951
1600	96.78488	97.76378	98.80243	100.817	101.6765	105.3445	112.7871	120.0698
2000	98.03161	98.89859	99.80244	101.3391	102.3794	106.2945	114.661	121.4169
2500	101.0821	102.1569	101.5607	102.8338	104.4015	107.4948	115.4462	121.9677
3150	107.8552	104.2623	103.5086	103.7468	105.0119	108.0446	115.6606	121.989
4000	115.8504	111.9798	106.4011	105.4548	105.9243	108.6181	115.4644	122.1897
5000	115.9202	118.3543	113.8342	108.7983	107.7888	109.5506	114.9618	121.7261
6300	111.1027	114.2165	117.1462	114.3797	110.6267	110.8994	114.4686	120.4194
8000	111.5504	110.8464	112.5128	117.1671	114.2826	112.4709	114.0567	118.647
10000	110.8866	112.3815	110.2624	113.5573	117.6454	114.1516	113.8321	116.8043
12500	110.4406	111.0459	111.2958	112.0619	117.5054	115.6162	113.848	115.4955
16000	109.5072	110.5402	109.7547	112.5191	114.1128	115.9968	113.6106	114.0275
20000	108.4916	109.512	108.9179	111.2503	112.5993	114.7382	112.8743	112.4739
25000	107.2967	108.2151	107.8228	110.1075	111.7674	112.2398	111.3795	110.9874
31500	105.1649	106.0255	106.1948	108.1105	109.2296	109.7849	108.9549	108.8884
40000	103.5343	104.4329	105.4408	106.179	107.196	107.8145	106.5982	106.8391
OASPL	126.7856	127.4799	126.7352	127.4264	128.5564	128.3705	130.4536	135.9263

Table C.19: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=600.6$ K)

NPR = 3.15, Stagnation Temperature = 621.4 °F, Chamber Temperature = 70 °F
 Relative Humidity = 62.5 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.17036	75.43868	76.45389	77.25945	77.4568	79.76456	83.94127	88.5638
250	77.19913	77.20733	78.21549	79.19547	79.92727	83.30498	87.41025	91.77379
315	77.46719	79.27144	80.80463	81.54087	82.85516	86.64559	89.0196	94.75123
400	80.36722	82.51412	83.47644	84.04952	86.03053	89.02776	94.17122	98.07284
500	82.99677	84.11852	84.29751	85.54987	86.96705	92.08448	96.61482	101.4952
630	85.0238	85.47294	86.3772	86.9915	90.04132	95.79597	100.4668	104.7171
800	86.26399	88.07294	89.19831	90.31951	94.00093	99.49831	104.6942	108.5358
1000	88.08938	89.56404	90.23255	92.22457	95.55713	102.1298	106.565	110.6246
1250	90.04006	91.53189	93.27198	94.54307	99.20783	105.814	111.014	113.4287
1600	92.04806	93.83169	95.38645	97.49425	101.6933	109.1673	113.2252	114.7686
2000	93.94183	95.55106	96.94114	99.3557	104.5191	112.0472	115.4979	115.6496
2500	95.92052	97.38195	98.62317	100.8738	106.7091	114.2202	117.0498	116.496
3150	98.02041	99.59459	101.1149	102.7985	108.4889	116.0239	117.8787	117.3641
4000	98.4526	100.2357	101.7628	104.303	109.2966	116.7588	118.4629	118.228
5000	99.75368	100.9194	102.7035	105.4	110.0938	116.8597	118.9503	118.6031
6300	101.3469	102.0186	103.5756	106.3892	110.5135	116.5385	119.1333	118.2591
8000	105.5641	103.7281	104.2079	107.2224	110.7452	115.7161	118.5571	117.2867
10000	108.5972	106.8958	105.6843	107.8255	110.5433	114.5466	117.5007	115.9739
12500	108.4044	108.4119	107.0217	108.7163	110.2148	113.4833	116.1969	114.5911
16000	106.479	107.4448	107.4182	109.2288	109.5236	112.3053	114.8076	113.0938
20000	105.2736	105.896	106.5678	109.2234	108.9873	110.9568	113.4746	111.4131
25000	104.1994	104.4648	105.1647	108.0291	107.9986	109.5503	112.0853	109.9013
31500	102.2568	102.3284	103.3715	105.7489	105.914	107.4225	110.0714	107.9683
40000	100.6328	100.7434	102.5052	103.7387	103.8525	105.7099	108.2716	106.2871
OASPL	120.2074	120.2032	120.5215	122.708	125.0939	130.3695	132.9328	132.3867

Table C.20: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=602.6$ K)

NPR = 4.22, Stagnation Temperature = 625 °F, Chamber Temperature = 70 °F
 Relative Humidity = 62.5 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.76108	78.75574	79.76559	80.17082	80.70036	82.76915	86.45026	91.37118
250	80.60003	78.24874	80.44597	82.04219	82.47114	85.16228	89.50217	94.3744
315	81.59109	82.30974	84.66952	85.23677	86.1839	89.19311	91.19697	98.56095
400	84.37239	85.86541	87.05699	87.35519	88.82287	90.92919	96.37598	100.9526
500	86.66962	87.92316	87.59795	88.86054	89.40998	93.84288	98.73788	104.9155
630	88.42036	88.82104	89.28007	89.62917	92.09049	97.42831	103.1148	108.4906
800	88.18233	90.0559	91.94505	93.0165	95.52019	100.9538	107.3801	112.1934
1000	91.21011	92.4577	93.02319	95.00219	97.08063	103.9232	109.5726	114.5884
1250	92.549	93.77697	95.23989	96.27236	100.3479	107.2449	113.5918	116.7497
1600	94.2889	95.54501	97.32036	99.35226	102.7138	110.6803	115.9514	118.1678
2000	96.5919	97.4165	98.62831	101.0492	105.3173	113.6662	118.273	118.7737
2500	98.07353	99.24025	100.6449	102.3633	107.4238	115.9676	119.719	119.0602
3150	100.0199	101.0763	102.7237	104.1517	109.024	117.8952	120.692	119.8072
4000	100.8997	102.2741	103.7902	105.8759	110.0446	119.3072	122.5491	122.1221
5000	101.4326	102.1012	103.937	106.3737	110.993	119.6685	121.2836	119.1206
6300	105.8785	104.3239	105.0237	107.4809	111.6845	119.878	121.1922	117.602
8000	109.3204	108.0654	106.0827	108.3585	112.104	119.6161	120.0286	116.5849
10000	108.5203	110.1526	108.2174	109.1103	112.1841	118.8646	118.6772	115.1699
12500	107.3002	109.2434	109.5015	110.2303	112.0138	117.8721	117.5168	113.828
16000	106.597	107.9478	108.2834	110.8993	111.4853	116.7758	116.2786	112.2993
20000	105.406	107.2958	107.0673	110.3486	111.112	115.5781	115.053	110.8567
25000	104.2048	105.9483	106.1781	108.9708	110.2931	114.1731	113.6475	109.3726
31500	101.9386	103.7362	104.4748	106.8273	108.1274	112.168	111.5983	107.2299
40000	100.167	102.0275	103.6003	104.8606	106.1762	110.6162	109.6603	105.4519
OASPL	121.0402	122.0276	122.0683	123.9985	126.5733	133.6181	135.2723	134.0667

Table C.21: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=600.9$ K)

NPR = 4.89, Stagnation Temperature = 622 °F, Chamber Temperature = 70 °F
 Relative Humidity = 62.5 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.97022	80.44194	81.43334	82.1543	82.86408	84.43059	88.07136	93.49706
250	81.37391	80.64222	83.17363	84.46172	84.53495	87.2813	91.54944	96.53665
315	83.14908	84.65651	86.97915	87.42966	88.22709	91.04736	92.88398	100.3764
400	86.35349	87.86637	89.23423	89.67405	90.99054	92.56403	98.77049	103.0224
500	89.09281	90.26411	89.93769	90.9004	91.45307	96.01496	100.9667	107.3776
630	90.66807	90.88584	91.59074	91.65503	93.60818	99.27063	105.1493	110.7544
800	90.6295	92.27165	94.14721	94.95651	97.39303	102.8796	109.3763	114.3344
1000	93.43421	94.61737	95.60179	97.11713	99.06354	105.9533	111.7532	116.7733
1250	94.77421	96.26256	97.40145	98.23152	102.2752	108.9682	115.7712	119.0941
1600	96.35638	97.55089	99.31204	101.7272	104.5466	112.7291	118.3614	120.4041
2000	98.48577	99.50189	100.5938	103.1579	106.8959	115.2636	120.3483	120.6299
2500	100.0106	101.319	102.4128	104.703	108.9749	117.6054	121.9464	120.8576
3150	104.5741	105.3124	106.3659	108.94	111.0138	119.6212	125.9114	125.3356
4000	103.2024	104.3348	105.7068	107.9091	111.5495	120.5226	123.5596	122.0637
5000	107.7765	105.606	106.1269	108.3094	112.4797	121.0468	122.6846	119.4342
6300	114.8296	112.3541	108.2056	109.7463	113.1576	121.3533	122.0976	118.4132
8000	113.6522	114.8127	111.0003	111.0842	113.7276	121.174	120.7965	117.3465
10000	110.8628	113.502	113.9324	112.3492	113.8348	120.5447	119.6374	115.7762
12500	110.509	111.4219	112.8696	114.2824	114.0205	119.7389	118.4212	114.4429
16000	109.6346	110.9249	110.7243	114.3744	113.7785	118.5482	117.1941	113.0831
20000	108.6593	109.9884	110.118	113.0741	113.5665	117.4339	116.1092	111.5028
25000	107.3836	108.7016	109.1467	111.6864	112.6439	116.1041	114.7638	109.8432
31500	105.2781	106.4691	107.3804	109.5418	110.4926	114.1422	112.7908	107.7354
40000	103.6796	104.9536	106.5971	107.6582	108.5971	112.7121	110.991	106.0194
OASPL	125.384	125.9602	125.5651	127.0336	128.4824	135.2456	137.1944	135.981

Table C.22: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=608.2$ K)

NPR = 5.7, Stagnation Temperature = 635 °F, Chamber Temperature = 70 °F
Relative Humidity = 62.5 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	89.97676	91.86548	93.20176	94.32942	94.75633	95.77643	99.30818	105.0992
250	90.12042	92.08317	94.23939	96.12801	96.53404	98.9997	103.2076	108.3824
315	94.01542	96.78274	98.6704	99.15028	100.9678	103.2529	105.0971	113.4993
400	98.28283	100.2134	101.7332	101.9398	103.3102	104.6166	110.5774	115.3817
500	101.2034	102.4547	102.3201	102.9673	103.0036	107.3215	112.4846	119.4585
630	102.4202	102.4583	102.8523	103.1265	104.8537	110.3872	116.7532	122.7485
800	101.9106	103.7883	105.3889	106.3835	108.4921	114.1748	121.1098	126.5745
1000	105.0904	106.1128	107.1431	108.6923	110.1194	116.8889	123.052	128.7056
1250	106.1137	107.6384	108.4523	109.7561	113.4077	120.2107	127.2246	130.8135
1600	107.2137	108.6356	110.4852	112.4675	115.353	123.69	129.7983	132.0941
2000	109.4455	110.5856	111.8792	113.7468	117.4827	126.4115	131.9751	132.4225
2500	110.7214	112.4293	113.2634	115.1215	119.3255	128.6651	133.5918	132.9965
3150	113.3672	114.1201	115.4364	117.4027	120.8486	130.2253	134.7531	133.8972
4000	115.9646	115.6809	116.4688	118.0779	121.9104	131.6155	134.4063	131.8097
5000	123.171	119.283	117.7814	119.1596	122.9314	132.5208	134.057	129.8686
6300	127.0539	125.7649	121.1453	121.052	123.9374	133.0435	132.5912	128.6489
8000	124.6754	127.8303	125.3415	123.1736	124.826	133.1764	130.9464	127.599
10000	122.5518	124.4452	127.0601	125.6344	125.4299	132.7684	129.9928	126.0748
12500	122.8928	123.4538	123.9842	127.4675	126.0437	131.696	128.8905	124.8483
16000	121.9828	123.383	122.6481	126.6118	125.9763	130.4769	127.6813	123.5581
20000	121.2017	122.2401	122.4835	125.1561	125.6959	129.4907	126.5194	122.043
25000	120.0274	121.0035	121.1368	124.071	124.6328	128.2516	125.274	120.5034
31500	118.0015	118.7954	119.395	121.9819	122.505	126.4079	123.2655	118.4277
40000	116.5094	117.2827	118.6027	120.1198	120.6916	125.0796	121.4646	116.6812
OASPL	137.6085	138.319	137.9152	139.2391	139.9333	146.9167	147.7814	146.6239

Table C.23: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.88$, $T_0=603.1$ K)

NPR = 2.76, Stagnation Temperature = 625.9 °F, Chamber Temperature = 70 °F
 Relative Humidity = 62.5 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	71.62692	73.98812	74.69594	75.52899	75.39888	77.61569	81.66951	85.88873
250	74.21145	75.47493	76.29834	77.59485	78.45798	81.36588	84.90372	88.99611
315	75.61185	77.61624	79.01839	79.97899	80.49896	84.92057	87.00249	92.18852
400	78.1453	80.36556	80.82332	81.80302	83.60682	86.93016	91.43824	95.55109
500	80.86862	82.1683	82.1918	83.69147	85.26246	90.18226	94.26313	99.00325
630	83.20956	84.02965	84.68677	85.24493	88.18223	93.64938	98.14473	102.3612
800	84.40241	86.16365	87.38818	88.42547	91.67993	97.02978	102.1359	105.8848
1000	86.48767	87.8183	88.64088	90.49358	93.79903	100.094	104.331	108.4967
1250	88.24326	89.77802	91.63588	92.72159	97.4079	103.6532	108.611	111.049
1600	90.10576	91.85822	93.61068	95.37635	99.57689	106.5386	110.6966	112.6074
2000	91.94085	93.74289	95.38913	97.50392	102.2288	109.6465	113.2351	113.7476
2500	93.75798	95.61029	97.05212	98.98549	104.5072	111.7529	114.7848	114.687
3150	95.99348	97.47319	99.14896	100.7875	106.1012	113.3026	115.5413	115.6882
4000	96.36719	98.42904	100.0139	102.2595	106.9636	113.9725	116.1897	116.6782
5000	97.87914	99.11741	101.1653	103.5322	107.5843	113.6672	116.3148	116.9888
6300	98.97669	100.1444	101.9041	104.5581	108.1033	113.0964	116.6134	116.9913
8000	101.8796	101.2472	102.4504	105.215	108.3253	112.1586	116.0253	116.2551
10000	106.1797	104.4086	103.6819	105.8799	108.2911	111.1446	115.1427	115.0733
12500	107.8766	107.0115	105.2449	106.7059	107.9098	110.2173	113.8118	113.671
16000	106.0793	107.2416	105.8574	107.6195	107.3064	109.1342	112.2921	112.0108
20000	104.4294	105.4377	105.7207	107.8791	106.946	107.9046	110.8469	110.3991
25000	103.4135	103.8356	104.2874	106.9354	106.1867	106.5018	109.2392	108.7931
31500	101.3515	101.7912	102.3977	104.6825	104.1624	104.3197	106.9979	106.7234
40000	99.76755	100.1291	101.5331	102.4191	101.9866	102.338	104.8731	104.9656
OASPL	118.8376	118.9938	119.0859	121.0461	122.841	127.3301	130.473	130.8811

Table C.24: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.19$, $T_0=617.6$ K)

NPR = 2.36, Stagnation Temperature = 1012 °F, Chamber Temperature = 71.8 °F
Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	73.03327	73.99691	74.73976	75.30144	75.97923	78.57108	81.91129	85.65998
250	73.86532	74.50396	74.86388	76.14452	78.03803	81.8056	85.22486	88.77777
315	75.82938	77.4957	78.64007	79.57118	81.3675	85.19656	87.17596	92.45968
400	78.29129	80.5783	80.67188	81.23684	84.31486	87.14112	91.53925	95.00316
500	80.84218	81.85176	82.11456	83.3172	85.7091	90.42946	94.27601	98.50704
630	83.25257	84.20822	84.42868	85.54887	89.08281	94.27206	98.13609	101.6126
800	85.7338	86.89792	87.65486	89.11594	93.68282	98.43546	102.4783	105.469
1000	87.09475	88.60006	88.82907	91.32465	95.57507	101.1802	104.4199	107.6502
1250	89.14873	90.8337	92.37623	94.25375	99.31752	104.5192	108.3426	109.9567
1600	91.43283	93.33212	94.36535	97.25556	102.2367	107.9385	110.5779	111.503
2000	93.39637	95.14723	96.56656	99.36367	105.0813	110.7676	112.7168	112.1895
2500	95.44803	97.32041	98.85957	101.6479	107.892	113.1259	114.1751	113.0402
3150	97.83527	99.40798	101.1908	103.9813	110.1386	114.9143	114.6959	113.953
4000	98.56531	100.8622	102.4589	105.6697	111.1837	115.8166	115.811	115.7386
5000	100.2293	102.2237	103.8288	106.9143	112.0639	116.4235	117.967	118.3917
6300	100.0896	102.3873	104.2148	107.6715	111.9009	115.1071	116.3686	116.2335
8000	100.2655	102.5348	104.1404	108.0127	111.422	113.9114	114.732	114.0237
10000	100.4944	102.584	104.303	108.149	110.6703	112.8649	113.7555	112.9163
12500	101.1751	102.8508	103.9605	107.9804	109.6896	111.671	112.5707	111.5786
16000	101.5729	102.709	103.2615	107.4397	108.399	110.1947	110.9196	109.5853
20000	100.9995	102.2221	102.5778	106.6497	107.2796	108.727	109.5373	107.7793
25000	99.45707	100.9412	101.5279	105.2633	105.7559	107.0513	107.861	106.0062
31500	97.17901	98.46589	99.58257	102.9837	103.3356	104.755	105.6619	103.7743
40000	95.3592	96.67548	98.50324	101.0124	101.3779	103.0162	103.8546	102.1081
OASPL	115.5588	117.2897	118.6251	122.1364	125.5008	129.0466	130.0433	129.7958

Table C.25: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.3$, $T_0=818.2$ K)

NPR = 2.72, Stagnation Temperature = 1013 °F, Chamber Temperature = 71.8 °F
 Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.23844	75.00188	76.22182	77.20827	77.73896	80.0014	83.29313	88.13981
250	75.149	75.41566	76.83597	78.86795	80.2506	83.41649	86.9686	91.08772
315	77.42053	79.1824	80.71928	81.53771	83.71491	87.29808	89.36679	94.81037
400	80.55147	82.53059	82.9023	82.99226	85.92971	88.72127	93.53873	96.93747
500	82.64991	83.78508	84.02879	85.16602	87.3431	92.41083	96.16818	100.7076
630	84.74343	85.55319	86.13467	87.24318	90.79403	96.2637	100.33	104.0588
800	86.25744	87.98141	89.24233	90.66448	95.19021	100.3513	104.6916	107.8671
1000	88.38225	89.80897	90.5265	93.01155	97.01517	103.2217	106.8303	110.1828
1250	90.46678	91.8946	93.4623	95.15923	100.8227	106.5851	110.6489	112.2315
1600	92.34798	94.50198	95.8235	98.62981	103.7545	110.1016	113.004	113.7968
2000	94.35431	96.17607	97.67509	100.7019	106.5724	112.917	114.9526	114.2996
2500	96.50725	98.24462	99.90399	102.8144	109.4351	115.4637	116.4958	115.2048
3150	98.55168	100.5116	102.1863	105.1912	111.7009	117.1035	116.9509	115.9398
4000	99.20004	101.3533	103.219	106.7474	112.9861	117.9949	117.3452	116.6372
5000	100.9742	102.6944	104.6548	107.8424	113.4217	118.6434	119.7798	119.8975
6300	101.5343	103.3566	105.3296	108.8519	113.5142	118.1186	119.2757	118.5182
8000	102.277	103.7022	105.4544	109.3675	113.2568	116.8665	117.2685	115.664
10000	106.2714	105.2222	106.0223	109.708	112.5464	115.8488	116.0016	114.0881
12500	107.9213	107.1118	106.3135	109.8253	111.677	114.6987	114.8921	112.865
16000	106.5313	107.5934	106.4579	109.6123	110.4166	113.2277	113.4207	111.149
20000	104.5908	106.2013	106.1945	109.1694	109.3418	111.8547	112.0296	109.4775
25000	103.2617	104.3904	105.0654	108.1594	108.0151	110.3294	110.5909	107.8022
31500	101.0362	102.0097	102.944	105.9558	105.9317	108.2394	108.6328	105.7158
40000	99.39083	100.2766	101.9974	104.063	104.1931	106.8068	107.0109	104.1357
OASPL	119.3245	120.0388	120.7163	123.9265	127.2698	131.6292	132.3203	131.5549

Table C.26: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=805.9$ K)

NPR = 3.12, Stagnation Temperature = 991 °F, Chamber Temperature = 71.8 °F
 Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.48354	76.80574	77.08338	78.09256	78.62105	80.73008	84.3765	88.37082
250	77.19391	77.81093	79.11659	80.64841	82.0136	85.19085	88.57155	92.55939
315	78.41506	80.32116	81.80498	83.04223	84.45006	88.03237	90.25977	95.98346
400	82.01059	84.01354	84.58398	85.23362	87.81932	90.67067	95.55883	99.31166
500	83.89314	85.48835	85.36498	86.89738	88.58506	93.63637	97.70993	102.3794
630	86.00383	87.20772	87.69534	88.67106	92.20272	97.87826	102.2823	106.0908
800	87.16844	89.08119	90.45929	92.05471	96.13812	101.4455	106.1661	109.4696
1000	89.35123	90.93854	91.493	94.17303	98.3768	104.5534	108.2721	111.6704
1250	91.46826	93.02416	94.497	96.45176	101.8928	107.7811	111.9786	113.6205
1600	93.23285	95.1963	96.74465	99.40624	104.7863	111.2535	114.1244	114.8406
2000	95.36399	96.84894	98.68115	101.5531	107.8408	114.1281	115.9816	115.358
2500	97.39772	98.83259	100.731	103.439	110.6678	116.3702	117.0767	115.8808
3150	99.18209	101.033	102.9575	105.6052	113.1421	118.0884	117.5626	116.5519
4000	99.82697	102.0343	104.1854	107.5068	114.7704	119.0968	118.2056	117.3434
5000	101.1223	103.186	105.499	108.7676	115.6662	119.8102	119.1837	117.9132
6300	102.2078	104.2736	106.6836	109.971	115.9058	120.211	119.4602	117.4613
8000	104.1178	105.2376	107.2758	110.6828	115.7199	120.3058	118.7526	116.8278
10000	107.0641	106.8595	107.9395	111.164	115.0447	119.4715	117.3104	115.5159
12500	108.3687	108.7516	108.6835	111.4341	114.1483	118.1743	116.1319	114.1049
16000	107.0185	108.9286	108.7257	111.4114	112.8995	116.5972	114.8715	112.5932
20000	105.5656	107.6385	108.3735	110.9841	111.8971	115.2976	113.6733	111.0275
25000	104.3093	106.0874	107.2146	109.8587	110.6232	113.9336	112.3445	109.4019
31500	102.2609	103.9504	105.3029	107.6314	108.545	112.0202	110.3559	107.2982
40000	100.6355	102.3671	104.395	105.6907	106.7098	110.5613	108.5422	105.6795
OASPL	120.1043	121.4554	122.5894	125.3267	129.4525	133.8414	133.078	131.904

Table C.27: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=810.9$ K)

NPR = 4.17, Stagnation Temperature = 1000 °F, Chamber Temperature = 71.8 °F
 Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.81336	79.91699	81.04344	82.08989	82.07129	83.97668	88.14869	93.06061
250	80.2612	80.06763	82.45022	84.14912	84.70392	87.81917	92.32151	96.85701
315	82.36159	84.4947	86.1547	86.52235	88.51298	91.27904	94.13762	100.733
400	85.76209	87.35453	88.59827	88.7748	90.93496	93.35469	99.24705	102.9372
500	87.66243	89.05476	89.341	89.90261	91.78613	96.52911	101.18	106.6605
630	89.4883	90.32884	90.78855	91.29114	94.88425	100.937	105.7752	110.211
800	90.20184	92.06956	93.50175	95.22741	98.93812	104.83	110.2276	114.0798
1000	92.77761	94.41808	95.0639	97.11864	100.6853	107.8618	112.1908	115.9017
1250	94.09282	96.40212	97.43615	98.54846	104.358	111.1596	115.7288	117.5319
1600	95.76729	97.72032	99.35498	101.7315	106.744	114.5428	117.7944	118.4755
2000	98.11548	99.68055	100.8461	103.501	109.5583	117.3001	119.2776	118.4138
2500	99.70758	101.3553	102.5742	105.463	112.2807	119.4469	120.2727	119.0882
3150	101.3391	103.1857	104.4732	107.1907	114.5245	121.1437	120.7772	119.5183
4000	101.957	104.3131	105.963	108.9136	116.2951	122.0976	121.2514	119.2976
5000	102.9918	105.0724	106.8246	110.0519	117.3619	122.679	121.1148	118.2438
6300	104.8242	106.295	108.0018	111.3201	117.9639	123.0069	120.319	117.3469
8000	107.9854	107.8652	108.6852	112.2448	118.0398	122.8873	119.266	116.9163
10000	108.996	110.2399	109.677	112.9404	117.4748	122.0092	118.4156	115.9298
12500	108.4735	110.6602	110.5493	113.3599	116.6964	120.7764	117.3564	114.8038
16000	107.748	109.7211	110.2985	113.3793	115.3838	119.3472	116.115	113.455
20000	106.912	108.9569	109.2975	112.8902	114.2313	118.1252	114.7996	111.8133
25000	105.5867	107.8313	108.1917	111.6426	112.9416	116.8048	113.4193	110.0624
31500	103.5108	105.4812	106.4348	109.2986	110.8118	114.9525	111.3638	107.9231
40000	101.8456	103.9274	105.6029	107.5101	109.0734	113.6186	109.6022	106.3906
OASPL	121.6751	123.3685	124.0437	127.0699	131.5449	136.6811	135.2039	133.8698

Table C.28: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=809.3$ K)

NPR = 4.85, Stagnation Temperature = 997 °F, Chamber Temperature = 71.8 °F
 Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.03361	82.27273	83.15807	83.65205	83.61684	85.77797	90.11218	95.45269
250	81.62908	81.95224	84.02546	85.4699	85.72022	89.08327	93.5167	98.41962
315	83.70578	85.91239	87.57634	88.00671	89.83037	92.85057	95.48139	102.7078
400	87.57894	89.40865	90.2579	90.97047	92.81019	94.96955	100.7717	104.7883
500	90.31313	91.3129	91.15183	92.51926	93.06007	97.9686	102.8603	108.874
630	91.16005	92.24321	92.29488	93.39581	95.78699	101.6965	107.3034	112.3446
800	91.581	93.52316	95.08392	96.41166	99.61662	105.6299	111.5359	115.7498
1000	94.67648	95.97227	96.79051	98.63234	101.7763	108.7819	114.0111	117.997
1250	95.71218	97.7611	98.89233	100.1549	105.0105	111.8032	117.315	119.4352
1600	97.2593	98.90164	100.8079	103.3636	107.6291	115.6159	119.7743	120.3819
2000	99.98327	101.1155	102.1269	104.8617	110.3125	118.5216	121.6598	120.4977
2500	101.3349	102.6067	104.1095	106.5031	112.8553	120.7037	122.5848	120.697
3150	103.1811	104.445	106.2358	108.2096	114.9385	122.8694	123.8764	121.3542
4000	104.1625	106.1014	108.4393	109.9847	116.2752	124.1912	125.6386	121.7725
5000	106.5049	106.3746	107.5827	110.8873	117.339	124.2881	122.6091	118.5644
6300	112.3745	109.4752	109.1853	112.302	117.966	124.3009	121.3769	117.545
8000	115.2512	113.8897	110.6731	113.3022	118.0842	123.8039	120.4293	116.8007
10000	112.4382	115.1798	112.8133	114.1843	117.7656	122.5959	119.192	115.3057
12500	111.0977	112.9574	114.1468	115.3854	117.2991	121.3924	118.0517	114.1594
16000	110.7069	111.7656	112.3982	115.8798	116.4003	120.0584	116.8456	112.7707
20000	109.5238	111.1901	111.0938	115.4738	115.6825	118.9568	115.6388	111.1365
25000	108.3896	109.7965	110.1968	114.025	114.5813	117.6027	114.2236	109.487
31500	106.3028	107.6681	108.3515	111.6672	112.6035	115.755	112.1723	107.3828
40000	104.5963	106.1169	107.5825	109.8609	110.9281	114.3721	110.3388	105.8163
OASPL	125.7642	126.4467	126.2907	128.8848	132.0543	137.8886	137.3497	135.2262

Table C.29: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=811.5$ K)

NPR = 5.67, Stagnation Temperature = 1001 °F, Chamber Temperature = 71.8 °F
 Relative Humidity = 70 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.38007	83.30888	84.49421	85.03933	85.45389	87.71046	91.6496	96.76288
250	82.12489	83.64866	86.04328	87.40785	87.63715	90.56769	94.92427	100.0171
315	84.82466	87.85839	89.57837	90.08764	91.75195	93.83515	96.69585	104.6765
400	89.54288	91.53636	92.76426	93.02848	94.42621	96.76996	102.8109	107.093
500	92.45148	93.26467	93.20756	93.95185	94.84708	99.55204	104.6482	111.1985
630	93.04845	93.58366	93.95331	94.60272	96.65628	102.9848	108.6434	114.3202
800	93.09958	94.79049	96.50233	97.99615	100.6156	106.8976	113.2457	117.9674
1000	95.90684	97.49858	98.47169	100.0439	102.4358	109.8436	115.4491	119.9764
1250	96.67705	99.24498	100.2027	101.4893	105.9407	113.1419	118.9991	121.5344
1600	98.12298	100.0206	102.2138	104.5592	108.5878	117.0052	121.3528	122.4412
2000	100.5607	102.1166	103.306	105.7382	110.8216	119.4624	122.9173	122.5373
2500	101.9594	103.8364	105.1918	107.386	113.3406	121.9416	123.9683	122.6142
3150	105.211	105.708	107.293	109.5478	115.3153	124.3302	126.6657	123.1076
4000	105.6598	106.4485	108.1163	110.503	116.6223	124.8771	124.2768	121.2098
5000	111.0078	108.7268	109.1008	111.5074	117.7943	125.4561	123.0534	119.6693
6300	116.9381	113.8168	111.3004	113.2084	118.5439	125.3772	121.7672	118.8061
8000	115.6859	118.0361	113.9438	114.6277	118.921	124.5814	120.9625	117.9724
10000	113.0726	116.4079	116.7722	116.0458	118.8605	123.1599	119.6403	116.5348
12500	113.1117	114.1371	116.4042	117.3753	118.5646	122.069	118.656	115.2191
16000	112.2555	114.0184	114.0516	117.8631	117.7195	120.8506	117.5026	113.8664
20000	111.4915	113.1171	113.4637	117.3073	117.0354	119.7204	116.385	112.0968
25000	110.4406	111.9375	112.5752	115.7343	115.9683	118.5509	115.0716	110.5689
31500	108.4748	109.8379	110.7599	113.5129	114.0158	116.6999	113.0966	108.4103
40000	106.9399	108.3009	109.946	111.7116	112.386	115.3656	111.3405	106.6884
OASPL	127.7692	128.7915	128.6687	130.5282	132.9725	138.8327	138.198	136.7231

Table C.30: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.2$, $T_0=988.2$ K)

NPR = 2.36, Stagnation Temperature = 1319 °F, Chamber Temperature = 68.5 °F
 Relative Humidity = 67.8 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	88.73059	93.78289	96.07247	98.31338	100.5442	101.7895	102.9946	106.2243
250	75.08314	76.90955	78.67359	80.35928	82.38805	85.3804	88.04149	91.47775
315	77.85674	79.75887	80.79204	82.55969	84.16664	87.87141	89.95678	94.33488
400	84.00004	86.7463	84.00904	90.18338	90.55388	94.23601	98.2477	99.07654
500	82.6937	83.74435	84.0748	86.03082	88.26591	92.84829	95.97957	100.0517
630	84.83969	85.74736	86.5187	88.06217	91.77094	96.81227	100.055	103.37
800	87.05117	88.28788	89.22387	91.21078	95.93903	100.5281	104.2076	106.7729
1000	88.6445	89.94038	90.27989	93.59451	97.63539	103.0866	106.0186	108.7407
1250	90.89687	92.46644	93.64921	95.66466	101.1888	106.1654	109.3044	110.5169
1600	92.95977	95.1304	95.87532	99.30745	104.0552	109.5237	111.4827	111.7478
2000	94.77269	96.87081	98.14027	101.8611	107.3754	112.7179	113.4631	112.3817
2500	96.68852	98.83144	100.6394	104.1061	110.1601	114.8572	114.4525	113.0919
3150	98.7681	101.055	102.8678	106.5388	112.748	116.6626	115.0146	113.9895
4000	100.0223	102.6005	104.4256	108.4541	114.1731	117.7331	116.5544	116.0834
5000	101.7874	104.0438	105.7883	109.6061	115.2043	118.6461	118.9305	118.6056
6300	101.9097	104.4395	106.4925	110.3207	115.0293	118.0825	118.1212	117.2142
8000	101.8877	104.6807	106.8676	110.6839	114.2482	116.5715	115.827	114.2768
10000	101.9747	104.8797	106.9722	110.717	113.2332	115.3955	114.6205	112.9179
12500	102.8552	105.2268	106.7862	110.6229	111.9605	114.4043	113.5752	111.5246
16000	102.8741	104.9237	106.2164	109.9116	110.4929	112.8923	111.8748	109.7138
20000	102.123	104.2559	105.3531	108.8931	109.1671	111.5536	110.3736	107.9661
25000	100.5319	102.827	104.1141	107.4713	107.7753	110.0645	108.8306	106.089
31500	98.31451	100.5083	102.1519	105.1776	105.5409	108.0084	106.6753	103.7916
40000	96.62704	98.85332	101.0603	103.1418	103.8724	106.5599	104.9796	102.1512
OASPL	116.9587	119.3322	121.0766	124.6705	128.1571	131.3661	130.985	130.1201

Table C.31: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.29$, $T_0=977$ K)

NPR = 2.67, Stagnation Temperature = 1299 °F, Chamber Temperature = 67.2 °F
 Relative Humidity = 78.6 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.81515	77.45947	78.96127	79.11433	79.41822	81.75366	85.21559	89.27161
250	75.29363	76.63393	78.49102	79.85688	81.23151	84.30024	87.58276	91.38172
315	78.05822	80.28682	81.82155	82.21958	83.84174	87.78999	89.77609	95.18514
400	81.2886	83.0798	83.60598	84.18085	87.25925	90.10586	95.07301	98.18254
500	83.6231	84.82091	85.28803	86.53717	88.77946	93.89953	97.6251	101.9973
630	85.9217	86.69445	87.2038	88.02702	92.05794	97.68726	101.5694	105.1951
800	87.60851	88.94558	89.99879	91.8327	96.61573	101.6891	106.0288	108.7893
1000	89.69123	90.88423	91.18267	94.19593	98.81156	104.7926	108.3065	110.9083
1250	91.44004	92.95578	94.16502	96.28729	102.7911	107.988	111.558	112.4574
1600	93.85947	95.20777	96.35157	99.73799	105.6855	111.6234	114.1732	114.0639
2000	95.40556	97.18507	98.51094	102.2752	108.6575	114.4839	115.7426	114.4659
2500	97.45511	99.03509	100.5359	104.2338	111.5817	116.6252	116.6352	115.275
3150	99.28624	101.0316	102.9428	106.5982	113.8998	118.3548	117.0942	116.0688
4000	100.3893	102.0684	104.1909	108.3773	115.2719	119.0895	117.9504	117.1144
5000	101.6485	103.5496	105.4852	109.544	116.2809	119.6914	119.3929	118.4128
6300	102.6532	104.5784	106.5611	110.8852	116.5082	120.2284	120.494	119.152
8000	102.94	105.0684	106.9325	111.281	116.0873	119.1263	118.1405	116.0552
10000	104.6477	105.678	107.283	111.6048	115.2031	118.017	116.5056	114.52
12500	107.1238	107.0341	107.3668	111.6921	114.0893	116.9364	115.6512	113.3376
16000	106.8902	107.6968	107.246	111.3467	112.7331	115.48	114.2465	111.6871
20000	105.1608	107.2397	106.8686	110.8385	111.5558	114.0879	112.8833	110.0289
25000	103.6442	105.5791	105.8307	109.7462	110.2219	112.5348	111.4137	108.3742
31500	101.6838	103.2228	103.926	107.5859	108.1131	110.5343	109.347	106.3221
40000	99.91688	101.6367	102.9555	105.6388	106.3273	109.1233	107.6736	104.7671
OASPL	119.4065	120.7636	121.6947	125.6502	129.7896	133.3487	132.908	131.6776

Table C.32: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.4$, $T_0=997$ K)

NPR = 3.09, Stagnation Temperature = 1299 °F, Chamber Temperature = 73.8 °F
 Relative Humidity = 57.1 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	77.52474	78.95638	79.88869	81.09759	82.31555	84.37149	87.52162	91.35307
250	78.37294	79.60714	80.71235	82.13703	83.47466	87.21326	90.69821	94.51928
315	79.81569	81.668	83.76793	83.86948	85.93636	90.33499	92.26114	97.83527
400	83.48916	85.45414	85.88222	86.83885	89.71771	92.59679	97.4336	100.7195
500	85.37661	87.44236	86.6435	88.47277	90.89569	96.40455	99.89906	104.3918
630	87.84385	89.0602	88.95709	90.37101	94.72189	100.7114	104.5228	108.146
800	89.59363	90.78934	92.14058	94.04421	99.04131	104.311	108.3443	111.3767
1000	91.48426	93.12055	93.3619	96.25285	101.321	107.7797	110.8451	113.6819
1250	93.46017	95.17179	96.27681	98.51275	105.282	111.0113	114.2118	115.292
1600	95.5203	97.45664	98.52016	101.9913	108.2054	114.653	116.4281	116.2996
2000	97.55285	99.39014	100.4125	104.0648	111.1027	117.2359	117.8688	116.8365
2500	99.57129	100.933	102.543	106.4008	114.0589	119.4591	118.9083	117.808
3150	101.247	102.994	104.9017	108.5574	116.3955	121.0596	119.7783	118.9233
4000	102.1815	104.397	106.1952	110.3196	117.9461	121.8399	120.5343	119.5993
5000	103.3968	105.5029	107.2118	111.1939	118.672	122.1714	121.1712	119.6064
6300	104.0945	106.1905	108.2031	112.1541	118.7922	122.0328	120.5273	118.4586
8000	105.3186	107.1284	108.7212	112.6662	118.3482	121.2875	119.1383	117.2979
10000	107.3209	108.0753	108.8906	112.7474	117.2354	120.0735	117.7712	115.7386
12500	108.175	109.144	109.0964	112.8483	115.9428	118.8265	116.567	114.1651
16000	107.062	109.1689	108.8536	112.2996	114.4758	117.5021	115.1649	112.6676
20000	105.7315	108.1382	108.1131	111.656	113.2671	116.3141	113.8813	110.9475
25000	104.4197	106.6456	106.9405	110.4402	111.886	114.9951	112.5302	109.1882
31500	102.2714	104.4134	105.0243	108.1855	109.8625	113.1004	110.5714	107.038
40000	100.5833	102.8348	104.2052	106.3652	108.2384	111.8594	108.9687	105.6066
OASPL	120.6852	122.4466	123.2998	126.896	132.0084	135.7058	134.4845	133.2615

Table C.33: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.6$, $T_0=974.3$ K)

NPR = 4.14, Stagnation Temperature = 1294 °F, Chamber Temperature = 73.8 °F
 Relative Humidity = 57.1 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	88.60937	90.89864	92.51618	94.3505	96.96958	99.1274	101.89	105.8336
250	80.71765	81.73708	83.55978	84.91599	86.38813	89.76325	93.33839	97.71432
315	82.98126	85.5074	87.23464	87.59416	89.52011	92.90422	95.50672	101.9198
400	86.4997	87.96458	89.58871	90.44065	92.33699	95.55959	100.6628	104.1408
500	88.76852	90.50878	90.41299	91.78567	93.09212	98.60623	102.5488	107.8222
630	90.02459	91.65637	91.87811	92.9323	96.37015	102.7712	107.2682	111.2107
800	91.31119	92.92878	94.7962	96.39958	100.4878	106.3494	111.3911	114.6683
1000	93.65796	95.35319	96.14246	98.63177	102.8127	109.6879	113.8485	116.5649
1250	95.06217	97.51462	98.96463	100.2168	106.3737	112.7628	117.1313	117.9948
1600	97.13866	99.18873	100.7672	103.8335	109.3081	116.2782	119.2485	118.592
2000	99.31649	100.8608	102.3967	105.4707	112.1904	118.8278	120.499	118.8215
2500	101.0872	102.8103	104.3993	107.8489	115.0528	120.9004	121.3095	119.4321
3150	102.2601	104.5931	106.398	109.7925	117.4052	122.2733	121.8124	119.6967
4000	103.3574	105.6265	107.8035	111.8327	119.2371	123.3744	122.3499	119.4603
5000	104.5156	106.7478	108.7744	113.1145	120.5329	123.9536	121.9955	118.2709
6300	106.001	107.9066	110.1542	114.5207	121.4312	124.1005	120.9698	117.8389
8000	108.2024	108.9228	110.9638	115.1877	121.449	123.5027	120.2266	117.2029
10000	109.3844	110.4645	111.5912	115.5001	120.8287	122.2574	119.1313	116.0015
12500	108.8343	111.241	111.9967	115.5467	119.7826	120.9749	118.047	114.6837
16000	108.0547	110.3367	111.5565	114.9679	118.1993	119.7576	116.6415	112.9053
20000	107.3575	109.3632	110.6478	114.1532	116.9156	118.4235	115.3295	111.0194
25000	106.0644	108.1655	109.3959	112.6192	115.5309	117.0753	113.8046	109.3367
31500	104.0293	105.9327	107.5644	110.357	113.5297	115.2241	111.6883	107.1945
40000	102.5203	104.4315	106.8123	108.6093	112.0358	113.9384	110.0069	105.7141
OASPL	122.2434	124.109	125.6738	129.2245	134.6358	137.563	136.1517	134.072

Table C.34: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.7$, $T_0=982$ K)

NPR = 4.82, Stagnation Temperature = 1309 °F, Chamber Temperature = 73 °F
Relative Humidity = 73.2 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	82.38629	83.33938	84.33401	84.41452	84.78004	88.02069	92.34916	97.60404
250	82.29756	83.51367	85.44749	86.53282	87.34747	90.90031	95.00993	99.82111
315	84.52384	87.46396	89.12646	89.29061	91.3825	94.33519	97.04564	103.9941
400	88.34076	89.93837	91.19954	92.60198	94.0344	97.18026	102.5601	106.1958
500	90.75133	91.88275	92.04884	93.08696	94.59473	99.9178	104.2448	110.0184
630	92.02999	92.80527	93.37506	94.06421	97.52785	103.9986	108.8751	113.5468
800	92.41096	94.23884	95.7853	97.82742	101.9589	107.9198	113.11	116.7013
1000	94.90809	96.60381	97.54188	99.76062	103.711	111.0416	115.4033	118.5543
1250	96.25037	98.52114	99.88822	101.4174	107.8141	114.1892	118.2216	119.5304
1600	98.09611	100.0202	102.0126	104.7515	110.3961	118.0246	120.6897	120.3329
2000	100.4353	101.8019	103.3676	106.4218	113.275	120.5893	121.8884	120.278
2500	102.215	103.2859	105.1507	108.4408	116.1212	122.5069	122.5693	120.6745
3150	103.3703	105.0168	106.9199	110.2362	118.4375	124.1684	123.022	120.5029
4000	104.4324	106.398	108.3966	111.6845	119.9367	125.0701	123.2007	119.7987
5000	106.0677	107.5726	109.3013	113.0363	121.3975	125.2749	122.2367	118.6261
6300	109.8334	109.4038	110.7099	114.3654	122.1982	125.0351	121.1769	117.9197
8000	113.8703	112.2493	112.0505	115.1852	122.4645	123.9616	120.4939	117.4208
10000	113.2941	115.1358	113.4477	115.8284	122.1995	122.7211	119.464	116.1727
12500	111.6484	114.3893	114.7202	116.3228	121.2227	121.7075	118.492	115.1404
16000	110.9367	112.7232	114.2495	116.2344	119.7555	120.3144	117.2342	113.6263
20000	110.0461	111.9629	112.6767	115.6743	118.587	119.0608	115.8833	111.838
25000	108.9526	110.8253	111.4249	114.2557	117.2791	117.7513	114.4744	110.1517
31500	106.9692	108.6734	109.6187	112.036	115.3594	115.8576	112.4311	107.9958
40000	105.3642	107.2197	108.8587	110.2928	113.9702	114.6678	110.7055	106.4755
OASPL	125.5421	126.8351	127.4235	129.9384	135.8228	138.7013	136.9779	135.0997

Table C.35: SPL and OASPL for the Mach 1.5 Nozzle ($M_j=1.8$, $T_0=977.6$ K)

NPR = 5.64, Stagnation Temperature = 1300 °F, Chamber Temperature = 73.8 °F
 Relative Humidity = 69.3 %, $\gamma = 1.34$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	99.58463	99.16561	99.15301	100.1223	104.3819	106.9566	110.2392	114.3068
250	84.53302	85.37085	86.58508	88.25607	89.92335	93.30026	96.93888	101.8697
315	86.18307	88.6712	90.5781	91.66921	93.71658	96.9659	99.50035	106.3682
400	91.69808	92.18423	95.80313	97.9212	97.19199	104.2705	106.9508	109.9991
500	93.22929	94.36356	94.54757	95.35239	96.63739	101.9866	106.3483	112.5632
630	94.2544	94.54833	94.99559	96.06966	98.84159	105.2387	110.6629	115.8172
800	93.68888	95.47295	97.32407	99.26134	103.3107	109.2655	114.9122	118.8961
1000	96.06926	98.19409	99.3423	101.0625	104.6684	112.2179	117.2346	120.8101
1250	97.59608	100.0935	101.4554	102.8251	108.1832	115.0526	119.9674	121.8188
1600	99.15951	101.0328	103.4643	105.6371	111.0594	118.8935	122.0987	122.2295
2000	101.3498	103.2595	104.4297	107.2285	113.475	121.3009	123.3847	122.4344
2500	103.0332	104.793	106.1791	109.0877	116.2633	123.6277	124.3397	122.6937
3150	104.599	106.2181	108.0193	110.9038	118.4311	125.359	124.9011	122.2787
4000	105.8515	107.6174	109.2626	112.621	119.9462	126.0588	124.0128	121.1581
5000	109.5934	109.3377	110.1837	113.7641	121.3798	126.2248	122.8691	119.9147
6300	115.1467	112.6312	112.0126	115.2724	122.2421	125.7483	121.8938	119.0532
8000	116.4381	117.0219	113.8975	116.2912	122.7212	124.5705	121.0215	118.2532
10000	113.7016	117.8493	115.8998	117.2532	122.5075	123.2495	119.9399	117.0086
12500	113.1068	115.4449	116.9748	117.9768	121.752	122.2451	118.8943	115.6415
16000	112.5595	114.5955	115.1949	118.007	120.3137	120.8407	117.687	114.2097
20000	111.596	114.0487	113.8688	117.4766	119.1041	119.6951	116.215	112.4055
25000	110.4209	112.7069	112.883	115.9357	117.7986	118.3781	114.8526	110.682
31500	108.4445	110.5395	111.0453	113.6637	115.9154	116.5042	112.7604	108.5671
40000	106.8881	109.1028	110.2169	111.9644	114.4528	115.2779	111.0595	107.1511
OASPL	127.6014	129.2174	128.9998	131.3398	136.0815	139.5352	138.1341	136.8072

Table C.36: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.3$, $T_0=287.7$ K)

NPR = 2.76, Stagnation Temperature = 58.1 °F, Chamber Temperature = 68.5 °F
 Relative Humidity = 74 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	71.79676	73.46556	73.30022	73.48418	71.94756	73.20655	75.65339	82.71093
250	72.15969	74.1368	73.21507	74.99026	74.7327	75.55745	77.91987	84.33579
315	73.30368	75.37963	76.3354	77.30124	76.23525	77.78114	79.7099	85.4487
400	74.96172	77.45686	78.49584	79.36448	79.35269	81.75766	84.39144	89.68674
500	77.11869	78.33396	79.78347	80.40954	81.1682	83.03299	86.40725	92.09905
630	79.76145	80.5157	81.91392	82.82809	83.62182	86.08353	90.01157	95.08185
800	81.37093	83.19435	84.26182	85.08685	85.68014	87.96863	92.8669	97.85231
1000	82.15836	84.03813	84.73281	85.98273	86.27526	89.64385	94.21333	100.1786
1250	84.14512	85.74147	87.35923	88.16581	89.54569	92.55857	97.80973	102.8144
1600	85.94318	87.63722	88.73943	89.94869	90.83752	93.94006	98.88732	103.9465
2000	86.64255	88.55841	89.6379	90.75154	91.82993	95.28932	100.2692	104.9393
2500	87.82484	89.55385	90.4144	91.5581	93.04818	96.25294	100.6752	104.4494
3150	88.87337	90.45984	91.61112	92.68372	94.33321	97.24769	100.3081	103.0062
4000	89.41435	90.93444	91.81644	93.64829	94.87584	97.54709	99.87985	101.2701
5000	90.15722	91.41568	92.18946	93.81109	95.31077	98.01358	99.36894	99.89966
6300	91.40779	92.20844	92.82083	94.41221	95.74327	98.13805	98.96375	98.85812
8000	95.40308	93.67422	93.4847	95.10324	96.16602	98.16529	98.34006	97.94781
10000	99.77842	98.23777	95.27719	95.67388	96.38495	97.90766	97.76207	96.98672
12500	100.3078	100.2364	97.60045	96.83064	96.61811	97.72065	97.12382	96.10273
16000	98.2397	98.95514	97.86324	98.66186	97.18647	97.31904	96.50802	95.23993
20000	97.35829	97.24002	96.33644	98.68283	97.94422	97.21571	95.75306	93.95964
25000	96.39247	96.34183	94.94227	97.20218	97.46696	96.69389	94.69389	92.63072
31500	94.47551	94.11725	93.4008	94.91791	95.0067	94.64371	92.49752	90.36049
40000	92.97394	92.56981	92.64192	92.91726	92.4056	92.0225	89.73436	87.72018
OASPL	111.7862	111.6915	110.7537	111.8029	112.0556	113.4868	115.1267	117.7191

Table C.37: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.4$, $T_0=286.7$ K)

NPR = 3.17, Stagnation Temperature = 56.4 °F, Chamber Temperature = 68.5 °F
Relative Humidity = 74 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.17834	73.56872	73.9675	74.35014	73.7679	74.54784	78.61044	85.2467
250	74.03111	74.41531	75.42098	76.72963	76.42344	76.75228	81.20546	86.54029
315	75.034	76.87456	78.17514	78.96527	77.89524	79.66673	81.98152	87.85383
400	76.83987	78.91144	80.35322	79.99855	80.78302	82.65696	86.16496	91.70662
500	78.87802	80.50113	80.87532	81.84874	82.18975	83.75057	87.96458	93.84456
630	81.4616	82.6501	83.55936	83.91125	84.40516	86.59334	91.58256	97.60844
800	82.89093	84.83236	86.3459	86.95234	87.4094	89.43518	94.99538	100.7014
1000	84.32213	85.87994	86.74437	88.01524	88.29226	91.43136	96.72322	103.2963
1250	85.89827	87.43659	89.18555	90.16923	91.09522	94.15241	100.2259	105.9607
1600	87.91409	89.52184	91.0472	92.1769	92.82075	95.94837	102.0256	108.0277
2000	88.38151	90.68324	91.62605	92.98489	93.94032	97.65519	103.4969	108.9089
2500	89.62197	91.55137	92.41303	93.66822	95.3395	98.60032	103.7937	108.2342
3150	90.72338	92.2555	93.55965	94.69498	96.36553	99.28743	103.4431	107.0511
4000	92.65305	92.79194	93.68934	95.58172	97.39656	100.4255	103.3328	105.4568
5000	94.77507	93.94973	94.32527	95.64669	97.40535	99.91794	102.284	103.8008
6300	103.0713	99.53131	96.53227	96.9204	97.91785	100.3401	101.6106	102.1946
8000	108.6625	107.8559	102.8221	99.77154	99.59152	100.9227	101.1459	101.1881
10000	106.3231	107.9975	106.287	103.7128	101.2686	101.0765	100.7463	100.1414
12500	104.0579	104.8122	105.4398	106.5152	105.0935	102.7857	101.0458	99.75351
16000	104.4126	103.918	102.417	105.4799	106.7217	104.7061	101.7809	99.5718
20000	103.0785	103.4772	101.9204	103.4642	105.8495	105.1407	102.2245	98.85195
25000	102.1108	102.1215	100.8416	102.3539	103.4305	103.5794	101.4398	98.22521
31500	100.2016	100.0022	99.2322	100.1999	100.4369	99.99667	98.46974	96.08302
40000	98.53797	98.49829	98.48189	98.16203	98.13141	97.01136	94.90628	93.26339
OASPL	118.6937	118.7207	117.1848	117.522	117.9	117.7985	118.6573	121.4792

Table C.38: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=286.1$ K)

NPR = 3.66, Stagnation Temperature = 55.3 °F, Chamber Temperature = 68.5 °F
Relative Humidity = 74 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	76.40316	77.39269	77.12181	76.9267	75.88786	77.30145	80.75582	89.1189
250	76.8467	77.80903	78.77845	79.83297	79.81284	79.25711	81.96752	89.11137
315	78.61226	80.95908	82.22914	83.14827	81.24079	81.96226	83.59784	90.33031
400	80.82081	83.32809	83.83226	83.94083	83.5441	84.65845	87.10519	93.19507
500	82.65327	84.31229	85.03113	85.45694	85.1231	85.67247	89.75842	95.88631
630	84.98506	86.7327	87.96249	88.54052	88.05086	89.37519	94.07414	99.73176
800	87.39466	89.21903	90.31198	91.04269	91.36124	92.62358	98.19591	103.569
1000	88.16856	90.31463	91.32384	92.62132	92.29661	95.18618	100.4978	106.5367
1250	90.00206	91.7788	93.41486	94.45415	95.24712	98.65207	105.3644	110.4559
1600	92.21739	94.13231	95.21822	96.41025	96.98049	101.1664	107.9186	112.8167
2000	93.16751	95.40576	96.30146	97.68195	98.78283	103.229	109.9324	114.2267
2500	94.16103	95.9883	97.10325	98.30435	100.0304	103.8916	109.9145	113.2697
3150	95.46091	97.6512	99.66396	99.65704	101.1564	104.9612	110.2088	113.1983
4000	96.85245	97.59165	98.49568	99.82451	101.3437	105.0913	109.3614	111.7575
5000	103.3716	101.22	99.74433	100.5266	101.9244	105.3301	108.4775	110.3356
6300	108.6338	112.6537	108.2715	104.4104	103.4016	105.9243	107.9471	109.4005
8000	104.9727	108.5774	107.4547	105.3844	104.3331	105.9545	106.7866	108.2876
10000	103.3877	104.0891	105.8982	107.684	106.722	106.4626	106.2009	107.1046
12500	104.062	104.4614	103.4551	106.695	108.8993	107.6976	106.0019	106.0906
16000	102.7681	103.7706	103.1608	104.7813	108.0834	108.8945	105.9853	105.0362
20000	102.0744	102.7881	101.9941	104.1776	105.5306	108.3918	105.7447	103.9212
25000	101.0407	101.5471	100.9618	102.8113	103.7508	105.5864	104.4881	102.736
31500	99.17447	99.48821	99.2982	100.8723	101.5331	102.4223	101.6035	100.4047
40000	97.4795	97.87932	98.39111	98.73416	99.0682	100.1246	98.499	97.54416
OASPL	118.666	120.8578	119.3372	119.6445	120.5637	122.133	124.1727	126.8757

Table C.39: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.6$, $T_0=285.7$ K)

NPR = 4.26, Stagnation Temperature = 54.5 °F, Chamber Temperature = 68.5 °F
Relative Humidity = 74 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.12668	76.9277	77.89649	78.21883	77.93965	78.53618	81.66965	86.83683
250	79.49684	77.10181	79.00131	80.50017	80.57203	80.2249	83.70636	89.41488
315	80.34069	81.2048	82.96284	84.4585	83.09165	84.89508	86.44971	92.48725
400	82.21881	84.01178	85.04681	85.29849	86.01916	87.18899	90.24302	96.32871
500	84.13542	85.10323	85.68682	86.75065	86.50149	87.53528	91.78105	98.85066
630	85.61193	86.63869	87.22995	87.99692	88.92012	90.62605	95.55922	102.6151
800	87.32351	88.70783	90.51132	90.97805	91.96599	93.60393	99.72112	106.4672
1000	89.076	90.33332	90.79491	92.25176	92.64822	95.74076	101.4702	109.2015
1250	89.85136	90.91612	92.85317	93.98292	95.2028	98.78132	105.249	111.9168
1600	91.92303	93.24454	94.66058	96.216	96.92469	100.2141	107.0604	113.8474
2000	92.56457	94.66241	95.72066	97.15836	97.88241	101.7488	108.95	115.3599
2500	93.42538	95.58797	96.42621	97.76116	99.34706	102.7549	109.8307	115.622
3150	95.27667	96.86448	98.14317	98.60779	100.0863	103.6293	109.7579	115.7299
4000	99.13563	97.84868	98.09238	99.26646	100.8058	103.9733	109.2222	115.9824
5000	107.6322	103.678	99.89708	100.1695	101.432	104.3146	108.1536	114.9926
6300	110.5542	110.9577	105.4807	102.7507	102.7379	104.8281	107.4142	114.002
8000	107.5567	110.314	110.1761	106.7881	104.7896	105.491	106.7398	113.0066
10000	104.9524	106.6733	108.4309	109.9613	107.7063	106.1635	106.1244	111.6618
12500	105.2675	105.8356	105.0876	108.7186	110.5666	107.6352	105.8379	110.3831
16000	104.2754	105.2368	104.4194	106.2242	109.923	108.8677	105.7175	109.0736
20000	103.5872	104.4453	103.5982	105.5885	107.354	108.8937	105.4834	107.6722
25000	102.4676	103.2811	102.4531	104.3141	105.2711	106.4357	104.2558	105.8712
31500	100.5449	101.1349	100.8155	102.2185	102.9841	102.6998	101.3433	103.1768
40000	98.70992	99.50307	99.88948	100.2351	100.4931	100.2669	98.04612	100.348
OASPL	120.6594	121.3362	120.3758	120.875	121.6478	121.8576	123.8596	129.7997

Table C.40: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.7$, $T_0=285.1$ K)

NPR = 4.92, Stagnation Temperature = 53.5 °F, Chamber Temperature = 68.5 °F
Relative Humidity = 74 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.04322	79.27762	79.5766	80.63645	81.3071	81.45052	83.14244	88.59631
250	79.66916	79.05265	81.06019	82.6794	82.8295	82.30279	85.65787	91.53561
315	81.45272	82.79562	84.53518	85.77917	85.08261	86.89902	88.1139	94.42998
400	83.97407	85.8763	86.73335	87.13014	87.95067	88.70891	92.3754	98.59662
500	86.14334	87.54569	87.53437	88.73213	88.86376	89.43915	93.67597	101.1913
630	87.83711	88.32545	89.01706	90.10351	90.75092	92.74157	97.43946	104.6982
800	88.85063	90.53066	91.737	92.65135	93.67994	95.42246	101.6317	108.576
1000	90.59376	92.18576	92.58303	93.69392	94.17207	97.32694	103.032	110.8406
1250	91.51143	92.66549	94.46647	95.68961	96.70922	100.0387	106.7822	113.582
1600	93.68319	94.92099	96.29471	97.82011	98.23767	101.7995	108.634	115.4341
2000	94.30687	96.07699	97.07913	98.37508	99.24917	102.9603	110.5832	116.7345
2500	95.19701	96.96546	97.905	99.17918	100.7555	104.358	111.7793	117.373
3150	97.01536	98.20788	99.72826	100.2537	101.6451	105.2106	112.181	117.8899
4000	100.4382	99.37543	99.67262	100.8803	102.2859	105.7014	111.9891	118.2145
5000	106.5887	104.2573	100.9628	101.6364	102.8975	106.0308	111.1019	117.7776
6300	106.9092	108.4931	105.5498	103.2247	103.7103	106.3606	110.1376	117.0784
8000	104.4843	106.9422	107.8259	106.3016	104.9697	106.6701	109.2137	116.1928
10000	103.6128	104.6875	105.5511	107.9275	107.1711	106.9574	108.2862	114.9545
12500	103.3466	104.7568	103.6765	106.4032	108.8547	107.4656	107.5153	113.6601
16000	102.5147	103.8008	103.3934	105.0986	107.6203	107.7981	106.7207	112.1195
20000	101.5264	103.0659	102.3632	104.6713	105.6967	107.4389	105.9418	110.5927
25000	100.4253	101.7745	101.3154	103.4775	104.2807	105.3764	104.6383	108.9973
31500	98.34776	99.56793	99.62642	101.357	102.1073	102.2389	101.9064	106.7003
40000	96.4051	97.78472	98.70363	99.26778	99.76328	99.79431	98.85314	104.2907
OASPL	118.6249	119.6221	119.1712	120.0166	120.8795	122.1661	125.8814	132.1366

Table C.41: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.9$, $T_0=288$ K)

NPR = 6.7, Stagnation Temperature = 58.8 °F, Chamber Temperature = 71.1 °F
Relative Humidity = 38.5 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.04409	81.90238	82.91844	83.79358	84.51681	84.99763	88.07122	94.47604
250	80.52082	82.14704	84.00513	85.8737	86.0976	86.61811	90.66739	96.68955
315	84.92824	87.01563	88.48714	89.34623	89.59177	91.67179	92.04202	99.83447
400	88.31842	90.21317	91.20911	91.23625	92.20433	93.15579	96.62536	102.7908
500	90.53311	91.52285	91.47359	92.29811	92.65395	93.8919	97.89023	105.6705
630	92.09007	92.19126	92.58526	93.34711	94.16213	96.16875	101.1902	108.9333
800	92.1503	93.97346	95.19924	95.99096	97.16015	99.17535	105.5255	113.2372
1000	94.44488	95.94553	96.27497	97.40367	97.92177	101.0103	107.0228	115.5711
1250	95.57829	96.42364	98.22382	99.02156	100.2778	103.7929	111.0895	118.2786
1600	96.85216	98.39913	99.65921	100.9819	101.4431	105.3648	113.0006	119.9119
2000	97.87018	99.41542	100.583	101.6961	102.5675	106.9139	114.9997	121.2583
2500	99.35884	100.8147	101.4646	102.8677	104.1868	108.1317	116.4581	121.7772
3150	103.567	102.5595	103.4448	103.6884	105.2528	108.9682	117.253	122.3373
4000	110.0069	106.8557	104.3413	104.8268	106.0685	109.5812	117.3073	122.6753
5000	110.7175	111.8781	108.7848	106.3395	106.9991	109.9799	116.9166	122.2596
6300	108.5782	110.6931	111.9692	109.7429	108.2441	110.509	116.3624	121.0663
8000	108.3136	108.6545	109.7784	111.9128	110.3243	110.9715	115.7112	119.4576
10000	107.6077	109.1613	108.0996	110.1642	112.3066	111.4606	114.9119	117.8461
12500	107.0497	108.2849	108.4159	109.2369	112.0188	112.0235	114.1497	116.4246
16000	106.0249	107.482	107.2965	109.2072	110.0101	111.8987	113.2063	114.8353
20000	105.0123	106.4732	106.4019	108.5781	108.8059	110.8635	112.208	113.3012
25000	103.7076	105.1147	105.3846	107.5288	107.9359	109.0309	110.8335	111.8437
31500	101.7175	103.0461	103.892	105.6907	106.13	106.7214	108.6543	109.9086
40000	100.2857	101.6663	103.4129	104.0709	104.3351	105.0079	106.4744	108.0473
OASPL	122.715	123.5256	123.4339	124.1045	124.7544	126.2622	131.4137	136.2578

Table C.42: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.0$, $T_0=289.1$ K)

NPR = 7.79, Stagnation Temperature = 60.7 °F, Chamber Temperature = 71.1 °F
 Relative Humidity = 38.5 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.60014	84.02788	85.00929	85.86454	86.86216	87.09887	89.55046	95.14103
250	82.67484	84.04211	85.80267	87.61063	88.24019	89.06642	92.43085	97.92772
315	86.4726	88.56917	90.39125	91.39214	91.77191	93.70091	93.63316	100.9797
400	90.2402	91.96266	93.3487	93.72913	94.68738	95.01281	98.57581	104.7328
500	92.97399	93.88759	93.7371	94.46661	94.62816	96.25679	99.52376	107.6487
630	94.56198	94.42946	94.34603	95.15704	96.294	98.38762	102.9661	111.3894
800	93.86936	95.67398	97.11632	97.86497	99.00134	100.9312	106.9988	115.1409
1000	96.23404	97.45628	98.19614	98.89215	99.54173	103.1817	108.9207	117.8502
1250	97.10948	98.04816	99.73701	100.4988	102.0243	105.548	112.6249	120.3741
1600	98.49174	100.1444	101.1179	102.8013	103.2829	107.0691	114.827	122.3844
2000	99.7717	101.2454	102.3073	103.2362	104.0629	108.1679	116.9254	123.7347
2500	103.0805	103.0828	103.4419	104.618	105.6327	109.3821	118.1417	124.1674
3150	111.0907	107.4745	106.0126	105.5966	106.7938	110.1309	118.9725	124.4075
4000	115.5308	114.9847	109.756	107.5527	107.7405	110.7095	119.2992	124.3674
5000	113.178	116.3924	116.2022	111.0544	109.4655	111.5799	119.1838	123.2971
6300	111.1748	113.028	115.6919	115.6426	112.1233	112.6764	118.9958	121.3988
8000	111.6448	112.2914	112.1154	115.4513	115.3565	113.9551	118.365	119.5956
10000	110.516	112.5821	111.9935	112.5802	117.0442	115.0794	117.7739	118.1329
12500	110.0008	111.7246	111.7734	112.8017	115.6266	115.8928	117.1082	116.7925
16000	108.8873	110.8189	110.7753	112.4663	113.2252	115.4197	116.2269	115.2887
20000	107.7769	109.7698	109.7463	111.6413	112.1914	113.9767	115.0996	113.8389
25000	106.5224	108.4901	108.7214	110.6437	111.1405	112.1892	113.711	112.4494
31500	104.6266	106.376	107.1657	108.8476	109.2168	110.0739	111.5625	110.5121
40000	103.2488	105.0701	106.7112	107.2006	107.6389	108.3891	109.5462	108.7213
OASPL	126.3197	127.5158	127.4048	127.6256	128.3618	129.0379	133.7121	137.8587

Table C.43: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.1$, $T_0=289.5$ K)

NPR = 9.18, Stagnation Temperature = 61.5 °F, Chamber Temperature = 71.1 °F
 Relative Humidity = 38.5 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.91482	85.57099	86.91991	88.32327	89.15372	89.06399	91.41579	97.09255
250	83.40309	85.68118	87.66158	89.64663	90.12467	91.19333	94.65248	100.1055
315	88.30545	90.5833	92.65564	93.53771	94.08928	95.55923	95.49194	103.3604
400	92.94287	94.62291	95.7392	95.72341	96.92134	97.37186	100.5971	106.45
500	95.39876	96.50609	95.94851	96.20018	96.41834	98.49251	101.434	109.6043
630	96.90762	96.4139	96.1109	96.62677	97.72635	100.59	104.9303	113.2456
800	95.34399	97.17409	98.78284	99.10201	100.7922	102.7577	108.4433	116.9447
1000	97.86326	99.51251	99.83419	100.6808	101.6765	105.0893	110.5422	119.6842
1250	99.11861	99.87173	101.116	102.164	103.6018	106.9659	114.1401	122.4819
1600	99.94878	101.5025	102.7141	104.1023	104.4749	108.4549	116.3724	124.4154
2000	102.3478	103.2456	103.4678	104.8257	105.4849	109.3384	118.0635	125.5104
2500	108.6323	106.1761	105.5503	105.9828	107.0418	110.3635	119.453	125.943
3150	116.9872	113.5487	109.3755	107.7627	108.2895	111.0683	120.3685	125.9421
4000	116.9552	119.5548	115.6182	111.2731	109.8351	111.9662	120.9808	125.1723
5000	113.3565	116.2394	119.5523	116.2807	112.5634	113.3001	121.1604	123.072
6300	113.6779	113.8534	115.2432	119.1564	116.0691	115.0929	121.3127	120.7493
8000	113.1709	115.0208	113.7198	115.7859	119.006	116.7427	120.7943	119.3629
10000	112.3912	113.9406	114.4963	114.6614	119.0928	118.0466	120.2319	117.7783
12500	111.7006	113.4849	113.4116	115.451	117.2257	118.5621	119.3647	116.6065
16000	110.6474	112.4762	112.5522	114.4355	115.3739	117.6249	118.1985	115.1697
20000	109.5563	111.452	111.4782	113.6982	114.5532	115.8542	117.0159	113.8277
25000	108.2836	110.1938	110.3863	112.5836	113.2903	114.2962	115.5718	112.3637
31500	106.468	108.0864	108.8576	110.6775	111.3334	112.2744	113.4873	110.3836
40000	105.1737	106.8191	108.4405	109.1267	109.7645	110.6643	111.4737	108.6099
OASPL	128.5375	129.7278	129.6285	130.086	130.8078	131.2518	135.6055	138.9856

Table C.44: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.72$, $T_0=589.3$ K)

NPR = 5.78, Stagnation Temperature = 601 °F, Chamber Temperature = 82.8 °F
 Relative Humidity = 62.2 %, $\gamma = 1.38$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.7582	82.50335	83.76051	84.72218	84.9188	86.02637	90.19078	95.66498
250	81.14458	82.38562	84.56539	86.21414	86.91306	89.36033	93.47925	98.56262
315	84.29958	86.70509	88.97701	89.45285	90.73961	93.1011	94.91944	103.0106
400	88.41932	90.24316	91.54411	92.05218	92.94881	94.86513	100.6014	104.9494
500	91.28663	92.11669	92.51705	93.26891	93.07409	97.6763	102.7185	109.3624
630	92.41915	92.67943	93.16263	93.51372	95.25754	100.9961	106.8743	112.7253
800	92.11338	93.83714	95.42227	96.56915	98.88496	104.1273	110.9292	116.2491
1000	95.04189	96.41804	97.00617	98.19843	100.3662	107.244	113.3395	118.5873
1250	96.46085	98.01719	98.86836	100.244	104.1123	110.405	116.8537	120.429
1600	97.46479	98.99065	100.6558	102.5222	105.9159	114.0374	119.5514	121.4719
2000	99.52238	100.7302	101.9216	103.8511	107.9722	116.7181	121.4374	121.8458
2500	100.8524	102.4631	103.5872	105.6131	110.2764	118.9983	122.8443	122.1298
3150	102.4947	103.8591	105.5805	106.9389	111.9309	121.1158	123.6647	122.2859
4000	103.0764	104.949	106.6086	108.3414	113.1316	122.5197	123.9243	121.5693
5000	104.07	105.3372	107.0622	109.42	114.2061	123.2193	123.7045	120.0858
6300	105.4805	106.7506	108.2092	110.595	114.8985	123.7224	122.6395	118.8994
8000	106.1017	107.6992	108.7511	111.221	115.2605	123.4925	121.2617	117.962
10000	106.4856	108.2433	109.2224	111.6528	115.2084	122.7599	120.2604	116.5543
12500	106.7503	108.5967	109.4155	112.0915	114.9612	121.5344	119.1758	115.2565
16000	106.3396	108.3837	109.1252	111.9215	114.1158	120.326	117.9045	113.7972
20000	105.7161	107.7773	108.6729	111.4629	113.2527	119.0901	116.7148	112.2588
25000	104.6209	106.6231	107.6875	110.3728	112.0134	117.8169	115.3463	110.6285
31500	102.5483	104.4955	106.0875	108.3603	109.9269	115.8742	113.2699	108.4289
40000	100.8197	102.8723	105.2472	106.4442	108.0445	114.4013	111.3221	106.5412
OASPL	120.8011	122.5558	123.8103	126.0777	129.3614	137.1834	137.462	136.1568

Table C.45: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.3$, $T_0=815.4$ K)

NPR = 2.73, Stagnation Temperature = 1008 °F, Chamber Temperature = 68.5 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	75.93104	76.26603	77.21356	77.5251	78.10884	80.80106	84.22128	88.90748
250	77.01324	76.99017	77.94535	79.48969	80.95332	84.24711	87.62699	91.64521
315	78.84861	80.24215	81.54515	82.47691	83.36154	87.55065	89.42765	94.54103
400	81.21084	83.07877	83.34104	84.15491	86.23671	89.50833	93.51761	96.97038
500	83.81225	84.57432	85.02505	86.45791	88.6547	93.30896	96.7685	100.7011
630	86.46009	87.5688	88.2475	89.20533	92.55645	97.16627	100.744	104.0888
800	89.32982	90.72075	91.71026	92.91723	96.98568	101.3676	105.3326	108.0056
1000	90.48639	92.29398	93.04304	95.23393	98.93582	104.3872	107.7065	110.4303
1250	92.63522	94.4456	96.104	97.4052	102.788	107.8677	111.4722	112.7678
1600	94.99868	96.97033	98.36817	100.8445	105.8675	111.5169	114.1318	114.4064
2000	96.65427	98.6272	100.2766	103.2245	108.4057	114.0428	115.8237	115.0251
2500	98.1801	100.416	102.1033	104.9408	110.7984	116.1682	117.0855	115.981
3150	100.0504	102.2361	104.0965	106.9942	112.8506	117.7191	117.7209	117.2192
4000	100.7668	103.1263	105.0516	108.4364	113.8282	118.2654	118.2897	118.1223
5000	101.676	103.7934	105.9625	109.0712	113.9022	117.8631	118.6696	118.4198
6300	102.1382	104.3417	106.7089	109.7402	113.5474	117.0608	118.2387	117.8194
8000	102.4025	104.7991	106.8828	110.0016	112.9423	116.0895	117.4837	116.7331
10000	102.7296	104.9947	107.0346	109.9107	112.2303	115.0227	116.3534	115.1236
12500	103.7107	105.4635	106.7788	109.8208	111.3572	113.9186	115.2436	113.5931
16000	103.2061	105.4254	106.3472	109.1391	109.9887	112.483	113.7197	111.8024
20000	102.3386	104.7821	105.6964	108.381	108.8547	110.978	112.344	110.1024
25000	101.2349	103.4975	104.6184	107.1852	107.6305	109.5069	110.9176	108.4208
31500	99.15355	101.2657	102.7309	104.9697	105.4159	107.438	108.8612	106.3643
40000	97.50768	99.5531	101.7956	103.004	103.5938	105.9199	107.239	104.7495
OASPL	117.6118	119.793	121.4988	124.2825	127.5644	131.4214	132.4615	131.8711

Table C.46: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.4$, $T_0=810.9$ K)

NPR = 3.12, Stagnation Temperature = 1000 °F, Chamber Temperature = 67 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	77.26777	77.10247	77.97172	78.61193	78.6981	81.14568	85.35424	89.46605
250	78.09435	77.717	78.85718	80.45504	81.42922	84.68121	88.49717	92.19762
315	79.4258	80.86389	82.14659	83.01091	84.47302	88.43777	90.1614	95.5509
400	82.265	84.31991	84.1103	85.1508	88.04821	91.1859	95.81586	99.36197
500	84.73767	85.60894	85.87481	87.02785	88.74198	94.37841	98.13475	102.8677
630	86.97037	88.00136	88.21322	89.13532	92.77516	98.23467	102.3329	106.1284
800	88.66309	90.21673	91.117	92.28725	96.84839	102.144	106.5963	109.6142
1000	90.3965	92.08241	92.65305	95.1659	99.25417	105.3061	108.8952	111.8684
1250	92.65861	94.16373	95.94963	97.47141	103.0498	108.6924	112.5644	114.0143
1600	94.62734	96.76145	98.2859	100.9295	106.353	112.4412	115.125	115.3118
2000	96.90545	98.48212	100.133	103.1927	109.2713	115.3098	117.0473	116.2918
2500	98.79585	100.4519	102.2849	105.1755	111.9241	117.3971	117.9976	116.9879
3150	100.888	102.499	104.2946	107.1549	113.7828	119.0016	118.8023	118.2746
4000	101.2588	103.6845	105.3488	108.8005	114.9559	119.5289	119.5344	119.1672
5000	102.4399	104.5967	106.4397	110.0751	115.2024	119.6169	120.4212	119.8023
6300	103.7547	105.5529	107.5379	111.1328	115.1803	119.6051	120.4313	119.1643
8000	106.5157	106.5984	107.9653	111.7539	114.8652	119.2163	119.5871	117.8853
10000	109.1845	108.4912	108.4998	112.0562	114.2765	118.2128	118.0825	116.0964
12500	109.3823	110.3833	109.1286	112.1877	113.364	117.111	116.7095	114.5919
16000	107.7948	109.8137	109.181	112.0419	111.9879	115.5927	115.4067	113.0031
20000	106.8768	108.4779	108.3734	111.6415	110.942	114.2618	114.1704	111.5768
25000	105.8168	107.1669	107.0591	110.4842	109.7669	112.8382	112.8155	110.0291
31500	103.8003	105.0387	105.0619	108.2965	107.7498	110.8806	110.8251	108.0509
40000	102.0957	103.4809	104.1296	106.3704	106.0702	109.5328	109.2428	106.5866
OASPL	121.5708	122.7178	123.0566	126.2529	129.1137	133.5395	134.0219	133.0697

Table C.47: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=816.5$ K)

NPR = 3.6, Stagnation Temperature = 1010 °F, Chamber Temperature = 67 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	78.01964	78.29154	79.74877	80.70522	80.86795	82.95006	86.84307	91.4693
250	78.92817	79.07583	80.61708	82.40014	83.83064	87.01257	90.96545	95.07215
315	81.67441	82.89334	84.27065	84.51361	86.35374	90.51471	92.60803	98.6136
400	84.53685	86.27824	86.88718	87.1686	90.03973	92.80453	98.2121	101.8905
500	86.5548	87.73399	88.11439	89.35838	91.17301	96.40495	100.596	105.4972
630	89.02902	89.60256	90.23248	90.81941	94.63046	100.5838	105.1133	109.1951
800	89.71099	91.52446	92.60753	93.96946	98.77464	104.3119	109.188	112.3319
1000	92.09646	93.96429	94.47633	96.57472	100.9626	107.4819	111.5985	114.5543
1250	93.6982	95.59956	96.92189	98.66803	104.9039	110.8593	114.9487	116.2117
1600	96.02466	97.66653	99.12133	102.0905	108.1122	114.698	117.4088	117.3275
2000	98.22198	99.786	101.0035	104.079	110.9628	117.5092	119.1233	118.0226
2500	99.88782	101.4909	102.9232	106.0881	113.4226	119.2914	119.8716	118.6498
3150	101.6529	103.4542	105.1501	108.0431	115.8693	121.0854	120.7586	119.6576
4000	102.3807	104.4363	106.4124	109.7097	116.5487	121.5836	121.8074	120.6155
5000	103.718	105.5182	107.5006	110.8847	116.9645	121.906	122.0126	120.0276
6300	106.4292	107.0223	108.5218	111.9071	116.9393	122.0625	121.7335	118.6749
8000	110.7533	109.341	109.5109	112.8585	116.6999	121.659	120.2624	117.5066
10000	112.8549	112.7003	111.2143	113.4371	116.2933	121.0663	119.3813	116.4133
12500	111.3191	113.6402	112.6821	114.0369	115.4613	119.718	118.1806	114.893
16000	109.5074	111.8312	112.1748	114.0217	114.0878	118.1332	116.8433	113.1773
20000	108.9045	110.3743	110.9071	113.6335	112.9857	116.975	115.6529	111.3849
25000	107.6824	109.3541	109.6257	112.3921	111.8242	115.6394	114.347	109.7738
31500	105.7087	107.1571	107.8082	110.0301	109.7985	113.7695	112.4103	107.7344
40000	104.0447	105.6719	107.0102	108.2454	108.2057	112.4932	110.8001	106.1625
OASPL	124.0344	125.1632	125.3807	127.7395	130.9844	135.9321	135.6862	133.9959

Table C.48: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.6$, $T_0=819.8$ K)

NPR = 4.17, Stagnation Temperature = 1016 °F, Chamber Temperature = 70 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.53137	79.73424	80.77652	81.63771	82.23516	84.49672	88.31194	93.40522
250	80.41477	80.5447	83.14546	84.46191	85.03275	88.12453	92.33988	96.87235
315	82.29159	84.13413	86.26882	86.64257	87.75714	91.45209	93.61365	100.5338
400	85.4464	87.31371	88.98449	89.08608	91.2034	93.31954	99.14079	103.1262
500	87.55816	89.45822	88.94314	90.45948	91.5801	96.87554	101.5438	107.1404
630	89.15014	89.78587	90.60423	91.40581	94.60773	100.3896	105.3032	110.0306
800	90.16911	92.06844	93.37642	95.06079	98.77227	104.3721	109.9653	113.8568
1000	93.11204	94.29333	95.32796	96.88908	100.4995	107.5593	112.3777	116.1723
1250	93.96455	96.30724	97.43065	98.39085	104.2167	110.5752	115.4679	117.5965
1600	95.69573	97.21573	99.24809	101.6659	106.8169	114.2152	118.0436	118.6363
2000	98.41191	99.48237	100.7121	103.4884	109.5882	117.0025	119.742	119.0546
2500	99.82027	101.0046	102.5846	105.1498	112.0992	119.2122	120.7584	119.3972
3150	101.3475	102.767	104.5478	106.9741	114.2586	121.1103	121.3457	119.8934
4000	102.1878	104.1309	106	108.8256	115.5447	122.5051	122.8607	120.4006
5000	103.476	104.573	106.3859	109.9137	116.5743	122.7935	121.4702	118.1995
6300	106.9457	106.3436	107.8226	111.2353	117.2727	123.0575	120.5361	116.8967
8000	111.9262	109.0178	108.7533	112.0089	117.3038	122.8293	119.2629	116.0605
10000	112.491	113.0659	110.3665	112.7565	116.9774	121.9083	118.1724	114.7948
12500	110.6564	113.0593	112.1575	113.6253	116.4227	120.6063	116.9584	113.3557
16000	109.3103	110.9295	112.062	114.1618	115.3999	119.2505	115.745	111.8763
20000	108.6361	109.9152	110.4543	114.2068	114.4412	118.1083	114.3948	110.1618
25000	107.5645	108.9179	109.2463	113.1227	113.318	116.7922	112.9701	108.5123
31500	105.619	106.7912	107.6016	110.7393	111.2838	114.8424	110.7826	106.343
40000	103.8714	105.1924	106.6724	108.728	109.4423	113.2897	108.7575	104.521
OASPL	123.9826	124.7635	124.8894	127.5565	131.1804	136.6524	135.5484	133.8917

Table C.49: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.7$, $T_0=813.7$ K)

NPR = 4.86, Stagnation Temperature = 1005 °F, Chamber Temperature = 70 °F
 Relative Humidity = 74 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	81.89422	81.45931	82.31625	83.34804	83.55537	85.78988	90.1142	95.28451
250	81.77879	82.17187	84.23743	85.40121	85.84449	89.04774	93.36913	98.30218
315	83.9093	86.3238	88.29336	88.69171	90.48743	92.92093	95.43216	103
400	87.6788	89.17721	90.44612	90.90071	92.81269	94.9416	100.9202	105.2087
500	90.0502	91.36712	91.12645	92.1004	93.04728	98.08831	102.8915	109.0119
630	91.03726	91.75002	92.29169	92.76816	95.90291	101.8022	107.2607	112.3501
800	91.69257	93.28204	95.11212	96.41198	99.97586	105.7181	111.5085	115.8167
1000	94.34023	95.81666	96.81168	98.52449	101.5986	108.7286	113.8642	117.8804
1250	95.27585	97.74557	98.72043	99.89656	105.2859	112.2039	117.2316	119.4835
1600	96.92081	98.6239	100.6918	102.7281	107.8671	115.8548	119.7548	120.1946
2000	99.48254	100.8658	101.8672	104.4905	110.5765	118.6193	121.2403	120.2009
2500	101.0783	102.2983	103.7104	106.1874	113.0722	120.7315	122.1239	120.6711
3150	102.5684	103.8939	105.373	107.8725	115.2747	122.6269	122.8268	120.7059
4000	103.1787	104.7813	106.6521	109.3989	116.7516	123.7043	122.9277	119.9967
5000	104.5505	105.6281	107.2546	110.6773	118.0568	124.3832	122.3953	118.6732
6300	107.612	107.1717	108.6037	112.0097	118.6972	124.4844	121.1328	117.6706
8000	110.0824	109.273	109.4402	112.8882	118.7709	123.9037	120.0254	116.9526
10000	109.584	111.1791	110.6719	113.5728	118.4241	122.6164	118.9565	115.6345
12500	108.9098	110.6458	111.5396	114.1741	117.6925	121.5026	118.021	114.2254
16000	108.3808	109.7303	110.7925	114.2668	116.7183	120.3541	116.801	112.7291
20000	107.4909	109.1619	109.7769	113.7826	115.7985	119.1532	115.5263	111.0184
25000	106.4863	108.0282	108.7596	112.5236	114.7232	117.8624	114.0733	109.3603
31500	104.4619	105.8583	106.968	110.2222	112.7035	115.9073	111.9847	107.118
40000	102.7158	104.2585	106.0639	108.238	110.9141	114.4423	110.0778	105.3188
OASPL	122.7866	123.8702	124.7563	127.8257	132.5251	137.9073	136.5906	134.9069

Table C.50: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.9$, $T_0=807.6$ K)

NPR = 6.62, Stagnation Temperature = 994 °F, Chamber Temperature = 70 °F
 Relative Humidity = 60.4 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	83.06743	84.74563	86.15073	87.01723	87.22196	89.22301	93.43062	98.86726
250	83.33179	85.82922	87.5809	89.1676	89.75549	92.82433	97.14201	102.3896
315	86.36732	89.47883	91.3664	91.97908	93.76914	96.3125	98.87166	106.6454
400	90.86052	93.17566	94.73312	95.28986	96.61768	98.4047	104.4962	108.7593
500	94.14097	95.61178	95.57312	96.20211	96.57714	101.3355	106.4268	113.0345
630	94.85718	95.53743	95.80055	96.29858	98.55376	105.0225	111.0269	116.526
800	94.65741	96.46725	98.20376	99.58432	102.4946	108.8104	115.137	119.4986
1000	97.14311	99.01189	100.2063	101.8932	104.2546	111.7933	117.5588	121.5479
1250	98.15366	100.6506	102.0962	103.533	107.6533	114.7874	120.5286	122.7519
1600	99.55575	101.667	104.0538	105.9408	110.3443	118.3475	122.7986	123.3358
2000	102.0474	104.0218	104.9157	107.4723	112.7878	121.0537	124.4596	123.4946
2500	103.0194	105.1622	106.7043	108.9978	115.3522	123.2727	125.2447	123.468
3150	104.9989	106.6163	108.1506	110.5988	117.4338	125.1891	125.5377	122.7611
4000	106.0379	107.6795	109.2179	112.0414	118.8834	126.1086	125.0009	121.7486
5000	109.4665	109.3681	110.4933	113.4968	120.3108	126.5073	123.9328	120.5294
6300	112.7363	112.7536	112.1558	114.8877	121.0206	126.189	122.825	119.6331
8000	112.4229	115.0314	113.8065	115.8883	121.3181	124.9668	121.9915	118.6762
10000	111.6116	114.1432	115.2097	116.6524	121.0555	123.6198	120.8048	117.2727
12500	111.8745	113.6498	114.6891	117.1585	120.4271	122.6417	119.7383	116.0379
16000	110.8649	113.5443	113.7597	116.8943	119.2638	121.3299	118.6115	114.5788
20000	109.9986	112.6392	113.1645	116.0743	118.3072	120.1674	117.3878	112.7866
25000	108.8201	111.3492	112.1919	114.707	117.0666	118.8597	116.0481	111.1661
31500	106.7378	109.1266	110.3776	112.4418	115.0313	116.9284	114.0046	109.0599
40000	104.9821	107.4504	109.5826	110.432	113.3372	115.4773	112.0928	107.4098
OASPL	125.6717	127.6391	128.2652	130.541	134.9565	139.6749	139.009	137.5637

Table C.51: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=2.0$, $T_0=823.2$ K)

NPR = 7.75, Stagnation Temperature = 1022 °F, Chamber Temperature = 71.1 °F
 Relative Humidity = 38.5 %, $\gamma = 1.35$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	85.9307	87.06833	88.02122	88.73455	89.12185	91.07905	95.15871	100.8967
250	85.73927	87.96659	89.27348	90.95892	91.31401	94.43395	98.94081	104.4829
315	88.03096	90.87204	92.91424	94.56762	96.10238	97.56942	100.9992	108.7635
400	93.19496	95.59044	96.59741	97.76035	98.03604	100.9774	106.1403	110.3705
500	96.33277	97.43931	97.75207	97.79329	98.62099	102.7461	107.7725	114.9477
630	97.45915	97.85988	97.48008	98.23865	100.0933	106.0512	112.5225	118.6527
800	96.08856	98.03752	99.85738	101.5707	104.0785	110.3496	116.9129	121.8481
1000	98.38721	100.5875	101.7592	103.6196	105.8279	112.9917	119.1831	123.8043
1250	99.4132	102.2917	103.8799	105.3411	108.6376	115.9144	122.0374	125.0955
1600	100.7758	102.8721	105.7051	107.5495	111.6395	119.8964	124.6464	125.9778
2000	103.6066	105.4156	106.6792	108.7705	113.946	122.365	126.1511	126.1277
2500	104.9435	106.8843	108.4491	110.4483	116.4974	124.725	127.2036	125.9262
3150	107.2639	108.2776	109.5641	111.8746	118.516	126.4861	127.3874	124.9263
4000	110.881	109.8954	111.0268	113.5131	119.9284	127.5949	126.6755	123.8207
5000	116.3019	113.8086	112.5333	114.7489	120.8776	127.8751	125.5714	122.5199
6300	116.5167	118.2898	115.3312	116.3879	121.6124	127.1884	124.454	121.4232
8000	114.5258	117.2594	118.0765	117.7026	121.895	125.9314	123.4585	120.499
10000	113.9018	115.2904	117.738	118.8137	121.7592	124.5696	122.1972	119.0007
12500	113.3653	115.1864	115.7884	119.1876	121.0887	123.3915	121.0038	117.5123
16000	112.3814	114.3473	114.9404	118.4042	119.9177	122.0639	119.6842	115.8651
20000	111.1565	113.2861	114.0105	117.1649	118.8363	120.763	118.3694	114.1381
25000	109.9183	111.8549	112.7785	115.7557	117.5034	119.468	117.0219	112.5076
31500	107.9833	109.8273	111.0968	113.6565	115.6142	117.6145	115.1308	110.628
40000	106.8636	108.7602	110.6874	112.2348	114.3328	116.5207	113.7107	109.5328
OASPL	128.474	129.7852	130.272	132.1699	135.6824	140.8554	140.6773	139.8215

Table C.52: SPL and OASPL for the Mach 1.8 Nozzle ($M_j=1.5$, $T_0=1208.2$ K)

NPR = 3.61, Stagnation Temperature = 1715 °F, Chamber Temperature = 100 °F
 Relative Humidity = 47.3 %, $\gamma = 1.32$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	79.92333	80.55789	81.98756	82.2983	82.92553	85.88578	89.75994	93.99275
250	79.53825	79.88481	81.96791	83.62278	85.32984	88.77922	92.3203	96.37541
315	82.26556	84.23893	86.2664	86.94581	89.49023	92.06472	95.11437	100.9962
400	85.70701	87.35094	88.69555	89.3291	91.99269	95.20547	99.92774	103.0336
500	87.82761	89.58146	89.99747	91.18796	93.48504	98.75869	102.2372	107.0906
630	89.5335	90.64312	91.33699	92.64726	96.8313	102.6429	106.5521	110.1195
800	90.89556	92.67614	94.36711	96.3338	101.9825	107.0258	111.0764	113.7059
1000	93.01309	94.97338	96.10229	98.55306	103.8972	110.0247	113.3121	115.3863
1250	95.07275	97.53217	98.63238	100.9729	107.6548	113.0831	115.9147	116.1423
1600	96.55307	99.2564	100.9165	104.442	110.858	116.7303	118.1128	117.0441
2000	98.65757	100.7179	102.3997	106.7026	113.7039	119.1948	119.0807	117.2847
2500	100.3295	102.395	104.5461	108.9317	116.5703	120.8782	119.5491	117.8074
3150	102.0689	104.2457	106.6139	111.322	119.1176	122.0463	119.9138	118.2534
4000	102.8954	105.6124	108.0342	113.0651	120.6739	122.3809	120.3911	118.2049
5000	104.3616	106.6805	109.3031	114.3728	121.6618	122.8969	120.5865	117.2685
6300	105.8053	108.0981	110.904	115.6105	122.083	122.7399	119.2744	116.3358
8000	108.0862	109.1551	111.6497	116.0402	121.9306	121.7555	118.3821	115.8446
10000	111.2584	110.9045	112.4654	116.2821	121.286	120.4608	117.2508	114.6886
12500	112.0239	112.6688	113.0727	116.2759	120.1592	119.3429	116.154	113.5903
16000	109.8897	112.4019	112.9167	115.5209	118.4727	117.8913	114.7408	112.2267
20000	108.7261	110.745	111.9974	114.699	117.2338	116.6764	113.4264	110.483
25000	107.6794	109.3286	110.5573	113.3684	115.9421	115.3107	111.9587	108.6236
31500	105.7129	107.2208	108.5697	111.1228	114.0028	113.4367	109.8169	106.3923
40000	104.3795	105.8488	107.78	109.4767	112.6879	112.133	108.1227	104.8187
OASPL	123.627	125.055	126.566	130.0902	135.4353	136.5143	134.5306	132.7648

Table C.53: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.2$, $T_0=289.7$ K)

NPR = 2.41, Stagnation Temperature = 61.8 °F, Chamber Temperature = 72 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	72.10843	74.42802	75.05392	74.82021	73.63369	73.81261	76.43507	79.10769
250	72.49339	73.03228	74.12268	75.19548	75.41177	75.64778	77.00707	80.26007
315	74.75909	76.47137	77.78097	78.61388	77.68041	78.72165	79.99378	83.26607
400	75.67504	77.89427	78.90648	78.96247	78.93789	80.55962	82.54434	86.92394
500	77.36701	78.89761	79.64249	80.25562	80.34019	81.88062	84.87628	89.4236
630	79.58025	80.74455	81.92013	82.39501	82.42079	84.23665	87.73921	92.07955
800	81.92074	83.62949	84.47731	84.85901	84.91337	86.74836	90.8258	95.0185
1000	84.20424	85.81091	86.18126	86.49476	85.81881	89.14539	93.51658	98.58802
1250	84.09129	86.07978	87.51044	87.94846	88.27372	90.92572	95.92424	99.97846
1600	84.71581	86.4327	87.34842	88.58155	89.07666	91.78306	95.99216	100.0741
2000	85.55028	87.41875	88.31263	89.55393	90.25236	93.24042	96.84887	100.0345
2500	86.94527	88.95007	89.71402	90.50563	91.34241	94.1756	97.18277	98.8798
3150	89.18206	90.63368	91.37941	92.26282	92.90499	95.10651	97.29803	97.82565
4000	90.5432	91.56651	92.1779	93.17952	93.52619	95.52505	96.75585	96.54747
5000	91.38295	92.55478	92.68848	93.20167	93.72132	95.50585	96.05341	95.37446
6300	91.95909	92.89589	92.82455	93.58197	93.98629	95.70534	95.59338	95.05678
8000	92.48847	93.15154	93.23615	94.0367	94.2229	95.63527	95.34764	94.77942
10000	92.50043	93.52084	93.36159	94.34273	94.137	95.31569	94.73533	94.14568
12500	93.24179	94.06962	93.37341	94.35458	93.88154	94.84083	94.14589	93.54764
16000	93.50176	94.01437	93.09197	94.3639	93.57457	94.11972	93.2353	92.43683
20000	95.66088	94.44574	92.98818	94.16677	93.54753	93.51585	92.21152	90.93528
25000	96.9765	96.17275	93.7235	94.1249	93.86532	93.12913	91.37536	89.71583
31500	95.31965	95.43818	94.36036	93.92343	93.39489	92.35687	90.02277	88.32162
40000	94.25221	94.2237	94.55291	93.6337	92.95836	91.93846	88.86949	87.30574
OASPL	109.6467	109.9554	109.6714	110.0733	109.9828	111.1572	112.182	113.8138

Table C.54: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.3$, $T_0=289.8$ K)

NPR = 2.76, Stagnation Temperature = 62 °F, Chamber Temperature = 71.5 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	72.13483	73.85792	74.94487	75.28338	73.51262	74.83652	78.67955	83.94146
250	72.24772	72.77059	74.1209	75.71373	75.7619	75.66456	79.12256	83.96293
315	74.79034	76.99826	78.2494	78.97379	77.94609	79.82542	81.93891	86.93466
400	76.42328	78.76313	79.90463	79.83432	80.26638	82.27504	85.28033	90.06805
500	78.71089	80.44218	81.07191	81.63138	81.94436	84.04407	88.14182	93.24609
630	81.25218	82.15263	83.53124	84.01306	84.63153	87.46163	91.60656	96.18042
800	83.23941	84.88689	85.95699	86.61749	87.32732	89.95891	94.47942	98.90905
1000	84.38743	86.3044	86.78847	87.67432	87.78012	91.88098	96.21921	101.3278
1250	86.43007	88.55344	89.97668	90.58107	91.35153	94.47759	99.66167	103.8642
1600	86.95597	89.05944	89.71486	90.83609	91.78039	95.14606	99.85806	104.204
2000	87.58696	89.45323	90.32071	91.9048	92.93963	96.38758	100.7186	104.2652
2500	88.83069	90.49215	91.26842	92.39078	93.62492	97.05822	100.7585	103.1946
3150	90.00115	91.67767	92.38823	93.4615	94.75991	97.88934	100.3593	101.5526
4000	91.15552	92.40961	93.0101	94.64764	95.69852	98.31269	99.82234	100.0878
5000	91.86703	93.21631	93.43271	94.73439	95.78325	98.16619	99.1907	98.83455
6300	92.79974	93.74182	93.9706	95.25117	95.95499	98.22944	98.55584	97.98329
8000	93.52774	94.19587	94.17346	95.51442	96.14998	97.91363	97.8721	97.02422
10000	95.76614	95.1159	94.5961	95.75815	95.96015	97.36739	97.09825	96.13613
12500	98.13222	97.6248	94.83468	96.04676	95.73389	96.7727	96.34372	95.38605
16000	97.55134	98.11865	96.10922	96.8612	95.51252	96.07158	95.48215	94.30847
20000	97.46762	97.41655	96.2784	97.64785	96.27353	95.55148	94.60613	93.06781
25000	98.28352	97.58718	95.82328	97.55458	96.65535	95.27177	93.89419	91.8529
31500	97.10654	96.88334	95.50402	96.46184	95.56516	94.4583	92.58495	90.23467
40000	96.37654	96.15974	95.83526	95.66038	94.48806	93.60939	91.34202	88.8634
OASPL	111.7947	111.9799	111.2903	112.179	112.0909	113.6294	115.3213	117.3943

Table C.55: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.4$, $T_0=289.8$ K)

NPR = 3.18, Stagnation Temperature = 62 °F, Chamber Temperature = 71.9 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.32579	76.28463	76.92419	77.35451	75.60933	76.6986	80.26428	85.13605
250	73.81269	74.89393	76.16996	77.2428	77.17435	77.7867	81.16705	86.10393
315	76.29045	78.71657	80.06419	81.09655	79.46434	81.89323	84.12959	89.21933
400	77.74795	81.17806	81.81669	81.90724	81.878	84.07519	87.79762	92.67333
500	80.69858	82.29665	82.77733	83.64685	83.97519	86.22501	90.45274	95.63275
630	82.49184	83.88349	85.08597	85.95208	86.25887	89.39099	94.22908	98.96428
800	84.7417	86.5688	87.55956	88.2579	88.96915	91.93678	97.09862	101.7715
1000	85.27941	87.49355	88.2497	89.26665	89.67675	93.57644	98.27946	103.6515
1250	87.17964	89.42124	90.83475	92.12949	92.98062	96.35687	102.0719	106.4148
1600	88.60096	90.52105	91.77704	93.14018	93.97039	97.74084	102.9718	107.2511
2000	89.64414	91.4089	92.54313	94.12973	95.14173	98.7154	104.0098	107.8002
2500	90.68402	92.26551	93.2448	94.48403	95.80816	99.47202	104.1078	106.833
3150	91.74634	93.30203	94.62722	95.5907	97.09286	100.2573	103.6471	105.6242
4000	92.29844	93.92861	94.95799	96.53287	97.84172	100.5689	102.7647	103.9208
5000	93.30476	94.49027	95.21909	96.60358	97.89916	100.5195	101.8566	102.3345
6300	96.86942	95.90815	95.93115	97.13502	98.07143	100.3892	100.9008	100.8432
8000	101.6421	99.48592	97.51351	98.34454	98.77138	100.3536	100.2042	99.83228
10000	103.4982	103.2625	100.2682	99.70466	99.00223	99.82182	99.43134	98.80873
12500	102.0149	103.0142	101.6221	101.5737	100.0354	99.76593	98.82242	98.19001
16000	101.7093	101.3581	100.4807	102.4435	101.2827	99.8902	98.51053	97.67994
20000	101.485	101.519	99.61417	101.7222	101.8045	100.1769	98.1921	96.658
25000	100.8078	100.7906	99.53502	100.8849	100.7711	99.74417	97.69022	95.83717
31500	99.55845	99.37489	98.59359	99.62725	98.67347	97.77978	95.90355	94.20996
40000	98.66802	98.53738	98.72596	98.50701	97.35751	95.92476	93.74895	92.25079
OASPL	115.75	115.7504	114.8203	115.6057	115.4081	116.3208	118.219	120.6071

Table C.56: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.5$, $T_0=289.9$ K)

NPR = 3.67, Stagnation Temperature = 62.1 °F, Chamber Temperature = 71.7 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	74.54524	74.56356	75.69413	75.9492	75.61698	76.88644	79.51248	83.53688
250	73.58131	74.26994	75.89843	77.42183	77.5596	77.64759	81.63754	86.90754
315	76.22465	78.66091	80.04098	81.4483	80.51253	82.70208	84.71729	90.38268
400	78.61573	81.35634	82.49582	82.51199	82.93592	85.19806	88.57314	93.85929
500	81.47918	82.54939	83.29207	83.98285	84.12276	86.51776	90.38255	96.47356
630	83.59431	84.49775	85.44105	86.33036	86.8965	89.49877	94.86515	100.4614
800	85.22681	86.95872	87.99033	88.99338	89.94813	92.59041	98.18438	103.663
1000	86.38286	88.34548	88.873	90.2441	90.93469	94.62511	99.71722	106.0926
1250	88.03359	89.94518	91.88105	93.03018	94.18827	97.51603	103.4296	108.6249
1600	89.44229	91.71572	93.03751	94.41363	95.28806	98.82526	104.5185	109.9455
2000	90.60203	92.51734	94.06467	95.37468	96.3999	100.2511	105.8939	110.6381
2500	91.68867	93.50838	94.44274	95.88223	97.42788	101.0012	105.8999	110.0563
3150	92.83232	94.61025	96.01126	97.30204	99.12227	101.8805	105.2346	108.6486
4000	93.98162	95.38511	96.361	98.00658	99.50386	102.2771	104.4453	106.9541
5000	100.4589	97.69312	97.05506	98.05843	99.19516	101.9039	103.582	105.3397
6300	108.772	105.4259	100.3997	99.75612	100.0998	102.1118	102.7971	103.8834
8000	110.1115	110.456	106.0523	102.45	101.413	102.4527	102.4113	102.9474
10000	106.6253	108.9847	109.0531	106.5418	103.2042	102.6203	101.7624	102.0385
12500	106.3773	105.9599	106.4557	108.4433	106.8652	103.7265	101.8684	101.9903
16000	105.7743	106.3346	104.0655	106.4177	108.3864	105.1642	102.1127	101.7661
20000	104.9536	105.1133	104.1523	104.7978	106.8859	105.9951	102.2028	100.9489
25000	104.0506	104.3878	103.0011	104.2574	104.2712	104.7189	101.7405	99.94622
31500	102.4857	102.7031	102.0102	102.5075	102.3364	101.5357	99.71051	98.01768
40000	101.4632	101.7719	101.9647	101.287	100.7415	99.54041	97.42175	95.82806
OASPL	120.8864	120.9654	119.6436	119.5832	119.6103	119.3429	120.2733	123.4508

Table C.57: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.6$, $T_0=289.9$ K)

NPR = 4.25, Stagnation Temperature = 62.2 °F, Chamber Temperature = 72 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	77.91263	76.48038	78.25167	78.23435	77.10133	77.99942	83.05108	88.77896
250	77.67779	77.10506	78.80114	79.83636	79.77696	79.91274	84.49997	90.11725
315	79.28786	81.27919	82.80152	83.54028	82.03494	83.90561	86.0098	91.93485
400	81.54271	84.26936	84.99867	85.0094	85.19036	86.60478	90.31595	95.55356
500	84.16334	85.55214	86.21458	87.06969	87.18012	89.21416	93.22292	98.80241
630	86.28403	87.70187	89.00557	89.69599	89.81085	92.43724	97.30192	102.2612
800	89.16488	91.03889	92.33267	93.03123	93.20749	95.38456	101.1149	106.1151
1000	90.16147	92.24968	93.22537	94.51513	94.21382	98.06602	103.4947	109.2134
1250	91.82674	93.92841	95.69127	97.04072	97.66172	101.8693	108.6181	113.0002
1600	93.82985	95.96172	97.33219	98.85996	99.4607	103.7639	110.1813	114.7317
2000	94.71008	96.82203	98.06262	99.83309	101.0132	105.2624	111.4713	115.3231
2500	95.90634	97.69369	98.77096	100.609	102.0427	106.0496	111.5582	114.3693
3150	98.90623	102.5447	102.4876	107.1564	107.2105	109.9273	114.1406	118.5873
4000	102.7632	100.9074	100.4981	101.9747	103.1622	106.7881	110.5617	112.6476
5000	109.3193	108.2462	104.452	103.0365	103.8431	106.8378	109.6916	111.7003
6300	110.8213	117.216	114.2922	106.7232	105.7647	107.384	108.9323	110.9273
8000	106.2111	108.6978	110.646	109.8197	107.2306	107.5241	108.0438	110.0133
10000	107.8007	106.889	107.3145	111.1782	109.9126	108.1454	107.3706	109.1764
12500	106.3594	108.854	106.7681	108.5409	111.5177	109.1301	107.1932	108.3411
16000	105.738	106.5193	106.248	107.3633	110.0194	109.9181	107.0768	107.2981
20000	104.804	106.1393	104.8488	106.8986	107.5986	109.2867	106.6185	105.9223
25000	103.7692	104.9748	104.0354	105.7672	106.1375	106.8217	105.4659	104.3166
31500	102.0981	103.2277	102.6829	104.1194	104.3964	104.2218	103.2126	102.2123
40000	100.9193	102.1632	102.4992	102.6976	102.5792	102.7284	100.9253	99.9674
OASPL	121.7521	124.6044	123.1658	122.8644	123.2321	123.9729	126.0707	129.1711

Table C.58: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.7$, $T_0=290.7$ K)

NPR = 4.95, Stagnation Temperature = 63.5 °F, Chamber Temperature = 71.5 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	78.4148	78.1269	79.62248	80.02843	79.85166	81.17521	84.54003	90.19521
250	78.50203	78.63426	80.78952	82.69746	83.13128	83.00991	86.46811	92.50571
315	80.93383	82.98078	84.60191	85.33767	84.23378	86.88988	88.625	94.91119
400	84.00711	86.36924	86.93339	87.2871	87.81301	89.27963	93.42982	98.74685
500	86.4222	87.5225	88.38798	89.19665	89.16377	91.2119	95.57372	101.621
630	88.26272	89.68809	90.90769	91.54608	91.90242	94.41275	99.49936	105.0628
800	90.55814	92.32046	93.54114	94.30931	95.21571	97.95984	103.8835	109.4863
1000	91.5099	93.79133	94.63717	96.2919	96.50725	100.2114	105.917	112.2281
1250	93.23788	95.3203	97.10883	98.63092	99.60799	103.318	110.2687	115.595
1600	95.41731	97.43187	98.81872	100.5433	101.4289	105.6874	112.2108	117.3645
2000	96.14732	98.25008	99.5259	101.5077	102.6396	107.1191	113.647	117.8388
2500	99.70921	101.7129	103.9832	107.0435	107.0694	109.8499	116.7514	122.2353
3150	100.9676	101.2704	102.8489	104.6254	105.4212	108.8295	114.8822	119.4619
4000	108.0764	105.1711	103.0269	103.5217	104.538	108.3086	113.1851	116.9922
5000	113.8425	118.194	114.3618	105.9468	106.2453	108.4823	112.0265	116.5125
6300	110.3058	115.068	113.5503	108.6036	107.0072	108.4676	111.0333	116.0189
8000	108.73	108.3834	111.3112	113.0813	109.2151	108.9017	110.0894	115.2545
10000	108.1061	109.5903	107.7949	111.6282	111.6023	109.187	109.2538	114.3449
12500	107.1785	108.8123	108.0938	108.8657	112.5556	110.1261	108.7362	113.151
16000	106.3498	107.6437	106.612	108.4728	110.4616	110.4697	108.3053	111.5225
20000	105.4778	106.6764	105.7861	107.6574	108.1888	109.6527	107.6665	109.9552
25000	104.5247	105.7225	104.8583	106.6689	107.1347	107.4741	106.5163	108.3265
31500	102.9141	103.957	103.6992	105.0831	105.3683	105.0873	104.297	106.3552
40000	101.7	102.8604	103.4807	103.6767	103.6651	103.516	102.1203	104.4218
OASPL	123.6079	126.4676	124.8283	124.2849	124.4698	125.0599	128.3768	133.1222

Table C.59: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.8$, $T_0=290.9$ K)

NPR = 5.75, Stagnation Temperature = 64 °F, Chamber Temperature = 71.7 °F
 Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	79.30682	79.63765	81.03391	81.6432	82.45782	83.23831	86.03047	92.88943
250	78.4714	79.59291	81.47936	83.39482	83.88904	84.1165	87.86924	94.0236
315	82.25737	84.13821	86.121	87.18379	86.55717	89.64214	90.4994	97.51134
400	85.98682	88.11984	89.46746	89.35847	89.66462	90.59523	94.88915	100.6717
500	88.29558	89.31922	89.20611	90.20912	90.0846	91.43391	96.31186	103.5401
630	89.43415	89.81491	90.27814	91.61348	92.37532	94.12964	99.68866	107.09
800	90.11669	91.9007	93.32589	94.26004	95.01338	97.21112	103.8797	111.2909
1000	92.86266	93.71687	94.36485	95.53064	96.1091	99.5321	105.6087	113.8282
1250	93.50485	94.3896	96.10396	97.72866	98.76792	102.5342	109.6028	116.4106
1600	95.12841	96.74814	97.89132	99.54531	99.92117	103.9842	111.2725	118.2603
2000	96.19651	97.89078	99.03366	100.307	100.999	105.151	113.247	119.4774
2500	97.74035	99.57799	100.8223	101.7721	102.8915	106.7434	114.2865	120.1196
3150	101.7728	101.3975	102.0417	102.3426	103.5488	107.0658	114.5799	120.3272
4000	109.5209	105.6964	103.0961	103.2885	104.2226	107.7922	114.4506	120.6978
5000	113.4572	113.9863	107.9882	105.0842	105.3139	108.0625	113.7161	120.3686
6300	110.762	113.4659	113.5333	108.9093	106.9382	108.5861	112.9414	119.4716
8000	108.6916	110.0124	112.2261	112.9912	109.4365	109.4678	112.2934	118.4043
10000	108.5425	109.193	108.7724	112.1179	112.5389	110.2872	111.6568	116.8952
12500	107.7625	108.9153	108.5472	109.6361	113.4111	111.4168	111.3214	115.4547
16000	107.0717	107.9868	107.7383	109.3074	110.9508	111.7486	110.7944	113.91
20000	106.2108	107.1862	106.9011	108.7708	109.0839	110.9397	110.1979	112.4304
25000	105.145	106.1109	106.0743	107.7598	108.2362	108.8187	108.8648	110.9517
31500	103.411	104.3182	104.7987	106.1855	106.3635	106.4519	106.5933	108.9383
40000	102.2265	103.0972	104.4873	104.7716	104.7072	104.7934	104.4632	106.9772
OASPL	123.8652	124.7291	124.1973	124.4348	124.7654	125.2607	128.8047	134.6096

Table C.60: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=1.9$, $T_0=290.8$ K)

NPR = 6.71, Stagnation Temperature = 63.8 °F, Chamber Temperature = 71.4 °F
Relative Humidity = 44.8 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	80.33116	81.21292	82.50049	83.72432	84.41891	84.34079	86.73772	93.46139
250	80.05752	82.03432	84.17974	85.85566	86.05361	86.43639	89.87779	95.8945
315	83.72866	86.38071	88.39275	89.48556	89.28425	91.54314	91.85411	99.80266
400	87.77281	89.6756	90.86541	91.40322	91.87901	93.11401	96.51727	102.5282
500	90.44115	91.42536	91.34534	92.14991	92.11409	93.46445	97.76567	105.5641
630	91.66162	92.04287	92.40852	92.82901	94.22895	96.30684	101.6291	109.1033
800	91.95607	93.77516	95.0665	96.0834	96.99286	98.98719	105.6348	113.1573
1000	94.2268	95.76281	96.0975	97.2375	97.6922	100.8673	107.1746	115.5031
1250	95.09011	95.89218	97.76337	99.00812	100.3991	104.4252	111.4545	118.211
1600	96.73652	98.22444	99.4598	100.894	101.4282	105.5772	113.0506	119.8511
2000	97.54079	99.23038	100.5145	101.6601	102.5116	107.216	115.3653	120.9047
2500	99.07193	100.6318	101.3386	102.9423	104.0351	108.2301	116.6825	121.5866
3150	102.8514	102.4541	103.1943	103.6592	105.1062	109.0899	117.4451	121.8501
4000	108.9424	106.4164	104.115	104.7347	105.7212	109.6984	117.9103	122.4244
5000	110.0626	111.4846	107.908	106.0606	106.6902	110.1166	117.4861	121.8853
6300	108.2479	110.2699	111.3268	108.9925	107.7254	110.4131	116.8525	120.633
8000	107.2735	108.2875	109.3964	111.2314	109.5371	110.745	116.1015	119.0458
10000	106.8523	108.2276	107.5398	109.872	111.3261	110.9854	115.4525	117.5637
12500	106.3288	107.8148	107.5547	108.8071	111.1726	111.2747	114.63	116.2315
16000	105.4811	107.0441	106.7803	108.6125	109.2691	110.9722	113.7071	114.5703
20000	104.6163	106.1842	106.0214	108.1651	108.1749	109.9516	112.6085	113.1059
25000	103.5872	105.1211	105.1558	107.2708	107.4061	108.2538	111.2749	111.6557
31500	101.8345	103.3216	103.9393	105.6429	105.7083	106.1669	109.1625	109.7785
40000	100.6071	102.1482	103.5279	104.1306	104.1191	104.55	107.0509	107.8305
OASPL	122.0905	123.157	122.9678	123.7226	124.152	125.9241	131.8141	135.9797

Table C.61: SPL and OASPL for the Mach 2.0 Nozzle ($M_j=2.1$, $T_0=292.9$ K)

NPR = 9.16, Stagnation Temperature = 67.5 °F, Chamber Temperature = 76 °F
 Relative Humidity = 64.7 %, $\gamma = 1.4$

3rd Octave Center Freq. (Hz)	Microphone Angle							
	80	90	100	110	120	130	140	150
200	84.38832	85.48468	86.65985	87.7741	88.76476	89.19944	91.5316	97.67738
250	84.1679	86.11658	88.18687	89.94766	90.007	90.69378	94.47089	100.0678
315	88.76053	90.88444	93.01644	93.70875	94.06443	96.39334	95.81354	103.6498
400	92.88949	94.49535	95.74876	95.87046	96.88577	97.65486	100.6328	106.1429
500	94.97773	95.97691	96.11101	96.85192	97.04727	98.77852	101.7396	109.7599
630	96.3001	96.09843	96.14895	96.87344	98.34763	100.5772	105.2482	113.3351
800	95.47951	97.05687	98.72762	99.21384	100.7762	103.0844	109.2244	117.0694
1000	97.80758	99.46881	99.69526	100.7328	101.6005	105.1691	110.8636	119.4327
1250	98.74297	99.77416	101.2014	102.3096	103.9388	107.4572	114.7745	121.9622
1600	99.7853	101.3453	102.6636	103.86	104.8287	108.9372	116.4656	123.4086
2000	101.0068	102.2049	103.2918	104.5971	105.6639	110.1283	118.7222	124.4997
2500	102.9408	103.8878	104.3795	105.6218	106.9939	111.389	120.1326	124.6702
3150	107.9063	106.5658	106.2951	106.4549	108.0641	112.1956	121.2503	124.7722
4000	109.304	110.7243	108.0692	107.6279	108.927	112.8011	121.8544	124.3679
5000	107.3687	109.8468	111.2336	109.6382	109.7783	113.2185	121.9806	122.9164
6300	107.5417	108.4954	109.8054	111.8531	110.9615	113.5904	121.8743	120.9532
8000	107.5363	109.2224	108.6499	110.8448	112.4523	113.8303	121.2838	119.5631
10000	106.8774	108.9554	109.1519	110.2872	112.942	113.9086	120.4558	118.2059
12500	106.5836	108.6496	108.7579	110.6826	112.1443	113.6564	119.342	116.7549
16000	105.6161	107.788	107.9981	110.4986	110.8424	112.8088	118.0667	115.2092
20000	104.5792	106.7947	107.0839	109.8982	110.0103	111.7524	116.8165	113.6339
25000	103.2351	105.4329	106.0781	108.8197	109.0882	110.2741	115.4481	112.0877
31500	101.0273	103.1042	104.2882	106.8091	107.0786	108.0695	113.2722	109.9609
40000	99.2434	101.336	103.4015	104.8343	105.0699	106.149	111.2128	107.9699
OASPL	122.313	123.8549	124.1377	125.4493	126.3206	128.6633	136.049	138.2899

REFERENCES

- [1] Ahuja. Designing clean jet-noise facilities and making accurate jet-noise measurements. *International Journal of Aeroacoustics*, 2(3):371–412, 2003.
- [2] F Shih Alvi, C Shih, R Elavarasan, G Garg, and A Krothapalli. Control of supersonic impinging jet flows using supersonic microjets. *AIAA journal*, 41(7):1347–1355, 2003.
- [3] Leo L Beranek and Harvey P Sleeper Jr. The design and construction of anechoic sound chambers. *The Journal of the Acoustical Society of America*, 18(1):140–150, 1946.
- [4] James Bridges and Clifford A Brown. Parametric testing of chevrons on single flow hot jets. *AIAA paper*, 2824:2004, 2004.
- [5] James Bridges and Clifford A Brown. Validation of the small hot jet acoustic rig for aeroacoustic research. *AIAA Paper*, 2846:2005, 2005.
- [6] Garry L Brown and Anatol Roshko. On density effects and large structure in turbulent mixing layers. *Journal of Fluid Mechanics*, 64(04):775–816, 1974.
- [7] S Cj Crow and FH Champagne. Orderly structure in jet turbulence. *Journal of Fluid Mechanics*, 48(03):547–591, 1971.
- [8] Benjamin J Day. *Turbulence measurements in supersonic jets with optical deflectometry*. Pennsylvania State University, 2010.
- [9] Michael J Doty and Dennis K McLaughlin. Acoustic and mean flow measurements of high-speed, helium-air mixture jets. *International Journal of Aeroacoustics*, 2(3):293–333, 2003.
- [10] Brenton J Greska. Supersonic jet noise and its reduction using microjet injection. 2016.
- [11] EJ Gutmark and FF Grinstein. Flow control with noncircular jets 1. *Annual review of fluid mechanics*, 31(1):239–272, 1999.
- [12] Brenda Henderson. Fifty years of fluidic injection for jet noise reduction. *International Journal of Aeroacoustics*, 9(1-2):91–122, 2010.
- [13] ISO ISO. 3745: 2003,acousticsdetermination of sound power levels of noise sources using sound pressureprecision methods for anechoic and hemi-anechoic rooms,. *International Organization for Standardization, Geneva, Switzerland*, 2003.
- [14] RAJAN KUMAR. Experimental study of physical mechanisms in the control of supersonic impinging jets using microjets. 2008.

- [15] Rajan Kumar, Sladana Lazic, and Farrukh S Alvi. Control of high-temperature supersonic impinging jets using microjets. *AIAA journal*, 47(12):2800–2811, 2009.
- [16] Ching-Wen Kuo, Dennis K McLaughlin, and Philip J Morris. Effects of supersonic jet conditions on broadband shock-associated noise. *AIAA Paper*, 1032:2011, 2011.
- [17] Michael J Lighthill. On sound generated aerodynamically. i. general theory. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, volume 211, pages 564–587. The Royal Society, 1952.
- [18] Michael J Lighthill. On sound generated aerodynamically. ii. turbulence as a source of sound. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, volume 222, pages 1–32. The Royal Society, 1954.
- [19] Huadong Lou, Chiang Shih, and Farrukh S Alvi. A piv study of supersonic impinging jet. *Aiaa paper*, 3263(9), 2003.
- [20] Philip Morris, Dennis McLaughlin, James Bridges, and Ching-Wen Kuo. On the scaling of small, heat simulated jet noise measurements to moderate size exhaust jets. *International journal of aeroacoustics*, 9(4-5):627–654, 2010.
- [21] Dimitri Papamoschou. Acoustic simulation of coaxial hot air jets using cold helium-air mixture jets. *Journal of Propulsion and Power*, 23(2):375–381, 2007.
- [22] Alan Powell. On the mechanism of choked jet noise. *Proceedings of the Physical Society. Section B*, 66(12):1039, 1953.
- [23] M Samimy, KBMQ Zaman, and MF Reeder. Effect of tabs on the flow and noise field of an axisymmetric jet. *AIAA journal*, 31(4):609–619, 1993.
- [24] John M Seiner, Michael K Ponton, Bernard J Jansen, and Nicholas T Lagen. The effects of temperature on supersonic jet noise emission. In *14th DGLR/AIAA aeroacoustics conference*, volume 1, pages 295–307, 1992.
- [25] Christopher KW Tam. Supersonic jet noise. *Annual Review of Fluid Mechanics*, 27(1):17–43, 1995.
- [26] Christopher KW Tam, Michel Golebiowski, and John M Seiner. *On the two components of turbulent mixing noise from supersonic jets*. American Institute of Aeronautics and Astronautics, 1996.
- [27] Christopher KW Tam, K Viswanathan, KK Ahuja, and J Panda. The sources of jet noise: experimental evidence. *Journal of Fluid Mechanics*, 615(1):253–292, 2008.

- [28] HK Tanna. An experimental study of jet noise part i: Turbulent mixing noise. *Journal of sound and Vibration*, 50(3):405–428, 1977.
- [29] Puja Upadhyay, Jonas PR Gustavsson, and Farrukh S Alvi. Development and characterization of high-frequency resonance-enhanced microjet actuators for control of high-speed jets. *Experiments in Fluids*, 57(5):1–16, 2016.
- [30] K Viswanathan. Jet aeroacoustic testing: issues and implications. *AIAA journal*, 41(9):1674–1689, 2003.
- [31] Krishna Viswanathan, MB Alkisar, and MJ Czech. Characteristics of the shock noise component of jet noise. *AIAA journal*, 48(1):25–46, 2010.
- [32] Krishnamurthy Viswanathan. Aeroacoustics of hot jets. *Journal of Fluid Mechanics*, 516:39–82, 2004.
- [33] Christopher K W. Tam. Mach wave radiation from high-speed jets. *AIAA journal*, 47(10):2440–2448, 2009.
- [34] JE Ffowcs Williams. The noise from turbulence convected at high speed. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 255(1061):469–503, 1963.
- [35] CD Winant and FK Browand. Vortex pairing- the mechanism of turbulent mixing-layer growth at moderate reynolds number. *Journal of Fluid Mechanics*, 63(2):237–255, 1974.
- [36] T Worden, Chiang Shih, and F Alvi. Supersonic jet impingement on a model-scale jet blast deflector. *AIAA Paper*, 1015, 2016.
- [37] Theodore J Worden, Jonas PR Gustavsson, Chiang Shih, and Farrukh S Alvi. Acoustic measurements of high-temperature supersonic impinging jets in multiple configurations. In *19th AIAA/CEAS Aeroacoustics Conference*, pages 2013–2187, 2013.
- [38] Theodore J Worden, Puja Upadhyay, Jonas PR Gustavsson, and Farrukh S Alvi. Studies on microjet control effectiveness in high-temperature supersonic impinging jets. *AIAA Journal*, 52(8):1757–1769, 2014.

BIOGRAPHICAL SKETCH

Joseph Craft was born in Pensacola, Fl on January 11th, 1991. He attended Florida State University and earned a Bachelor's Degree in Mechanical Engineering in the Spring of 2014. He is furthering academic experience by pursuing a Master's Degree in Mechanical Engineering under the guidance of Dr. Farrukh Alvi.