NASA/CR—2003-212316

Detailed Studies of the Quick Mixing Region in Rich Burn Low-NO_x Combustion

D. St. John and G.S. Samuelsen
University of California, Irvine, Irvine, California

August 2003

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/CR—2003-212316

Detailed Studies of the Quick Mixing Region in Rich Burn Low-NO_x Combustion

D. St. John and G.S. Samuelsen
University of California, Irvine, Irvine, California

Prepared under Grant NAG3–1110

National Aeronautics and
Space Administration

Glenn Research Center

August 2003

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

TABLE OF CONTENTS

TABLE OF FIGURES

1.0 MOTIVATION

NO_x reduction is a driving force in combustor design today. The fuel-air mixing process can have a significant effect on NO_x production. This report describes a set of experiments carried out to assess fuel-air mixing sensitivities to geometric variation in the Rich-Burn/Quick-Mix/Lean-Burn (RQL) combustor concept utilized in stationary gas turbine engine applications and proposed for advanced transport aircraft engines. Specifically, three (3) parameters in the quick-mix zone were examined: jet injection angle, jet-to-expansion distance, and jet count (number of jets).

2.0 APPROACH

Figure 1 is a general depiction of the RQL concept and illustrates the variable parameters investigated in this study.

Three values for each of the three variables were selected so as to bracket the optimum case. The combustor was fired on propane and air. Table 1 lists the fixed and variable design conditions.

Table 1. Fixed and variable design conditions.

Fixed	
Pressure	1 atm
Rich Zone Equivalence Ratio	1.66
Overall Equivalence Ratio	0.45
Lean Zone Expansion Angle	90°
Momentum Flux Ratio	25
Duct Radius, R	40 mm
Variable	
Θ, Jet Injection Angle	45.0°, 67.5°, 90.0°
N, Jet Count	7, 9, 11
L, Jet-to-Expansion	1.2 R, 1.7 R, 2.5 R

The test matrix shown in Table 2 was generated via the Box-Behnken technique, reducing the total number of test conditions from twenty-seven (27) to thirteen (13).

Emissions measurements were made across two planes downstream of the jets, described in the next section, for each of the test conditions. Sensitivity of fuel-air mixing to geometric variation can be assessed by comparing the results of the test conditions.

Table 2. Test Matrix.

Case	Θ	N	L
1	67.5°	7	1.2 R
2	90.0°	9	1.2 R
3	45.0°	9	1.2 R
4	67.5°	11	1.2 R
5	90.0°	7	1.7 R
6	90.0°	11	1.7 R
7	45.0°	7	1.7 R
8	45.0°	11	1.7 R
9	67.5°	9	1.7 R
10	67.5°	7	2.2 R
11	90.0°	9	2.2 R
12	45.0°	9	2.2 R
13	67.5°	11	2.2 R

3.0 EXPERIMENT

3.1 Facility

The experiment was conducted on a UCICL test stand described in detail elsewhere (e.g., Leong and Samuelsen, 1996), and slightly modified to accommodate the current experiment. A schematic of the modified test stand is shown in Figure 2. Nine stainless steel quick-mix jet modules, one quartz-windowed expansion chamber, and three jet-to-expansion spacers were fabricated in order to accommodate the jet injection angle, jet-to-expansion distance, and jet count variations. The expansion chamber and one of the jet modules is shown in Figure 3. The diameter of the main duct is 80 mm, and the L/d of the jets is a constant value of 5 for all of the modules. The expansion chamber dimensions in duct-diameters are 2L x 1W x 3H.

A new, larger plenum was also constructed to house the modules. Detailed drawings of the plenum, expansion chamber, and nine modules are included in the Appendix. The entire facility is shown in Figure 4.

3.2 Diagnostics

A double-jacketed, water-cooled, stainless steel probe was mounted such that its 45° angled tip could be positioned on the measurement plane of interest. Pointwise measurements of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbon (HC), oxygen (O_2), and nitrogen oxide and nitrogen dioxide (NO_x) concentrations were made by traversing the combustor in the horizontal plane and drawing gas samples continuously through a bank of emission analyzers.

Two planes were sampled for each experimental condition, as shown in Figure 5. Plane 1 was located precisely at the step expansion, and Plane 2 was located 30 mm downstream of the expansion, which gave the flow approximately 1 ms in residence time from the expansion. Emissions were also measured at a third plane, one duct-diameter (40 mm) upstream of the jet centerline, in order to verify a uniform rich entry section.

Figure 6 shows the location of the sampling points for each of the three planes.

4.0 RESULTS

All graphical species concentration profiles were generated from pointwise data using a geostatistical interpolation algorithm known as kriging. The raw, tabulated data are attached in the Appendix.

4.1 Rich Zone Verification

Table 3 shows the species concentrations across the rich zone of Figure 5. The species concentrations present in this zone are consistent with chemical kinetics predictions. These measurements were repeated for several cases and the result was the same each time: the upstream conditions provide a rich product environment that is uniform and consistent enough to provide a practically fixed boundary condition.

Table 3. Rich Zone Verification.

Point	CO (%)	CO_2 (%)	HC (ppm)	O_2 (ppm)	NO_x (ppm)
1	12.5	5.66	2154	0	9.6
2	12.45	5.69	2580	0	9.3
3	12.42	5.73	3300	0	10.4
4	12.5	5.68	3071	0	9.7
5	12.3	5.82	3126	0	9.6
6	12.28	5.81	3641	0	10.1
7	12.45	5.7	3230	0	9.8

4.2 Plane 1

Figures 7-9, 10-12, 13-15, and 16-18 illustrate species concentration profiles at Plane 1 for CO, CO_2, O_2, and NO_x, respectively. Also shown on these figures are the area-averaged values for each case. Plots of HC are not shown because measurements were essentially zero in all cases. Figure 19 was generated from a verification of the entire plane for a single case. Figure 19 shows the essential symmetry of Plane 1, validating the technique of measuring in only one sector in order to generate a finer sampling grid.

Table 4 shows the area-averaged values of Plane 1 for each condition. This table also presents a carbon balance using the Spindt technique. The large errors indicate that perhaps the grid density used was not quite fine enough to resolve all of the fluctuations.

Table 4. Area-averaged data for all cases.

	Area-Averaged Values				Carbon Balance		
case	CO	CO2	O2	NOx	F/A, Spindt	F/A, metered	% error
1	0.67	3.9	14.1	16.2	0.0201	0.0266	32.3%
2	0.71	5.1	12.4	18.1	0.0258	0.0298	15.5%
3	1.6	4.2	12.8	16.5	0.0222	0.0298	34.5%
4	0.95	4.7	12.5	16.2	0.0243	0.0298	22.6%
5	0.46	4.3	13.6	16.0	0.0219	0.0266	21.6%
6	0.46	4.8	13.1	17.2	0.0241	0.0298	23.7%
7	0.72	4.5	13.3	16.7	0.0230	0.0266	15.8%
8	1.23	4.8	12.2	18.8	0.0249	0.0298	19.7%
9	0.50	4.9	13.1	18.2	0.0243	0.0298	22.8%
10	0.3	4.2	14.2	16.0	0.0209	0.0266	27.3%
11	0.32	5.0	13.2	18.8	0.0245	0.0298	21.8%
12	0.55	4.7	13.2	18.7	0.0235	0.0298	26.9%
13	0.45	4.9	12.8	17.9	0.0247	0.0298	20.7%

4.3 Plane 2

Measurements in Plane 2 were made for each case, in the quarter-plane region described by Figure 6, and figures are included in the Appendix. However, a verification sampling of the entire plane, shown in Figure 20, suggests a large-scale recirculation at work in the expansion chamber. These results were the same regardless of the orientation of the expansion chamber, indicating the coupling of downstream room conditions with the aerodynamics inside the expansion chamber. This phenomenon renders the measurements made in Plane 2 essentially unusable.

4.4 Modified Plane 2

In an attempt to isolate the aerodynamics of the expansion chamber from downstream room conditions, an exploratory test was conducted whereby a 40% blockage was installed on the exit plane of the expansion chamber. A reduced set of measurements were made across the length of the expansion chamber, revealing no asymmetry. This confirms the hypothesis that the asymmetry was produced by downstream interactions, and indicates that a 40% blockage is sufficient to isolate the measurement plane from downstream conditions. The species concentration profiles are shown in Figure 21.

5.0 SUMMARY

This report presents the results of an extensive set of experiments undertaken with the goal of assessing the sensitivity of mixing to three geometric parameters in an RQL combustor.

6.0 REFERENCES

Leong, M.Y., and Samuelsen, G.S. (1996). Quick-Mixing Studies Under Reacting Conditions, NASA Contractor Report 195375, September.

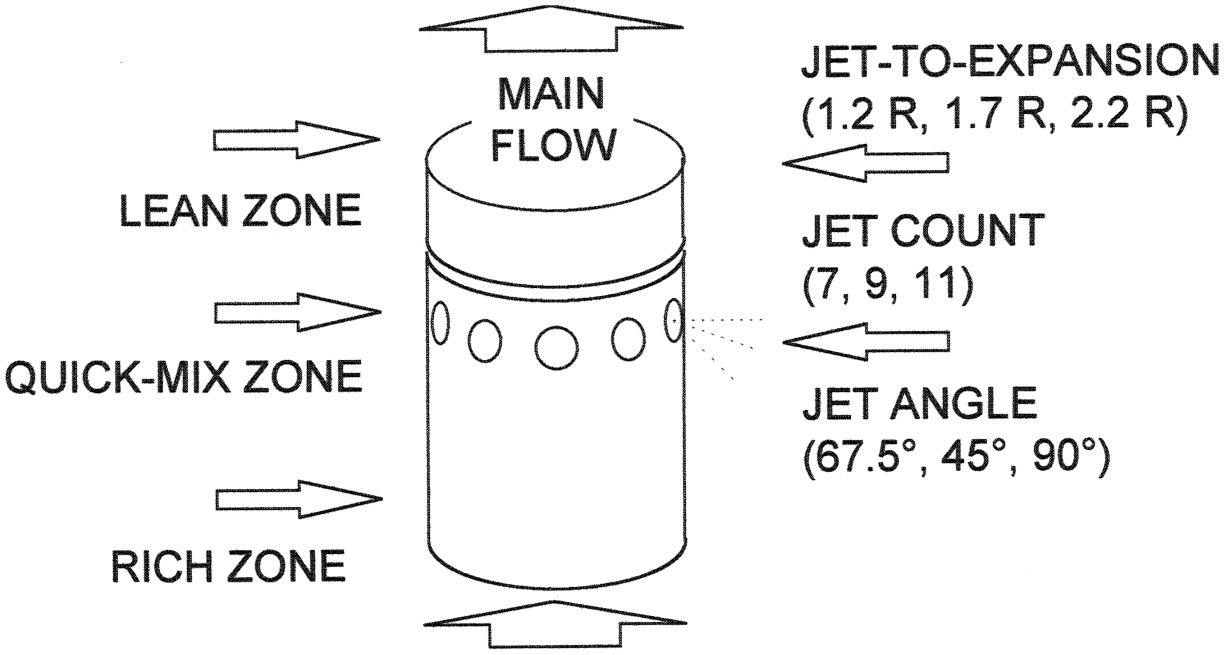


Figure 1. RQL concept and variable parameters.

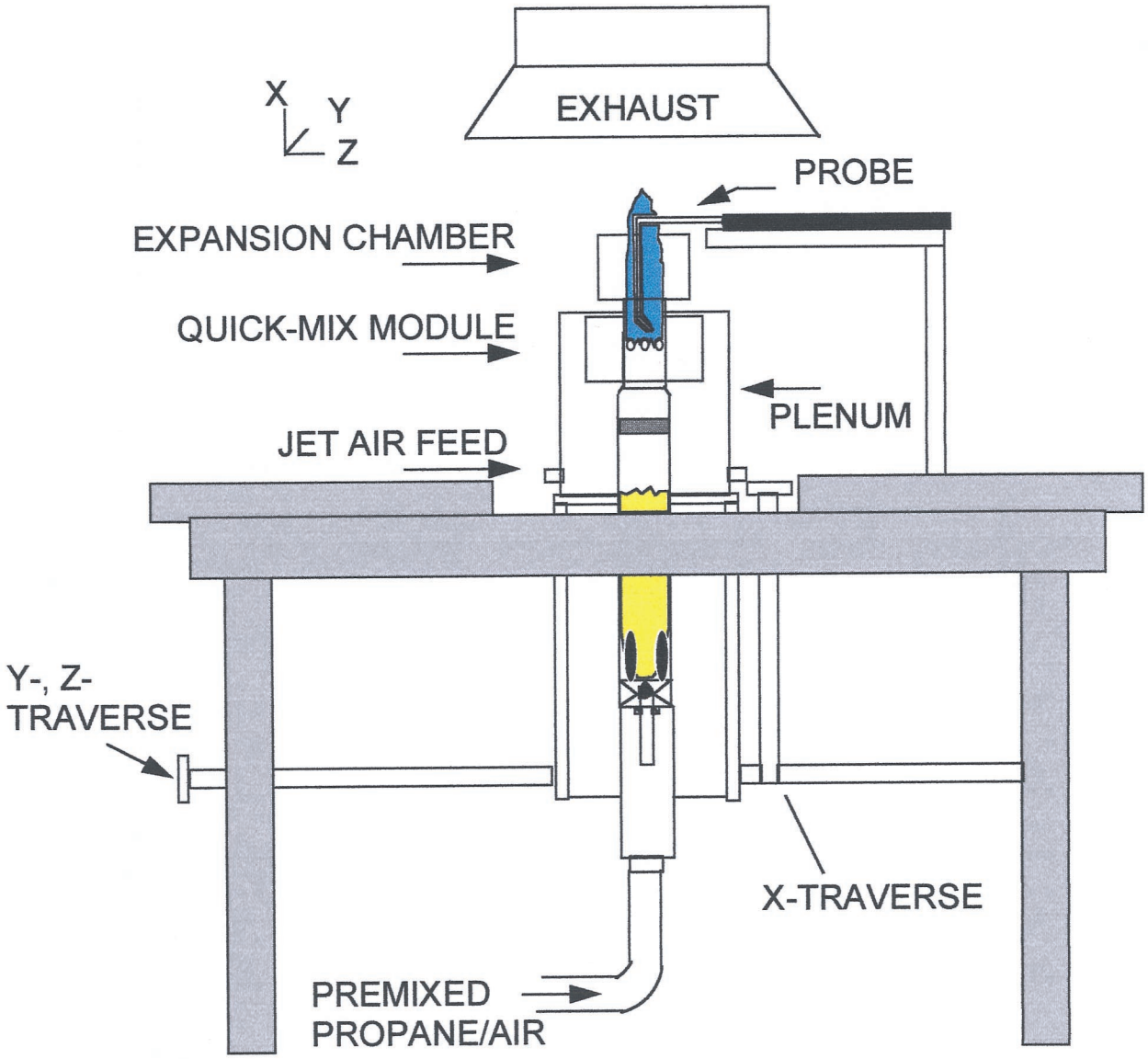


Figure 2. Experimental facility schematic.

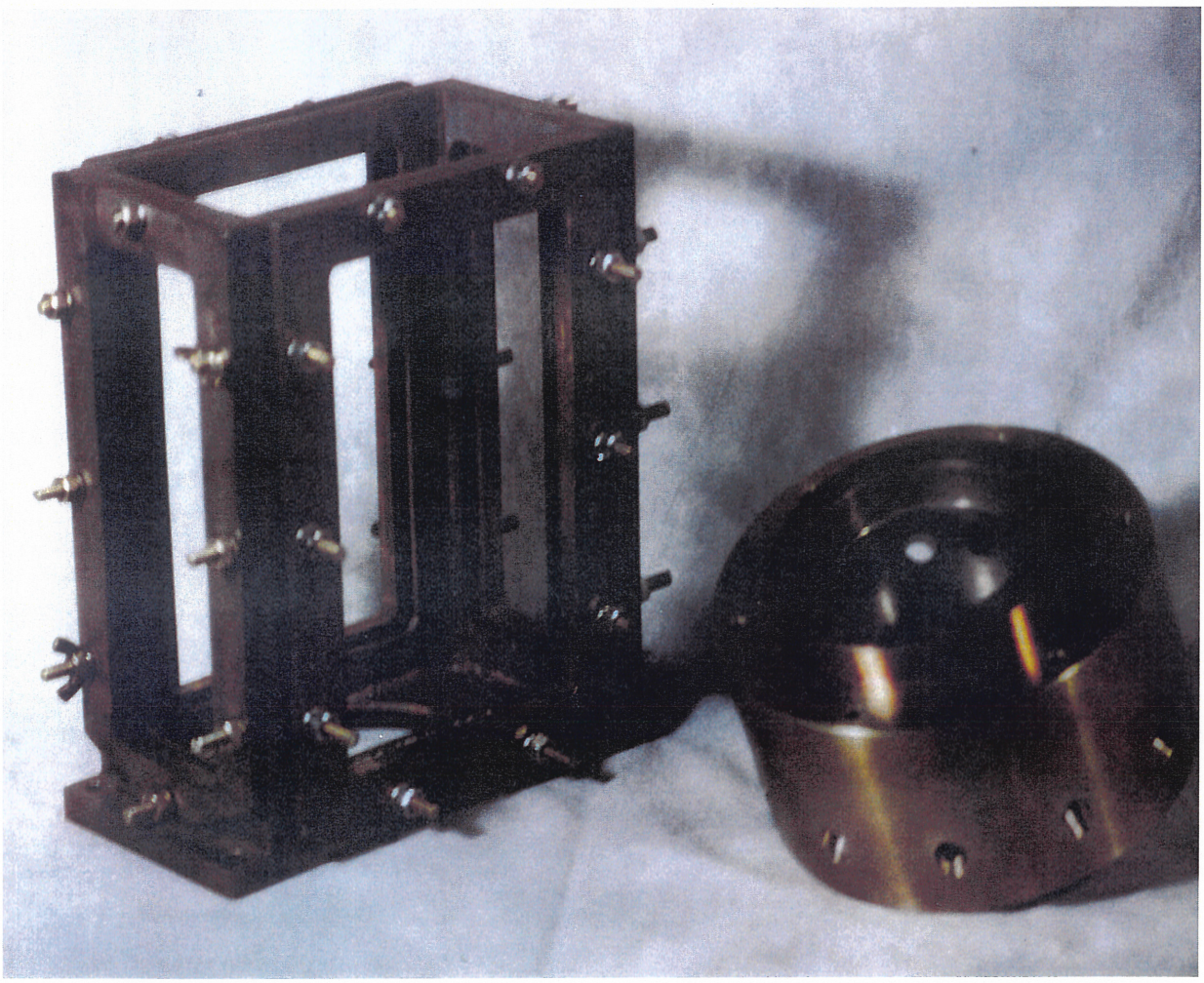


Figure 3. Expansion chamber and typical jet module.

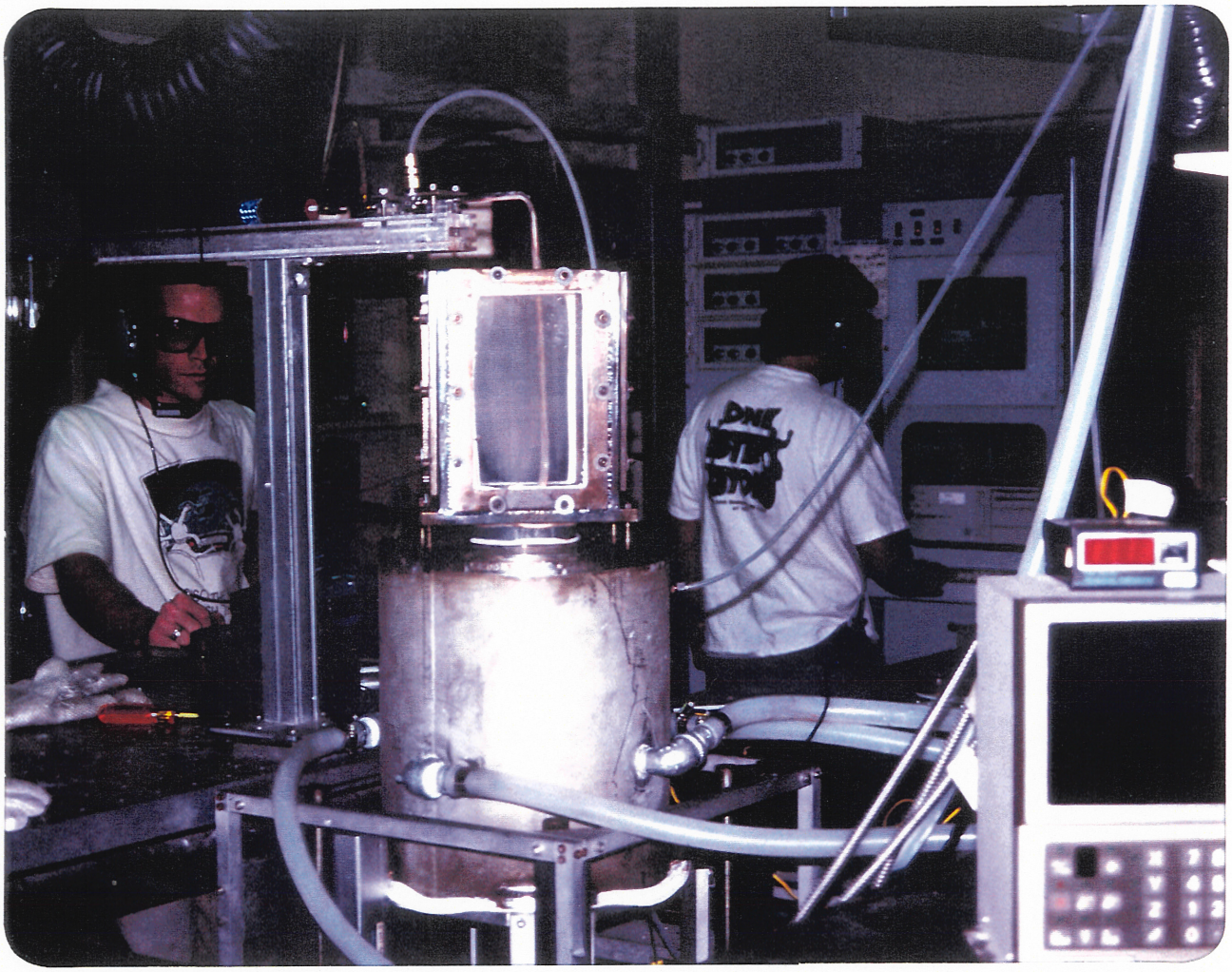


Figure 4. Entire facility.

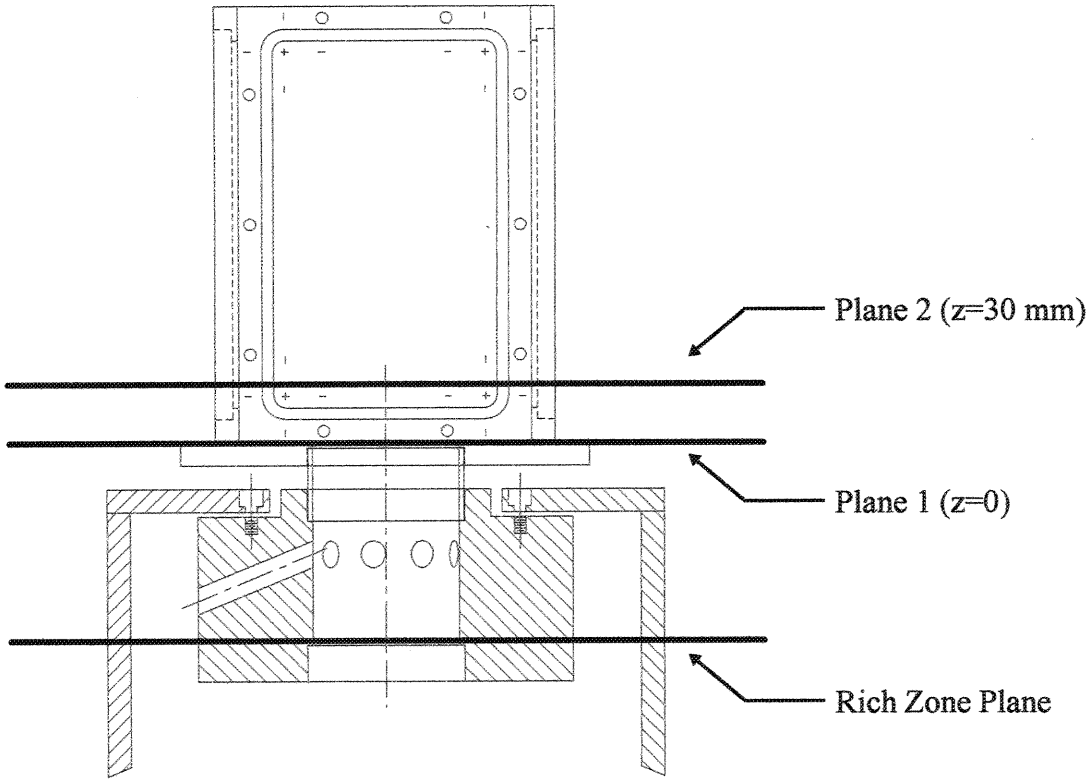


Figure 5. Sampling planes.

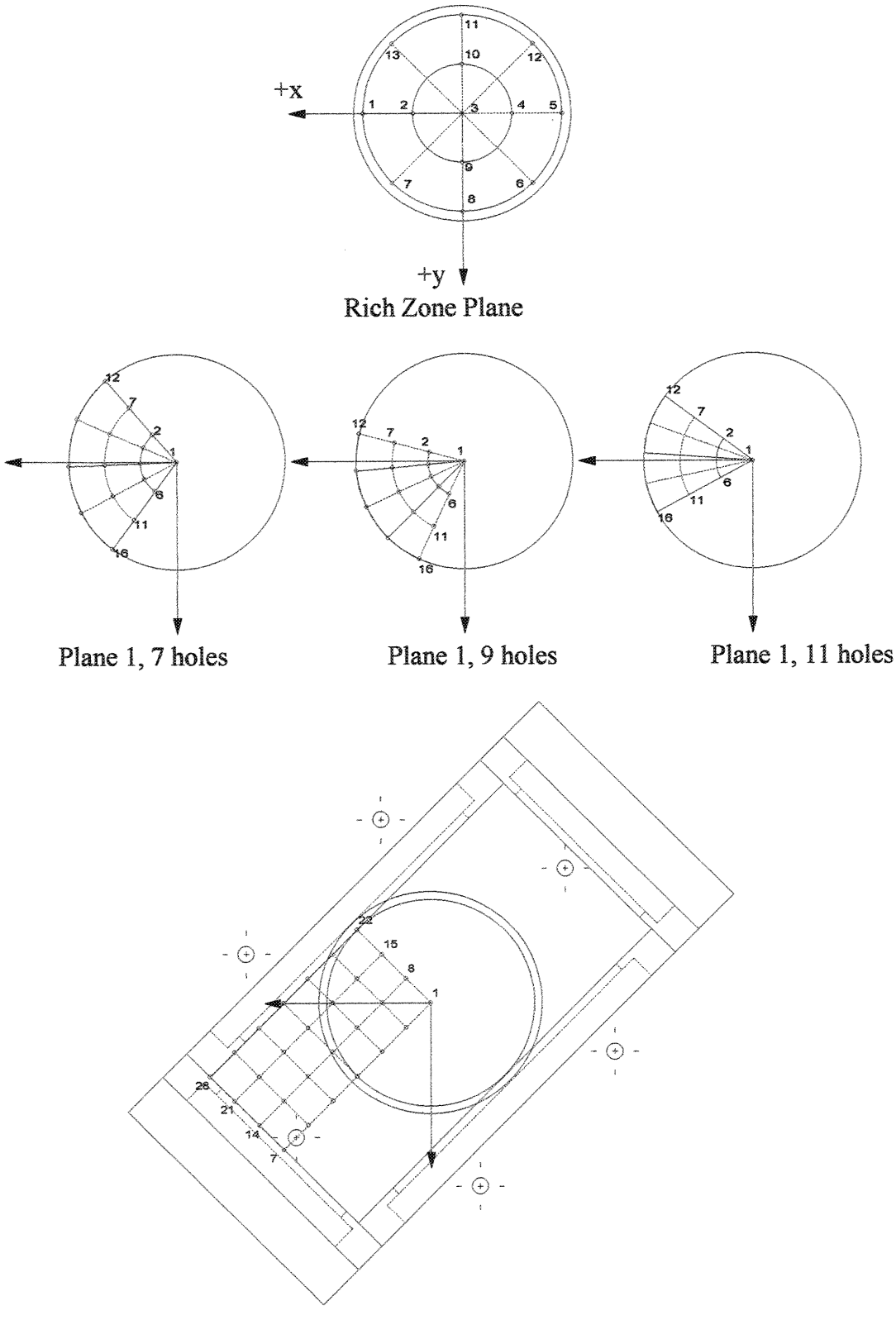


Figure 6. Sampling point locations

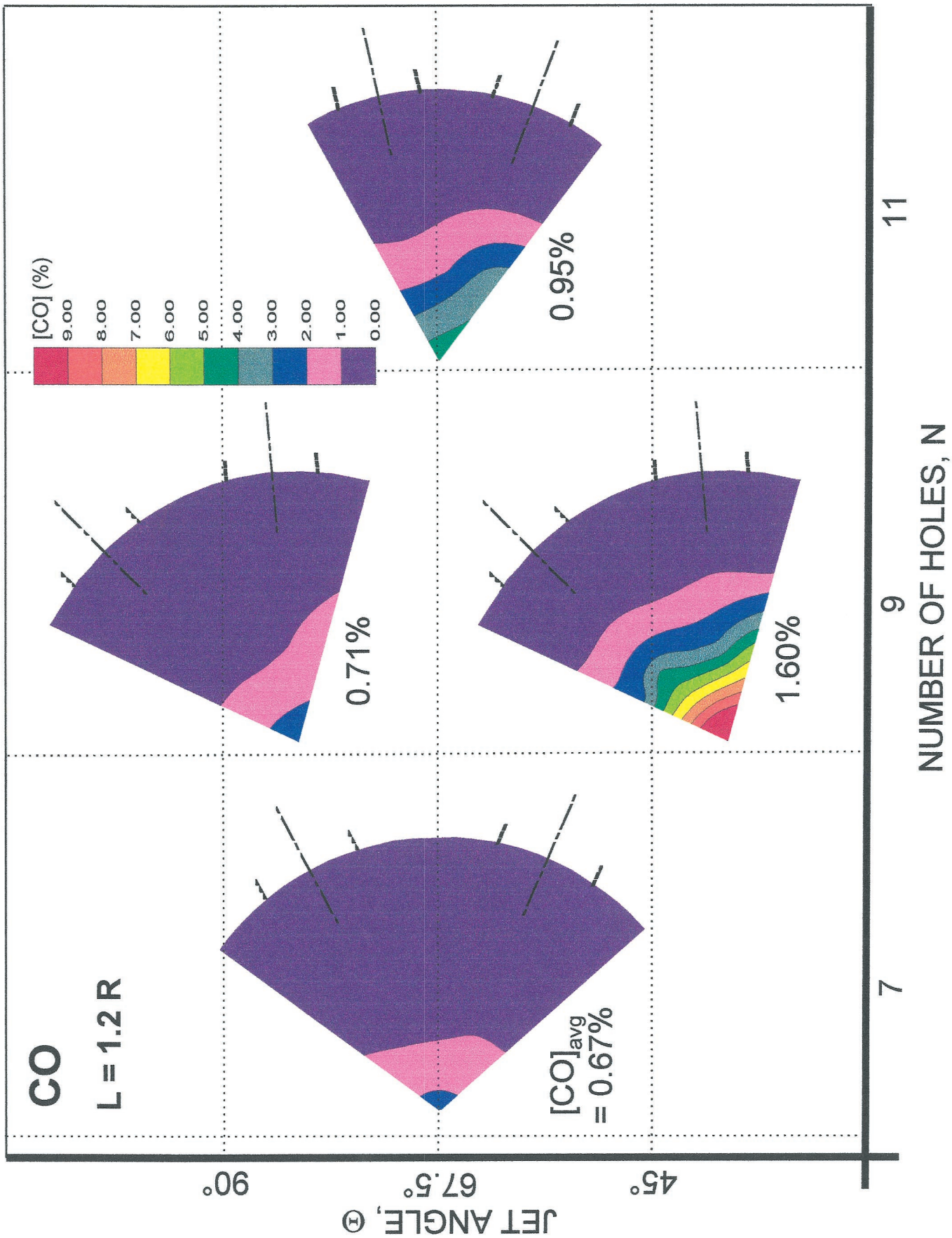


Figure 7. CO concentration profiles, plane 1, cases 1 through 4 (L = 1.2 R).

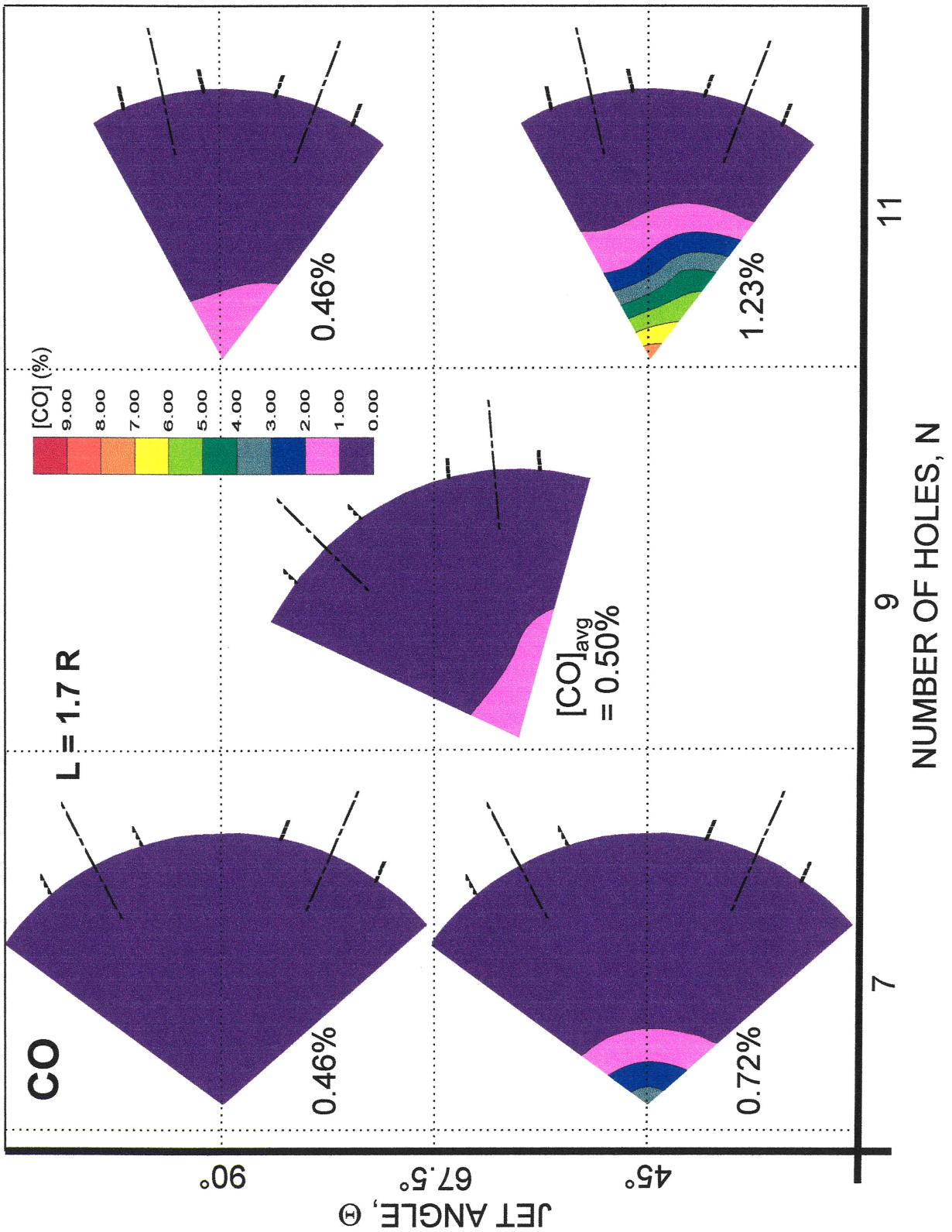


Figure 8. CO concentration profiles, plane 1, cases 5 through 9 (L = 1.7 R).

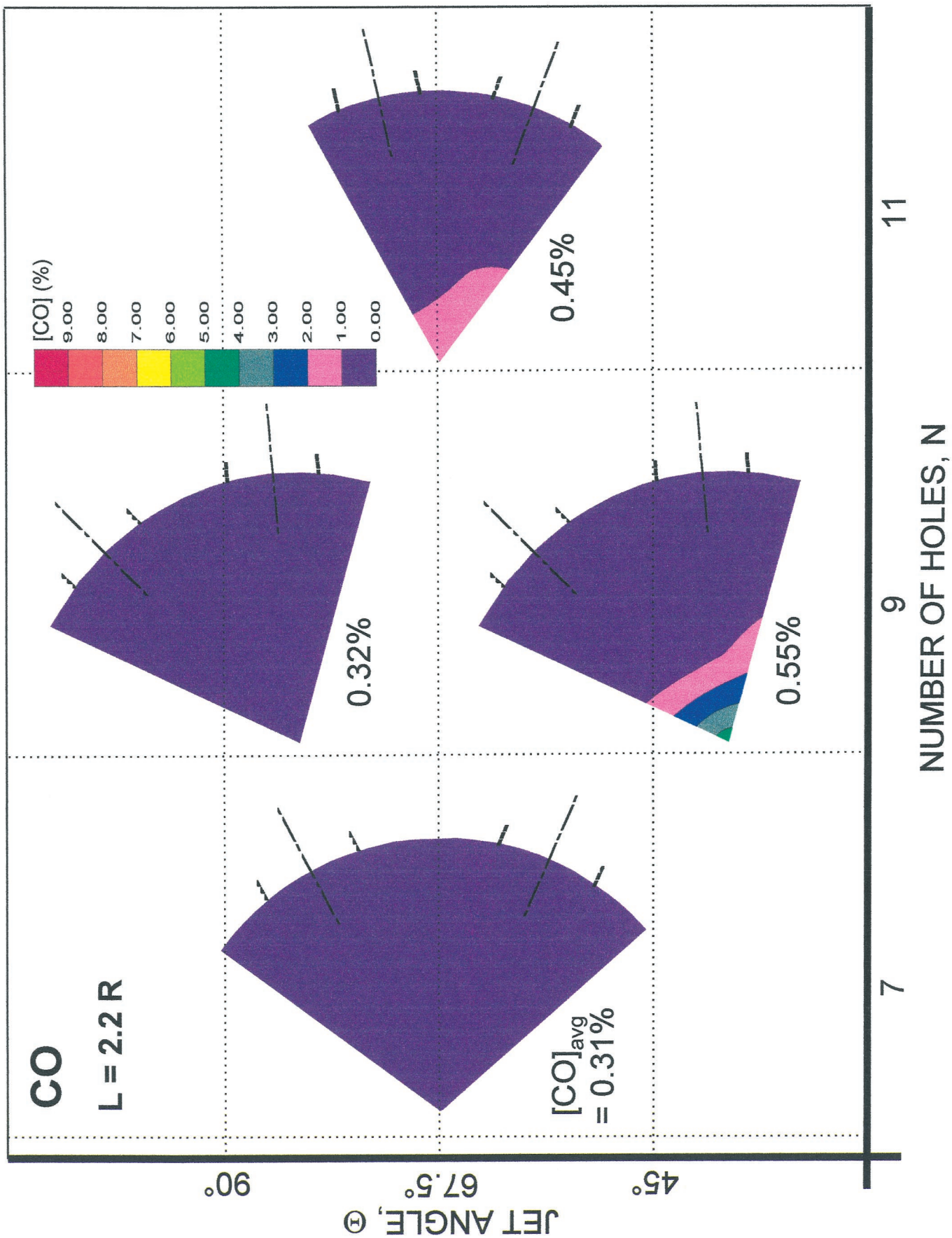


Figure 9. CO concentration profiles, plane 1, cases 10 through 13 (L = 2.2 R).

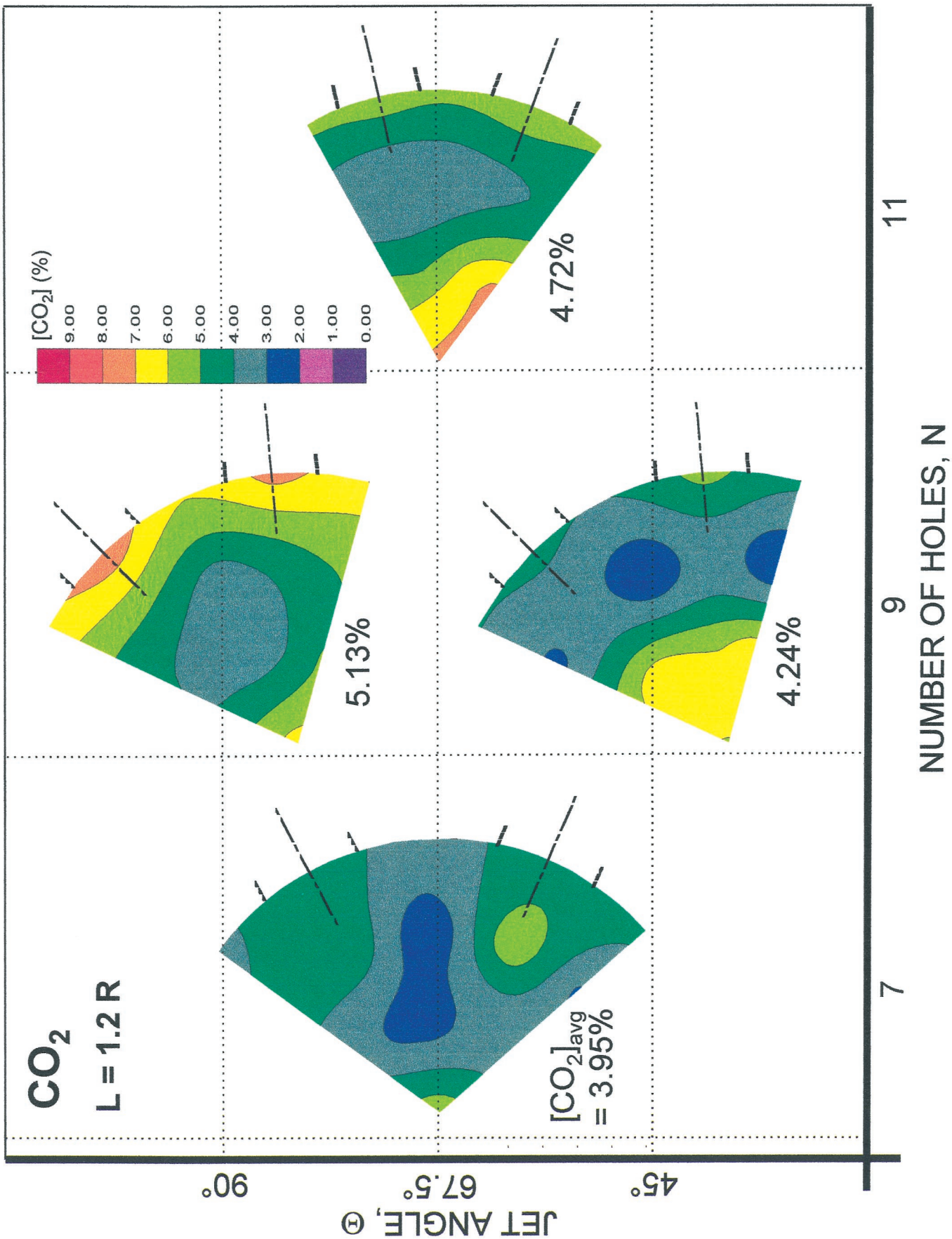


Figure 10. CO_2 concentration profiles, plane 1, cases 1 through 4 (L = 1.2 R).

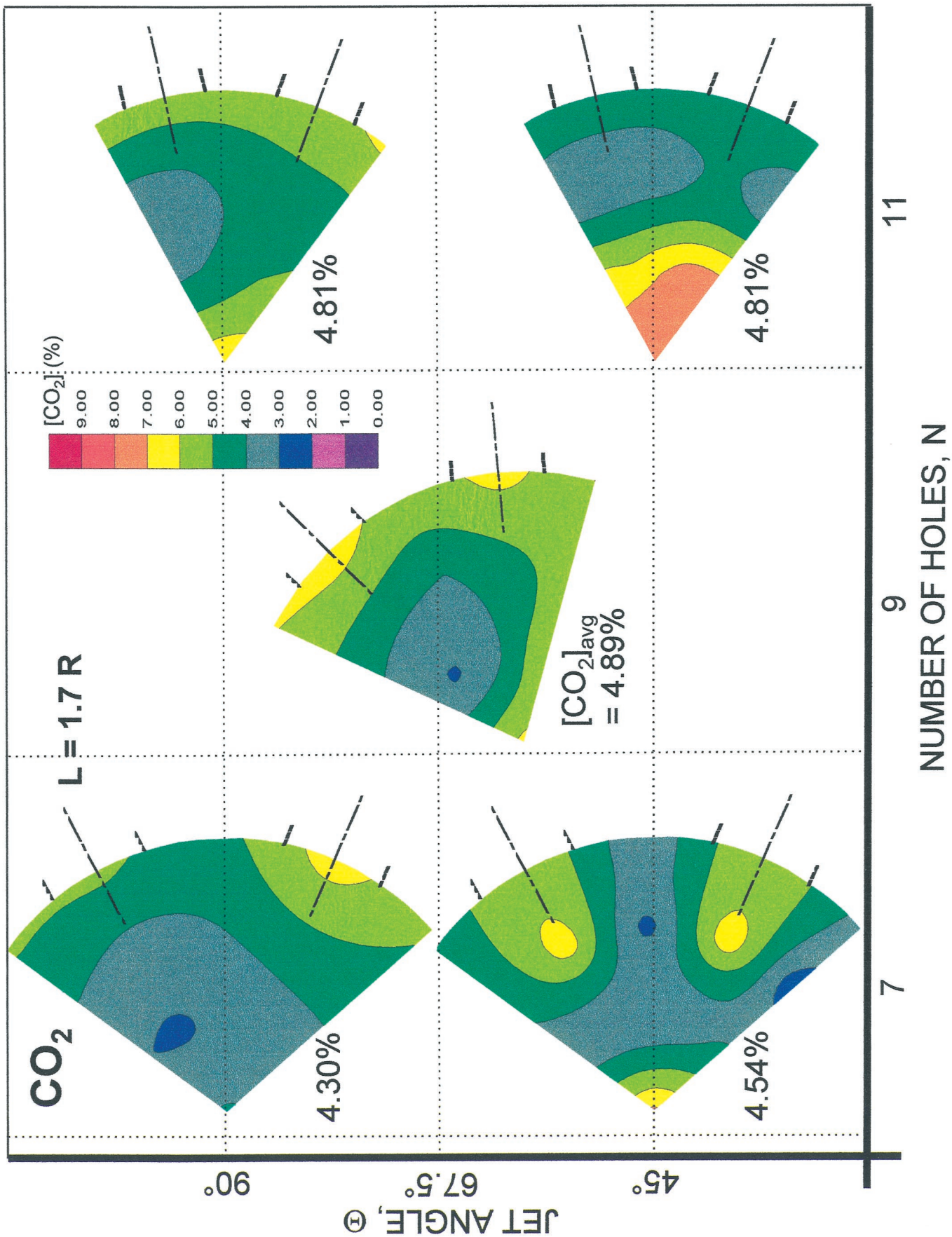


Figure 11. CO_2 concentration profiles, plane 1, cases 5 through 9 (L = 1.7 R).

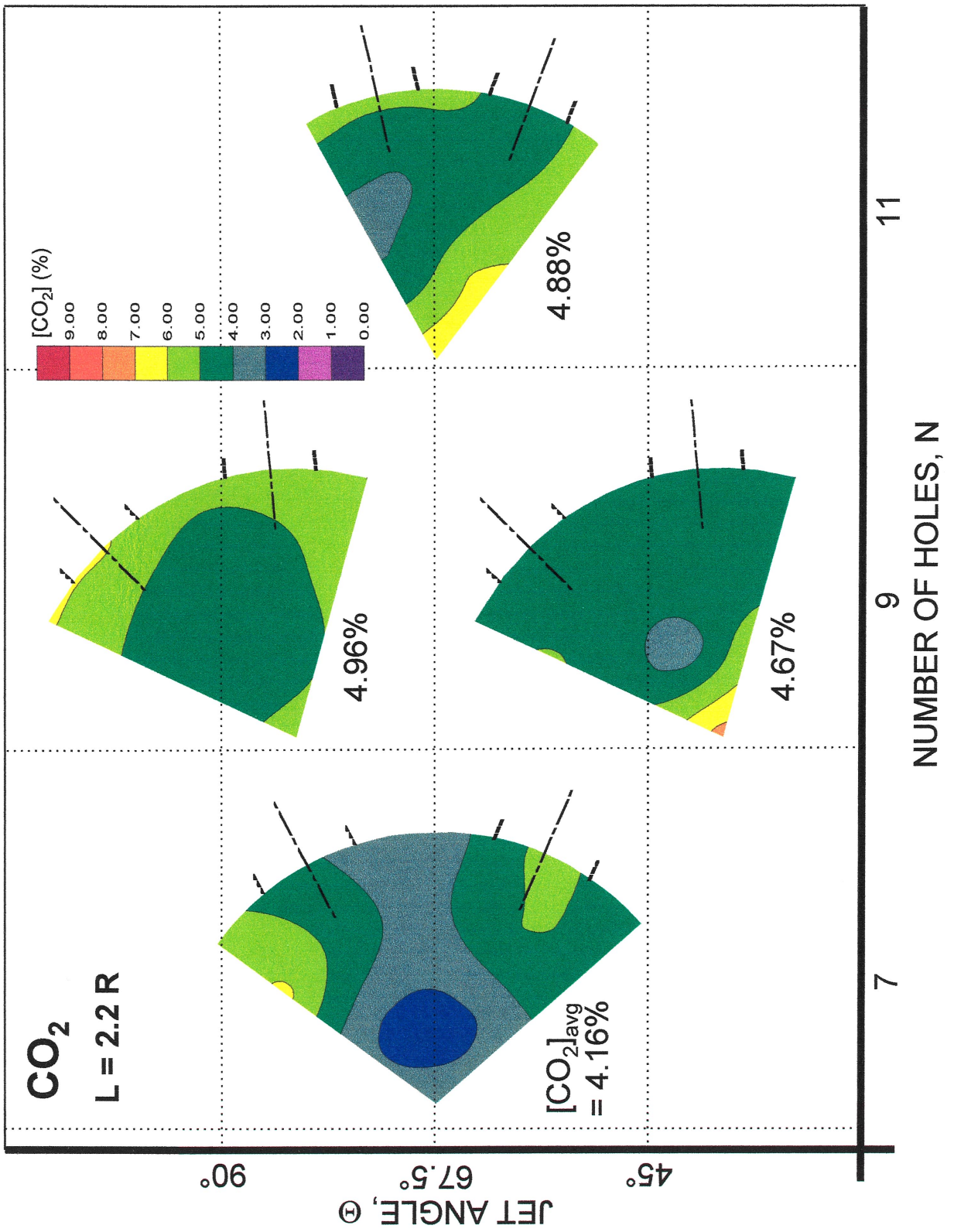


Figure 12. CO_2 concentration profiles, plane 1, cases 10 through 13 (L = 2.2 R).

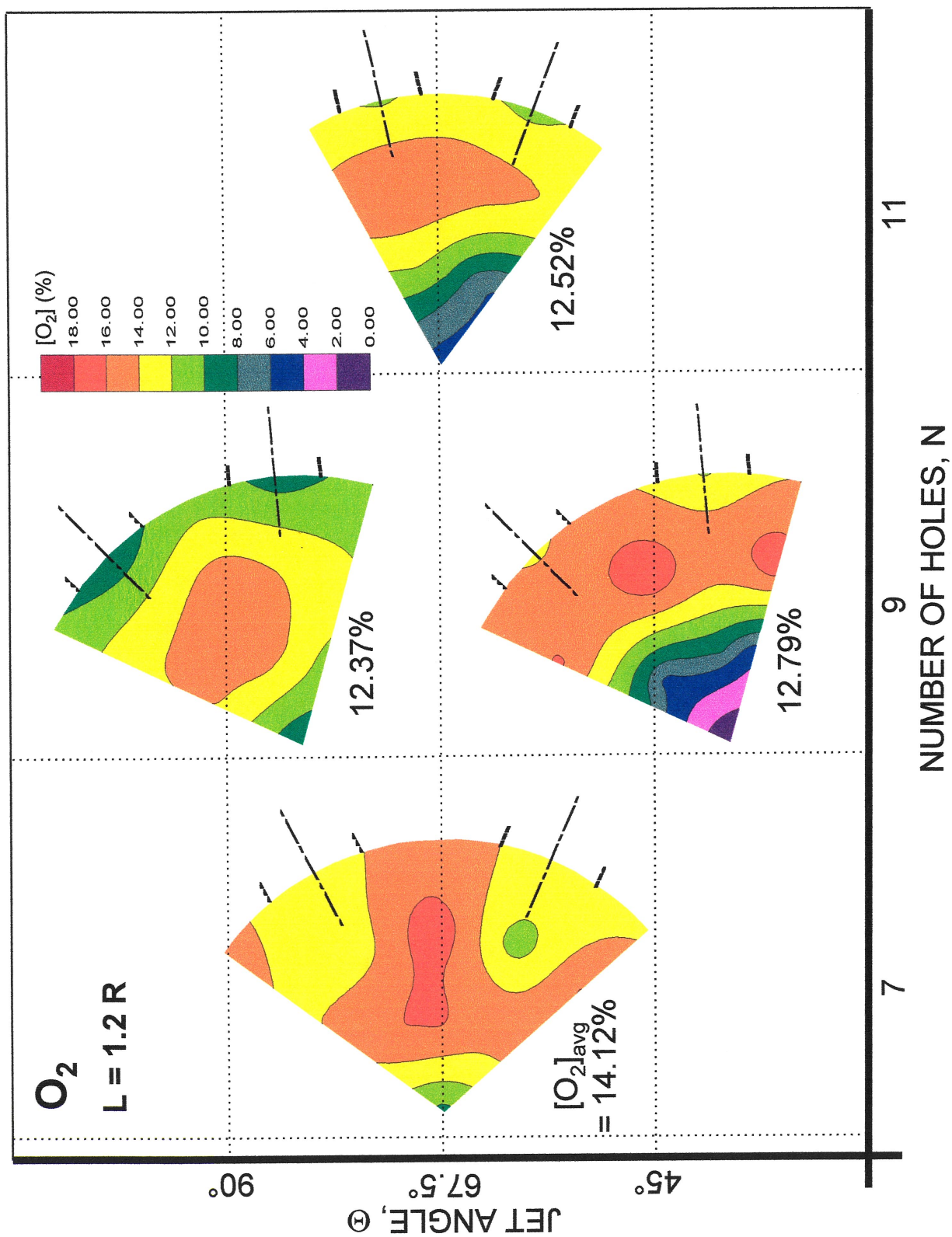


Figure 13. O_2 concentration profiles, plane 1, cases 1 through 4 (L = 1.2 R).

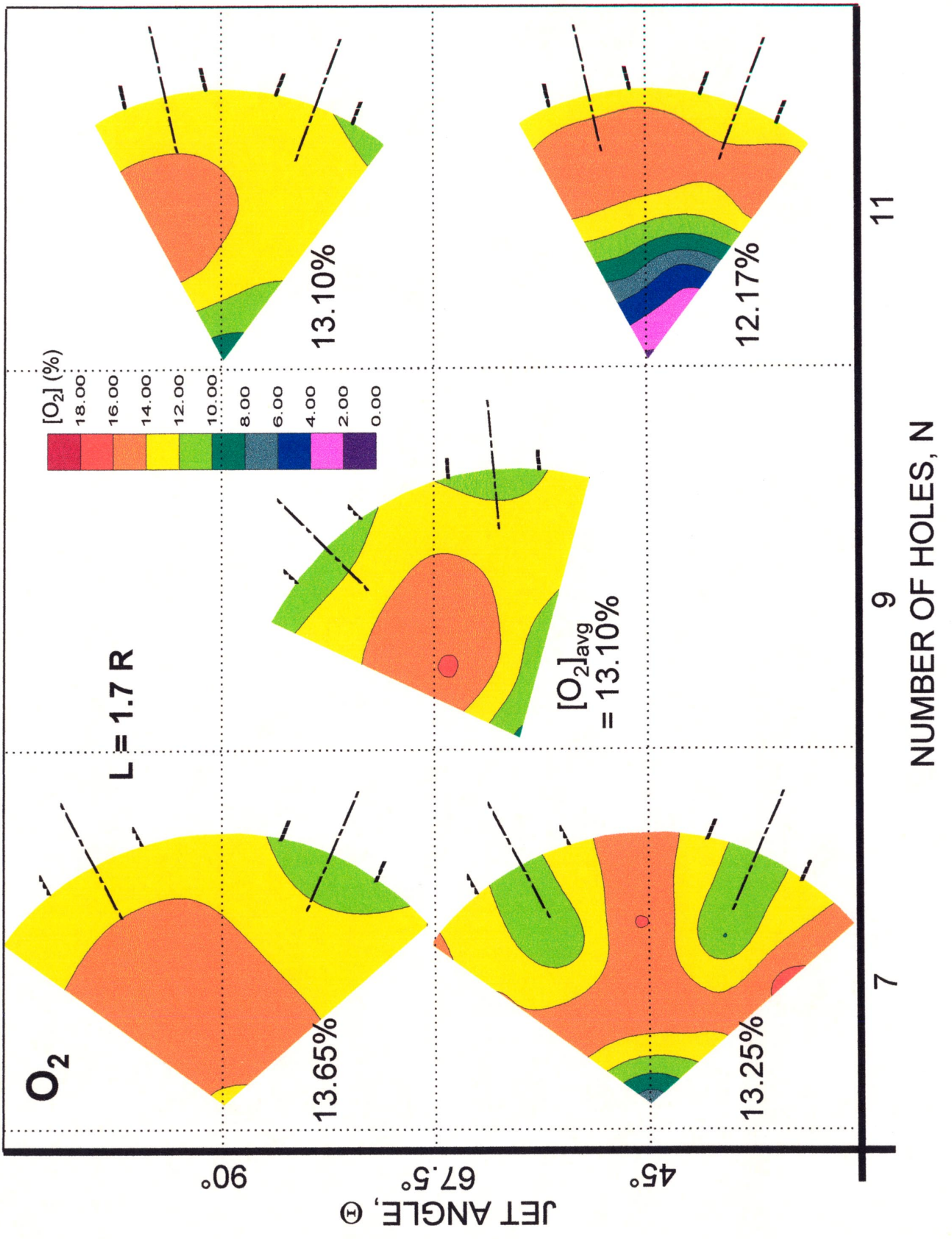


Figure 14. O_2 concentration profiles, plane 1, cases 5 through 9 (L = 1.7 R).

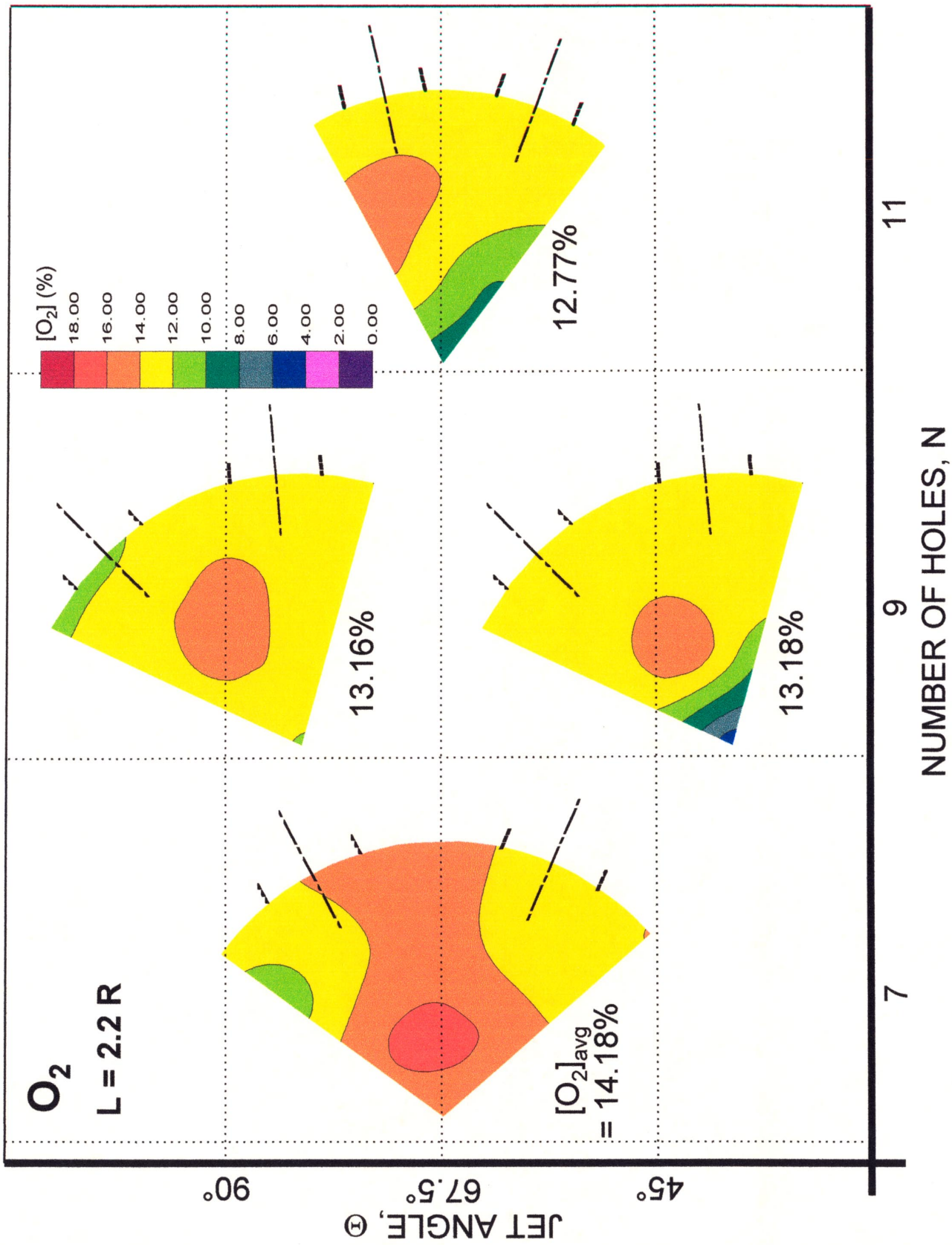


Figure 15. O_2 concentration profiles, plane 1, cases 10 through 13 (L = 2.2 R).

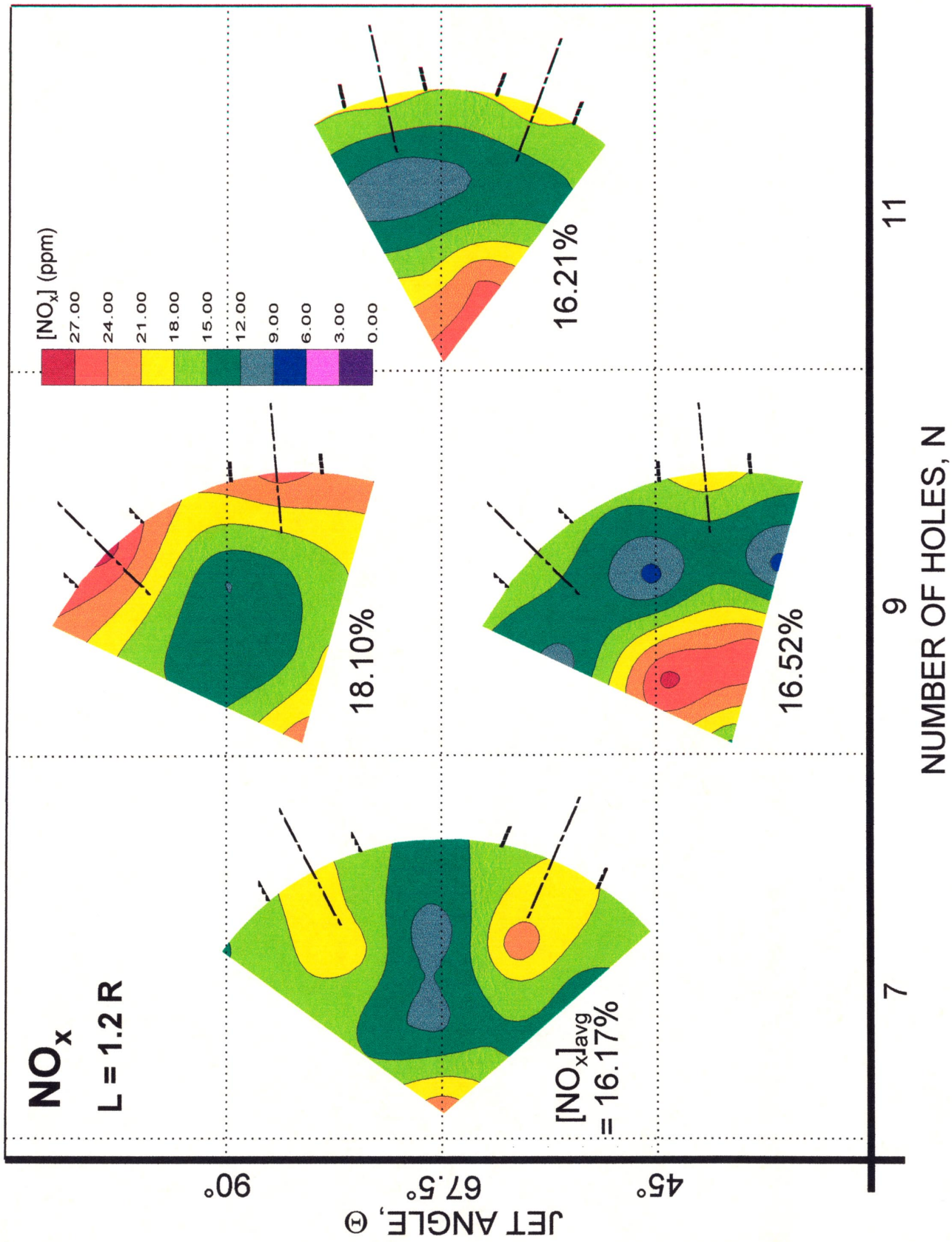


Figure 16. NO_x concentration profiles, plane 1, cases 1 through 4 (L = 1.2 R).

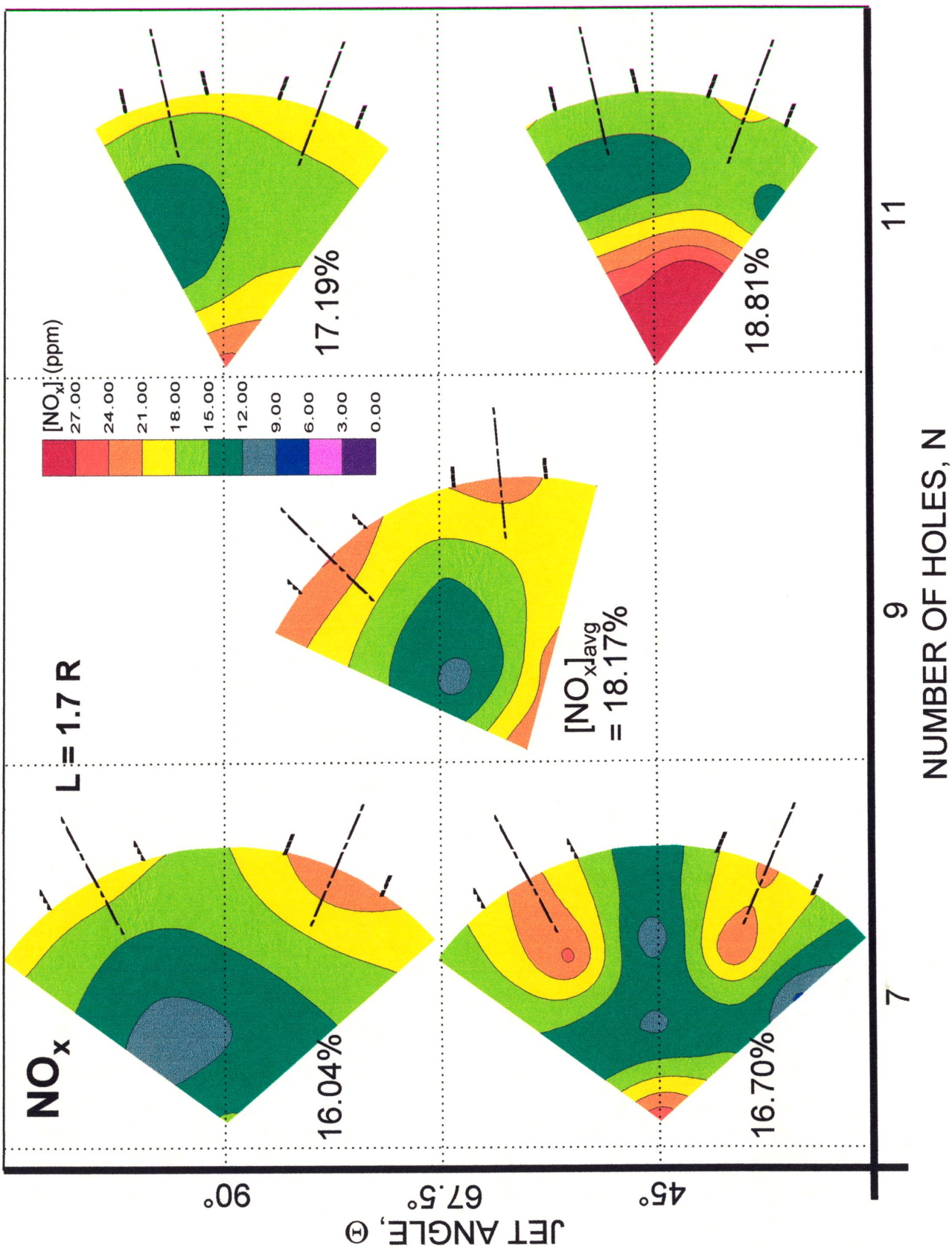


Figure 17. NO_x concentration profiles, plane 1, cases 5 through 9 (L = 1.7R).

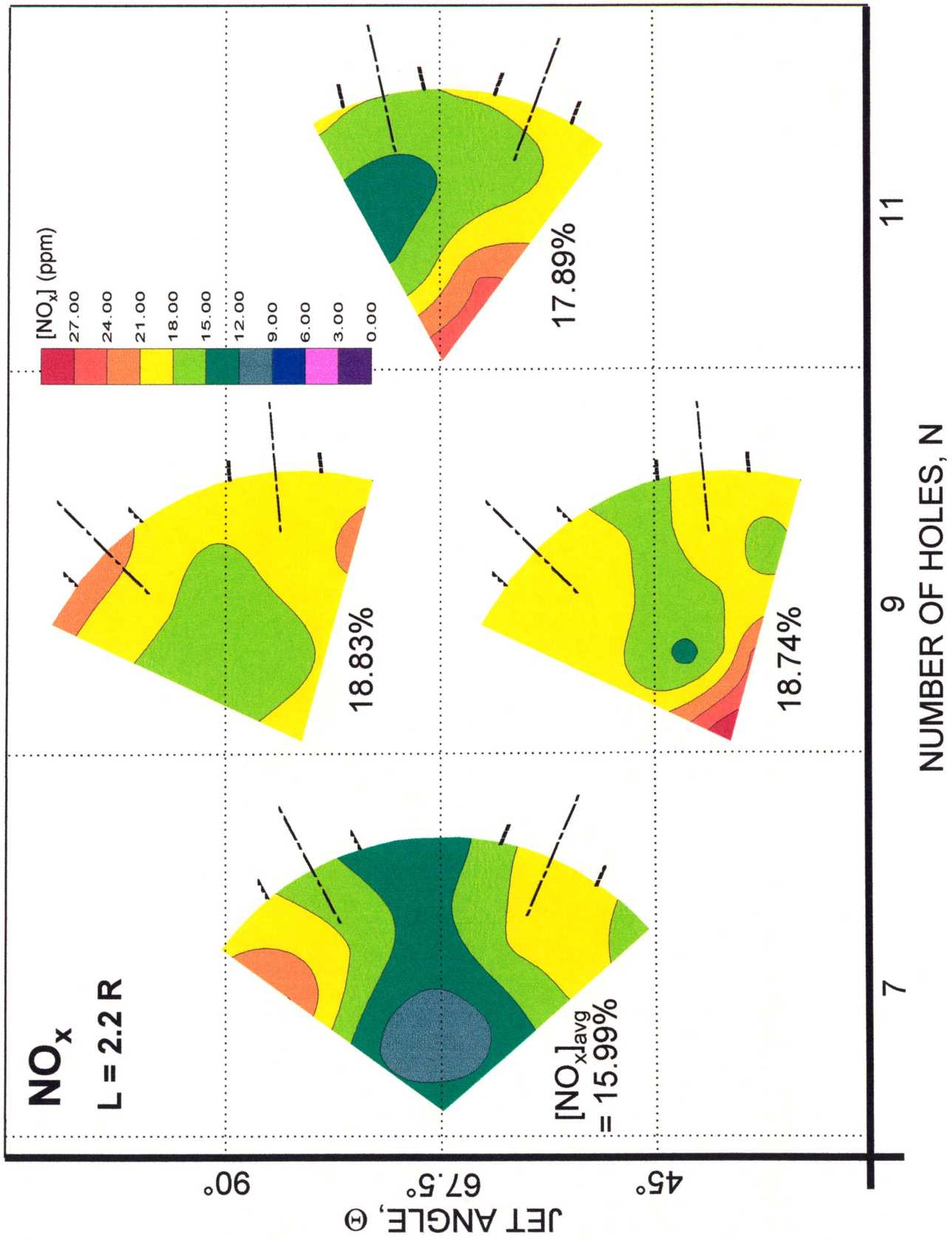


Figure 18. NO_x concentration profiles, plane 1, cases 10 through 13 (L = 2.2R).

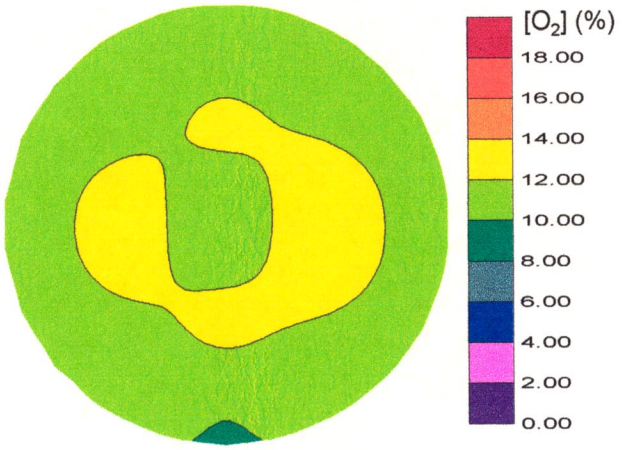


Figure 19. Plane 1 O_2 concentration measurements across entire region, case 6.

Figure 20. Plane 2 O_2 concentration measurements across entire region, case 6.

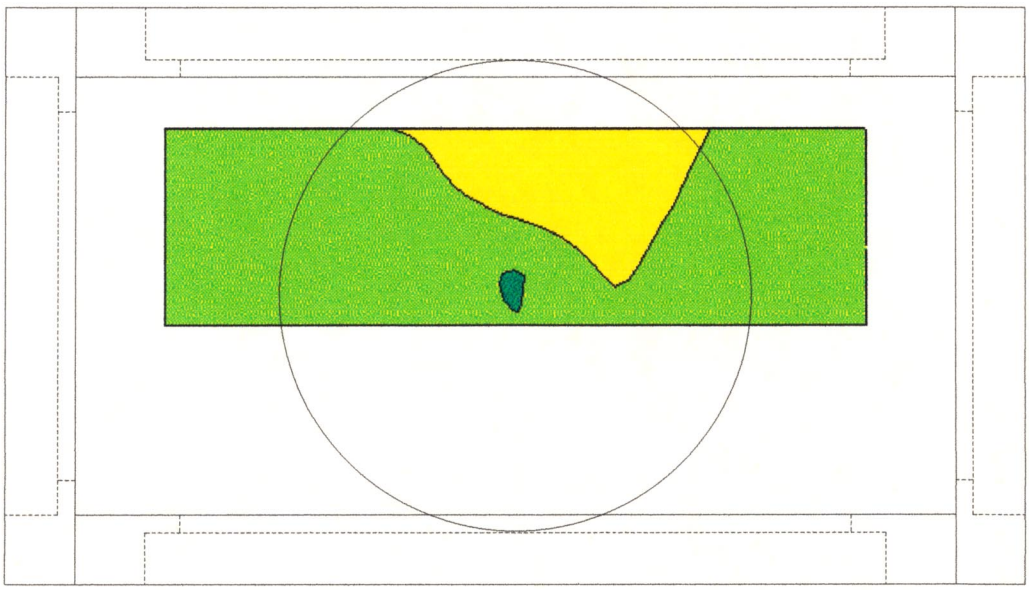
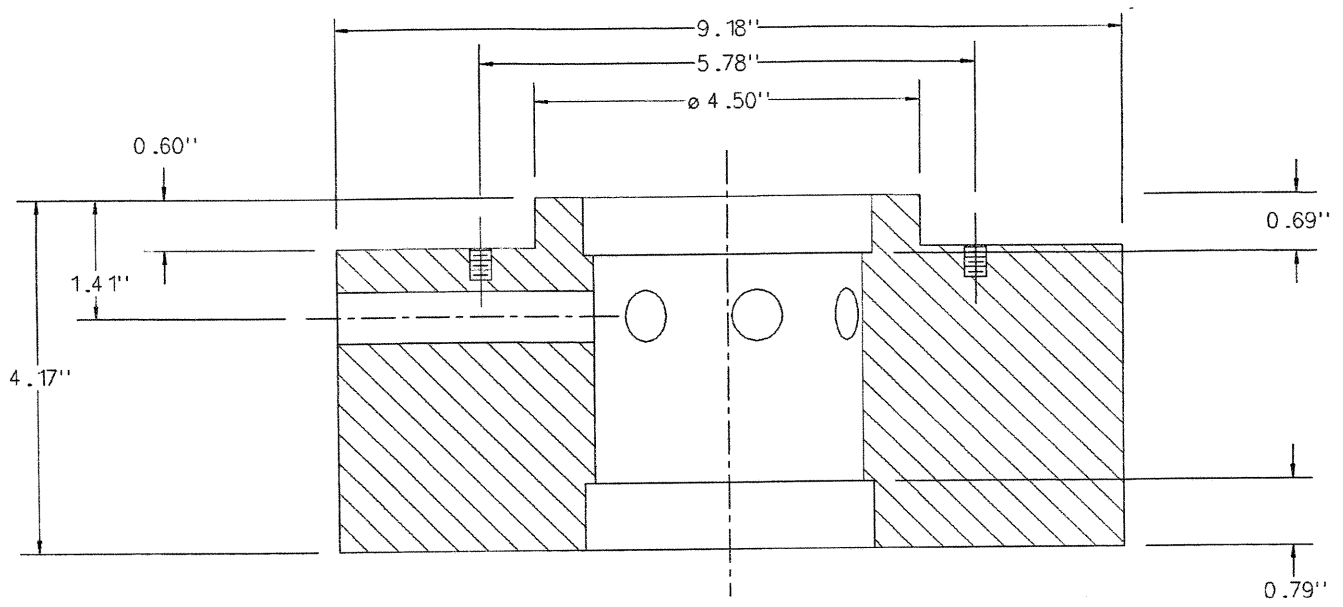


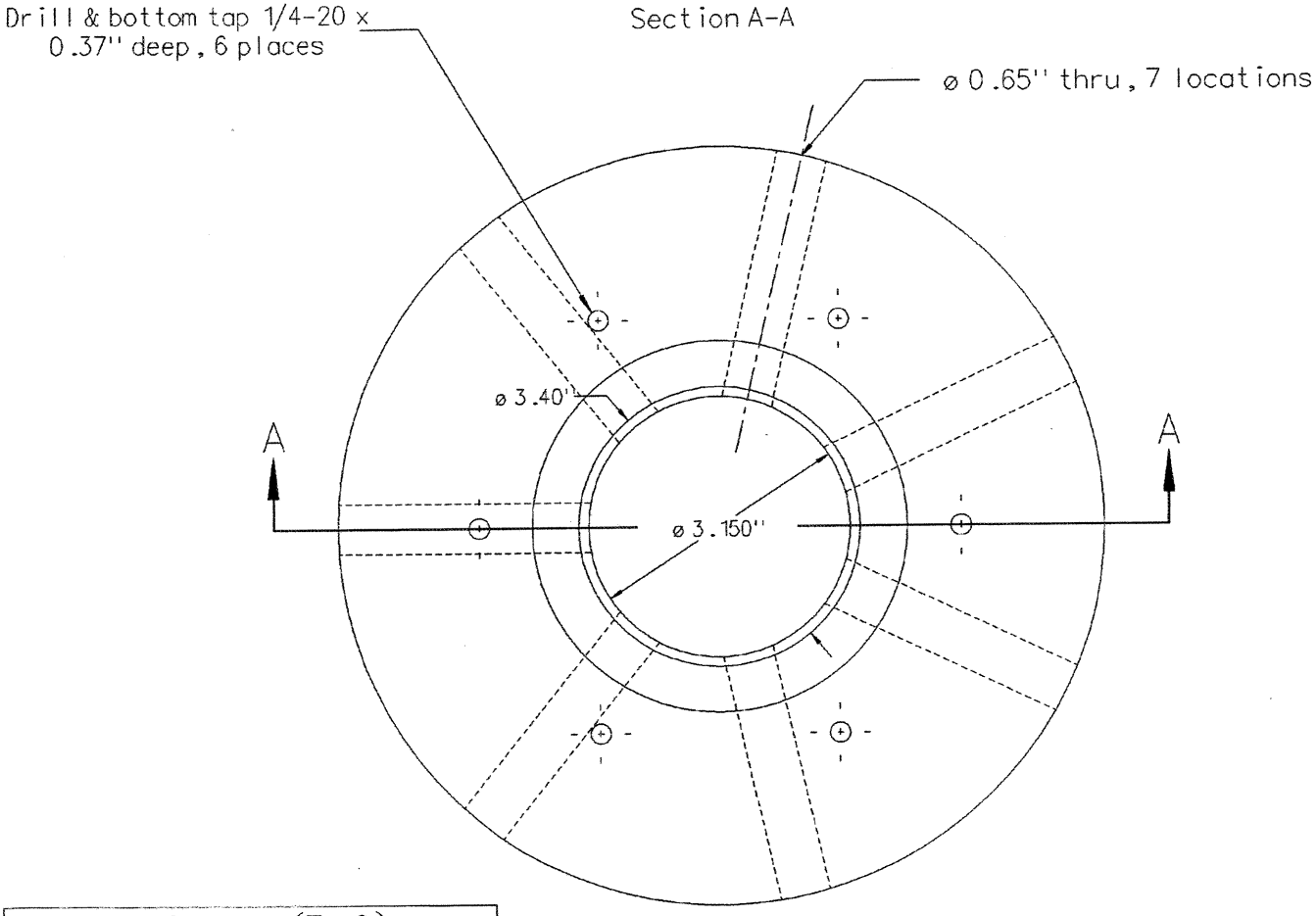
Figure 21. Plane 2 reduced O_2 concentration profiles, with 40% restriction, case 6.

Appendices

A. Drawings

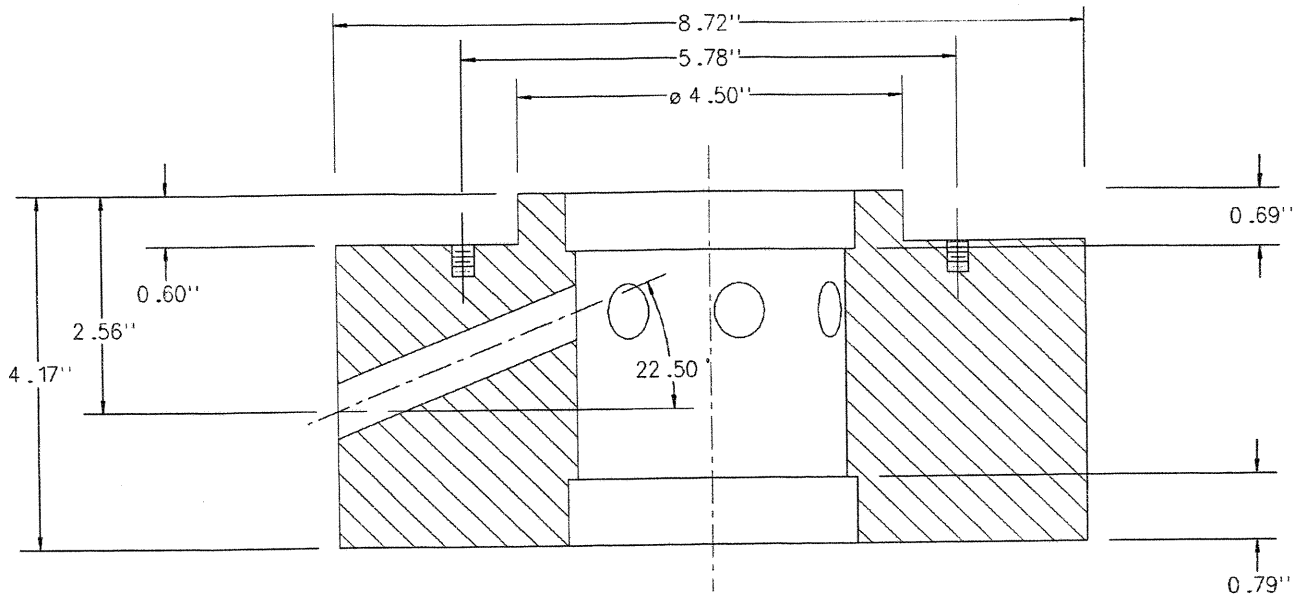


Section A-A

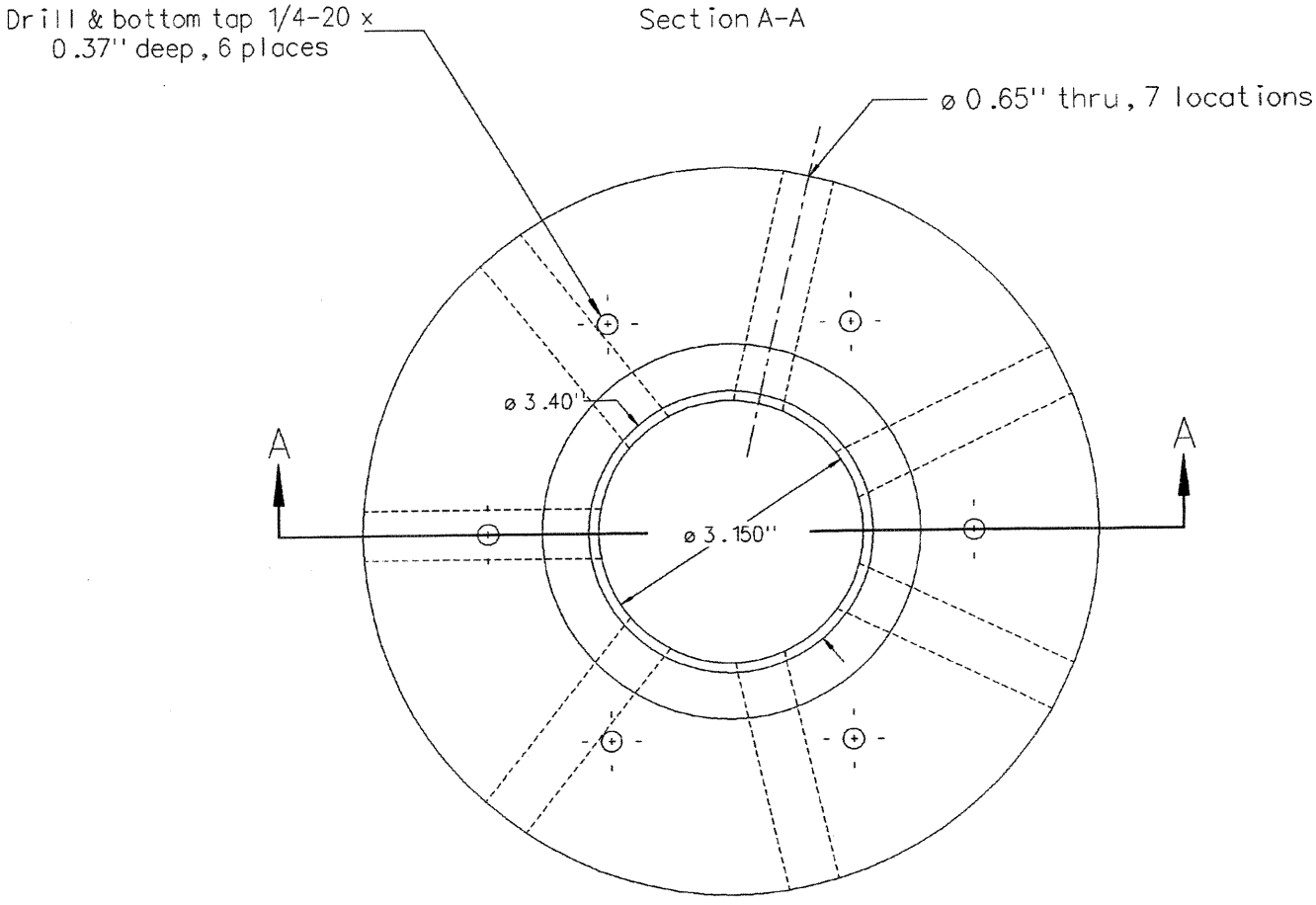


QM Collar (7, 0)	
Scale: 2:1	Material: SS
# holes: 7	Jet ang: 0°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

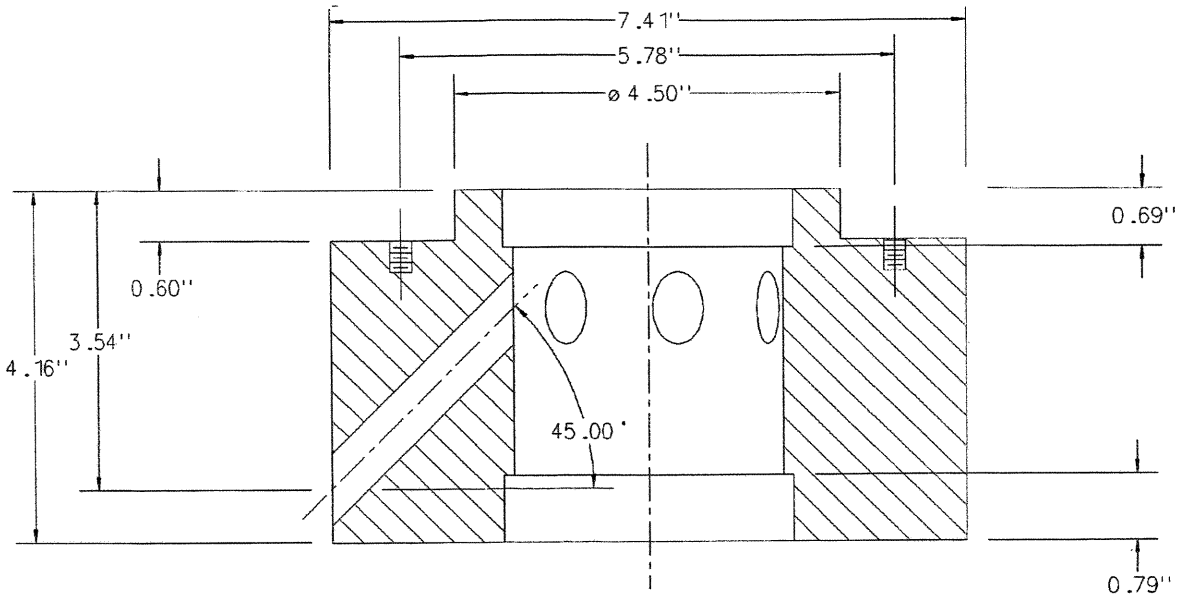


Section A-A

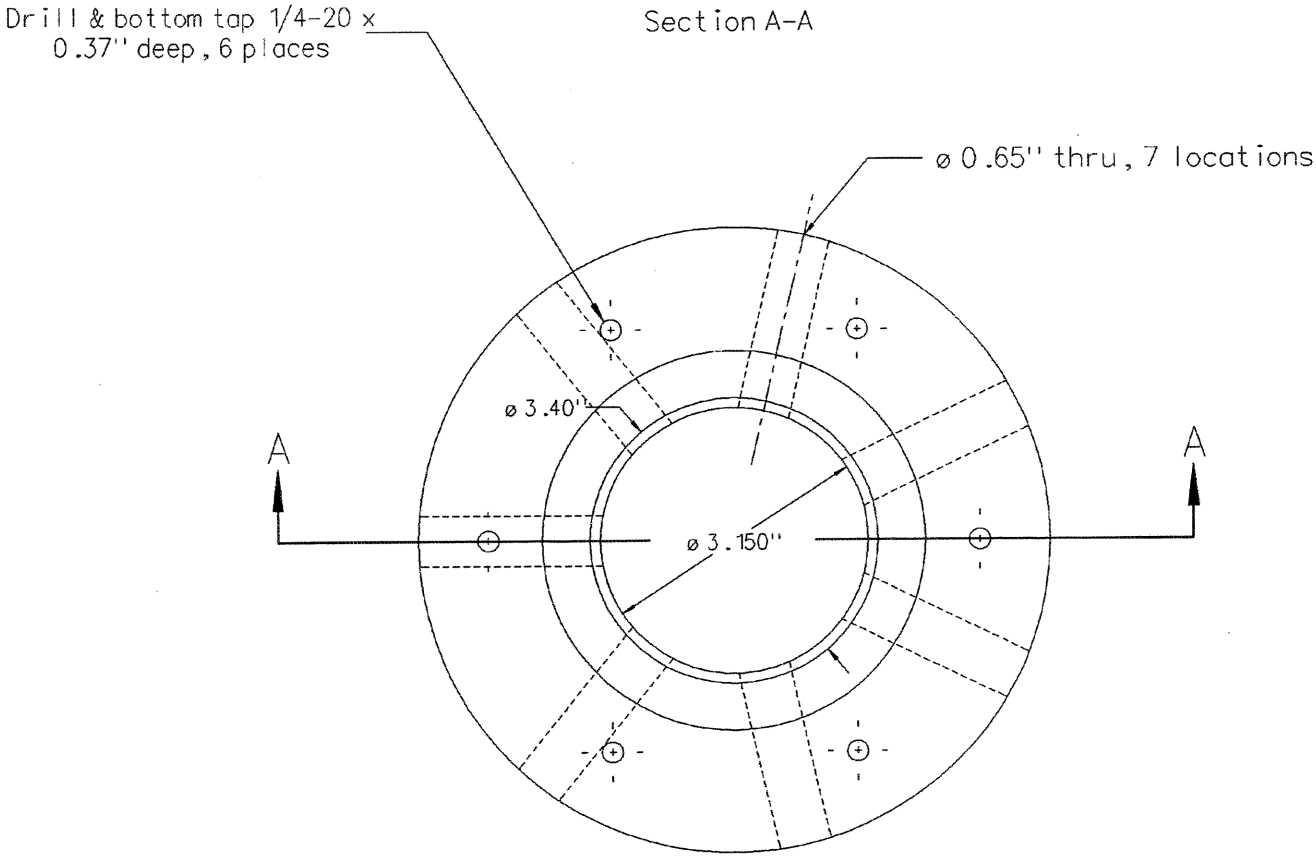


QM Collar (7, 22.5)	
Scale: 2:1	Material: SS
# holes: 7	Jet ang: 22.5°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

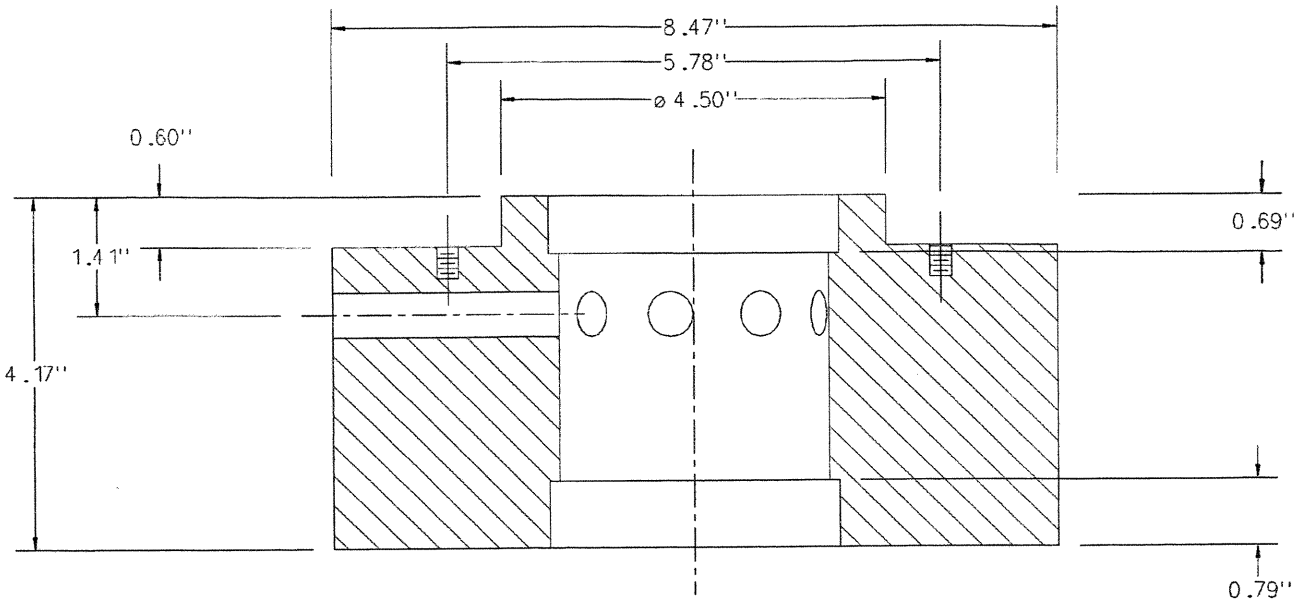


Section A-A

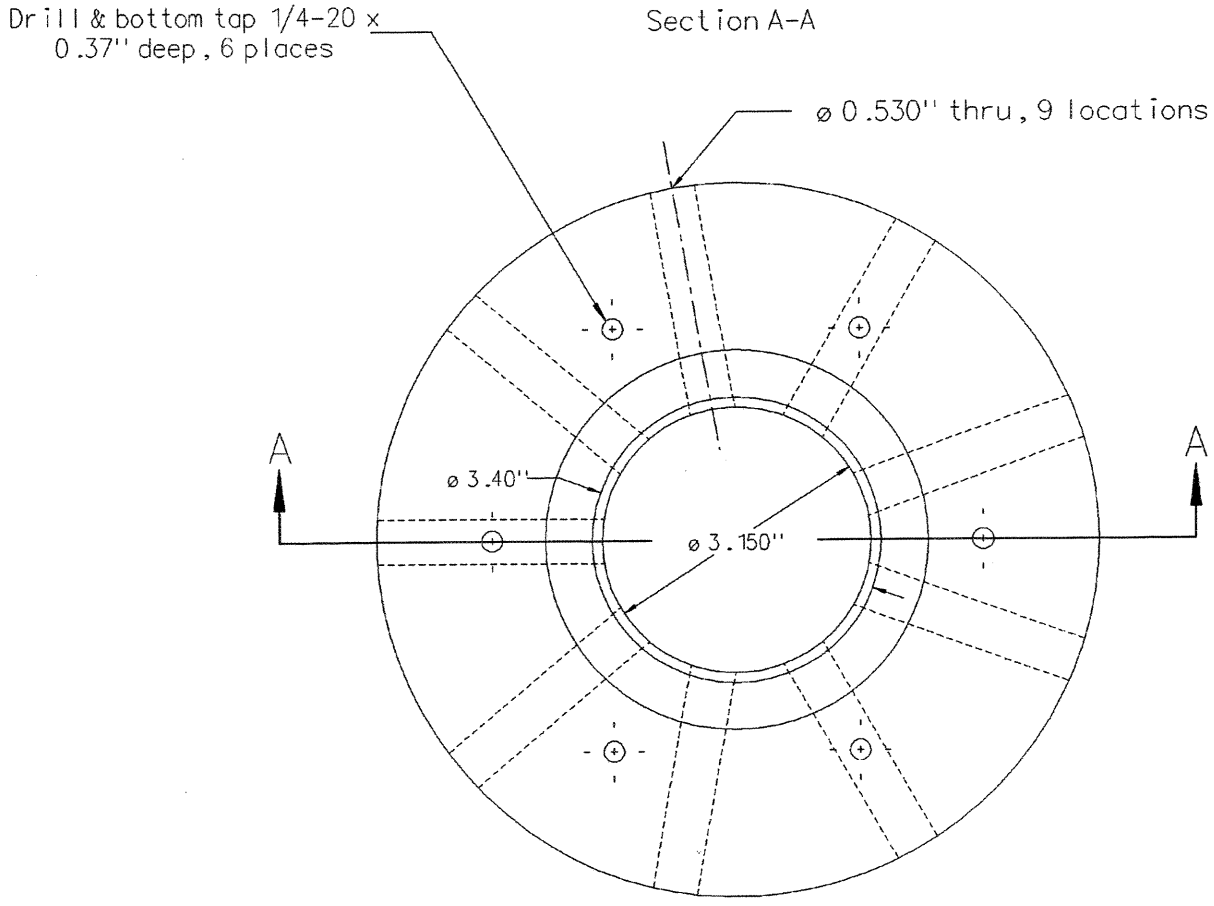


QM Collar (7, 45)	
Scale: 2:1	Material: SS
# holes: 7	Jet ang: 45°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

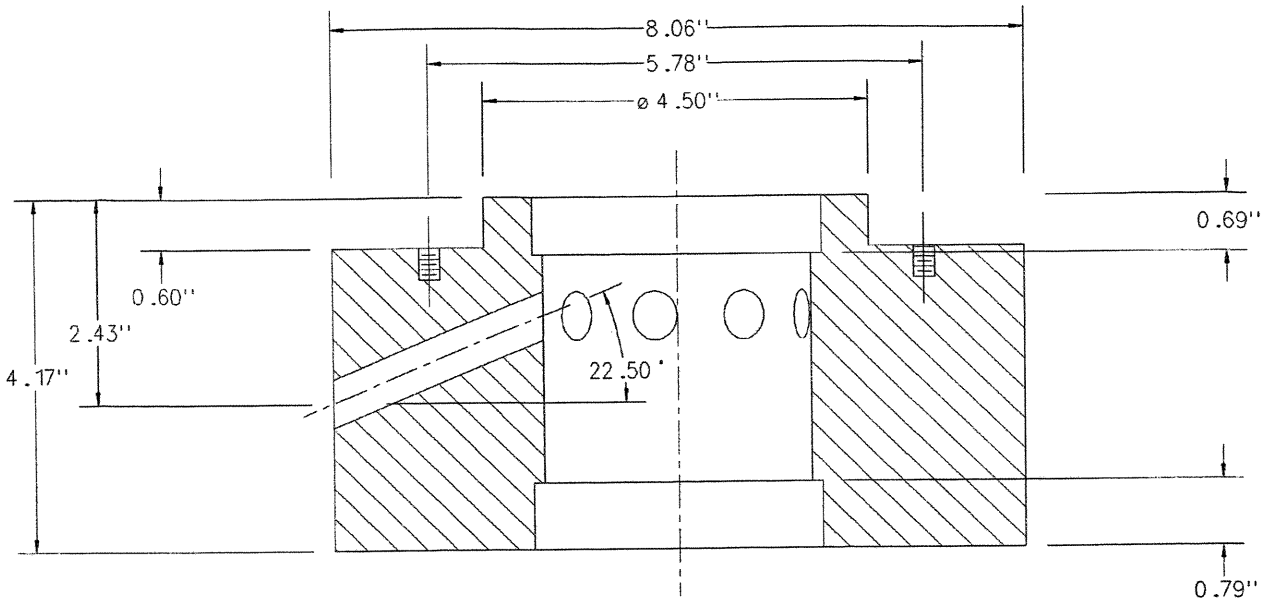


Section A-A

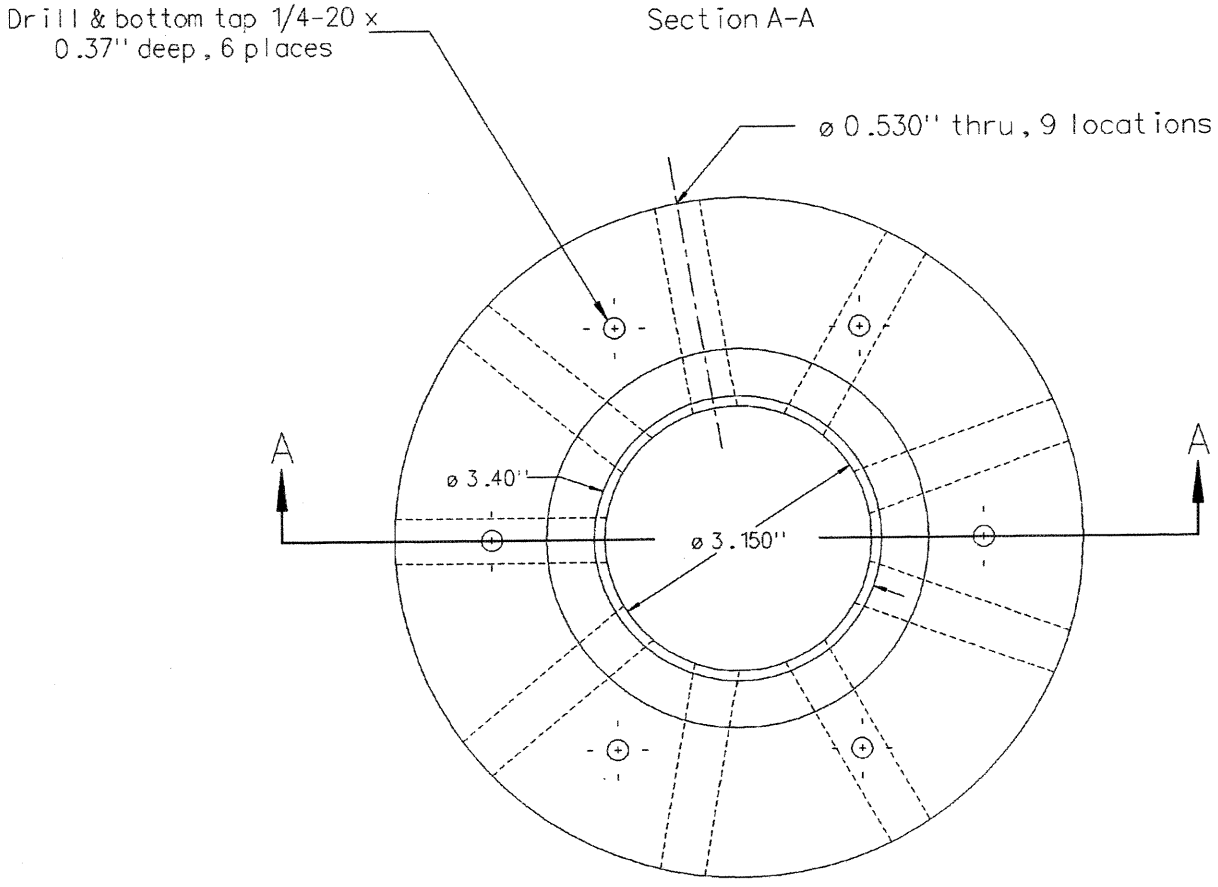


QM Collar (9, 0)	
Scale: 2:1	Material: SS
# holes: 9	Jet ang: 0°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

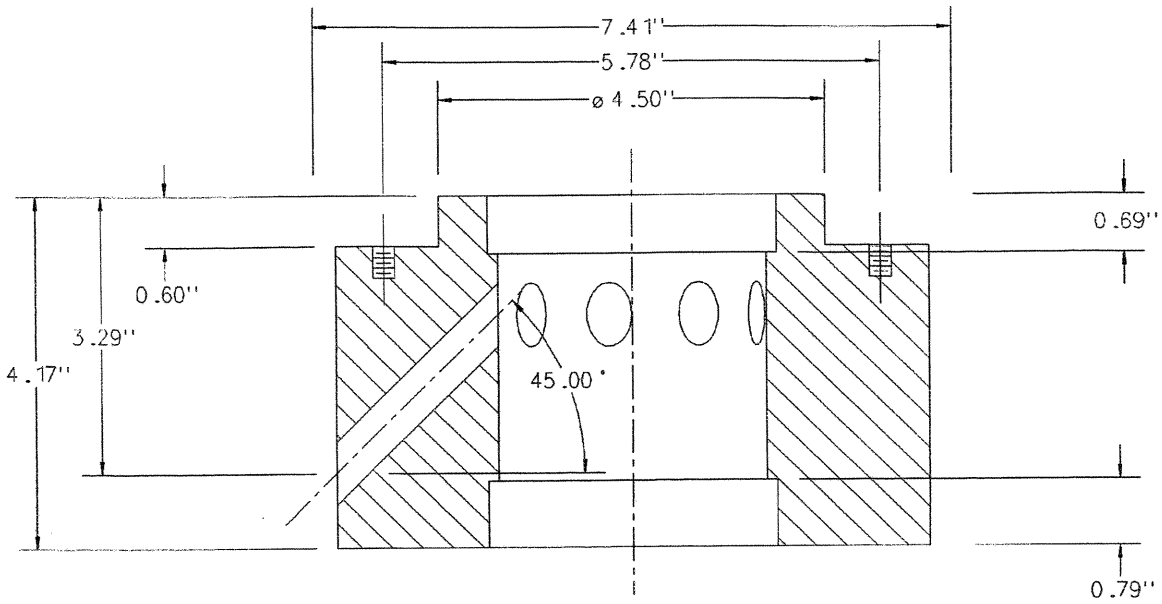


Section A-A

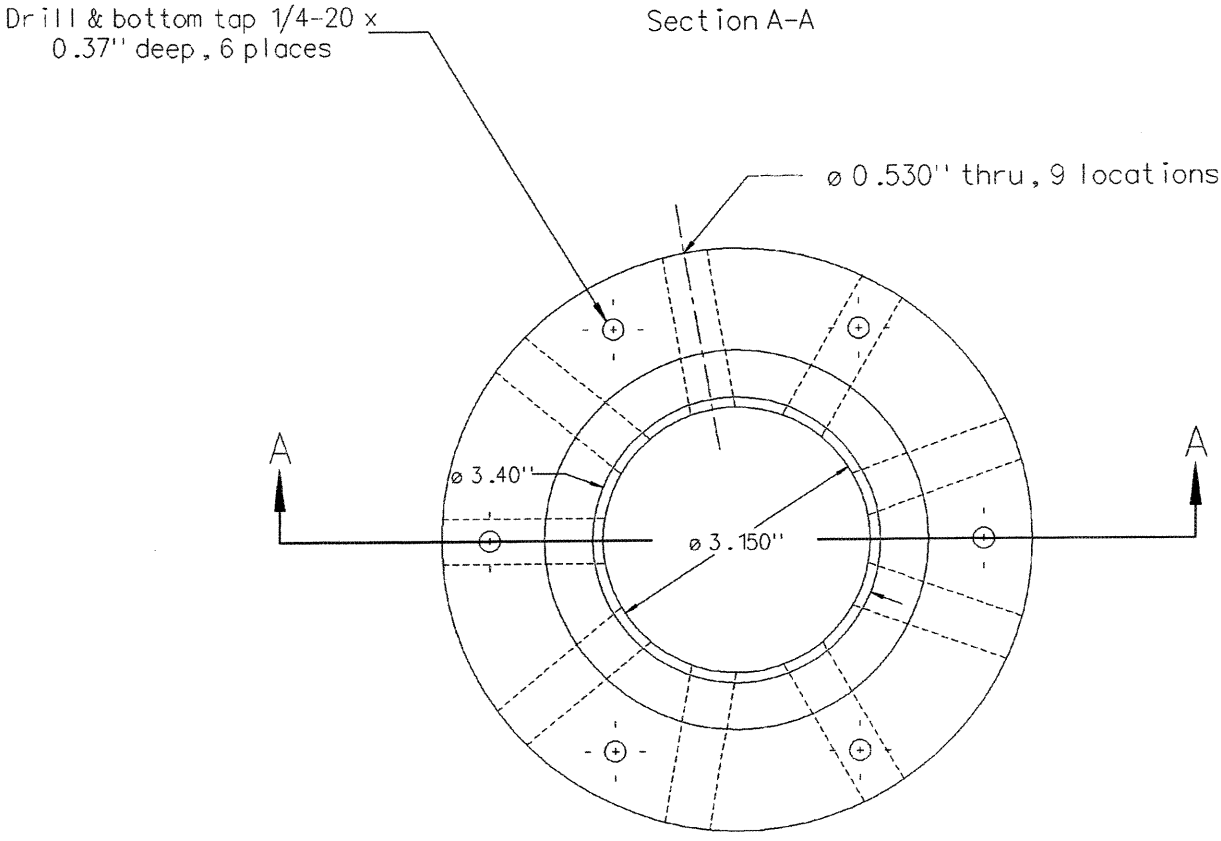


QM Collar (9, 22.5)	
Scale: 2:1	Material: SS
# holes: 9	Jet ang: 22.5°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

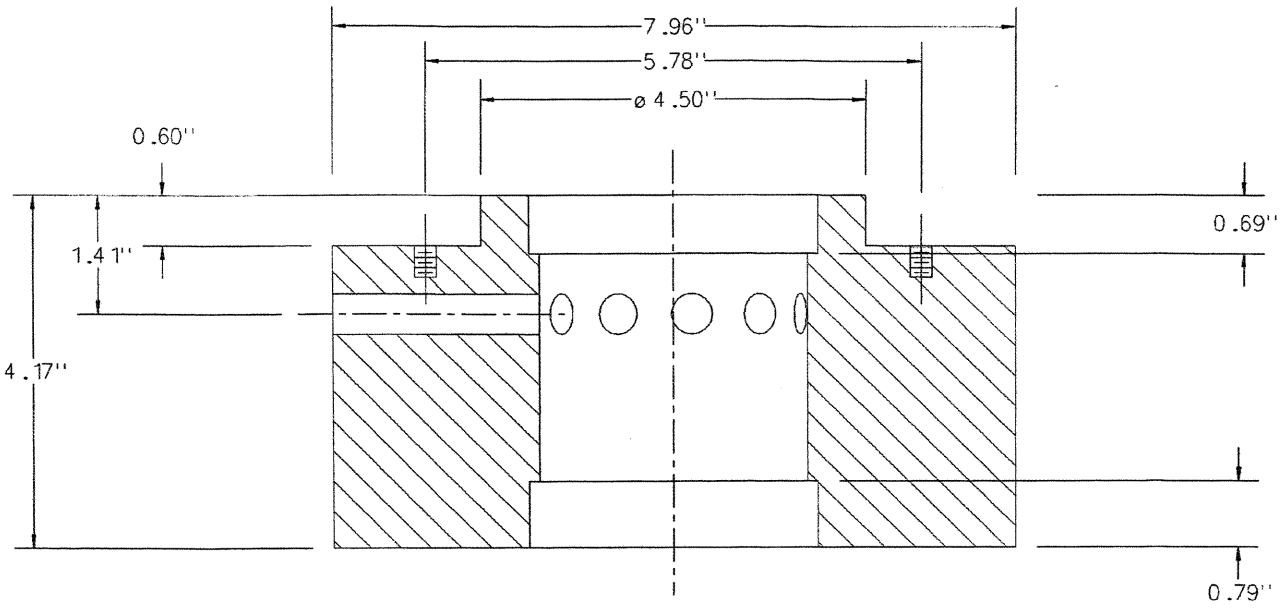


Section A-A

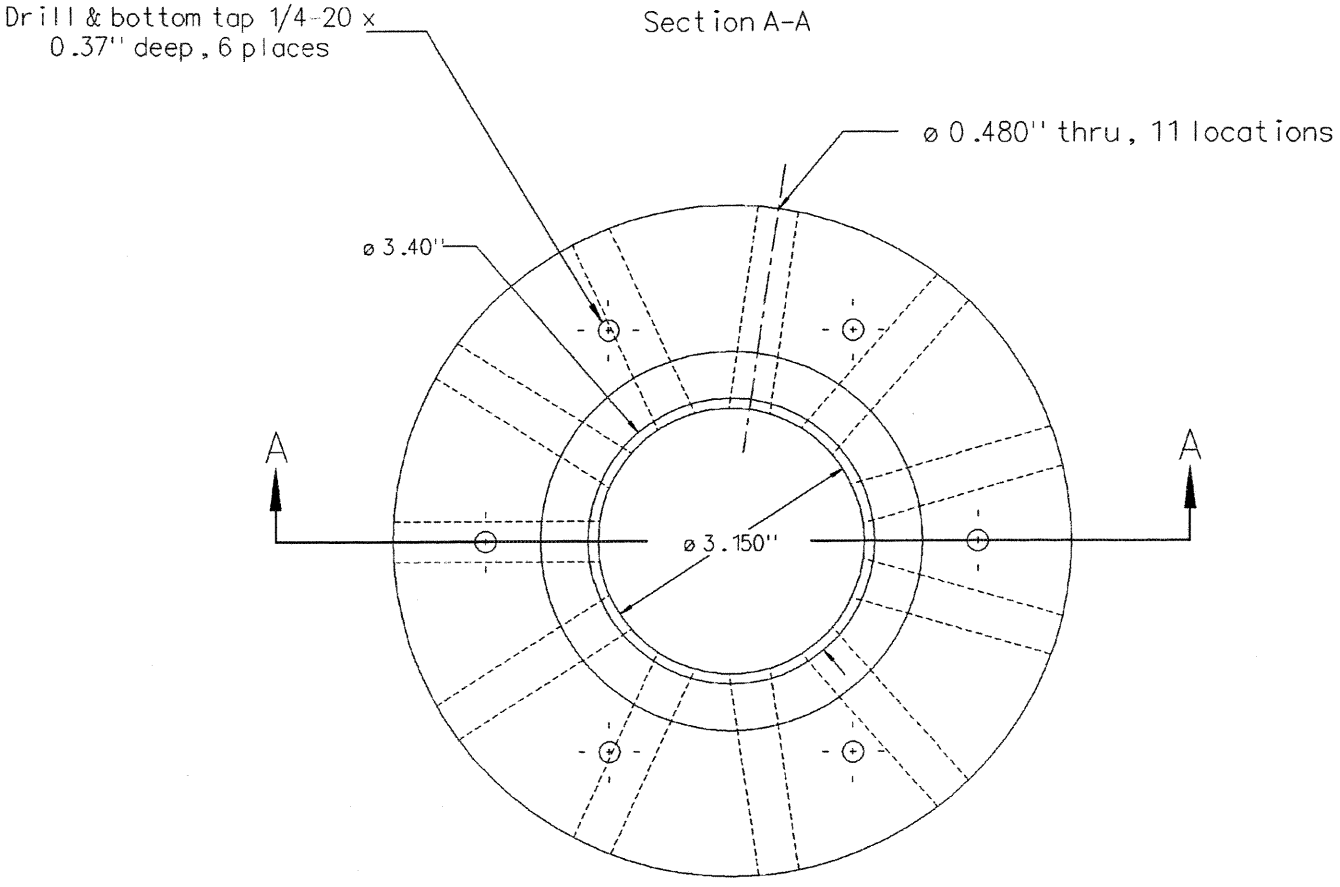


QM Collar (9, 45)	
Scale: 2:1	Material: SS
# holes: 9	Jet ang: 45°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

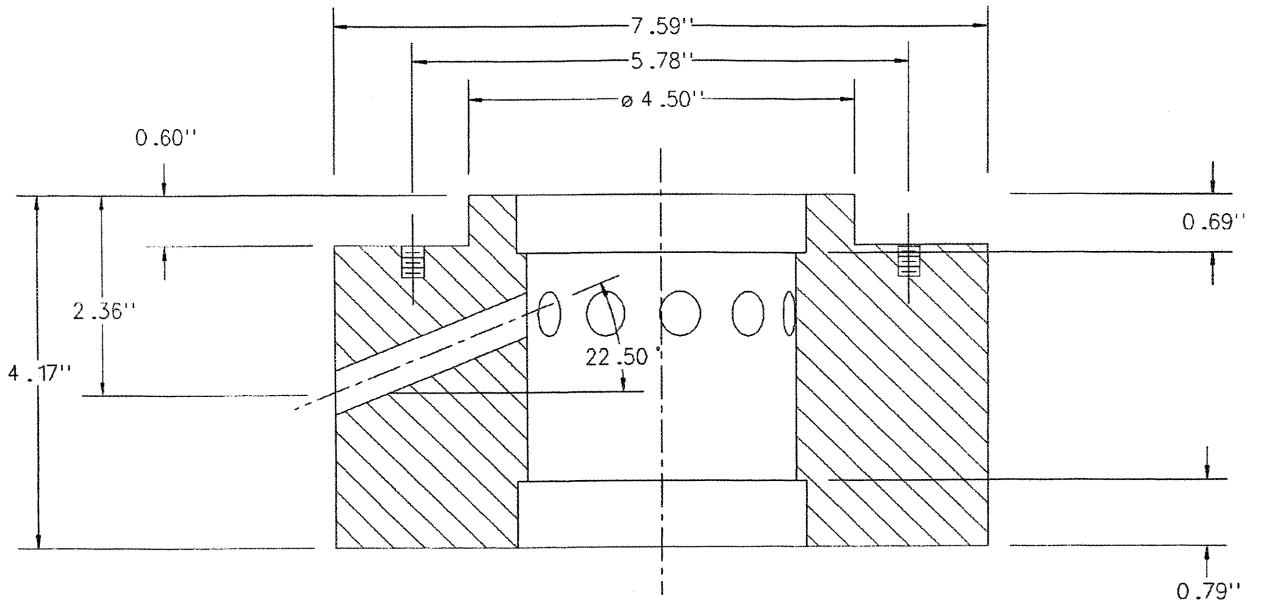


Section A-A

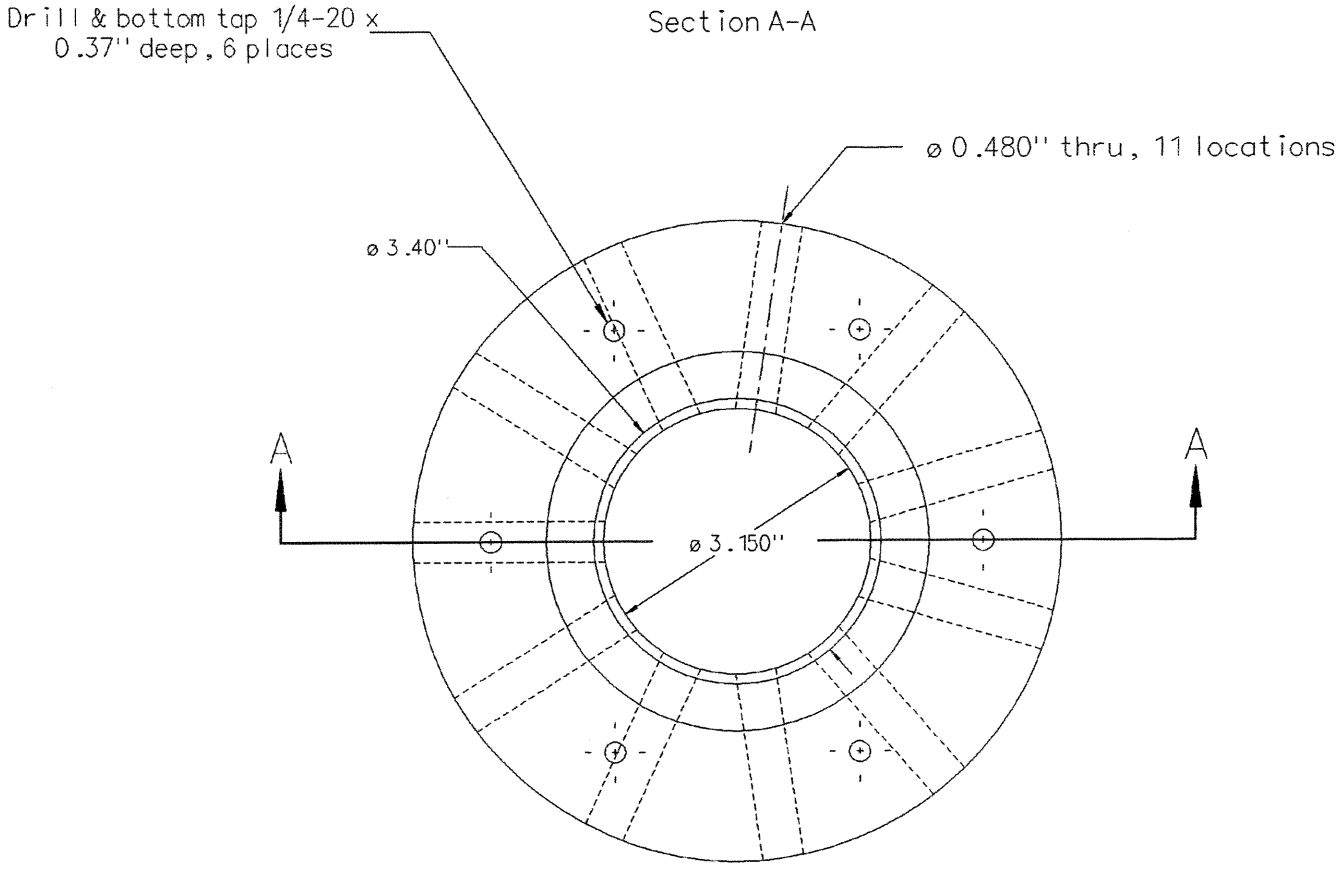


QM Collar (11, 0)	
Scale: 2:1	Material: SS
# holes: 11	Jet ang: 0°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

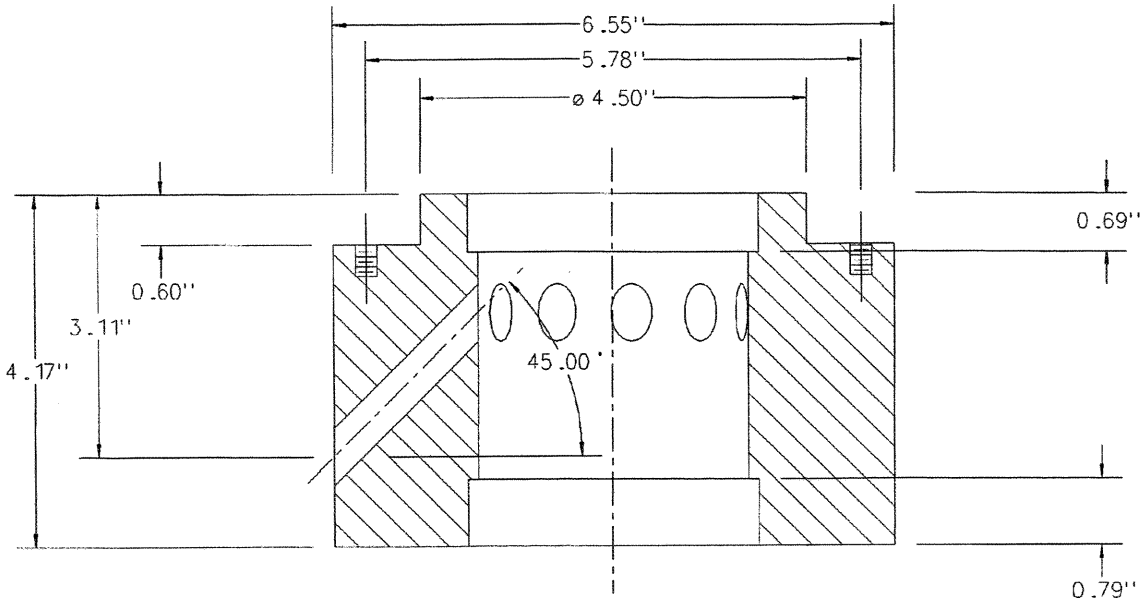


Section A-A

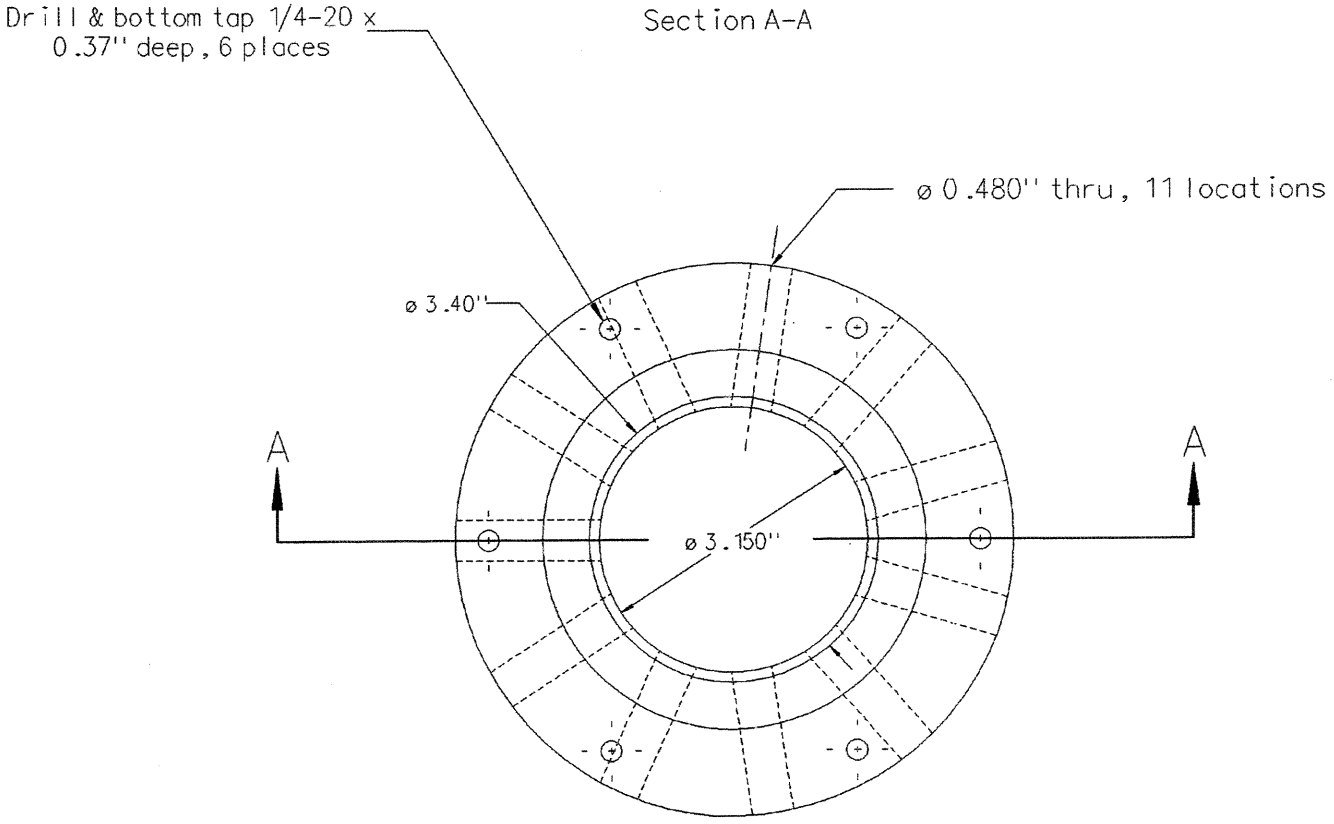


QM Collar (11, 22.5)	
Scale: 2:1	Material: SS
# holes: 11	Jet ang: 22.5°
L/D = 5	04/25/95
file: collars.cad	By: dsj

Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

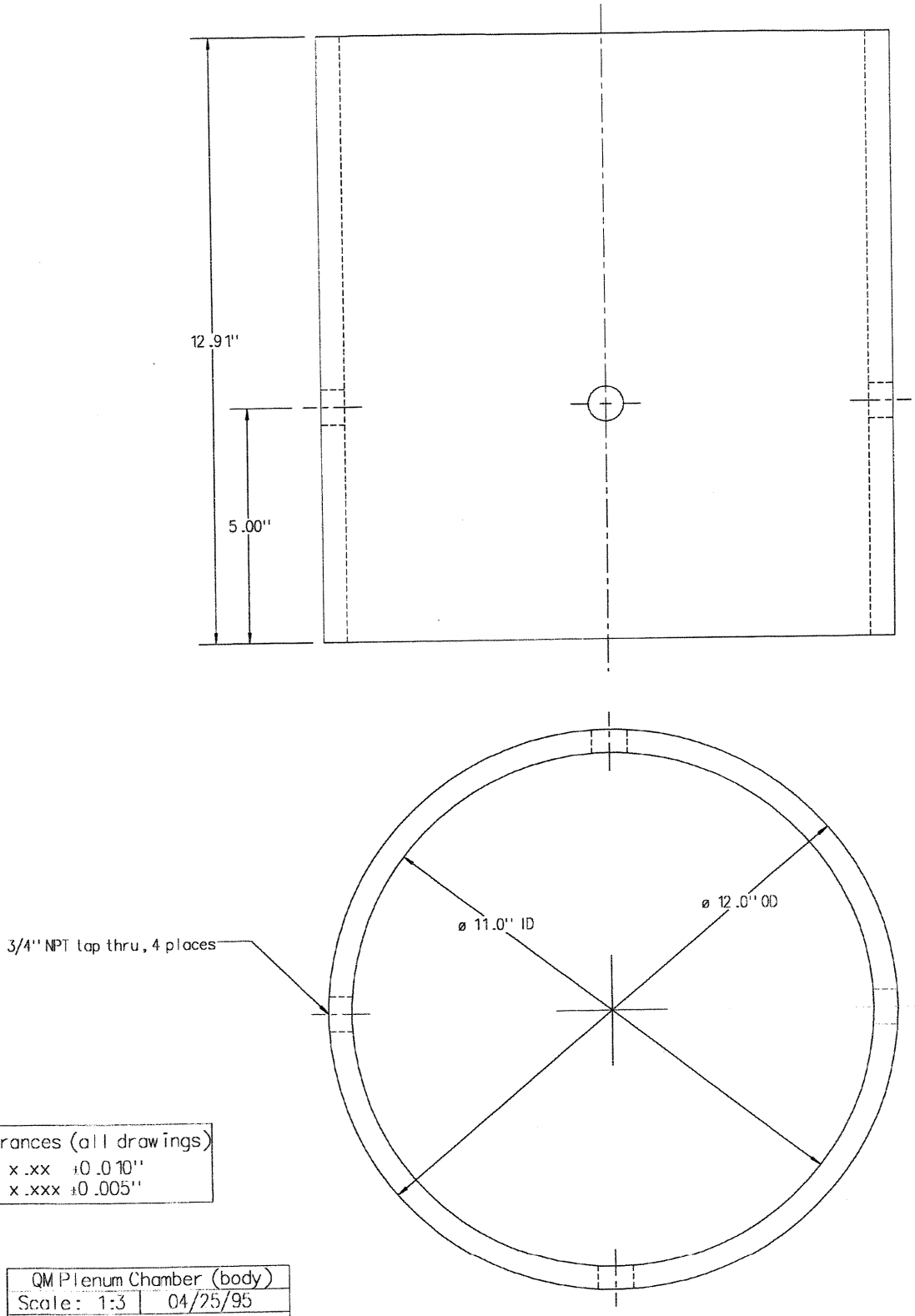


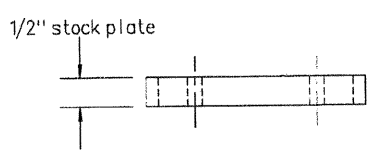
Section A-A

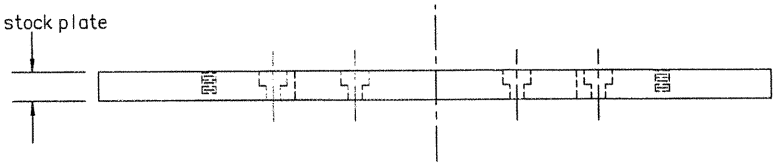


QM Collar (11, 45)	
Scale: 2:1	Material: SS
# holes: 11	Jet ang: 45°
L/D = 5	04/25/95
file: collars.cad	By: dsj

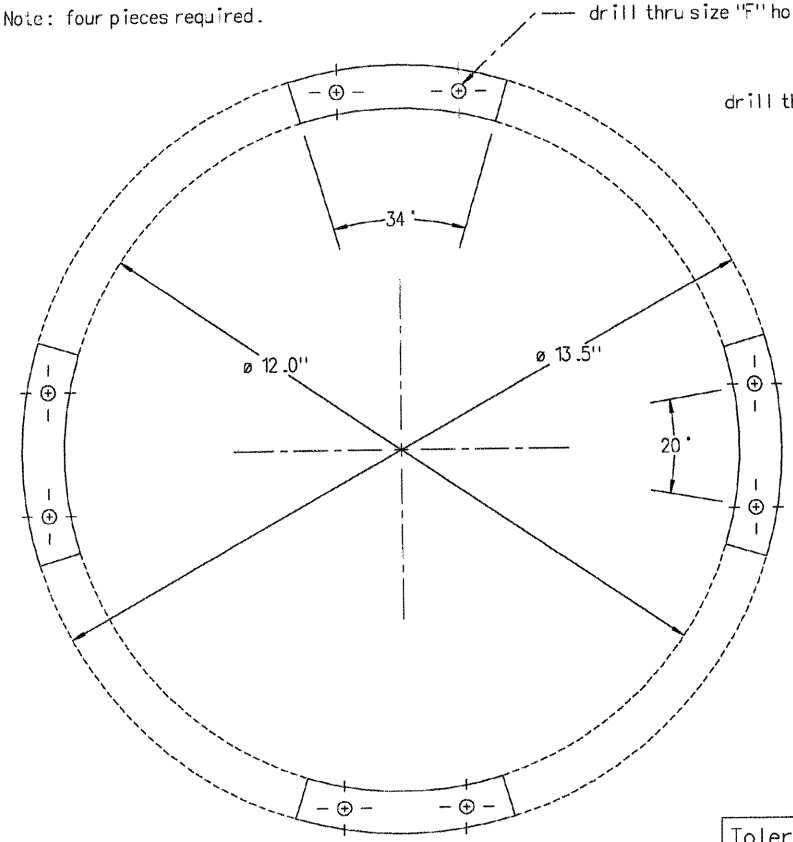
Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

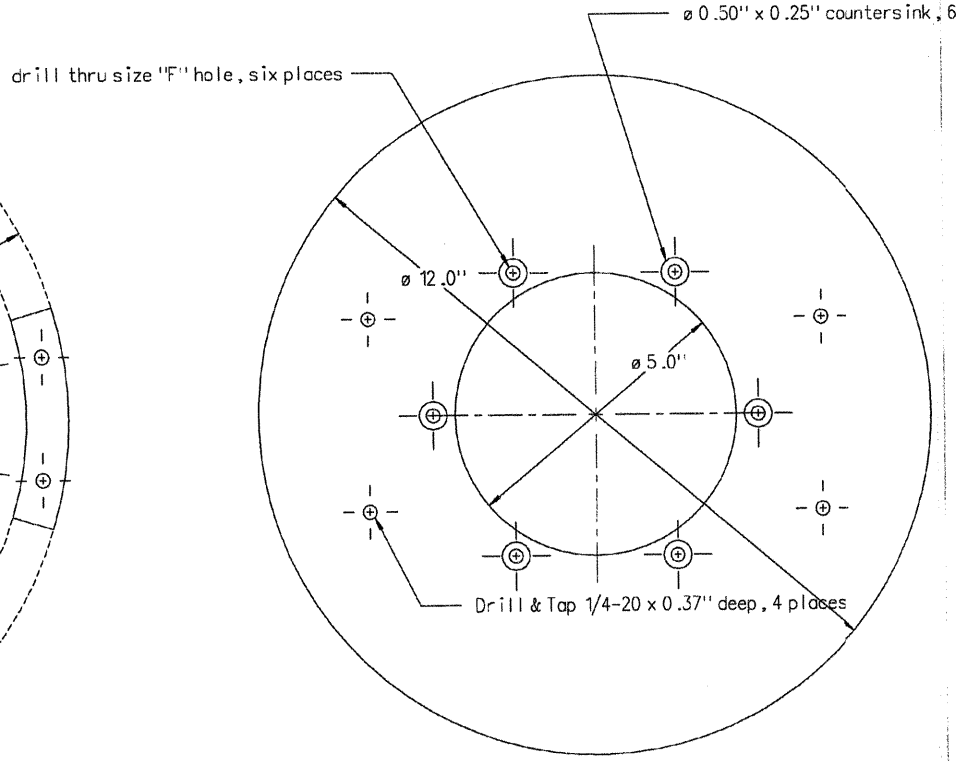

12.91"
5.00"
ø 11.0" ID
ø 12.0" OD
3/4" NPT tap thru, 4 places
Tolerances (all drawings)
x .xx ±0.010"
x .xxx ±0.005"
QM Plenum Chamber (body)
Scale: 1:3 | 04/25/95
Material: 316SS
file: pl-body.cad | By: dsj





Note: four pieces required.

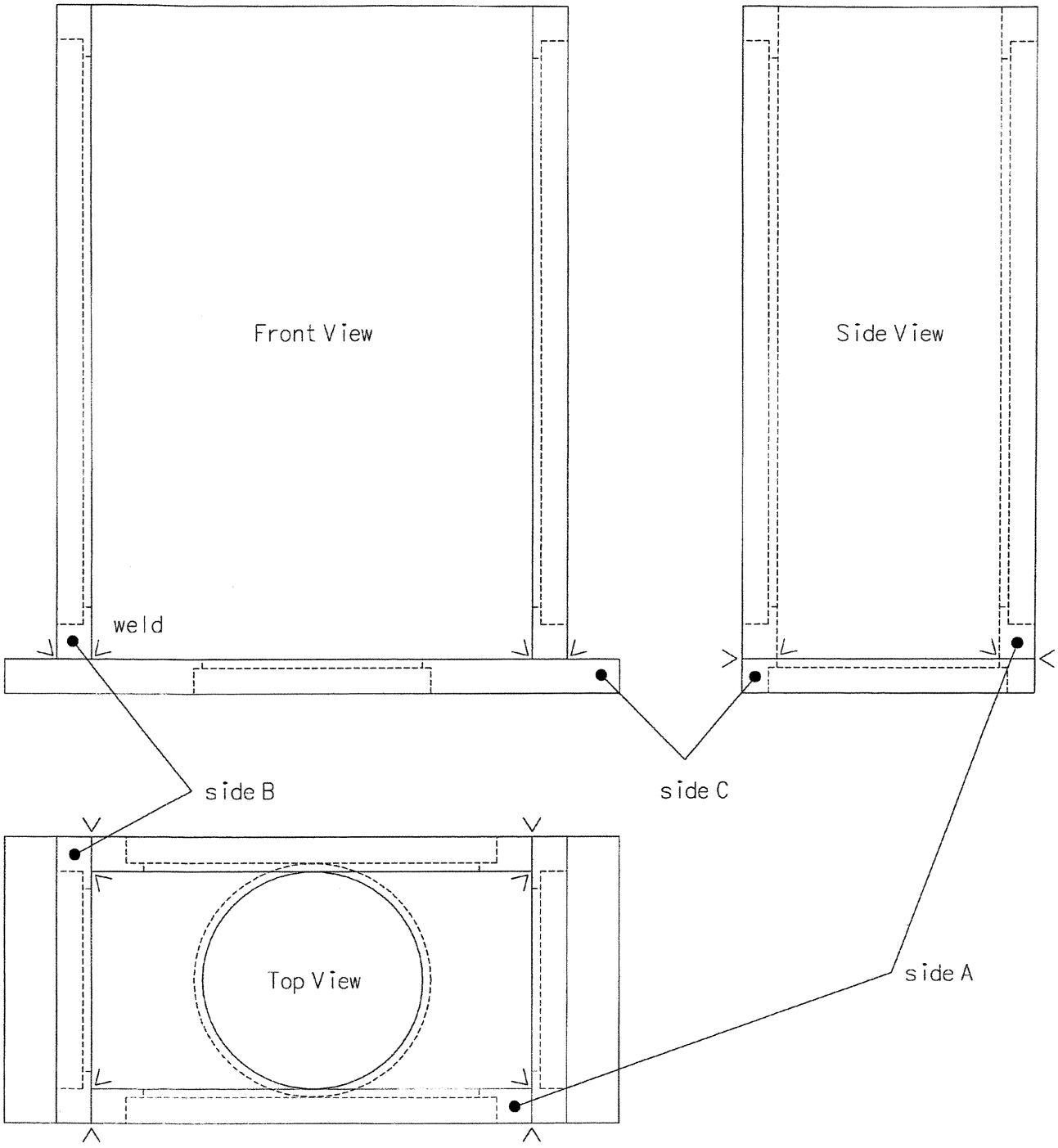




Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

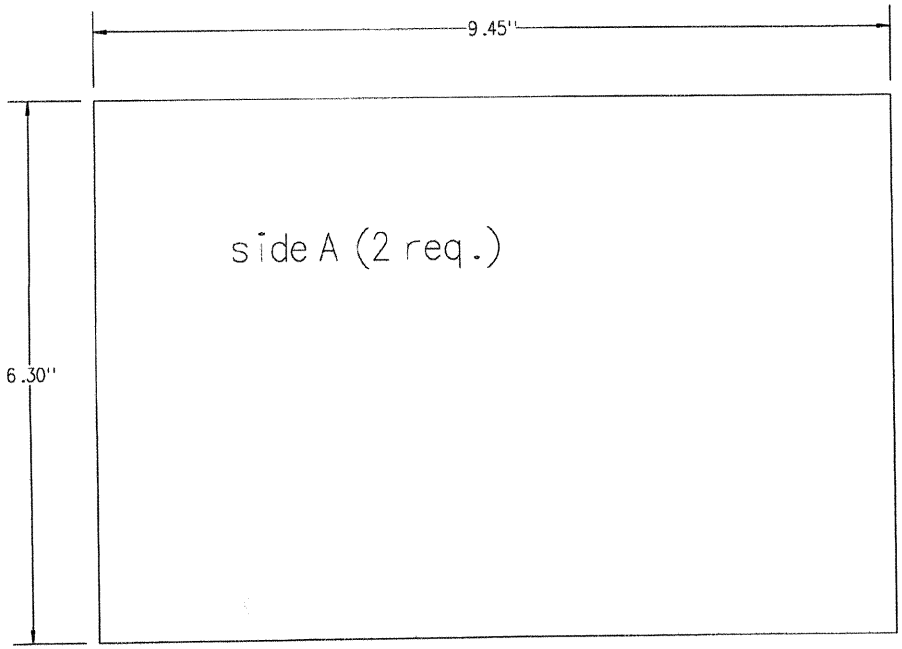
QM Plenum Chamber (flanges)	
Scale: 1:3	04/25/95
Material: 316SS	
file: pl-top.cad	By: dsj

QM Plenum Chamber (lid)	
Scale: 1:3	04/25/95
Material: 316SS	
file: pl-top.cad	By: dsj



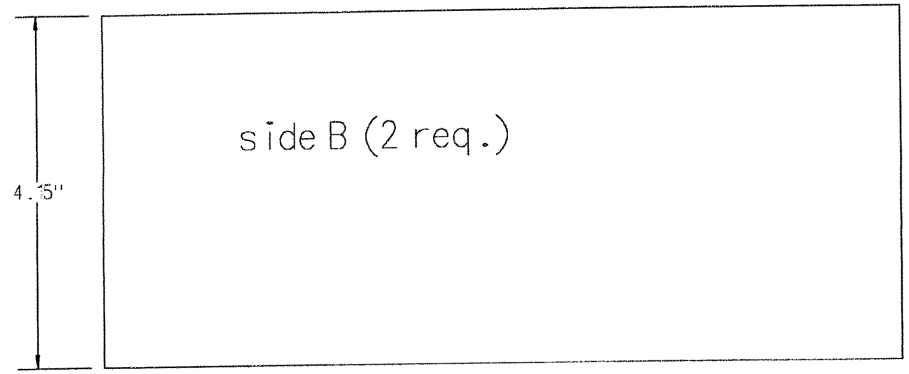
QM Expansion Box, Assembly	
Scale: 1:2	4/18/95
Material: 316SS (1/2" plate)	
file: asembly.cad	By: dsj

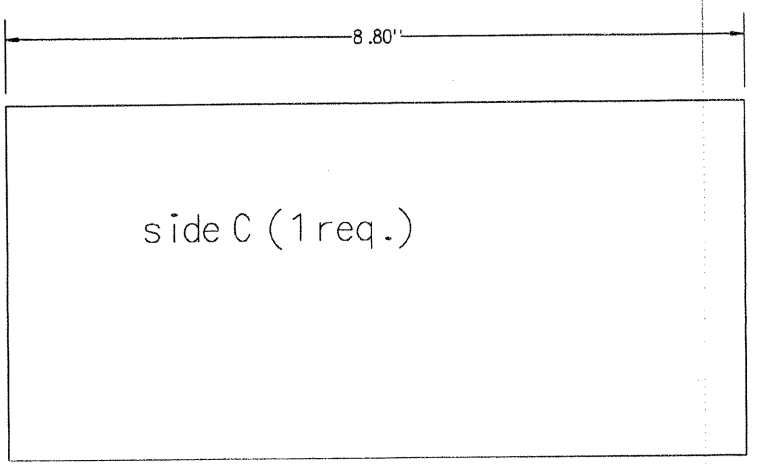
Note: For assembly orientation only
(all details not shown)

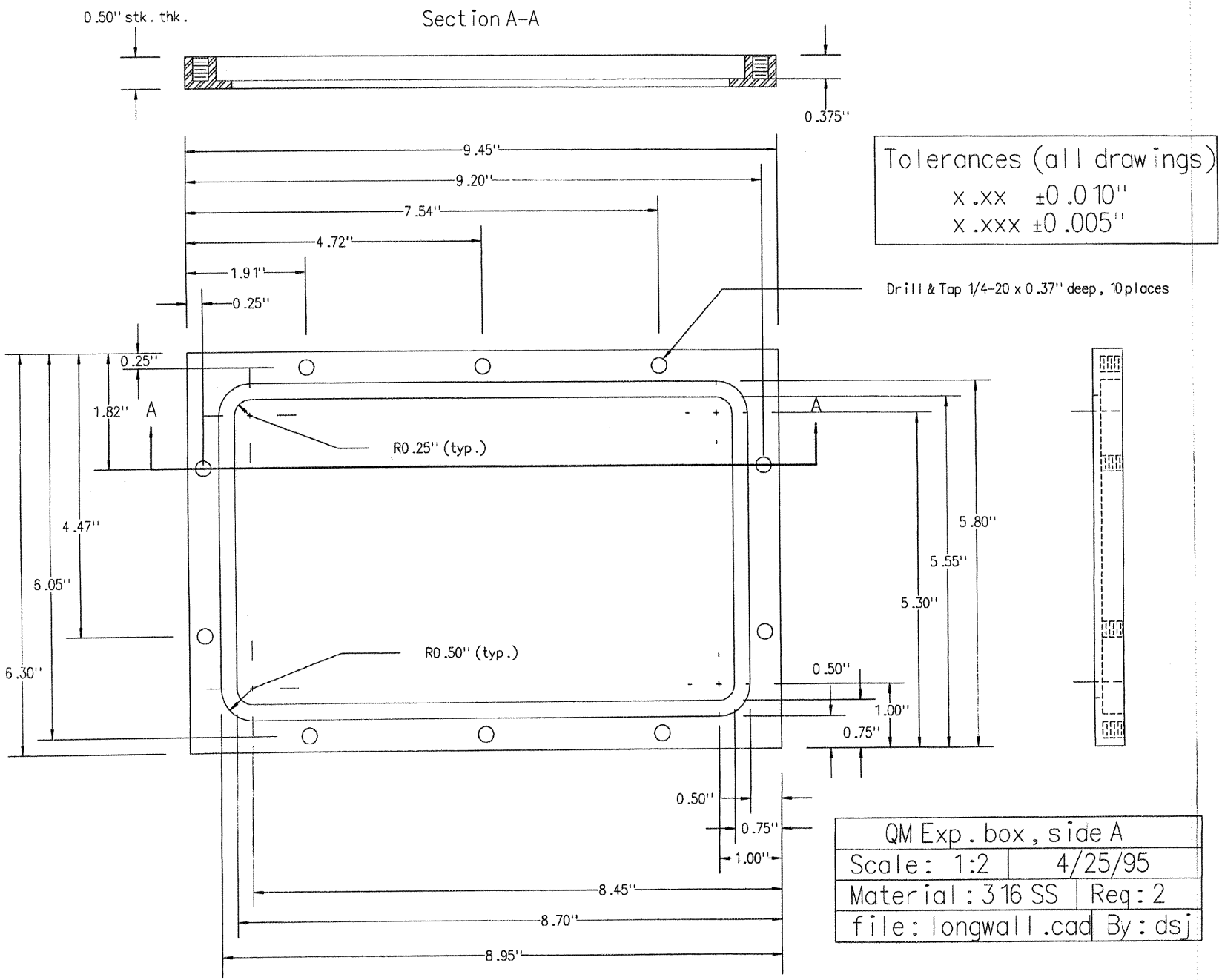


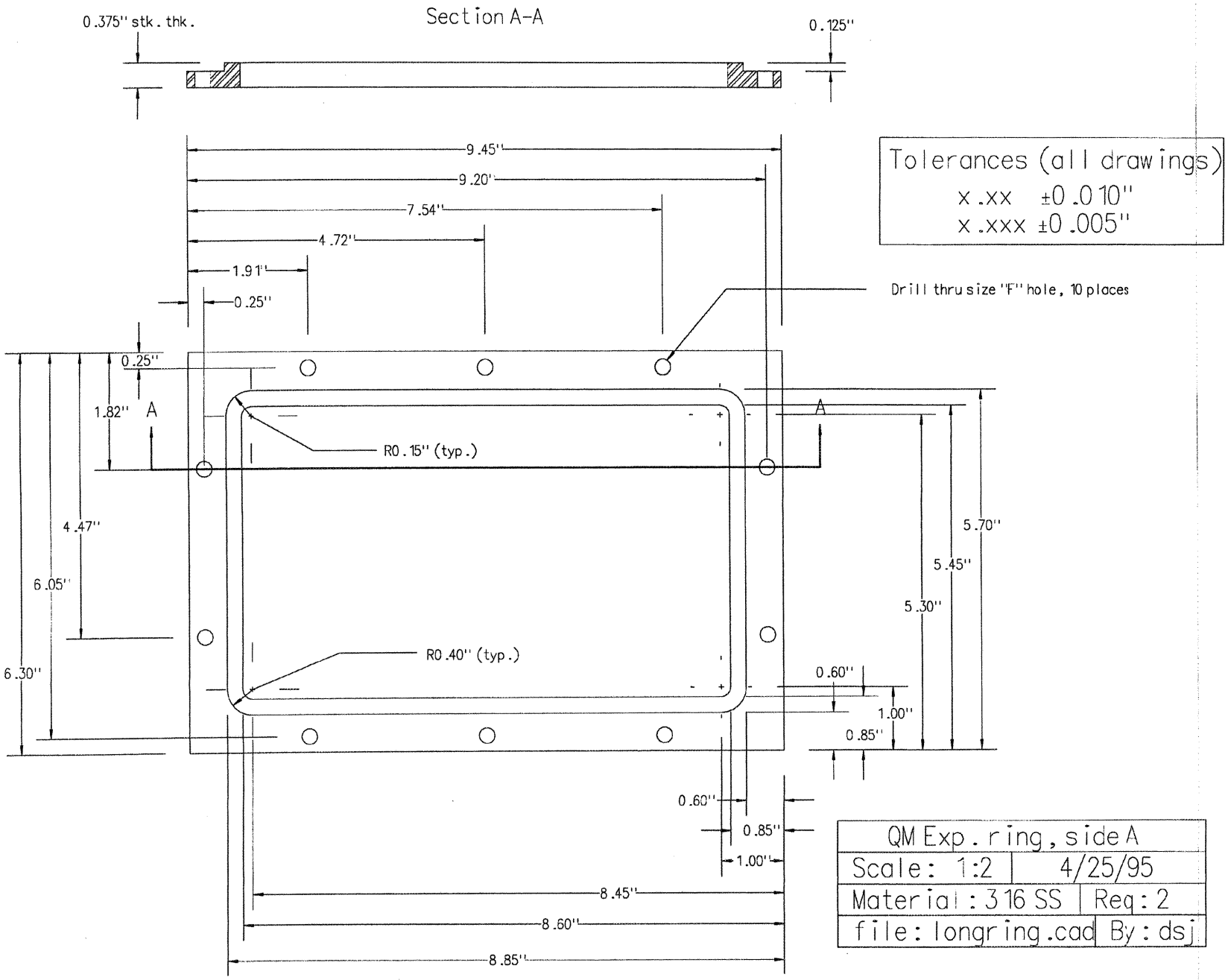
Tolerances (all drawings)
x.xx ±0.010''
x.xxx ±0.005''

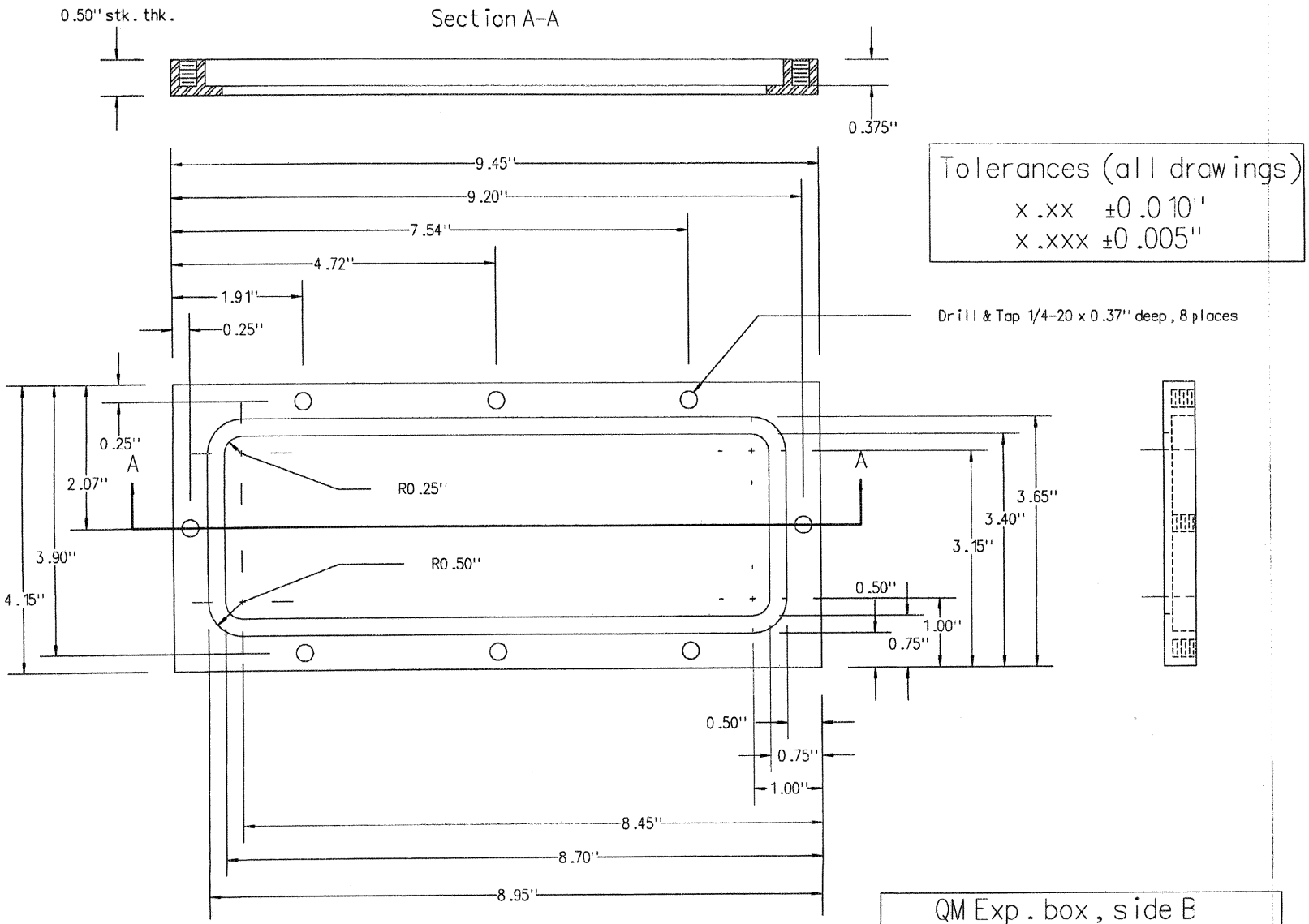
QM Expansion Box (req. stock)	
Scale: 1:2	4/18/95
Material: 316SS (1/2'' plate)	
file: stock.cad	By: dsj



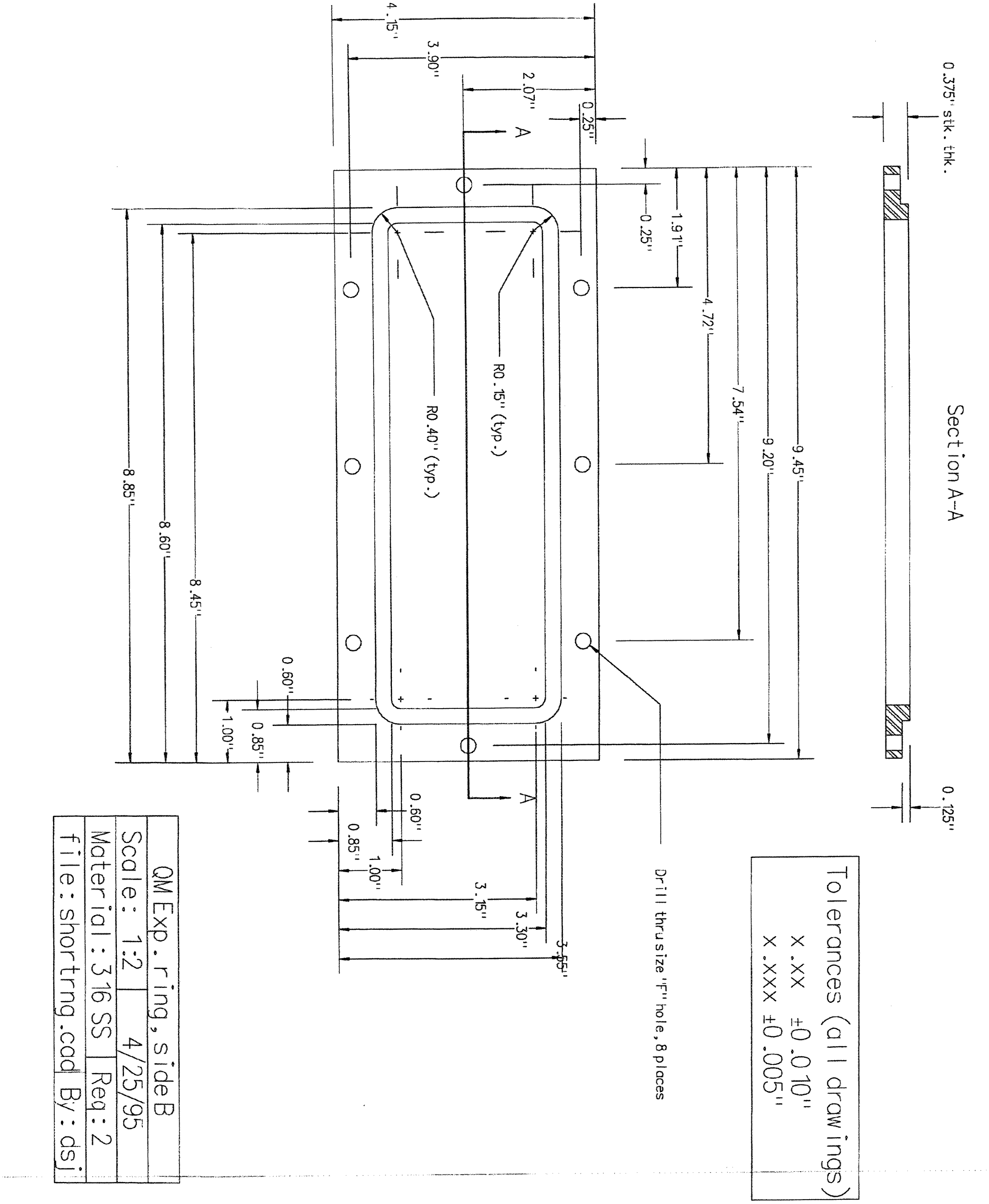



0.50" stk. thk.
Section A-A
0.375"
9.45"
9.20"
7.54"
4.72"
1.91"
0.25"
Drill & Tap 1/4-20 x 0.37" deep, 10 places
Tolerances (all drawings)
x .xx ±0.010"
x .xxx ±0.005"
0.25"
1.82"
A
R0.25" (typ.)
4.47"
6.05"
6.30"
R0.50" (typ.)
5.80"
5.55"
5.30"
0.50"
1.00"
0.75"
0.50"
0.75"
1.00"
8.45"
8.70"
8.95"
QM Exp. box, side A
Scale: 1:2
4/25/95
Material: 316 SS
Req: 2
file: longwall.cad
By: dsj

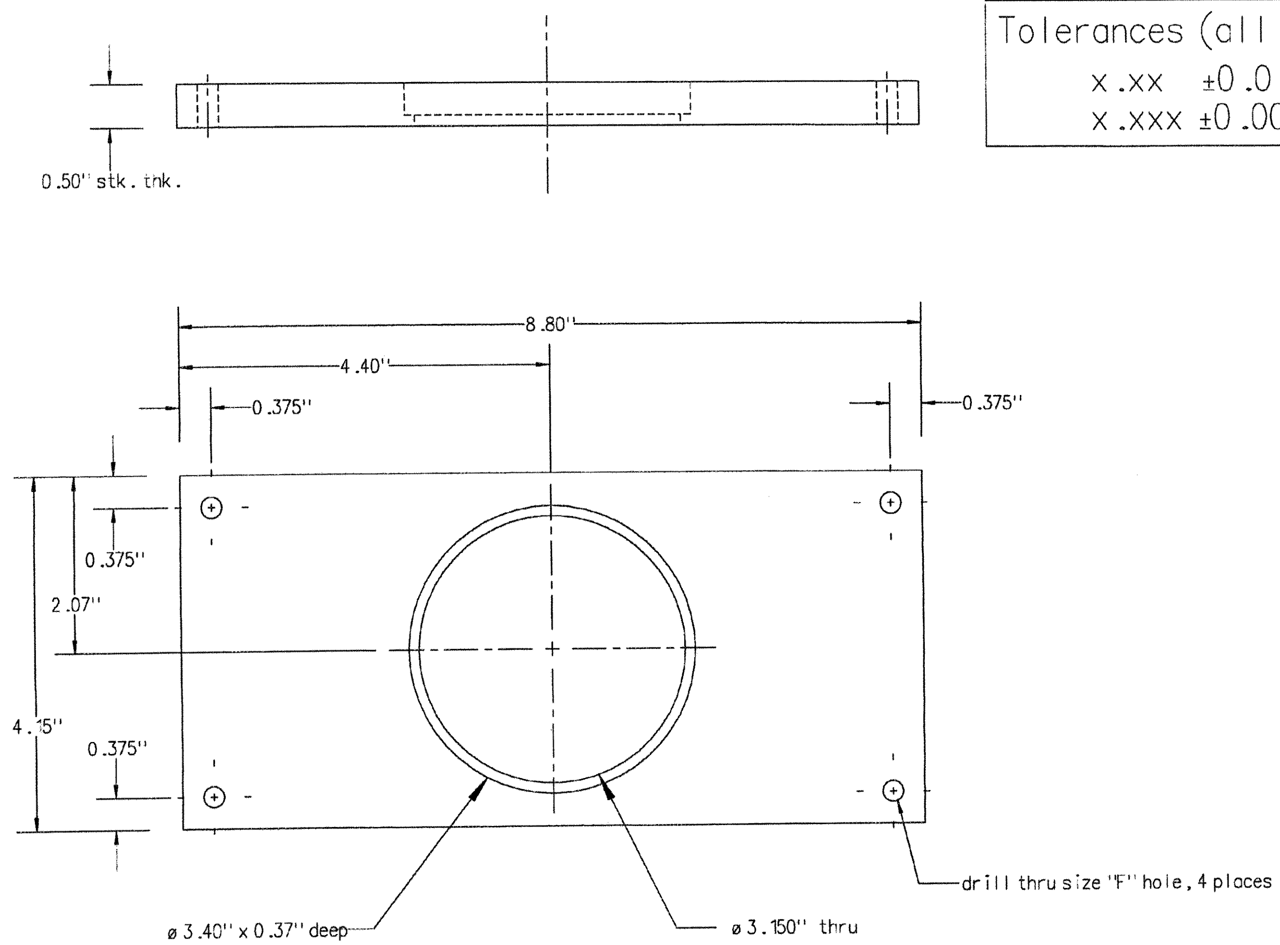

Section A-A
0.375" stk. thk.
0.125"
9.45"
9.20"
7.54"
4.72"
1.91"
0.25"
Drill thru size "F" hole, 10 places
0.25"
1.82"
A
A
R0.15" (typ.)
4.47"
6.05"
6.30"
5.70"
5.45"
5.30"
R0.40" (typ.)
0.60"
1.00"
0.85"
0.60"
0.85"
1.00"
8.45"
8.60"
8.85"
Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"
QM Exp. ring, side A
Scale: 1:2
4/25/95
Material: 316 SS
Req: 2
file: longring.cad
By: dsj



NASA/CR—2003-212316

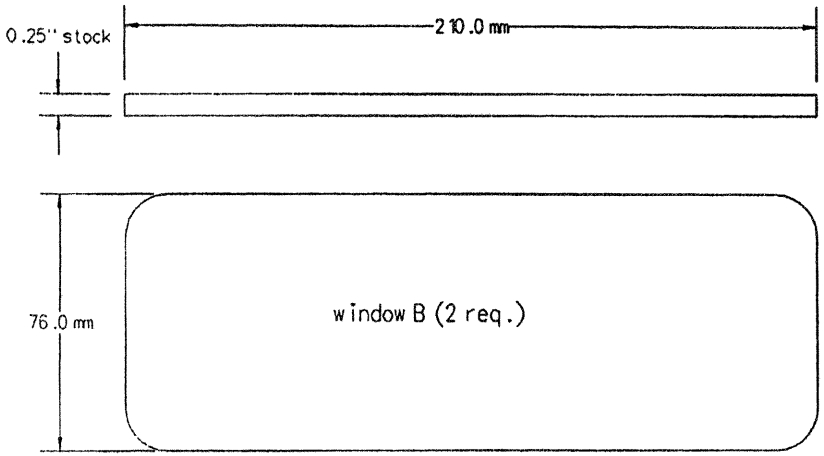


0.375" stk. thk.
Section A–A
0.125"
Tolerances (all drawings)
x .xx ±0.010"
x .xxx ±0.005"
Drill thru size "F" hole, 8 places
R0.15" (typ.)
R0.40" (typ.)
A
A
4.15"
3.90"
2.07"
0.25"
0.25"
1.91"
4.72"
7.54"
9.20"
9.45"
8.85"
8.60"
8.45"
0.60"
1.00"
0.85"
0.60"
0.85"
1.00"
3.15"
3.30"
3.55"
QM Exp. ring, side B
Scale: 1:2
4/25/95
Material: 316 SS
Req: 2
file: shortrng.cad
By: dsj



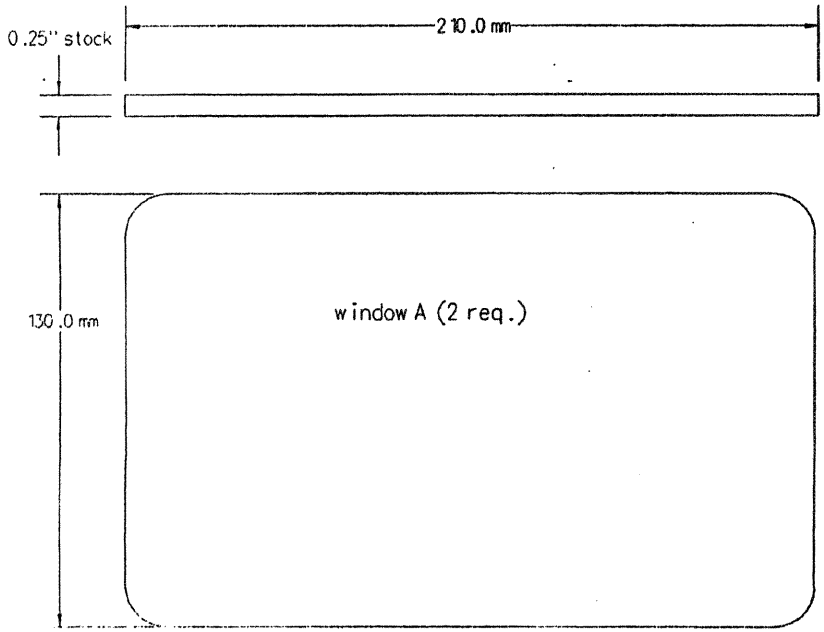
Tolerances (all drawings)
x.xx ±0.010"
x.xxx ±0.005"

QM Exp. box, side C	
Scale: 1:2	4/25/95
Material: 316SS	Req: 1
file: bottom.cad	Ey: dsj

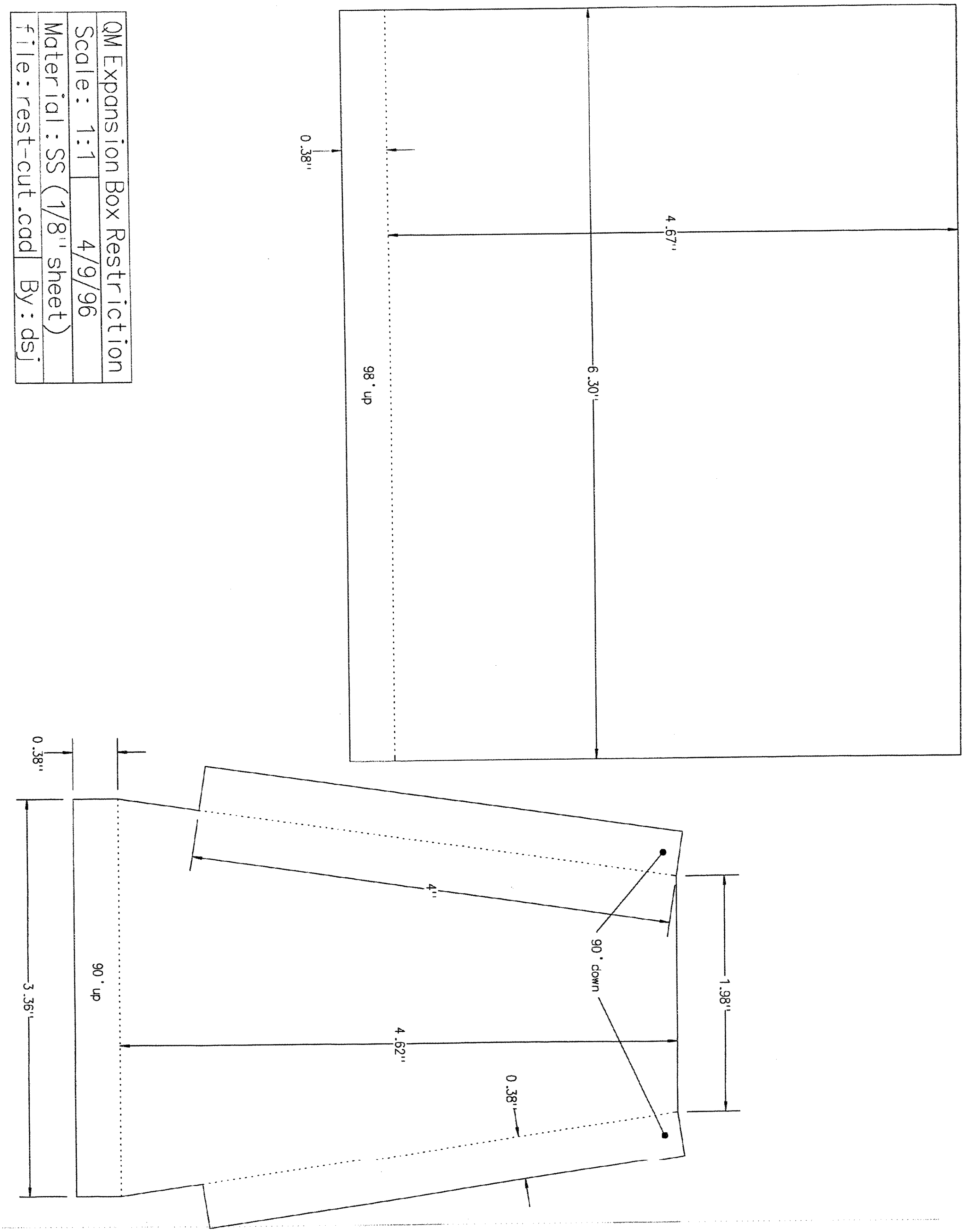


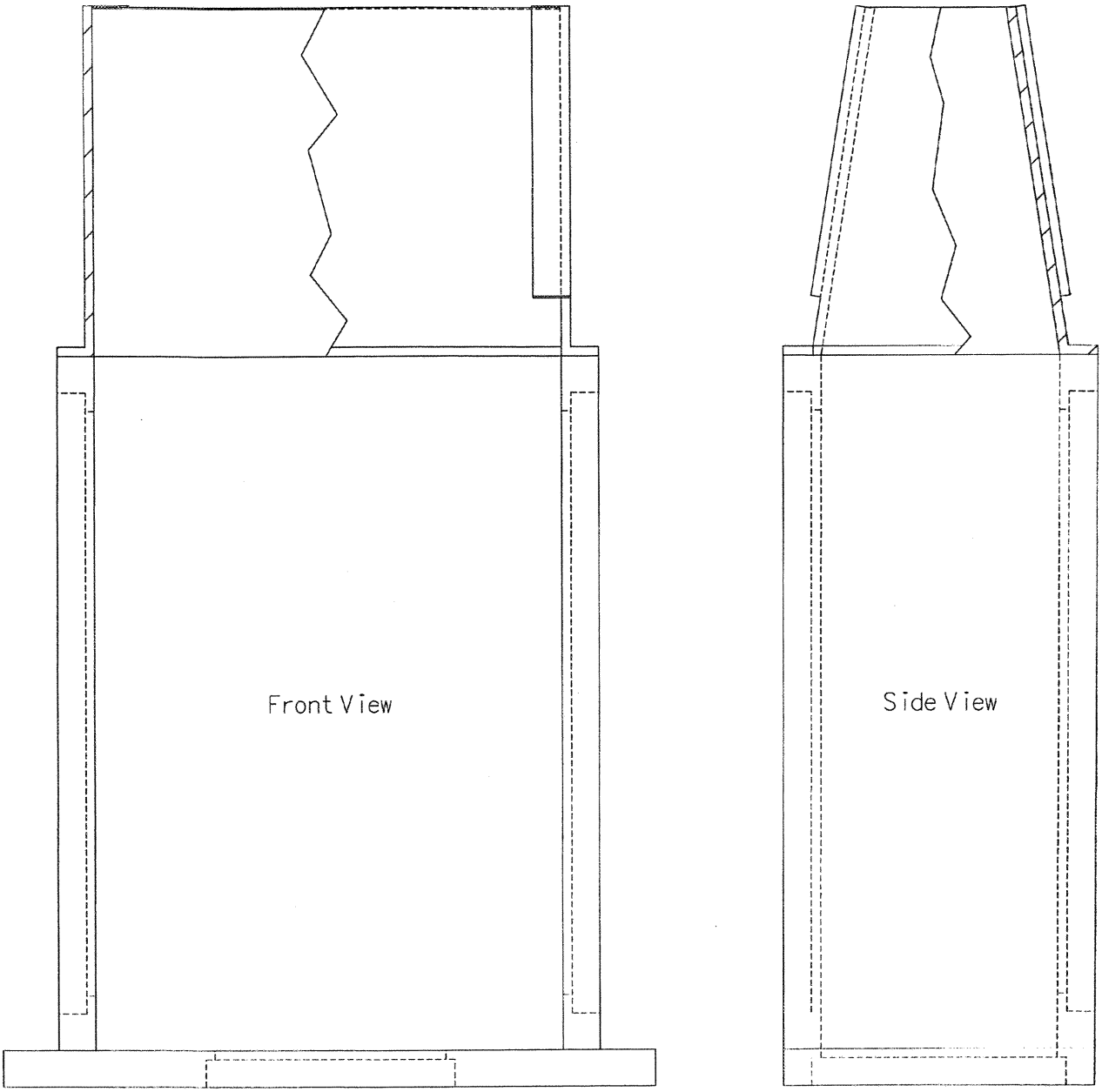
QM Expansion Box, Windows	
Scale: 1:2	4/20/95
Material: quartz (1/4" plate)	
file: windows.cad	By: dsj

tolerance: x.x ± 1mm



NASA/CR—2003-212316


QM Expansion Box Restriction
Scale: 1:1
4/9/96
Material: SS (1/8" sheet)
file: rest-cut.cad
By: dsj
0.38"
4.67"
6.30"
98° up
0.38"
3.36"
90° up
4"
90° down
1.98"
4.62"
0.38"



QM Expansion Box, Assembly	
Scale: 1:2	4/9/96
Material: 316SS (1/2" plate)	
file: rest-ass.cad	By: dsj

B. Raw Data

Case #1	Θ =	67.5°	N =	7	L =	1.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	2.44	5.83	47.3	9.27	23.9
1	2	8.7	-10.1	0.94	3.41	2.3	14.63	14.6
1	3	12.2	-5.3	0.92	3.4	1.9	14.68	14.4
1	4	13.3	0.5	0.64	2.54	1.2	16.32	11
1	5	11.8	6.2	0.71	2.75	1.7	15.91	12.3
1	6	7.9	10.7	1	3.66	2.7	14.17	15.1
1	7	17.4	-20.2	0.44	2.74	0	16.26	12.5
1	8	24.4	-10.7	0.77	5.98	0	10.86	23.5
1	9	26.6	1	0.32	2.05	0	17.41	9.4
1	10	23.6	12.5	0.54	4.93	0	12.77	19.8
1	11	15.8	21.5	0.55	4.19	0	13.92	17.2
1	12	26.1	-30.3	0.7	4.18	0	13.74	16.8
1	13	36.7	-16	0.68	4.66	0.5	13.02	18.1
1	14	40	1.5	0.36	3.33	0.4	15.4	13.8
1	15	35.4	18.7	0.75	4.9	0.9	12.55	19.1
1	16	23.8	32.2	0.52	3.55	0.1	14.92	14.3
2	1	0	0	0.62	3.69	0	14.54	14.6
2	2	9.4	9.4	0.42	2.93	0	15.97	11.6
2	3	18.9	18.9	0.34	5.07	0	12.77	19.5
2	4	28.3	28.3	0.3	4.84	0	13.17	18.4
2	5	37.7	37.7	0.08	2.76	3.2	16.6	11.6
2	6	47.1	47.1	0.034	5.23	0	12.85	20.1
2	7	56.6	56.6	0.037	4.89	0	13.36	18.9
2	8	9.4	-9.4	0.48	3.17	0	15.53	12.5
2	9	18.9	0	0.32	2.62	0	16.54	10.3
2	10	28.3	9.4	0.28	4.59	0	13.57	17.2
2	11	37.7	18.9	0.22	3.81	0	14.83	14.9
2	12	47.1	28.3	0.081	2.22	7.7	17.43	9.2
2	13	56.6	37.7	0.039	5.13	0	13	20.1
2	14	66	47.1	0.035	5.27	0	12.78	20.6
2	15	18.9	-18.9	0.37	4.55	0	13.53	17.7
2	16	28.3	-9.4	0.36	6.18	0	11	23.7
2	17	37.7	0	0.32	4.15	0	14.21	16.4
2	18	47.1	9.4	0.16	2.78	3.7	16.5	11.3
2	19	56.6	18.9	0.074	2.29	4.3	17.35	17.35
2	20	66	28.3	0.051	4.46	0.2	14.04	14.04
2	21	75.4	37.7	0.04	5.24	0	12.84	12.84
2	22	28.3	-28.3	0.37	4.63	0	13.42	13.42
2	23	37.7	-18.9	0.29	5.88	0	11.57	11.57
2	24	47.1	-9.4	0.098	5.13	0	12.93	12.93
2	25	56.6	0	0.043	4.37	0	14.18	14.18
2	26	66	9.4	0.067	2.56	2.3	16.95	16.95
2	27	75.4	18.9	0.057	3.73	0.9	15.18	15.18
2	28	84.9	28.3	0.042	4.79	0	13.54	13.54

Case #2	Θ =	90.0°	N =	9	L =	1.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	2.66	6.5	104.2	8	23.4
1	2	12.9	-3.5	1.55	5.06	36.3	11.48	18.4
1	3	13.3	1.2	1.04	4.07	17.7	13.58	14.7
1	4	12.1	5.6	0.83	3.56	11.9	14.58	12.9
1	5	9.4	9.4	0.88	3.79	11.3	14.18	13.7
1	6	5.6	12.1	0.9	3.94	8.5	13.92	14.5
1	7	25.8	-6.9	0.83	5.14	5.7	12.23	18.2
1	8	26.6	2.3	0.59	4.4	4.5	13.62	15.3
1	9	24.2	11.3	0.42	3.4	4.2	15.31	11.9
1	10	18.9	18.9	0.45	4.48	3.9	13.65	15.8
1	11	11.3	24.2	0.48	4.56	3.7	13.52	16.3
1	12	38.6	-10.4	0.5	6.52	3.8	10.53	22.6
1	13	39.8	3.5	0.68	7.56	3.9	8.77	25.8
1	14	36.3	16.9	0.42	6.11	3.3	11.23	21
1	15	28.3	28.3	0.75	8.05	3.6	7.96	28.8
1	16	16.9	36.3	0.5	6.71	3.2	10.25	23.7
2	1	0	0	0.95	5.43	3.6	11.69	19.9
2	2	9.4	9.4	0.54	4.08	1.4	14.21	14.7
2	3	18.9	18.9	0.32	4.62	0.7	13.66	16.3
2	4	28.3	28.3	0.17	6.64	0.4	10.74	22.6
2	5	37.7	37.7	0.02	6.37	0.2	11.3	22.2
2	6	47.1	47.1	0.01	6.27	0.1	11.51	21.9
2	7	56.6	56.6	0.011	6.32	0	11.45	22.4
2	8	9.4	-9.4	0.83	5.11	1.3	12.31	18.8
2	9	18.9	0	0.61	4.76	0.4	13.12	17.4
2	10	28.3	9.4	0.33	4.8	0	13.39	16.8
2	11	37.7	18.9	0.16	6.03	0	11.7	20.7
2	12	47.1	28.3	0.015	6.36	0	11.38	22.3
2	13	56.6	37.7	0.0093	6.29	0	11.49	22.5
2	14	66	47.1	0.011	6.3	0	11.49	24.4
2	15	18.9	-18.9	0.42	5.52	0	12.21	20.6
2	16	28.3	-9.4	0.37	6.31	0	11.06	23.1
2	17	37.7	0	0.24	6.41	0	11.03	23
2	18	47.1	9.4	0.052	6.36	0	11.33	23
2	19	56.6	18.9	0.0095	6.33	0	11.46	26.5
2	20	66	28.3	0.0091	6.3	0	11.5	23.8
2	21	75.4	37.7	0.011	6.27	0	11.57	23.6
2	22	28.3	-28.3	0.23	6.52	0	10.92	24
2	23	37.7	-18.9	0.16	6.98	0	10.28	28.1
2	24	47.1	-9.4	0.052	6.41	0	11.29	24
2	25	56.6	0	0.011	6.28	0	11.55	23.9
2	26	66	9.4	0.0087	6.12	0.7	11.76	23.5
2	27	75.4	18.9	0.0095	6.25	0	11.6	23.8
2	28	84.9	28.3	0.011	6.25	0	11.58	24.5

Case #3	Θ =	45.0°	N =	9	L =	1.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	12.15	5.89	1711.5	0.12	14.3
1	2	12.9	-3.5	5.6	6.99	349.9	4.42	27.1
1	3	13.3	1.2	3.3	6.03	112.3	8.17	24.5
1	4	12.1	5.6	3.29	6.26	87.7	7.82	25.5
1	5	9.4	9.4	4.38	6.98	136.1	5.61	28.1
1	6	5.6	12.1	2.67	5.96	53.7	8.73	24
1	7	25.8	-6.9	0.48	1.96	2.8	17.43	7.7
1	8	26.6	2.3	0.78	3.55	1.2	14.71	14
1	9	24.2	11.3	0.41	1.95	0.5	17.59	7.6
1	10	18.9	18.9	0.74	3.39	0	15.01	13.5
1	11	11.3	24.2	0.54	2.76	0	16.2	10.6
1	12	38.6	-10.4	0.42	4.3	0.7	13.93	16.3
1	13	39.8	3.5	0.73	5.57	0	11.59	20.9
1	14	36.3	16.9	0.42	4.06	0	14.28	16
1	15	28.3	28.3	0.53	4.48	0	13.53	18.5
1	16	16.9	36.3	0.32	4.07	0	14.4	15.6
2	1	0	0	7.23	7.46	432.1	2.14	30
2	2	9.4	9.4	1.09	4.84	7.7	12.28	19.7
2	3	18.9	18.9	0.42	4.41	1.5	13.74	17.3
2	4	28.3	28.3	0.19	5.39	0	12.47	20.2
2	5	37.7	37.7	0.067	3.62	0.1	15.38	13.9
2	6	47.1	47.1	0.034	5.22	0	12.95	19.8
2	7	56.6	56.6	0.035	5.22	0	12.95	19.9
2	8	9.4	-9.4	2.42	6.56	29.7	8.02	27.2
2	9	18.9	0	0.51	3.14	1.4	15.59	12.8
2	10	28.3	9.4	0.37	4.52	0	13.64	17.4
2	11	37.7	18.9	0.26	4.63	0	13.58	17.5
2	12	47.1	28.3	0.039	4.96	0	13.32	18.6
2	13	56.6	37.7	0.031	5.2	0	12.98	20
2	14	66	47.1	0.035	5.22	0	12.95	20.1
2	15	18.9	-18.9	0.51	4.43	0	13.65	18.3
2	16	28.3	-9.4	0.46	5.18	0	12.53	20.8
2	17	37.7	0	0.3	5.26	0	12.57	20.1
2	18	47.1	9.4	0.14	3.96	0.1	14.76	15.7
2	19	56.6	18.9	0.033	5.14	0	13.08	19.9
2	20	66	28.3	0.029	5.23	0	12.95	20.2
2	21	75.4	37.7	0.034	5.21	0	12.98	20.8
2	22	28.3	-28.3	0.4	4.81	0	13.16	19.3
2	23	37.7	-18.9	0.3	4.93	0	13.09	19.5
2	24	47.1	-9.4	0.15	5	0	13.13	19.7
2	25	56.6	0	0.033	5.16	0	13.03	20.6
2	26	66	9.4	0.026	5.15	0	13.07	20.5
2	27	75.4	18.9	0.03	5.18	0	13.02	20.8
2	28	84.9	28.3	0.031	5.21	0	12.97	20.8

Case #4	Θ =	67.5°	N =	11	L =	1.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	4.67	7.2	262.4	5.08	25.4
1	2	10.7	-8	3.97	7.18	192.8	5.85	24.5
1	3	12.5	-4.7	2.82	6.59	108.4	7.5	23.8
1	4	13.3	-1	1.84	5.51	40.5	10.24	19.7
1	5	13	2.8	1.52	4.91	23.6	11.53	17.7
1	6	11.7	6.4	1.62	5.15	24.4	11.06	18.4
1	7	21.3	-16	0.6	4.05	0.6	13.92	14.1
1	8	25	-9.3	0.6	3.66	0.4	14.51	12.6
1	9	26.6	-1.9	0.52	3.19	0.4	15.3	11.2
1	10	26.1	5.7	0.45	2.99	0.6	15.68	9.9
1	11	23.4	12.8	0.48	3.23	0.2	15.29	10.8
1	12	32	-24	0.49	5.18	0	12.33	16.9
1	13	37.5	-14	0.25	6.13	0	11.17	20.1
1	14	39.9	-2.9	0.2	5.42	0	12.3	18.2
1	15	39.1	8.5	0.29	5.88	0	11.51	19.7
1	16	35.1	19.2	0.39	5.45	0	12.05	18.5
2	1	0	0	1.98	6.92	26.1	7.94	25.4
2	2	9.4	9.4	0.76	4.42	1.6	13.13	15.8
2	3	18.9	18.9	0.36	4.15	0	14.02	14.7
2	4	28.3	28.3	0.17	6	0	11.46	20.6
2	5	37.7	37.7	0.031	5.81	0	11.9	20.4
2	6	47.1	47.1	0.014	5.79	0	11.97	20.4
2	7	56.6	56.6	0.016	5.79	0	11.98	20.6
2	8	9.4	-9.4	1.69	6.74	11.9	8.56	24.8
2	9	18.9	0	0.57	3.99	0	14.02	14.3
2	10	28.3	9.4	0.34	4.08	0	14.17	14.1
2	11	37.7	18.9	0.16	5.72	0	11.88	19.4
2	12	47.1	28.3	0.021	5.76	0.1	12.01	20.2
2	13	56.6	37.7	0.013	5.78	0	11.99	20.3
2	14	66	47.1	0.016	5.75	0	12.02	20.6
2	15	18.9	-18.9	0.51	5.54	0	11.79	19.6
2	16	28.3	-9.4	0.36	5.03	0	12.72	17.9
2	17	37.7	0	0.25	5.3	0	12.43	18.2
2	18	47.1	9.4	0.062	5.67	0	12.07	20
2	19	56.6	18.9	0.014	5.76	0	12.01	20.3
2	20	66	28.3	0.014	5.71	0	12.08	20.7
2	21	75.4	37.7	0.015	5.75	0	12.04	20.6
2	22	28.3	-28.3	0.27	5.73	0	11.77	20.2
2	23	37.7	-18.9	0.25	5.6	0	11.99	19.4
2	24	47.1	-9.4	0.071	5.67	0	12.08	20.3
2	25	56.6	0	0.018	5.72	0	12.07	20.4
2	26	66	9.4	0.015	5.65	0	12.17	20.6
2	27	75.4	18.9	0.016	5.7	0	12.09	20.5
2	28	84.9	28.3	0.019	5.66	0	12.14	20.6

Case #5	Θ =	90.0°	N =	7	L =	1.7 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	0.81	4.12	1	13.54	15.6
1	2	8.7	-10.1	0.67	3.7	0.3	14.33	13.5
1	3	12.2	-5.3	0.65	3.53	0.2	14.6	13.1
1	4	13.3	0.5	0.55	3.17	0	15.27	11.6
1	5	11.8	6.2	0.47	2.91	0	15.74	10.8
1	6	7.9	10.7	0.46	3	0	15.61	10.9
1	7	17.4	-20.2	0.44	4.47	0	13.45	16.2
1	8	24.4	-10.7	0.48	4.64	0	13.14	16.7
1	9	26.6	1	0.41	3.96	0	14.22	15.3
1	10	23.6	12.5	0.33	3.52	0	14.96	13.3
1	11	15.8	21.5	0.32	4.01	0	14.24	15
1	12	26.1	-30.3	0.5	5.06	0	12.47	19.5
1	13	36.7	-16	0.54	6.54	0	10.22	24.1
1	14	40	1.5	0.41	4.62	0	13.22	17.4
1	15	35.4	18.7	0.43	5.34	0	12.11	20
1	16	23.8	32.2	0.37	5.2	0	12.38	19.5
2	1	0	0	0.37	3.46	0	14.99	13.1
2	2	9.4	9.4	0.3	3.21	0	15.43	12.3
2	3	18.9	18.9	0.24	4.13	0	14.14	15.7
2	4	28.3	28.3	0.2	4.54	0	13.56	17.5
2	5	37.7	37.7	0.051	5.17	0	12.8	19.6
2	6	47.1	47.1	0.038	5.17	0	12.82	19.9
2	7	56.6	56.6	0.039	5.29	0	12.76	20
2	8	9.4	-9.4	0.38	3.69	0	14.63	14.2
2	9	18.9	0	0.32	3.58	0	14.38	13.7
2	10	28.3	9.4	0.25	4.39	0	13.75	16.5
2	11	37.7	18.9	0.18	5.22	0	12.58	19.9
2	12	47.1	28.3	0.054	4.07	0.6	14.44	16.6
2	13	56.6	37.7	0.036	5.12	0	12.89	20
2	14	66	47.1	0.039	5.23	0	12.73	20.2
2	15	18.9	-18.9	0.3	4.83	0	13.03	18.6
2	16	28.3	-9.4	0.27	4.88	0	12.99	18.7
2	17	37.7	0	0.24	5.02	0	12.82	19.2
2	18	47.1	9.4	0.13	5.24	0	12.61	20
2	19	56.6	18.9	0.04	5.05	0	13	19.1
2	20	66	28.3	0.03	4.91	0	13.2	19.1
2	21	75.4	37.7	0.04	5.25	0	12.7	23.9
2	22	28.3	-28.3	0.27	5.21	0	12.52	20
2	23	37.7	-18.9	0.25	5.53	0	12.06	20.3
2	24	47.1	-9.4	0.14	5.31	0	12.51	20
2	25	56.6	0	0.04	5.2	0	12.77	20
2	26	66	9.4	0.03	5.22	0	12.76	19.9
2	27	75.4	18.9	0.03	5.23	0	12.76	19.9
2	28	84.9	28.3	0.03	5.26	0	12.69	19.9

Case #6	Θ =	90.0°	N =	11	L =	1.7 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	1.9	6.78	21.8	8.39	25.6
1	2	10.7	-8	1.01	5.21	2.8	11.83	19.4
1	3	12.5	-4.7	0.91	4.93	2.1	12.38	18.3
1	4	13.3	-1	0.79	4.49	1.3	13.2	16.8
1	5	13	2.8	0.68	4.07	1.1	13.96	15.1
1	6	11.7	6.4	0.66	3.96	1	14.15	14.7
1	7	21.3	-16	0.43	4.53	0.4	13.57	16.1
1	8	25	-9.3	0.44	4.66	0.3	13.37	16.6
1	9	26.6	-1.9	0.47	4.28	0.3	13.9	15.9
1	10	26.1	5.7	0.42	3.74	0.5	14.77	13.6
1	11	23.4	12.8	0.39	3.54	0.4	15.1	13.2
1	12	32	-24	0.21	6.28	0.2	11.15	20.6
1	13	37.5	-14	0.095	5.75	0.2	12.09	20.1
1	14	39.9	-2.9	0.062	5.6	0.2	12.33	19.1
1	15	39.1	8.5	0.1	5.63	0.2	12.25	19.1
1	16	35.1	19.2	0.13	5.84	0.2	11.88	19.8
2	1	0	0	0.8	6	1.3	10.84	21.4
2	2	9.4	9.4	0.45	4.26	0.4	13.88	15.2
2	3	18.9	18.9	0.31	4.08	0.3	14.33	14.5
2	4	28.3	28.3	0.14	5.54	0.2	12.3	18.8
2	5	37.7	37.7	0.022	5.62	0.2	12.31	19.4
2	6	47.1	47.1	0.017	5.6	0.1	12.34	19.6
2	7	56.6	56.6	0.021	5.56	0.2	12.4	20.3
2	8	9.4	-9.4	0.58	5.25	0.5	12.21	18.8
2	9	18.9	0	0.44	4.37	0.3	13.71	15.4
2	10	28.3	9.4	0.3	4.18	0.3	14.15	14.6
2	11	37.7	18.9	0.13	5.46	0.2	12.42	18.4
2	12	47.1	28.3	0.023	5.58	0.1	12.37	19.6
2	13	56.6	37.7	0.018	5.57	0.1	12.4	20.1
2	14	66	47.1	0.022	5.52	0.1	12.47	20.6
2	15	18.9	-18.9	0.28	5.28	0.2	12.53	18.2
2	16	28.3	-9.4	0.26	5.3	0.2	12.52	18.2
2	17	37.7	0	0.2	5.29	0.2	12.59	18.2
2	18	47.1	9.4	0.062	5.54	0.2	12.41	19.6
2	19	56.6	18.9	0.017	5.57	0.2	12.4	20.4
2	20	66	28.3	0.017	5.57	0.2	12.41	20.5
2	21	75.4	37.7	0.021	5.55	0.2	12.43	20.7
2	22	28.3	-28.3	0.12	5.84	0.3	11.89	20.2
2	23	37.7	-18.9	0.12	6	0.3	11.64	21.4
2	24	47.1	-9.4	0.064	5.62	0.2	12.27	20.1
2	25	56.6	0	0.017	5.51	0.4	12.48	20.4
2	26	66	9.4	0.014	5.41	0.7	12.64	20.2
2	27	75.4	18.9	0.017	5.54	0.2	12.45	20.7
2	28	84.9	28.3	0.02	5.51	0.2	12.48	21.1

Case #7	Θ =	45.0°	N =	7	L =	1.7 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	3.75	7.19	158.4	6.14	27.1
1	2	8.7	-10.1	1	4.12	7.3	13.57	15.7
1	3	12.2	-5.3	0.75	3.45	3	14.86	12.5
1	4	13.3	0.5	0.65	3.19	2.3	15.34	11.6
1	5	11.8	6.2	0.72	3.35	2.8	15.02	12
1	6	7.9	10.7	0.72	3.38	2.3	14.97	12.3
1	7	17.4	-20.2	0.34	2.19	0.3	17.16	7.9
1	8	24.4	-10.7	0.9	6.77	0	9.68	24.1
1	9	26.6	1	0.41	2.64	0.5	16.43	9.8
1	10	23.6	12.5	0.79	6.57	0	10.11	25
1	11	15.8	21.5	0.56	4.08	0	14.13	15.4
1	12	26.1	-30.3	0.44	3.63	0	14.93	13.1
1	13	36.7	-16	0.75	5.98	0	11.06	21.6
1	14	40	1.5	0.44	3.27	0.5	15.48	12.4
1	15	35.4	18.7	0.55	5.96	0	11.32	21.8
1	16	23.8	32.2	0.42	3.96	0	14.46	14.7
2	1	0	0	0.94	5.16	1.8	12.03	19.7
2	2	9.4	9.4	0.37	3.05	0.1	15.87	11.5
2	3	18.9	18.9	0.32	4.52	0	13.74	17.5
2	4	28.3	28.3	0.24	3.68	0.9	15.11	14.2
2	5	37.7	37.7	0.072	2.3	8.5	17.33	9.2
2	6	47.1	47.1	0.053	5.15	0	13.12	19.5
2	7	56.6	56.6	0.056	5.16	0	13.11	19.7
2	8	9.4	-9.4	0.47	3.38	0	15.29	12.6
2	9	18.9	0	0.31	2.9	0	16.18	11.5
2	10	28.3	9.4	0.26	5.83	0	11.83	21.3
2	11	37.7	18.9	0.18	3.63	1.4	15.27	14.8
2	12	47.1	28.3	0.066	1.73	11.2	18.22	7.3
2	13	56.6	37.7	0.058	5.15	0	13.11	19
2	14	66	47.1	0.057	5.18	0	13.08	19.6
2	15	18.9	-18.9	0.32	4.14	0	14.35	15.3
2	16	28.3	-9.4	0.29	6	0	11.55	21.6
2	17	37.7	0	0.32	4.99	0	13.07	19.1
2	18	47.1	9.4	0.14	3.32	2.4	15.77	13.5
2	19	56.6	18.9	0.065	1.87	8.4	18.02	8.2
2	20	66	28.3	0.061	5	0	13.33	18.1
2	21	75.4	37.7	0.062	5.13	0	13.15	20.2
2	22	28.3	-28.3	0.34	4.18	0	14.29	16.2
2	23	37.7	-18.9	0.34	4.68	0	13.51	18.2
2	24	47.1	-9.4	0.14	4.76	0	13.58	19.1
2	25	56.6	0	0.045	5.11	0	13.19	20.2
2	26	66	9.4	0.042	5.1	0	13.22	20.4
2	27	75.4	18.9	0.045	5.09	0	13.23	20.6
2	28	84.9	28.3	0.057	5.08	0	13.23	20.5

Case #8	Θ =	45.0°	N =	11	L =	1.7 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	7.86	7.41	679.7	1.62	29
1	2	10.7	-8	4.83	7.61	248.3	4.13	30.7
1	3	12.5	-4.7	4.19	7.5	182.4	4.87	30.8
1	4	13.3	-1	2.75	6.87	79.9	7.1	27.7
1	5	13	2.8	2.1	6.22	39.3	8.88	25.3
1	6	11.7	6.4	2.18	6.5	36.8	8.36	26
1	7	21.3	-16	0.53	3.59	2.3	14.81	14.2
1	8	25	-9.3	0.53	4.18	0.4	13.9	16.3
1	9	26.6	-1.9	0.48	3.5	0.2	14.99	13.8
1	10	26.1	5.7	0.4	3.37	0.2	15.28	12.9
1	11	23.4	12.8	0.41	3.18	0.1	15.55	12.3
1	12	32	-24	0.46	4.22	0.2	13.9	16.3
1	13	37.5	-14	0.33	5.1	0	12.66	19.2
1	14	39.9	-2.9	0.3	4.6	0	13.48	17.5
1	15	39.1	8.5	0.35	4.82	0	13.1	18.1
1	16	35.1	19.2	0.36	4.96	0	12.88	18.7
2	1	0	0	3.83	7.9	102.1	4.68	31.6
2	2	9.4	9.4	1.32	6.26	6.9	9.71	25.4
2	3	18.9	18.9	0.35	3.92	0.4	14.46	15.1
2	4	28.3	28.3	0.21	5.17	0	12.71	19.3
2	5	37.7	37.7	0.041	5.23	0	12.82	19.4
2	6	47.1	47.1	0.031	5.21	0	12.88	19.5
2	7	56.6	56.6	0.037	5.2	0	12.9	19.9
2	8	9.4	-9.4	2.09	7.24	21.6	7.29	29.1
2	9	18.9	0	0.77	5.02	1.1	12.28	20.3
2	10	28.3	9.4	0.31	3.94	0	14.52	15
2	11	37.7	18.9	0.18	5.2	0	12.7	19.3
2	12	47.1	28.3	0.036	5.21	0	12.86	19.6
2	13	56.6	37.7	0.03	5.23	0	12.85	20
2	14	66	47.1	0.035	5.24	0	12.84	20.2
2	15	18.9	-18.9	0.44	5.02	0	12.71	19.5
2	16	28.3	-9.4	0.31	5.14	0	12.66	19.8
2	17	37.7	0	0.26	50.9	0	12.8	19.6
2	18	47.1	9.4	0.083	5.17	0	12.89	19.7
2	19	56.6	18.9	0.029	5.24	0	12.84	20.6
2	20	66	28.3	0.029	5.24	0	12.85	20.4
2	21	75.4	37.7	0.033	5.26	0	12.83	20.3
2	22	28.3	-28.3	0.31	4.98	0	12.93	19.4
2	23	37.7	-18.9	0.29	4.93	0	13.02	19.2
2	24	47.1	-9.4	0.11	5.13	0	12.93	19.8
2	25	56.6	0	0.029	5.22	0	12.88	20.5
2	26	66	9.4	0.024	5.23	0	12.88	20.3
2	27	75.4	18.9	0.029	5.24	0	12.87	20.5
2	28	84.9	28.3	0.032	5.25	0	12.85	20.5

Case #9	Θ =	67.5°	N =	9	L =	1.7 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	1.77	6.25	18.1	9.53	24.1
1	2	12.9	-3.5	1.47	5.96	9.9	10.34	22.5
1	3	13.3	1.2	0.86	4.53	1.9	13.26	16.8
1	4	12.1	5.6	0.54	3.28	0.1	15.51	12.7
1	5	9.4	9.4	0.47	2.94	0	16.1	11.4
1	6	5.6	12.1	0.53	3.28	0	15.5	12.8
1	7	25.8	-6.9	0.6	5.3	0	12.4	20.5
1	8	26.6	2.3	0.45	4.76	0	13.36	17.7
1	9	24.2	11.3	0.35	3.96	0	14.68	14.6
1	10	18.9	18.9	0.33	4.31	0	14.18	15.9
1	11	11.3	24.2	0.34	4.61	0	13.7	17.4
1	12	38.6	-10.4	0.45	5.14	0	12.78	18.7
1	13	39.8	3.5	0.41	6.49	0	10.76	23.1
1	14	36.3	16.9	0.38	5.49	0	12.32	20.3
1	15	28.3	28.3	0.33	6.75	0	10.43	24.6
1	16	16.9	36.3	0.36	6.08	0	11.43	23
2	1	0	0	0.77	5.42	0.1	11.92	20.7
2	2	9.4	9.4	0.4	3.59	0	15.15	13.5
2	3	18.9	18.9	0.28	3.98	0	14.72	15
2	4	28.3	28.3	0.18	5.87	0	11.97	21.5
2	5	37.7	37.7	0.027	5.95	0	12.02	22.1
2	6	47.1	47.1	0.013	5.97	0	12.02	22.5
2	7	56.6	56.6	0.015	5.96	0	12.04	22.8
2	8	9.4	-9.4	0.77	5.43	0	11.92	20.9
2	9	18.9	0	0.51	4.69	0	13.35	17.8
2	10	28.3	9.4	0.28	4.63	0	13.73	17.2
2	11	37.7	18.9	0.18	5.56	0	12.43	20.2
2	12	47.1	28.3	0.019	5.93	0	12.07	22.3
2	13	56.6	37.7	0.013	5.95	0	11.98	23.2
2	14	66	47.1	0.015	5.95	0	11.97	23.9
2	15	18.9	-18.9	0.36	5.69	0	11.9	22.4
2	16	28.3	-9.4	0.29	6.2	0	11.17	23.6
2	17	37.7	0	0.24	5.76	0	11.86	21.9
2	18	47.1	9.4	0.055	5.85	0	12.09	22.4
2	19	56.6	18.9	0.013	5.93	0	12.25	23.1
2	20	66	28.3	0.013	5.93	0	12.29	23.2
2	21	75.4	37.7	0.016	5.92	0	12.29	23.4
2	22	28.3	-28.3	0.21	6.02	0	11.86	23.3
2	23	37.7	-18.9	0.19	6.18	0	11.64	23.5
2	24	47.1	-9.4	0.068	5.8	0	12.35	22.5
2	25	56.6	0	0.015	5.9	0	12.29	23.2
2	26	66	9.4	0.013	5.91	0	12.29	23.3
2	27	75.4	18.9	0.015	5.91	0	12.29	23.3
2	28	64.9	28.3	0.015	5.91	0	12.28	23.5

Case #10	Θ =	67.5°	N =	7	L =	2.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	0.51	3.5	0	14.97	13.5
1	2	8.7	-10.1	0.47	3.41	0	15.15	13.2
1	3	12.2	-5.3	0.39	2.89	0	16.04	11.1
1	4	13.3	0.5	0.34	2.58	0	16.57	10
1	5	11.8	6.2	0.35	2.76	0	16.3	10.7
1	6	7.9	10.7	0.38	3.23	0	15.53	12.7
1	7	17.4	-20.2	0.33	4.9	0	13.01	18.8
1	8	24.4	-10.7	0.31	4.95	0	12.94	18.7
1	9	26.6	1	0.28	3.75	0	14.87	14.3
1	10	23.6	12.5	0.27	4.64	0	13.48	17.8
1	11	15.8	21.5	0.33	6.24	0	10.9	24.4
1	12	26.1	-30.3	0.37	4.12	0	14.18	16.1
1	13	36.7	-16	0.28	5.28	0	12.46	20.2
1	14	40	1.5	0.21	3.19	2.1	15.79	12.4
1	15	35.4	18.7	0.26	4.11	0.7	14.32	15.7
1	16	23.8	32.2	0.32	5.19	0	12.58	20.3
2	1	0	0	0.3	3.05	0	15.87	11.9
2	2	9.4	9.4	0.26	3.44	0	15.35	13.4
2	3	18.9	18.9	0.19	5.71	0	11.9	22.4
2	4	28.3	28.3	0.17	4.58	0	13.69	18.1
2	5	37.7	37.7	0.046	4.22	1.2	14.29	16.4
2	6	47.1	47.1	0.038	5.2	0	12.87	20.3
2	7	56.6	56.6	0.041	5.18	0	12.9	20.5
2	8	9.4	-9.4	0.29	3.3	0	15.51	13
2	9	18.9	0	0.25	3.54	0	15.2	13.8
2	10	28.3	9.4	0.2	4.84	0	13.22	18.7
2	11	37.7	18.9	0.14	4.1	1	14.43	15.8
2	12	47.1	28.3	0.044	1.55	8.7	18.48	6.2
2	13	56.6	37.7	0.042	5.18	0	12.9	20.2
2	14	66	47.1	0.042	5.18	0	12.89	20.4
2	15	18.9	-18.9	0.23	4.98	0	13	19.4
2	16	28.3	-9.4	0.21	5.21	0	12.65	20.1
2	17	37.7	0	0.21	4.19	0	14.26	16.4
2	18	47.1	9.4	0.068	1.79	9.6	18.1	7.2
2	19	56.6	18.9	0.039	1.29	12.5	18.91	5.1
2	20	66	28.3	0.046	5.15	0	12.94	20.2
2	21	75.4	37.7	0.045	5.1	0	13.03	20.1
2	22	28.3	47.1	0.26	4.7	0	13.42	18.4
2	23	37.7	-18.9	0.22	4.94	0	13.07	19.4
2	24	47.1	-9.4	0.067	5.07	0	13.05	20
2	25	56.6	0	0.052	2.69	5.8	16.76	11
2	26	66	9.4	0.04	1.49	9.2	18.6	6.2
2	27	75.4	18.9	0.044	1.67	7	18.34	6.6
2	28	84.9	28.3	0.046	5.16	0	12.95	20.3

Case #11	Θ =	90.0°	N =	9	L =	2.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	0.79	5.47	0.2	11.75	20.6
1	2	12.9	-3.5	0.62	4.96	0	12.75	18.4
1	3	13.3	1.2	0.53	4.53	0	13.55	16.9
1	4	12.1	5.6	0.48	4.25	0	14.06	15.6
1	5	9.4	9.4	0.48	4.3	0	13.99	15.7
1	6	5.6	12.1	0.51	4.51	0	13.65	16.5
1	7	25.8	-6.9	0.37	5.62	0	12.11	21.3
1	8	26.6	2.3	0.34	4.62	0	13.66	19.9
1	9	24.2	11.3	0.3	4.18	0	14.38	16.5
1	10	18.9	18.9	0.26	4.49	0	13.94	18.1
1	11	11.3	24.2	0.3	4.88	0	13.33	18
1	12	38.6	-10.4	0.094	5.73	0	12.26	20.8
1	13	39.8	3.5	0.12	5.56	0	12.46	20.1
1	14	36.3	16.9	0.19	5.3	0	12.79	19.3
1	15	28.3	28.3	0.17	6.18	0	11.48	22.5
1	16	16.9	36.3	0.15	6.13	0	11.58	22.1
2	1	0	0	0.45	5.3	0	12.44	19
2	2	9.4	9.4	0.34	4.51	0	13.79	16
2	3	18.9	18.9	0.22	4.95	0	13.27	17.2
2	4	28.3	28.3	0.12	5.75	0	12.17	19.7
2	5	37.7	37.7	0.024	5.77	0	12.28	19.8
2	6	47.1	47.1	0.018	5.72	0	12.37	20
2	7	56.6	56.6	0.02	5.71	0	12.38	20
2	8	9.4	-9.4	0.42	5.51	0	12.16	19.4
2	9	18.9	0	0.32	4.94	0	13.15	17.3
2	10	28.3	9.4	0.22	4.82	0	13.46	16.7
2	11	37.7	18.9	0.13	5.4	0	12.7	18.3
2	12	47.1	28.3	0.019	5.74	0	12.34	19.8
2	13	56.6	37.7	0.016	5.73	0	12.37	20.2
2	14	66	47.1	0.02	5.72	0	12.39	20.3
2	15	18.9	-18.9	0.24	6.39	0	11.07	22.8
2	16	28.3	-9.4	0.19	6.16	0	11.46	22.1
2	17	37.7	0	0.17	5.45	0	12.58	19.2
2	18	47.1	9.4	0.044	5.63	0	12.48	20.7
2	19	56.6	18.9	0.015	5.72	0	12.38	20.5
2	20	66	28.3	0.017	5.71	0	12.4	20.4
2	21	75.4	37.7	0.02	5.7	0	12.41	20.5
2	22	28.3	-28.3	0.12	6.34	0	11.29	22.7
2	23	37.7	-18.9	0.098	6.08	0	11.72	21.7
2	24	47.1	-9.4	0.042	5.59	0	12.55	21
2	25	56.6	0	0.016	5.69	0	12.43	20.4
2	26	66	9.4	0.015	5.7	0	12.42	20.5
2	27	75.4	18.9	0.017	5.7	0	12.42	20.5
2	28	84.9	28.3	0.02	5.7	0	12.42	20.4

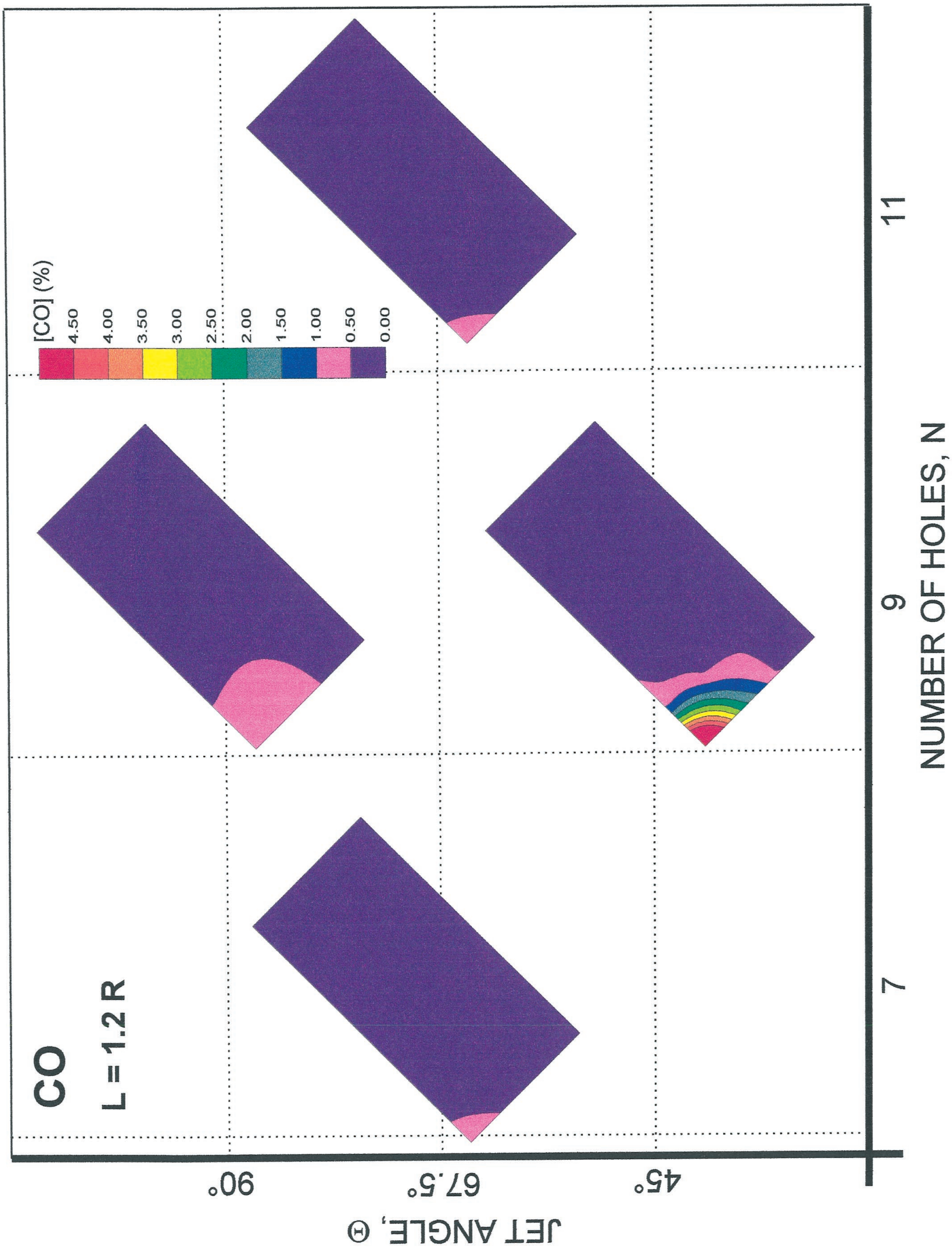
Case #12	Θ =	45.0°	N =	9	L =	2.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	4.66	7.55	174.9	4.44	31.1
1	2	12.9	-3.5	1.54	5.81	10.5	10.22	24.6
1	3	13.3	1.2	0.83	4.24	2.1	13.5	17.4
1	4	12.1	5.6	0.6	3.56	0.7	14.81	14.3
1	5	9.4	9.4	0.7	4.04	0.5	13.97	16.1
1	6	5.6	12.1	0.96	4.81	1.3	12.48	19.4
1	7	25.8	-6.9	0.46	4.37	0	13.77	17.2
1	8	26.6	2.3	0.34	4.93	0	13.02	18.9
1	9	24.2	11.3	0.32	4.48	0	13.75	17.3
1	10	18.9	18.9	0.33	4.72	0	13.35	20.7
1	11	11.3	24.2	0.31	5.07	0	12.83	19.9
1	12	38.6	-10.4	0.24	4.61	0	13.62	18.7
1	13	39.8	3.5	0.23	4.59	0	13.64	18.4
1	14	36.3	16.9	0.27	4.37	0	13.93	17.5
1	15	28.3	28.3	0.24	4.89	0	13.16	19.1
1	16	16.9	36.3	0.25	4.69	0	13.48	18.3
2	1	0	0	1.62	6.73	9.8	8.67	27.6
2	2	9.4	9.4	0.49	4.12	0.1	14.05	16.1
2	3	18.9	18.9	0.24	4.51	0	13.74	17.2
2	4	28.3	28.3	0.16	5.24	0	12.73	19.8
2	5	37.7	37.7	0.032	5.28	0	12.8	20.1
2	6	47.1	47.1	0.024	5.32	0	12.77	20.5
2	7	56.6	56.6	0.028	5.31	0	12.79	20.6
2	8	9.4	-9.4	1.27	6.23	3	9.87	25.5
2	9	18.9	0	0.46	4.48	0	13.57	17.8
2	10	28.3	9.4	0.21	5.16	0	12.79	19.6
2	11	37.7	18.9	0.15	5.1	0	12.96	19.4
2	12	47.1	28.3	0.027	5.29	0	12.82	20.3
2	13	56.6	37.7	0.023	5.33	0	12.78	20.6
2	14	66	47.1	0.027	5.33	0	12.78	20.9
2	15	18.9	-18.9	0.37	5.92	0	11.45	23.5
2	16	28.3	-9.4	0.29	5.82	0	11.69	22.8
2	17	37.7	0	0.26	4.76	0	13.39	18.5
2	18	47.1	9.4	0.074	5.14	0	13.01	19.9
2	19	56.6	18.9	0.023	5.31	0	12.82	20.9
2	20	66	28.3	0.023	5.33	0	12.79	21.3
2	21	75.4	37.7	0.027	5.33	0	12.8	21.4
2	22	28.3	-28.3	0.25	5.15	0	12.78	20.5
2	23	37.7	-18.9	0.17	5.22	0	12.78	20.9
2	24	47.1	-9.4	0.065	5.16	0	13.01	20.6
2	25	56.6	0	0.021	5.32	0	12.81	21.3
2	26	66	9.4	0.02	5.31	0	12.83	21.4
2	27	75.4	18.9	0.023	5.33	0	12.8	21.5
2	28	84.9	28.8	0.026	5.33	0	12.81	21.4

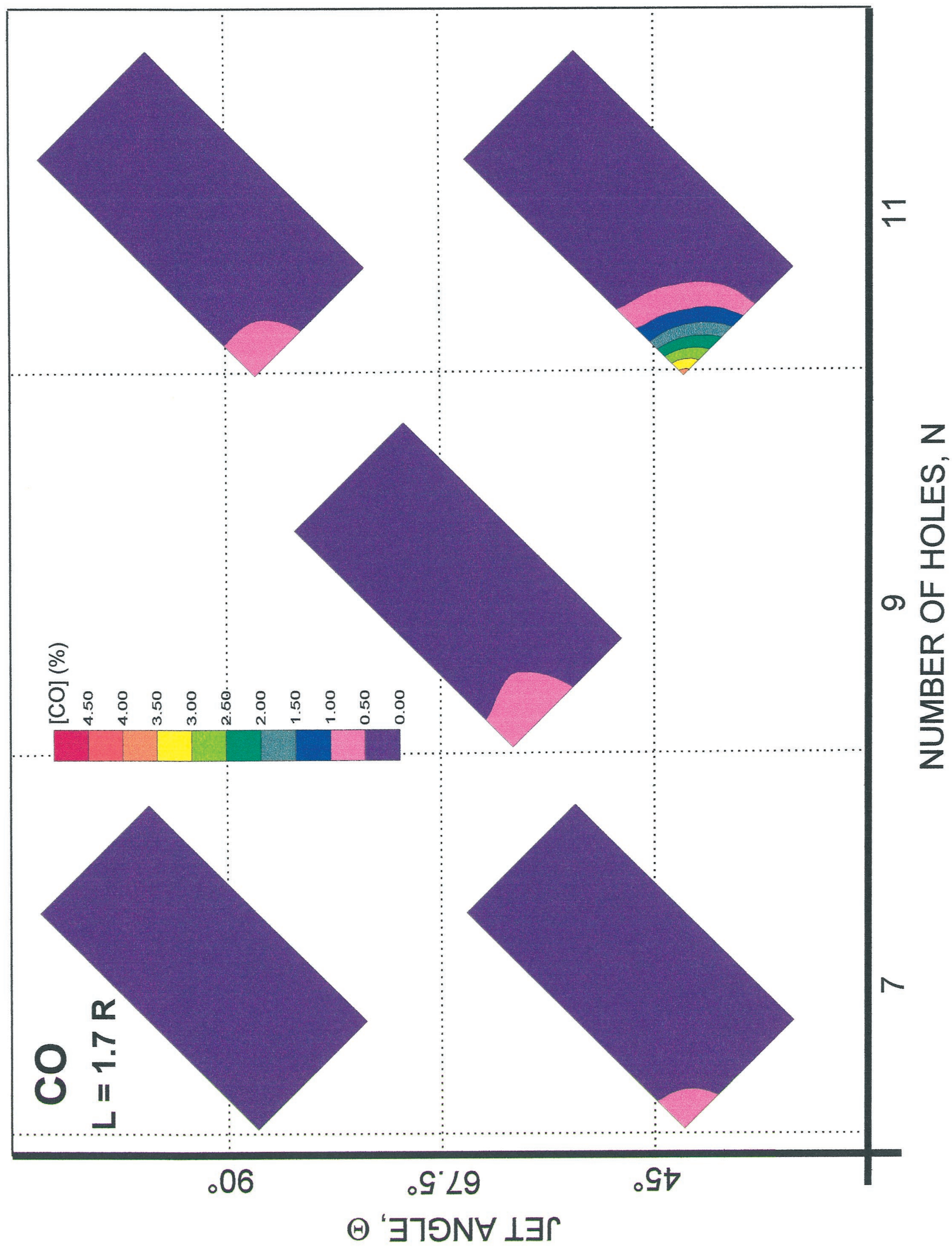
Case #13	Θ =	67.5°	N =	11	L =	2.2 R		
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
1	1	0	0	1.54	6.73	7.8	8.75	26.7
1	2	10.7	-8	1.21	6.35	2.8	9.73	24.6
1	3	12.5	-4.7	1.05	5.98	1.6	10.49	23.8
1	4	13.3	-1	0.82	5.2	0.7	11.95	19.8
1	5	13	2.8	0.65	4.45	0.4	13.3	17
1	6	11.7	6.4	0.59	4.1	0.4	13.9	15.5
1	7	21.3	-16	0.41	5.34	0	12.27	19
1	8	25	-9.3	0.4	4.88	0	12.97	17.2
1	9	26.6	-1.9	0.37	4.34	0.1	13.82	15.5
1	10	26.1	5.7	0.35	3.86	0.2	14.56	13.7
1	11	23.4	12.8	0.33	3.95	0.1	14.45	14
1	12	32	-24	0.25	5.39	0	12.36	18.7
1	13	37.5	-14	0.17	4.45	0	12.35	18.8
1	14	39.9	-2.9	0.1	5.35	0	12.57	18.4
1	15	39.1	8.5	0.18	5.24	0	12.66	18.2
1	16	35.1	19.2	0.22	5.5	0.1	12.25	19.1
2	1	0	0	0.75	6.18	0.3	10.57	23.6
2	2	9.4	9.4	0.4	4.13	0.1	14.13	15
2	3	18.9	18.9	0.27	4.06	0.1	14.39	14.9
2	4	28.3	28.3	0.14	5.47	0	12.39	19.4
2	5	37.7	37.7	0.028	5.51	0	12.48	20.3
2	6	47.1	47.1	0.018	5.51	0	12.49	20.4
2	7	56.6	56.6	0.022	5.49	0	12.52	21.4
2	8	9.4	-9.4	0.73	6.21	0.2	10.59	24
2	9	18.9	0	0.45	5.79	0.1	12.49	19.4
2	10	28.3	9.4	0.26	4.55	0.1	13.67	16.7
2	11	37.7	18.9	0.13	5.44	0	12.47	19
2	12	47.1	28.3	0.02	5.32	1.3	12.81	19.5
2	13	56.6	37.7	0.02	5.52	0	12.48	20.5
2	14	66	47.1	0.02	5.52	0	12.49	20.6
2	15	18.9	-18.9	0.28	5.63	0	12	20.7
2	16	28.3	-9.4	0.24	5.51	0	12.27	19.9
2	17	37.7	0	0.17	5.47	0	12.4	19.5
2	18	47.1	9.4	0.05	5.5	0	12.48	19.9
2	19	56.6	18.9	0.02	4.42	6.4	14.12	17.6
2	20	66	28.3	0.01	5.52	0	12.52	20.6
2	21	75.4	37.7	0.02	5.3	0	12.54	20.8
2	22	28.3	-28.3	0.16	5.31	0.1	12.69	19.3
2	23	37.7	-18.9	0.15	5.45	0	12.49	19.7
2	24	47.1	-9.4	0.06	5.44	0	12.59	19.7
2	25	56.6	0	0.02	5.49	0	12.56	20.4
2	26	66	9.4	0.02	5.5	0	12.55	20.2
2	27	75.4	18.9	0.02	5.51	0	12.53	20.8
2	28	84.9	28.3	0.02	5.51	0	12.53	20.5

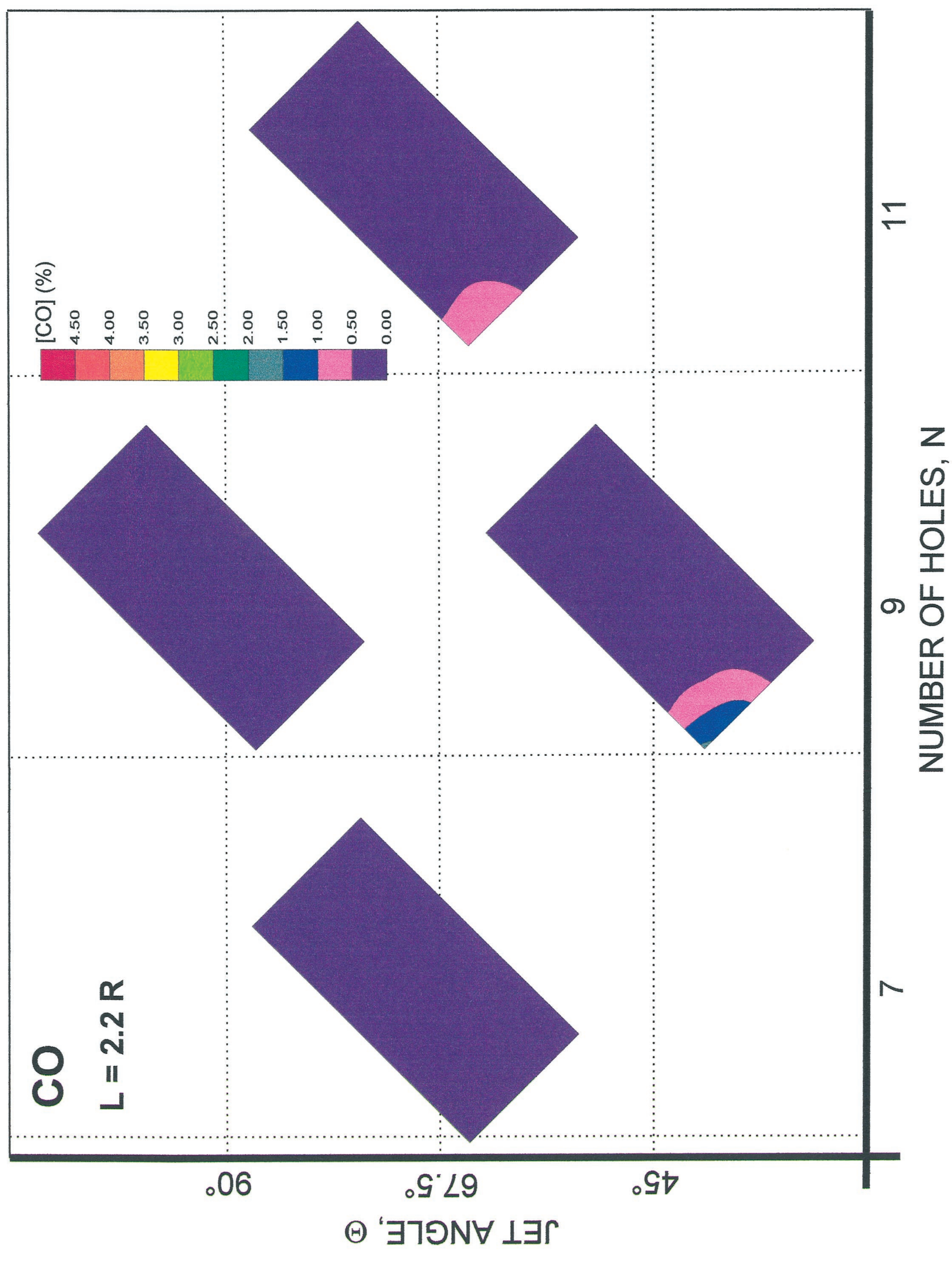
Raw Data

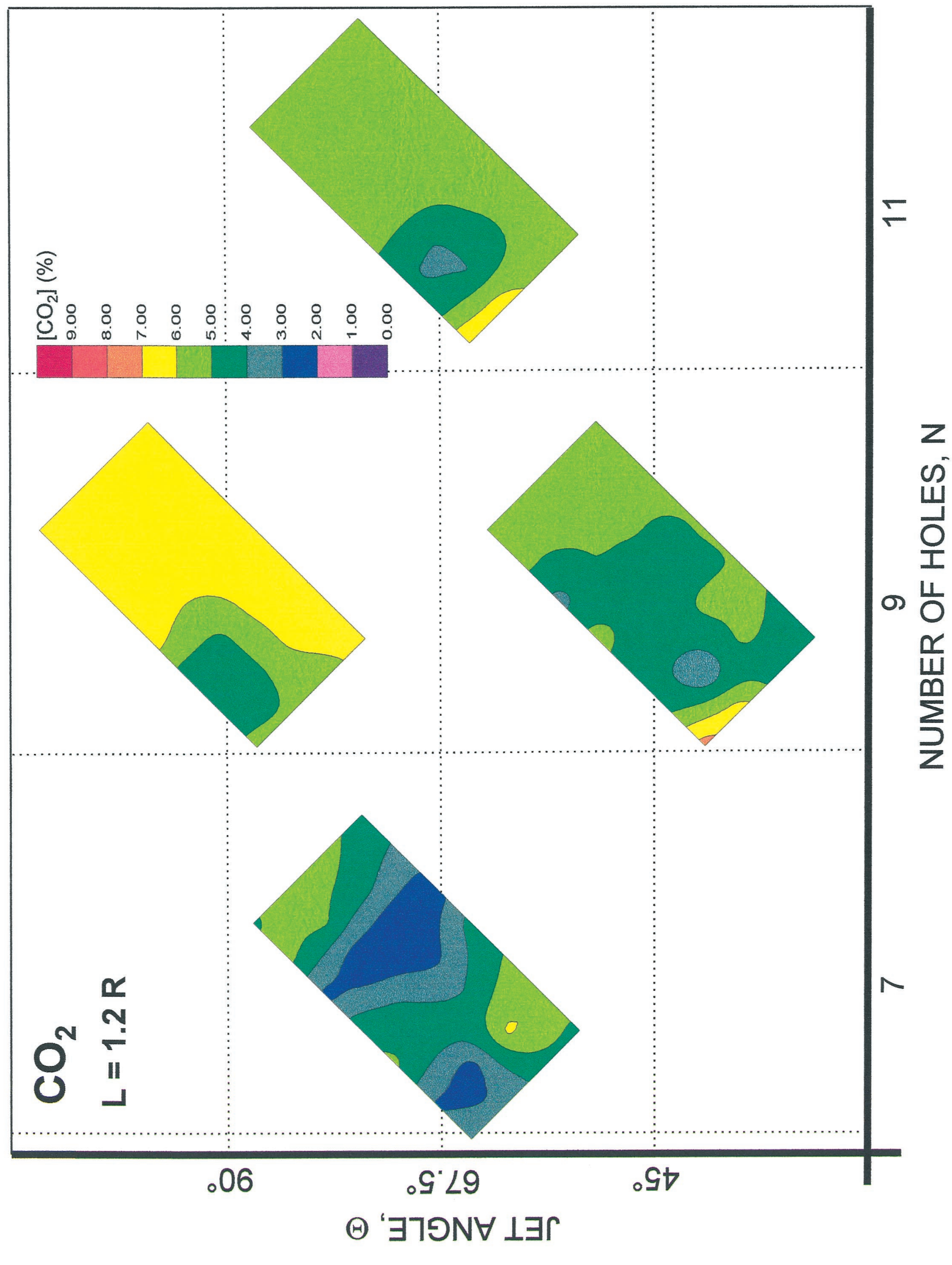
Case #RICH								
plane	point	x	y	CO (%)	CO_2 (%)	HC (ppm)	O_2 (%)	NO_x (ppm)
rich (z=-40)	1	0	0	12.5	5.66	2154	0	9.6
rich	2	8.7	-10.1	12.45	5.69	2580	0	9.3
rich	3	12.2	-5.3	12.42	5.73	3300	0	10.4
rich	4	13.3	0.5	12.5	5.68	3071	0	9.7
rich	5	11.8	6.2	12.3	5.82	3126	0	9.6
rich	6	7.9	10.7	12.28	5.81	3641	0	10.1
rich	7	17.4	-20.2	12.45	5.7	3230	0	9.8

C. Plane 2 Figures

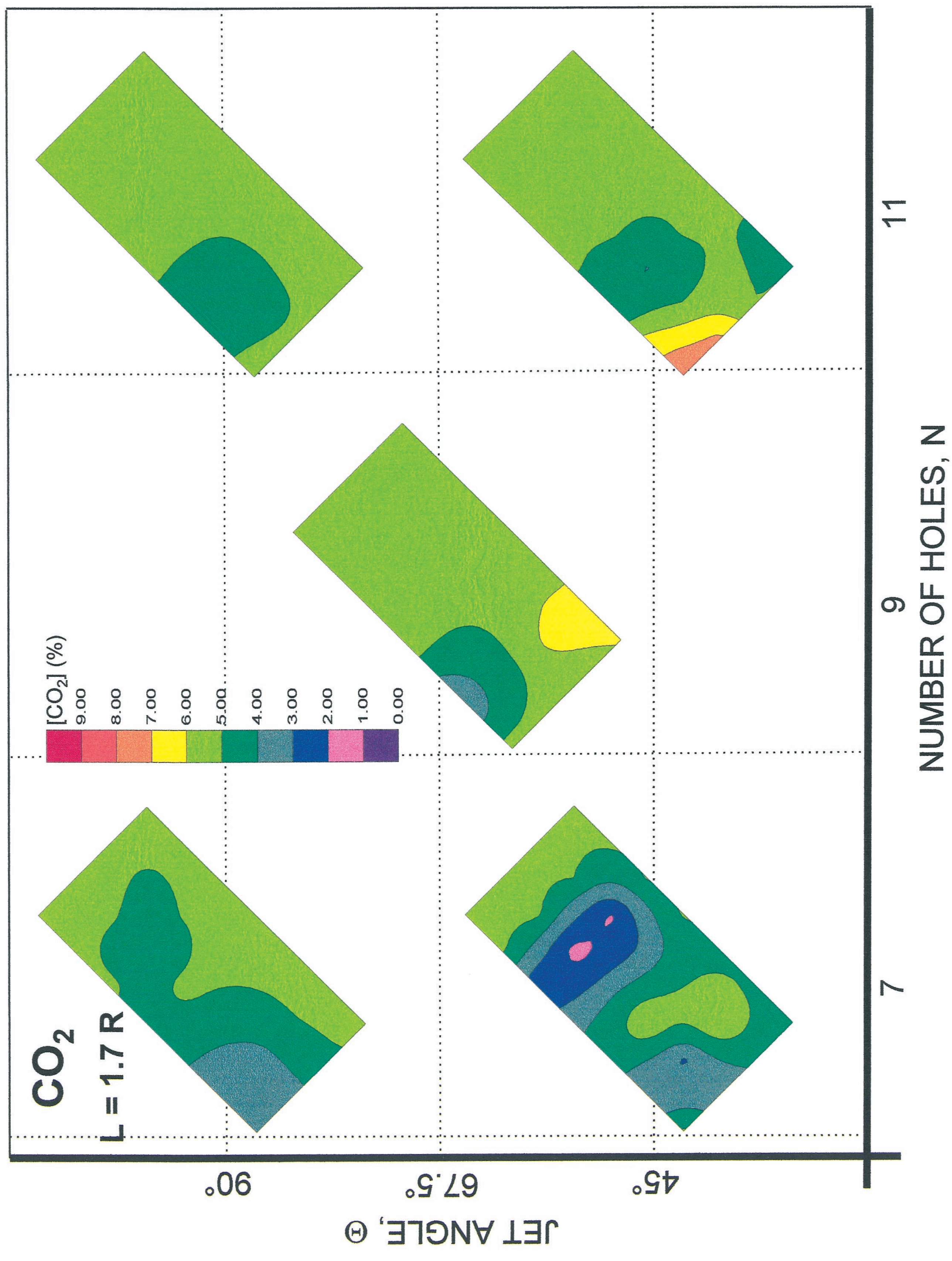

CO
L = 1.2 R
[CO] (%)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ

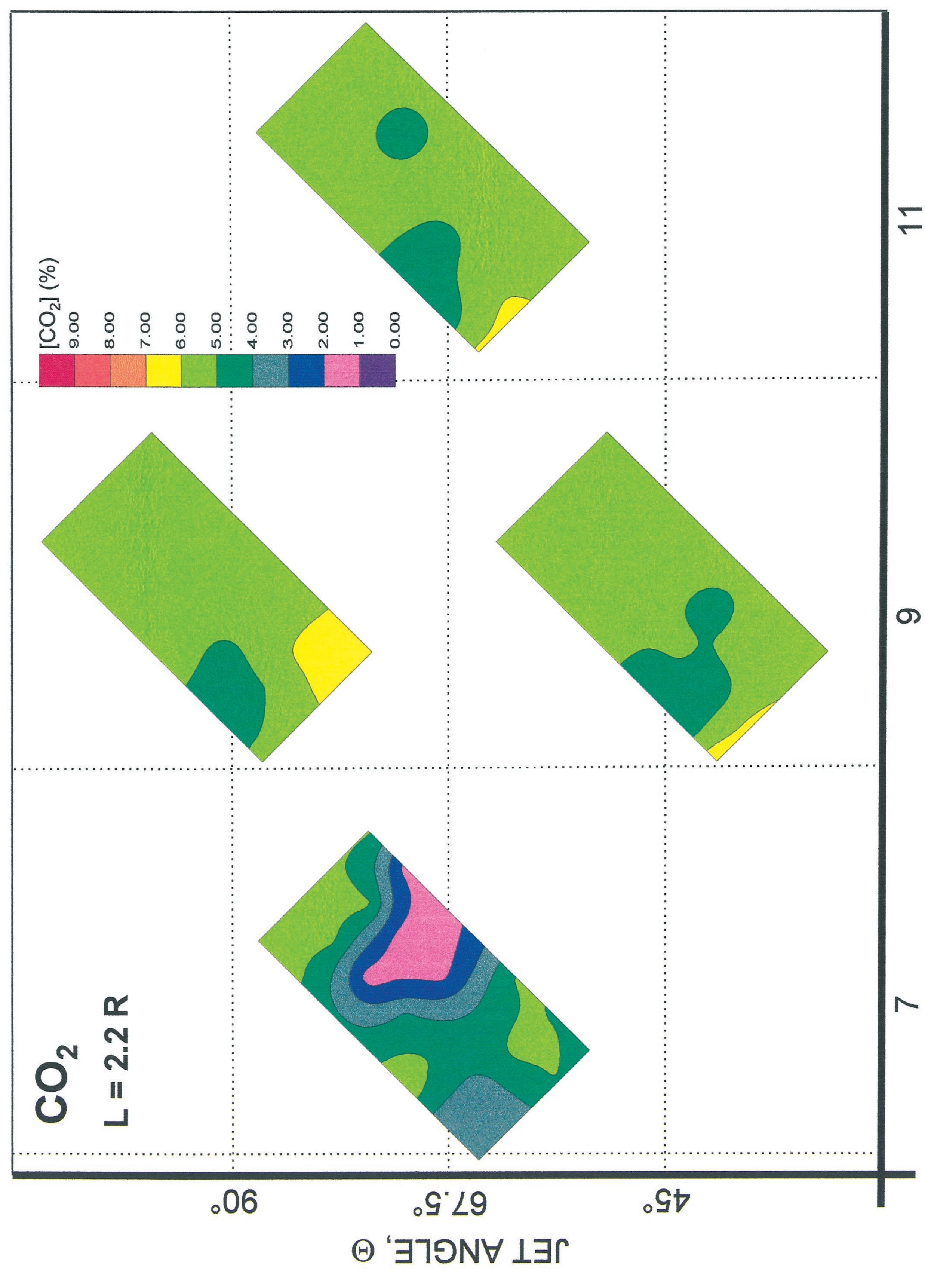

CO
L = 1.7 R
[CO] (%)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ

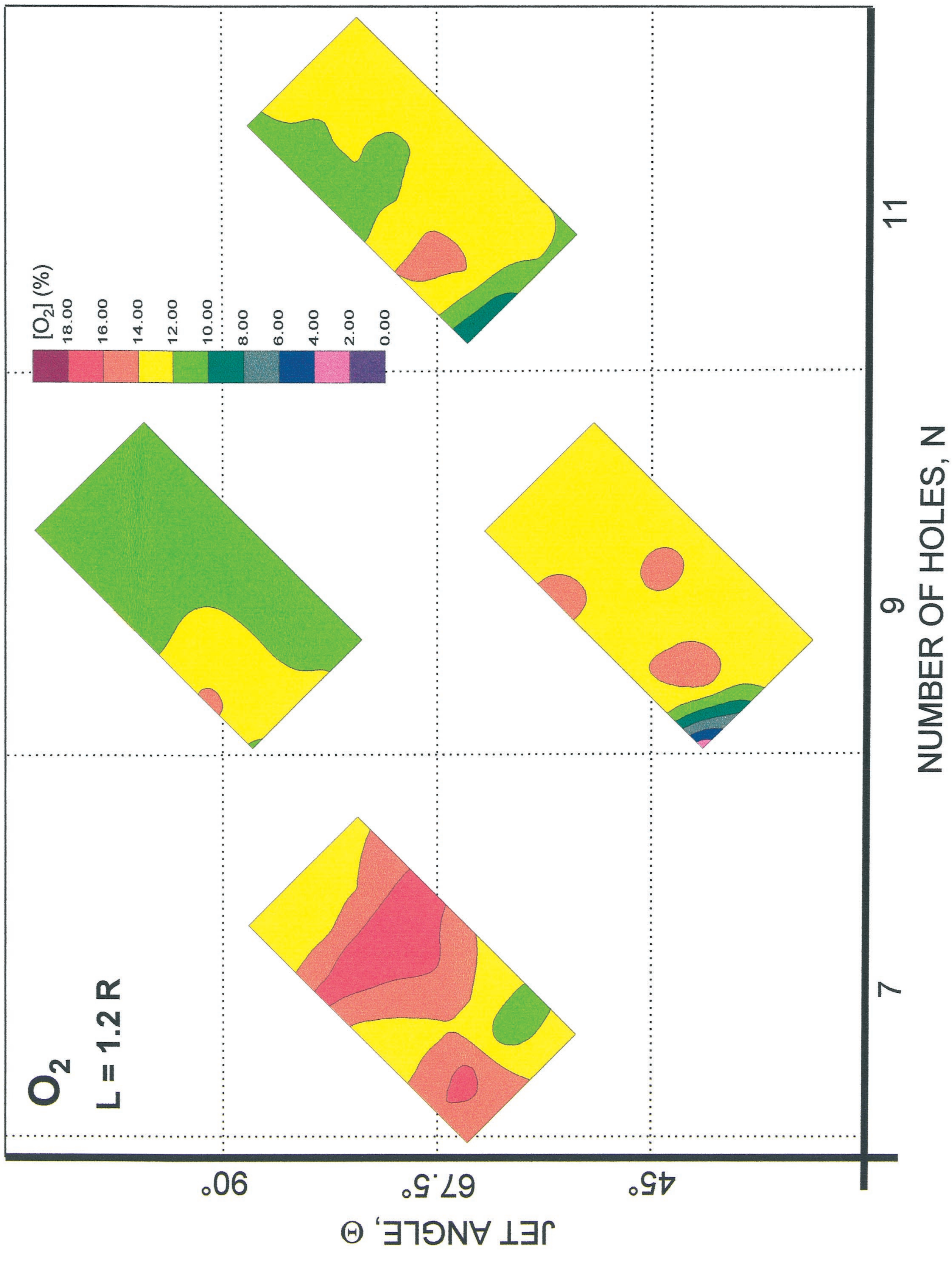

CO
L = 2.2 R
[CO] (%)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ



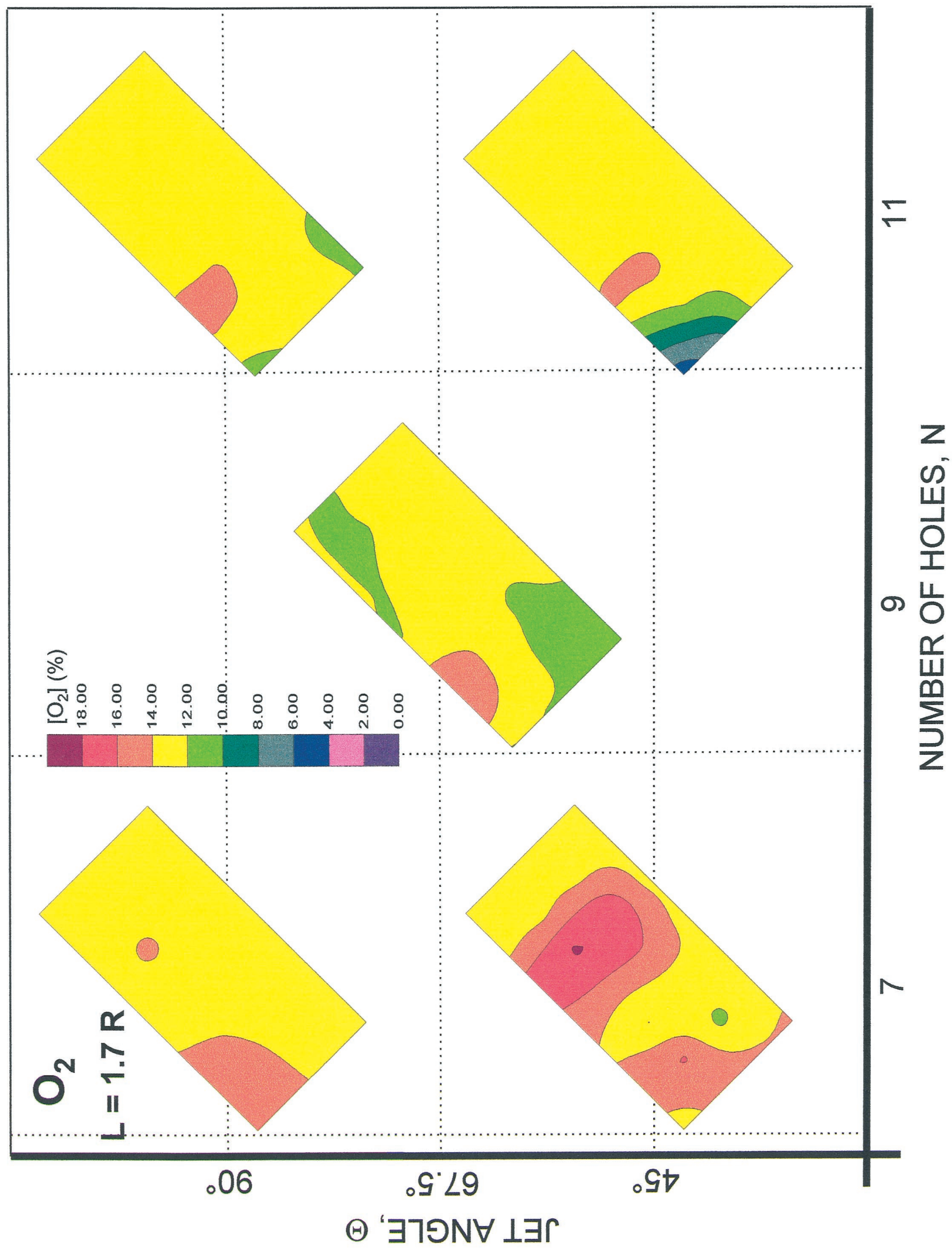
CO_2
L = 1.2 R
[CO_2] (%)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
JET ANGLE, Θ
90°
67.5°
45°
NUMBER OF HOLES, N
7
9
11

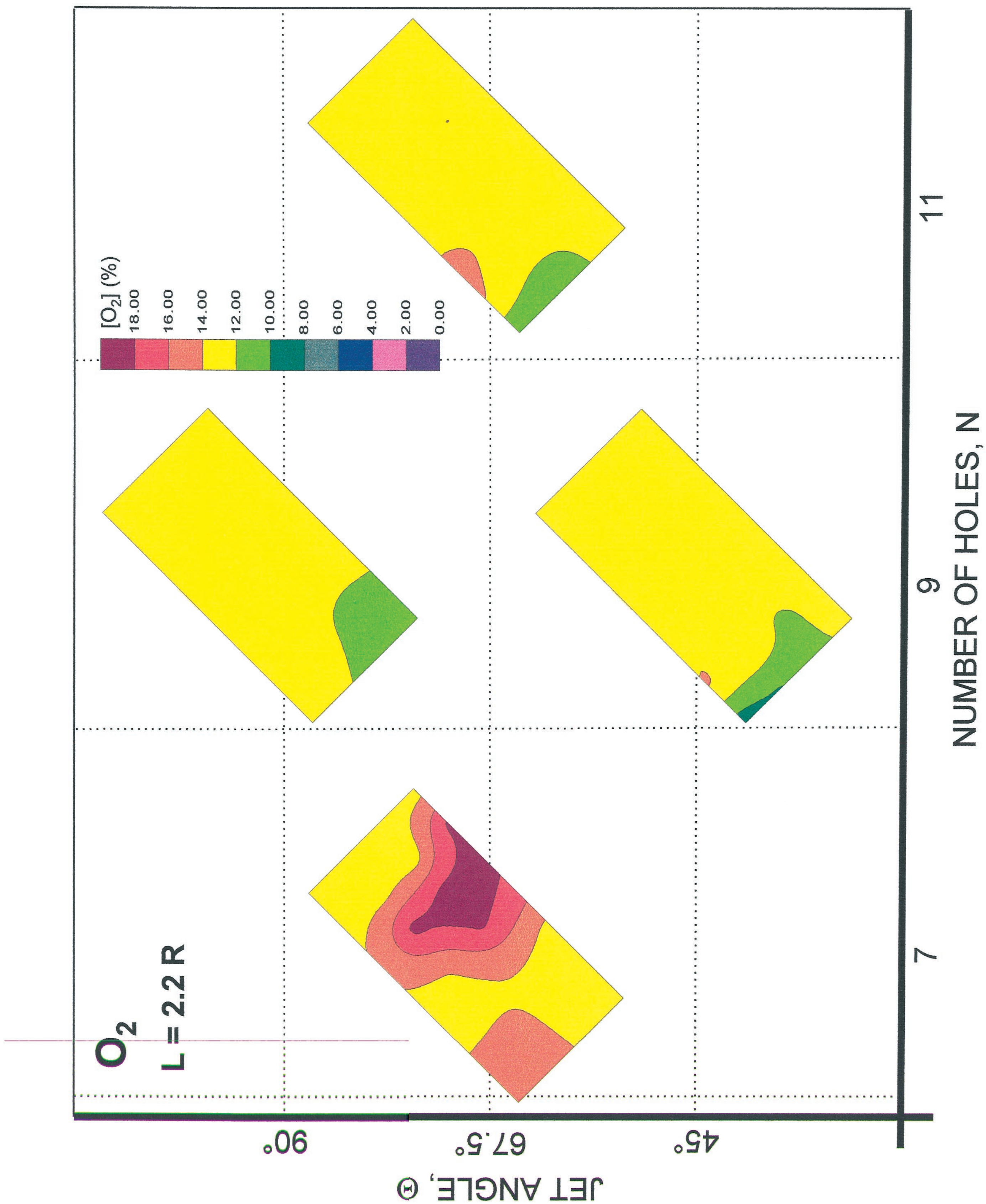

CO_2
L = 1.7 R
$[CO_2]$ (%)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ

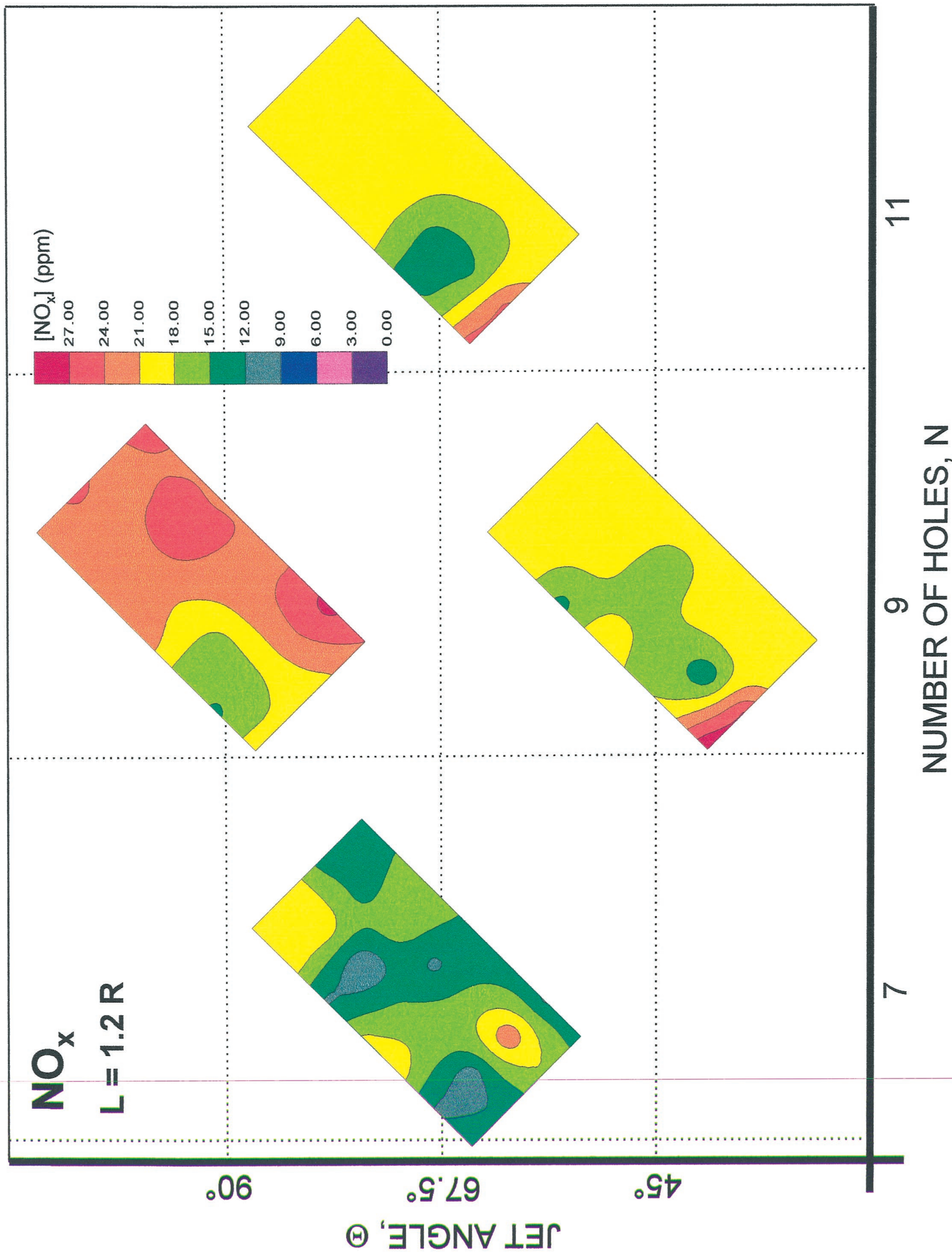

CO2
L = 2.2 R
[CO2] (%)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ

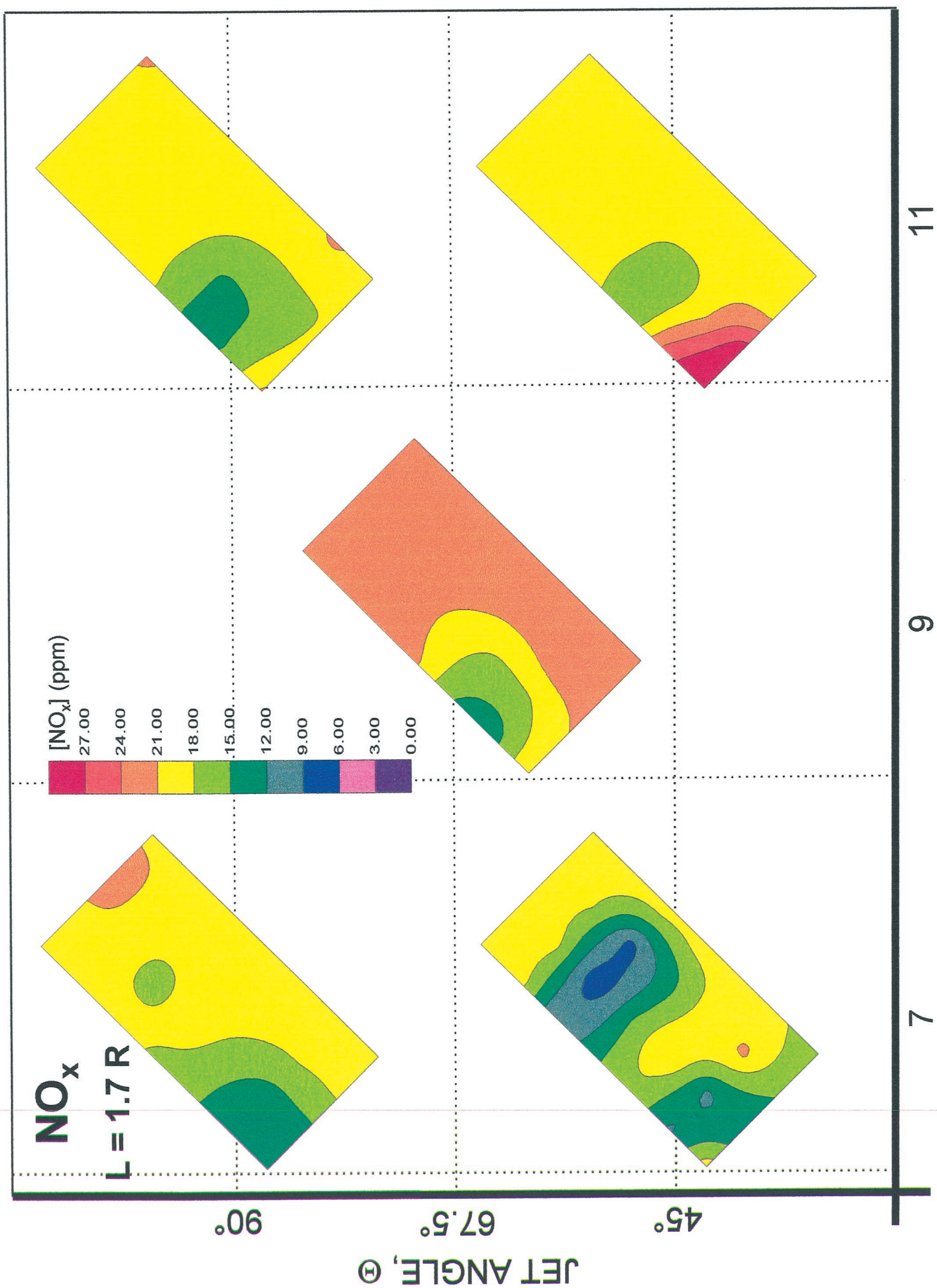


O_2
L = 1.2 R
$[O_2]$ (%)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ

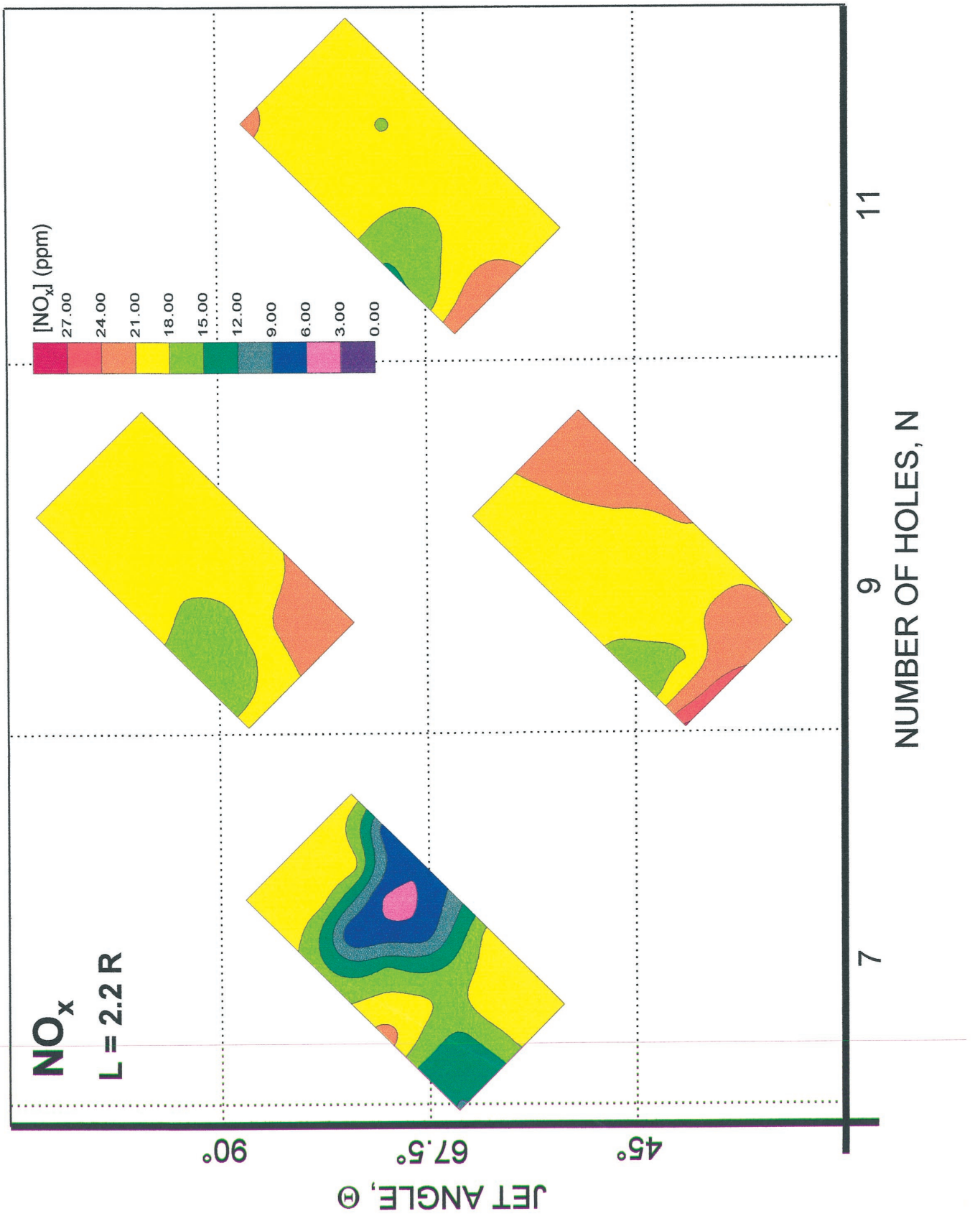

O$_2$
L = 1.7 R
[O$_2$] (%)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ


O2
L = 2.2 R
[O2] (%)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ


NOx
L = 1.2 R
[NOx] (ppm)
27.00
24.00
21.00
18.00
15.00
12.00
9.00
6.00
3.00
0.00
NUMBER OF HOLES, N
7
9
11
JET ANGLE, Θ
45°
67.5°
90°



NO_x
L = 1.7 R
$[NO_x]$ (ppm)
27.00
24.00
21.00
18.00
15.00
12.00
9.00
6.00
3.00
0.00
7
9
11
NUMBER OF HOLES, N
90°
67.5°
45°
JET ANGLE, Θ


NO$_x$
L = 2.2 R
[NO$_x$] (ppm)
27.00
24.00
21.00
18.00
15.00
12.00
9.00
6.00
3.00
0.00
JET ANGLE, Θ
90°
67.5°
45°
7
9
11
NUMBER OF HOLES, N

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2003	Final Contractor Report

4. TITLE AND SUBTITLE

Detailed Studies of the Quick Mixing Region in Rich Burn Low-NO_x Combustion

5. FUNDING NUMBERS

WBS–22–714–01–38
NAG3–1110

6. AUTHOR(S)

D. St. John and G.S. Samuelsen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of California, Irvine
UCI Combustion Laboratory
Irvine, California 92697–3550

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13904

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2003-212316

11. SUPPLEMENTARY NOTES

Project Manager, James D. Holdeman, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5840, 216–433–5846.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

NO_x reduction is a driving force in combustor design today. The fuel-air mixing process can have a significant effect on NO_x production. This report describes a set of experiments carried out to assess fuel-air mixing sensitivities to geometric variation in the Rich-Burn/Quick-Mix/Lean-Burn (RQL) combustor concept utilized in stationary gas turbine engine applications and proposed for advanced transport aircraft engines. Specifically, three (3) parameters in the quick-mix zone were examined: jet injection angle, jet-to-expansion distance, and jet count (number of jets).

14. SUBJECT TERMS

Gas turbine; Combustor; RQL mixer; Jet-in-crossflow; Reacting flow at atmospheric pressure; Emissions; NO_x

15. NUMBER OF PAGES

83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	