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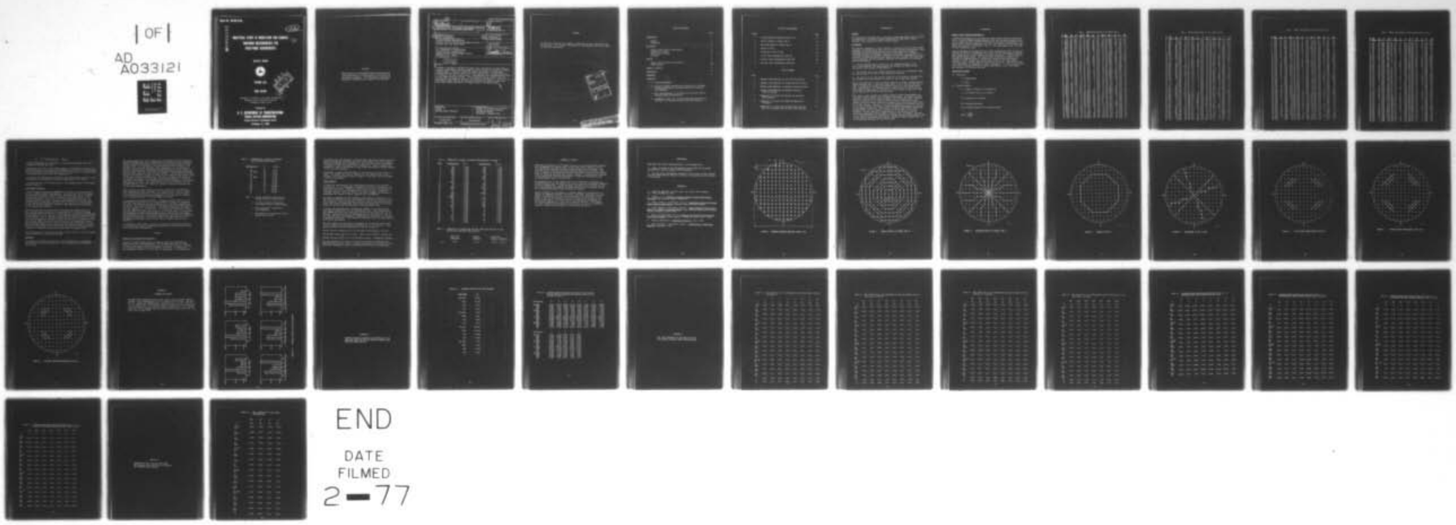

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ANALYTICAL STUDY OF MIXED-FLOW JT8D EXHAUST EMISSIONS MEASUREMENTS FOR FIXED-PROBE REQUIREMENTS

Gerald R. Slusher

OCTOBER 1976

FINAL REPORT

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16. Abstract

A method is outlined to optimize the shape, size, and location of fixed probe for acquiring representative emission samples from the exhaust of a mixed-flow JT8D-11 turbofan engine. Families of geometric shapes and mutually exclusive probe configurations are overlaid upon a 177-point traverse grid. A significance ratio is calculated and used to rank results. Representative and nonrepresentative areas of the exhaust plume are defined. Probe configurations are overlaid upon the traverse grid and ranked to obtain a representative configuration. An area of the JT8D exhaust plume suitable for acquiring representative emission samples was found which reduces the overall 177 sample points to 20 sample points.

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PREFACE

Mr. Daniel W. Riley III, FAA, NAFEC, accomplished the basic analytical work of this report. Mr. Riley's contribution is acknowledged with sincere thanks and grateful appreciation.

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INTRODUCTION

PURPOSE.

The purposes of this study were to optimize a fixed-probe shape, size, and location and define a technique to obtain representative sampling of exhaust emissions from a mixed-flow JT8D-11 turbofan engine.

BACKGROUND.

The Clean Air Amendments of 1970 (reference 1) specified that the United States Department of Transportation (DOT) and the Federal Aviation Administration (FAA) promulgate regulations enforcing the aircraft engine emission standards established by the Environmental Protection Agency (EPA). In an attempt to establish standards, an extensive compilation of emission measurements in 1971 (reference 2) involving 400 aircraft engines recorded by eight test teams under various geographic and environmental conditions has quantified the following statistical results:

1. For the landing/takeoff (LTO) cycle, the standard deviation of the total carbon monoxide (CO) mass emissions was estimated as approximately 30 percent of the average CO mass emission.

2. For the LTO cycle, the standard deviation of the total hydrocarbons (THC) was approximately 45 percent of the average mass emission.

3. For the LTO cycle, the standard deviation of the oxides of nitrogen (NO_x) mass emissions was approximately 15 percent of the average mass emission.

Quoted from reference 2: "The variability observed in exhaust emission measurements prescribes that a relatively large number of tests must be conducted in order to estimate the average mass emission levels for a particular engine mode. Specifically, it is estimated that to have 95-percent confidence that the average is known within 10 percent of its true value, as many as 36 tests may be required for CO and 81 tests for THC."

Since 1971, a major variability problem regarding emission measurements has been identified by industry and government study teams. The problem involves acquiring a representative emission sample from the exhaust plume. Stratification of emissions in the exhaust have been proven by detailed traverse probing across the exhaust plume and the analysis of profile and contour plots of CO, THC, and NO_x. Studies of the traverse emission plots indicate that the use of fixed probing techniques to provide representative samples is a problem of measurement variability. This problem is further compounded on mixed-flow turbofan engines by the mixing of the fan and the primary or core flows. Therefore, the FAA conducted an investigation at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey. The goal of the investigation was to determine the optimum sample probe locations in the exhaust plume by determining which areas consisted of gases representative of the average gas emissions for the entire plume.

DISCUSSION

EXHAUST PLUME TRAVERSE MEASUREMENTS.

A detailed investigation of the mixed-flow JT8D exhaust plume was necessary in order to first establish average emission levels for the entire exhaust plume and to furnish the data needed for evaluation of fixed-probe requirements. The exhaust plume traverse measurements and other test results concerning the JT8D engine were reported in references 3 and 4. These measurements were the basis for this statistical study.

Emission measurements consisting of CO, carbon dioxide (CO_2), THC, and NO_X were recorded for each of 177 sampling points across the 30-inch-diameter traverse-grid located in the vertical plane at an axial distance of 2 inches behind the JT8D engine exhaust nozzle. The traverse grid is depicted in figure 1 and features 177 sampling points, 2 inches apart vertically and horizontally. Complete 177-point traverse-grid samples were taken at four engine power conditions; idle, holding, approach and maximum continuous. The detailed emission measurements are tabulated in tables 1 through 4. It should be noted there are 16 sets of gas group throttle setting measurements, i.e., 4 gas groups, each measured at 4 throttle settings.

DEFINITION OF TERMS.

(1) Subscripts

C = Configuration

T = Total

(2) Primary Symbols

N = Number of items in a configuration

X = An observed value of a traverse

$\bar{\bar{X}}$ = Grand mean of traverse

$\bar{X}_C$ = Configuration mean.

S_T = Standard deviation for the gas-traverse

$$\text{Raw } t = \frac{\bar{X}_C - \bar{\bar{X}}}{S_T}$$

TABLE 1. EXHAUST PLUME EMISSIONS AT IDLE THROTTLE SETTING

PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM
1	13.3	44	0.11	0.8	60	17.8	9	0.05	0.5	119	245.9	548	1.80	14.5
2	67.7	180	0.51	3.4	61	38.8	60	0.15	1.6	120	296.0	557	1.70	13.2
3	143.0	237	0.82	5.4	62	104.3	205	0.55	4.4	121	301.9	543	1.70	12.7
4	183.0	367	1.10	7.3	63	177.8	421	1.25	10.3	122	200.9	434	1.50	11.5
5	217.9	436	1.55	11.4	64	195.1	486	1.50	12.9	123	121.0	254	0.82	6.2
6	217.9	540	1.75	14.0	65	167.3	478	1.35	11.9	124	64.4	117	0.35	2.8
7	189.6	508	1.70	14.5	66	178.3	448	1.45	12.4	125	28.8	35	0.10	1.1
8	189.6	501	1.65	14.0	67	131.0	244	0.70	5.8	126	18.9	5	0.02	0.5
9	217.9	540	1.77	14.7	68	88.8	120	0.30	2.6	127	18.9	10	0.05	0.6
10	217.9	545	1.77	14.2	69	83.2	120	0.30	2.5	128	44.4	69	0.15	1.6
11	223.4	4[illegible]6	1.57	12.9	70	37.8	31	0.10	0.9	129	106.5	212	0.55	4.2
12	201.0	377	1.10	9.0	71	17.8	4	0.02	0.3	130	200.9	397	1.12	8.3
13	167.3	290	0.77	6.2	72	35.5	44	0.12	1.2	131	262.1	553	1.75	13.0
14	145.1	230	0.57	4.3	73	71.0	120	0.32	2.5	132	251.0	553	1.85	14.0
15	65.5	73	0.20	1.7	74	108.9	205	0.55	4.0	133	267.9	543	1.75	13.5
16	25.6	18	0.06	0.6	75	142.0	290	0.80	6.0	134	267.9	439	1.30	10.0
17	51.1	63	0.17	1.6	76	108.9	241	0.70	5.3	135	206.3	347	1.10	8.5
18	122.9	203	0.52	4.2	77	106.6	229	0.65	5.2	136	146.5	254	0.82	6.4
19	189.9	352	1.05	8.5	78	117.8	263	0.72	5.7	137	100.0	154	0.47	3.9
20	212.0	508	1.60	12.9	79	57.6	94	0.25	2.1	138	56.5	62	0.20	1.8
21	223.5	550	1.75	14.5	80	41.1	49	0.12	1.2	139	27.8	15	0.02	0.6
22	212.0	525	1.72	15.0	81	35.5	44	0.11	1.1	140	34.4	22	0.07	0.6
23	234.1	525	1.70	14.5	82	16.6	3	0.02	0.4	141	62.1	69	0.17	1.5
24	307.0	592	1.80	15.5	83	40.0	65	0.15	1.4	142	117.8	161	0.42	3.1
25	268.0	545	1.70	13.4	84	60.0	103	0.26	2.2	143	184.0	310	0.86	6.5
26	228.5	451	1.30	9.7	85	54.4	10	0.25	2.1	144	279.0	540	1.67	12.5
27	140.0	252	0.70	5.0	86	38.8	51	0.15	1.5	145	301.9	565	1.75	13.0
28	94.3	138	0.35	2.7	87	48.8	80	0.22	2.1	146	256.5	443	1.30	9.3
29	113.2	176	0.45	3.2	88	40.0	49	0.15	1.4	147	146.5	280	0.70	4.7
30	65.5	93	0.25	1.9	89	22.2	14	0.05	0.5	148	84.4	145	0.40	3.0
31	13.3	4	0.02	0.2	90	20.0	9	0.05	0.4	149	52.1	95	0.27	2.1
32	12.2	4	0.02	0.2	91	17.8	9	0.05	0.4	150	35.5	60	0.17	1.4
33	22.2	31	0.10	0.8	92	13.3	9	0.02	0.5	151	23.3	30	0.10	0.7
34	59.9	120	0.32	2.6	93	11.1	4	0.02	0.3	152	15.5	2	0.02	0.2
35	135.3	315	0.90	6.8	94	14.4	9	0.02	0.6	153	41.0	50	0.12	1.1
36	212.0	505	1.55	12.4	95	13.3	4	0.02	0.4	154	55.5	89	0.25	1.7
37	200.9	540	1.77	16.3	96	11.1	1	0.02	0.3	155	107.5	200	0.51	3.7
38	195.1	535	1.72	15.0	97	14.4	16	0.06	0.7	156	234.0	431	1.20	8.0
39	273.5	592	1.77	15.0	98	46.6	103	0.27	2.2	157	268.0	439	1.22	8.2
40	256.5	550	1.67	13.7	99	104.5	172	0.47	3.4	158	200.9	281	0.72	5.0
41	212.0	444	1.30	10.3	100	153.2	269	0.72	5.3	159	107.5	128	0.34	2.4
42	135.3	252	0.67	5.7	101	223.1	436	1.40	10.4	160	57.6	50	0.15	1.1
43	62.1	74	0.20	1.8	102	245.5	534	1.75	13.4	161	36.6	20	0.07	0.5
44	65.4	81	0.20	1.7	103	212.0	525	1.80	14.7	162	24.4	10	0.06	0.3
45	46.6	47	0.12	1.1	104	200.9	525	1.80	14.7	163	20.0	7	0.05	0.3
46	16.6	1	0.02	0.3	105	250.9	580	1.85	14.[illegible]	164	32.2	20	0.07	0.5
47	23.3	9	0.05	0.5	106	301.0	601	1.90	14.7	165	74.4	101	0.27	2.0
48	54.4	73	0.20	1.8	107	262.0	545	1.87	14.7	166	161.9	268	0.70	4.8
49	123.2	229	0.60	5.2	108	223.1	436	1.45	11.6	167	189.8	310	0.80	5.6
50	206.5	487	1.47	12.4	109	167.2	283	0.82	6.1	168	121.0	188	0.47	3.4
51	206.5	552	1.77	15.2	110	100.3	126	0.35	2.8	169	55.5	82	0.20	1.6
52	200.9	527	1.72	15.0	111	44.6	35	0.11	1.1	170	20.0	15	0.06	0.4
53	212.0	543	1.72	15.0	112	21.1	4	0.02	0.4	171	15.5	2	0.02	0.1
54	185.2	408	1.20	9.5	113	38.8	29	0.10	1.0	172	15.5	2	0.02	0.1
55	131.0	238	0.62	5.0	114	84.4	96	0.26	2.2	173	41.0	50	0.15	1.2
56	113.1	211	0.51	4.1	115	156.2	234	0.62	5.0	174	77.6	132	0.34	2.5
57	46.6	56	0.12	1.3	116	245.9	299	1.27	10.0	175	84.4	136	0.35	2.6
58	35.5	31	0.10	0.8	117	273.9	550	1.82	14.5	176	62.2	82	0.25	1.7
59	15.6	1	0.02	0.3	118	234.4	540	1.87	15.2	177	22.2	10	0.06	0.4

TABLE 2. EXHAUST PLUME EMISSIONS AT HOLDING THROTTLE SETTING

PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM
1	11.6	16	0.11	1.2	60	6.4	9	0.06	0.5	119	55.5	346	1.87	18.5
2	26.2	96	0.51	4.9	61	11.8	40	0.20	1.8	120	75.8	356	1.75	16.9
3	38.8	175	0.86	7.9	62	26.7	130	0.60	5.6	121	79.0	337	1.72	16.3
4	45.6	233	1.22	11.0	63	43.8	268	1.32	12.4	122	54.4	286	1.62	15.8
5	53.3	325	1.75	15.6	64	44.8	303	1.52	14.5	123	29.9	169	0.90	8.9
6	50.4	344	1.85	17.2	65	38.4	271	1.37	13.2	124	17.1	76	0.40	3.9
7	47.5	329	1.82	17.7	66	44.8	296	1.52	14.5	125	8.5	21	0.11	1.2
8	48.5	325	1.77	16.9	67	28.8	130	0.60	5.8	126	5.3	4	0.02	0.2
9	54.3	355	1.90	18.3	68	21.4	68	0.30	2.9	127	6.4	6	0.02	0.3
10	60.1	370	1.92	18.3	69	20.3	61	0.27	2.7	128	11.8	37	0.15	1.6
11	60.1	322	1.72	16.1	70	10.7	19	0.10	0.9	129	27.8	132	0.55	5.1
12	51.4	233	1.20	10.8	71	6.4	4	0.02	0.2	130	57.7	272	1.17	10.3
13	42.6	173	0.84	7.7	72	8.5	31	0.15	1.5	131	79.0	374	1.80	16.3
14	34.9	126	0.60	5.5	73	17.1	77	0.37	3.5	132	72.6	373	1.87	18.0
15	15.5	25	0.15	1.5	74	23.5	120	0.57	5.3	133	77.9	371	1.75	16.3
16	7.8	4	0.06	0.5	75	28.8	170	0.82	7.7	134	77.9	279	1.27	11.7
17	11.6	25	0.15	1.6	76	23.5	134	0.65	6.3	135	60.8	215	1.15	9.8
18	25.2	106	0.51	4.9	77	25.6	146	0.71	7.0	136	38.4	166	1.01	8.7
19	35.9	209	1.10	10.5	78	29.9	163	0.77	7.6	137	26.7	106	0.55	5.7
20	43.6	307	1.65	15.6	79	13.9	49	0.22	2.2	138	17.1	49	0.26	2.6
21	50.4	351	1.85	17.5	80	10.7	25	0.11	1.2	139	8.5	11	0.07	0.8
22	46.5	340	1.82	17.5	81	8.5	16	0.07	0.8	140	8.5	14	0.06	0.5
23	52.4	344	1.82	17.7	82	6.4	4	0.02	0.2	141	13.9	37	0.15	1.6
24	67.9	365	1.92	18.5	83	8.5	31	0.15	1.6	142	24.6	93	0.40	3.8
25	62.1	344	1.80	16.9	84	12.8	56	0.27	2.6	143	38.4	184	0.84	7.5
26	56.2	278	1.42	12.9	85	11.8	47	0.25	2.2	144	64.1	337	1.70	15.8
27	34.9	156	0.75	6.9	86	8.5	31	0.15	1.6	145	74.8	362	1.82	16.9
28	25.2	82	0.40	3.7	87	13.9	56	0.27	2.7	146	65.1	276	1.32	12.2
29	27.2	93	0.45	3.9	88	9.6	31	0.15	1.5	147	39.5	140	0.70	6.3
30	15.5	35	0.17	1.8	89	6.4	9	0.06	0.4	148	23.5	76	0.40	3.7
31	8.5	1	0.02	0.1	90	5.3	6	0.05	0.2	149	17.1	56	0.30	2.9
32	7.5	1	0.02	0.2	91	4.3	6	0.05	0.2	150	12.8	40	0.22	2.1
33	8.5	14	0.10	0.8	92	4.3	6	0.02	0.3	151	8.5	21	0.11	1.2
34	17.1	64	0.34	3.2	93	5.3	4	0.02	0.2	152	6.4	4	0.02	0.2
35	32.0	183	0.88	8.5	94	5.3	9	0.02	0.5	153	10.7	31	0.12	1.3
36	49.1	324	2.17	15.6	95	4.3	4	0.02	0.2	154	12.8	49	0.20	1.9
37	51.3	347	1.85	17.7	96	4.3	1	0.02	0.1	155	24.6	113	0.46	4.4
38	55.5	351	1.82	17.5	97	4.3	9	0.07	0.7	156	61.9	277	1.15	10.2
39	75.8	385	1.90	17.7	98	13.9	56	0.32	2.8	157	81.2	297	1.25	10.9
40	71.5	351	1.77	16.4	99	21.4	106	0.51	4.6	158	63.0	187	0.75	6.5
41	59.8	286	1.42	12.9	100	29.9	156	0.77	6.8	159	33.1	88	0.32	2.8
42	40.6	163	0.77	7.0	101	47.0	276	1.50	13.6	160	18.2	29	0.12	1.0
43	21.4	52	0.25	4.6	102	53.4	329	1.80	17.4	161	9.6	14	0.07	0.5
44	19.2	47	0.22	2.1	103	44.8	329	1.85	18.0	162	7.4	9	0.05	0.3
45	12.8	21	0.11	1.1	104	49.2	340	1.85	17.7	163	6.4	6	0.05	0.2
46	6.4	4	0.02	0.1	105	61.9	281	1.92	18.5	164	8.5	9	0.06	0.4
47	8.5	9	0.02	0.4	106	75.8	389	1.95	18.3	165	17.1	52	0.25	2.2
48	13.9	44	0.20	1.9	107	68.4	355	1.92	18.5	166	39.5	159	0.71	6.2
49	28.8	146	0.70	6.8	108	55.5	282	1.57	14.7	167	51.3	202	0.88	7.8
50	50.2	322	1.60	15.1	109	41.6	172	0.86	8.1	168	34.2	134	0.57	5.1
51	51.3	351	1.82	17.5	110	21.4	70	0.35	3.2	169	18.2	63	0.71	2.6
52	53.4	344	1.80	17.2	111	9.6	14	0.07	0.7	170	7.4	16	0.10	0.8
53	58.7	351	1.80	17.2	112	6.4	4	0.02	0.2	171	5.3	4	0.02	0.1
54	45.9	244	1.17	10.8	113	10.7	16	0.10	0.9	172	5.3	1	0.02	0.1
55	32.0	140	0.60	5.8	114	19.2	56	0.25	2.5	173	10.7	31	0.15	1.4
56	31.0	130	0.55	5.4	115	37.4	146	0.62	5.8	174	19.2	83	0.37	3.4
57	15.0	40	0.15	1.8	116	58.7	278	1.35	12.5	175	22.4	93	0.42	3.8
58	9.6	16	0.07	0.9	117	63.0	355	1.90	18.5	176	17.1	59	0.27	2.6
59	5.3	4	0.02	0.2	118	51.3	343	1.92	19.1	177	8.5	11	0.07	0.7

TABLE 3. EXHAUST PLUME EMISSIONS AT APPROACH THROTTLE SETTING

PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NOx PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM
1	2.64	7	0.15	2.9	60	2.31	2	0.02	0.6	119	3.41	79	1.95	34.4
2	4.29	40	0.95	16.3	61	2.42	7	0.12	2.8	120	2.75	77	1.97	34.2
3	4.18	53	1.32	22.4	62	2.75	20	0.47	8.0	121	2.75	86	2.05	34.2
4	4.29	67	1.70	28.8	63	2.86	49	1.10	18.4	122	2.31	49	1.20	20.2
5	4.18	79	2.05	34.6	64	2.64	62	1.55	25.6	123	1.98	13	0.35	6.1
6	4.18	76	2.00	33.0	65	2.64	62	1.60	26.6	124	1.98	5	0.10	1.7
7	3.96	73	1.85	31.4	66	3.52	77	1.80	29.6	125	1.98	1	0.02	0.6
8	3.74	71	1.82	30.9	67	2.64	34	0.72	12.8	126	2.09	1	0.02	0.1
9	3.62	74	1.85	31.4	68	2.64	23	0.47	8.0	127	2.09	1	0.02	0.6
10	3.74	88	2.05	34.1	69	2.42	15	0.30	4.9	128	1.98	3	0.10	1.6
11	3.63	83	2.07	35.2	70	2.20	3	0.06	1.0	129	1.98	22	0.50	8.4
12	3.52	67	1.72	28.8	71	1.98	1	0.02	0.3	130	1.87	48	1.25	21.2
13	3.30	52	1.30	21.4	72	2.09	3	0.06	1.0	131	2.09	76	1.92	34.1
14	2.75	36	0.82	14.4	73	2.20	8	0.20	3.1	132	2.42	78	2.02	37.2
15	2.20	6	0.10	1.9	74	2.20	17	0.42	7.0	133	2.20	77	2.00	36.2
16	1.98	6	0.10	1.6	75	2.31	35	0.80	13.8	134	2.20	79	1.95	34.1
17	2.64	23	0.45	7.7	76	2.09	38	0.90	15.3	135	2.42	72	1.70	29.0
18	3.41	47	0.95	16.7	77	1.98	44	1.10	18.4	136	1.98	41	1.01	17.6
19	3.41	72	1.65	28.2	78	1.98	45	1.10	18.4	137	1.98	17	0.40	7.2
20	2.75	80	1.95	33.0	79	1.98	10	0.25	4.1	138	1.87	4	0.07	1.4
21	2.97	79	1.90	33.0	80	2.09	5	0.11	1.9	139	1.65	1	0.02	0.4
22	3.08	74	1.80	30.8	81	1.98	5	0.10	1.4	140	1.87	1	0.02	0.3
23	2.97	74	1.80	30.8	82	1.87	1	0.02	0.4	141	1.87	3	0.05	0.7
24	3.08	79	1.82	31.4	83	2.09	5	0.11	2.0	142	1.87	11	0.26	4.4
25	3.08	83	1.85	32.4	84	2.31	9	0.22	3.6	143	1.98	29	0.67	11.5
26	3.30	74	1.70	29.2	85	2.42	11	0.27	4.7	144	1.95	65	1.55	26.1
27	3.19	47	1.10	18.8	86	2.53	9	0.25	3.9	145	2.20	83	1.95	33.4
28	2.64	31	0.65	11.5	87	2.53	17	0.42	7.2	146	2.64	80	1.77	30.2
29	2.42	19	0.45	7.5	88	2.53	16	0.40	6.5	147	2.53	55	1.25	20.9
30	2.20	5	0.07	1.6	89	2.86	2	0.06	0.8	148	2.09	34	0.71	12.5
31	1.98	3	0.02	0.4	90	2.86	1	0.02	0.4	149	1.65	20	0.47	8.9
32	1.87	3	0.05	0.7	91	2.97	1	0.02	0.4	150	1.65	11	0.27	5.2
33	2.20	7	0.15	2.7	92	3.08	2	0.06	0.7	151	1.65	3	0.05	1.3
34	2.75	26	0.85	9.4	93	3.08	2	0.05	0.5	152	1.65	1	0.01	0.4
35	2.97	60	1.50	25.1	94	3.08	3	0.06	1.0	153	1.65	1	0.02	0.3
36	2.75	79	1.95	32.9	95	3.08	3	0.06	1.0	154	1.54	3	0.06	1.0
37	3.08	77	1.90	32.4	96	3.08	1	0.02	0.5	155	1.54	13	0.27	4.9
38	3.08	79	2.00	35.0	97	3.52	6	0.07	1.9	156	1.54	50	1.15	18.8
39	3.08	79	2.00	35.0	98	3.74	20	0.51	9.8	157	2.42	74	1.65	27.2
40	2.97	77	1.70	33.4	99	3.30	25	0.60	11.9	158	2.64	52	1.15	18.8
41	3.30	66	1.65	28.8	100	2.86	41	1.05	18.1	159	2.20	84	0.72	12.5
42	3.30	87	0.82	14.2	101	3.62	71	1.75	30.5	160	1.87	15	0.32	5.4
43	2.53	17	0.35	6.0	102	3.85	77	1.95	34.6	161	1.54	5	0.10	1.8
44	2.20	8	0.12	2.5	103	3.19	73	1.90	33.6	162	1.54	1	0.02	0.5
45	2.20	6	0.02	0.4	104	2.97	73	1.82	33.1	163	1.65	1	0.02	0.3
46	2.42	1	0.02	0.4	105	2.42	69	1.95	35.6	164	1.76	3	0.02	0.3
47	2.42	3	0.06	1.2	106	2.64	76	2.10	37.8	165	1.87	6	0.12	2.1
48	2.85	17	0.35	6.6	107	2.86	83	2.00	34.1	166	1.98	25	0.57	9.7
49	3.41	53	1.15	17.2	108	2.81	86	1.50	25.8	167	1.98	44	1.03	16.7
50	2.97	77	1.85	30.6	109	2.81	85	0.82	15.0	168	1.98	31	0.71	11.5
51	3.19	78	1.85	31.1	110	2.09	17	0.40	7.2	169	1.76	12	0.30	4.8
52	3.85	86	1.95	33.2	111	2.20	3	0.06	1.0	170	1.76	3	0.06	1.1
53	4.07	88	2.00	34.2	112	1.98	1	0.02	0.6	171	1.76	2	0.02	0.4
54	3.74	67	1.60	26.4	113	2.20	5	0.12	2.3	172	1.76	1	0.01	0.3
55	3.52	55	1.32	22.3	114	2.20	29	0.67	4.4	173	1.98	6	0.12	12.0
56	3.30	29	0.60	10.4	115	2.31	30	0.71	12.4	174	1.87	14	0.32	27.2
57	3.08	5	0.15	2.6	116	2.53	62	1.65	27.9	175	1.98	14	0.32	26.7
58	2.42	1	0.05	0.6	117	3.08	79	2.00	35.2	176	1.98	7	0.12	11.0
59	2.31	1	0.02	0.3	118	3.08	79	1.96	34.2	177	1.98	2	0.02	1.7

TABLE 4. EXHAUST PLUME EMISSIONS AT MAXIMUM CONTINUOUS THROTTLE SETTING

PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM	PT #	THC PPM-C	CO PPM	CO_2 %	NO_x PPM
1	1.9	4	0.46	15.5	60	1.4	5	0.32	10.3	119	0.1	31	2.48	86.8
2	1.9	20	1.72	56.3	61	1.1	14	0.11	31.5	120	0.1	31	2.50	87.8
3	2.3	27	2.40	81.6	62	1.0	21	1.65	53.7	121	0.4	35	2.45	81.6
4	2.4	35	2.70	93.0	63	0.7	30	2.25	75.4	122	0.7	28	2.10	67.2
5	2.4	36	2.47	89.9	64	0.6	34	2.50	88.8	123	1.3	11	0.75	23.5
6	2.4	31	2.53	87.8	65	0.5	37	2.65	94.0	124	1.7	5	0.15	5.1
7	2.4	30	2.38	86.8	66	0.5	36	2.55	88.8	125	1.7	2	0.06	2.0
8	2.1	31	2.32	80.6	67	0.6	31	2.25	75.4	126	2.6	2	0.01	0.3
9	1.7	31	2.35	80.6	68	1.0	19	1.40	45.4	127	1.4	2	0.06	1.9
10	1.5	35	2.50	83.7	69	1.4	7	0.47	16.0	128	1.4	3	0.15	4.6
11	1.2	38	2.65	87.8	70	1.5	4	0.11	3.6	129	1.2	10	0.72	24.2
12	1.2	34	2.57	82.6	71	1.7	2	0.02	0.6	130	0.6	21	1.75	56.8
13	1.4	25	1.97	64.0	72	1.7	2	0.06	1.3	131	0.4	31	2.50	86.8
14	1.8	11	0.75	23.7	73	1.4	5	0.30	9.8	132	0.2	32	2.55	89.9
15	1.3	3	0.05	0.7	74	1.2	12	0.97	31.7	133	0.2	32	2.58	90.9
16	1.9	6	0.46	14.4	75	0.8	21	1.70	54.2	134	0.4	33	2.28	74.4
17	1.4	17	1.50	48.6	76	0.7	28	2.20	72.8	135	0.4	32	2.10	66.1
18	0.6	28	2.35	80.6	77	0.2	36	2.68	93.0	136	0.6	22	1.55	47.5
19	0.6	34	2.70	93.0	78	0.7	24	1.97	65.1	137	1.2	11	0.65	20.1
20	0.7	34	2.68	91.9	79	0.8	17	1.40	44.9	138	1.5	4	0.06	1.9
21	0.8	31	2.80	87.8	80	1.1	12	0.95	30.4	139	1.4	1	0.02	0.3
22	1.1	31	2.45	84.7	81	1.3	5	0.25	7.3	140	1.7	1	0.02	0.1
23	1.2	32	2.40	81.6	82	1.4	1	0.02	0.5	141	1.8	4	0.10	3.0
24	1.1	38	2.42	79.5	83	1.5	3	0.15	6.2	142	1.4	9	0.55	18.6
25	1.0	38	2.52	83.7	84	1.2	9	0.65	21.7	143	1.0	17	1.35	43.4
26	1.1	33	2.38	77.5	85	1.2	14	1.10	36.1	144	0.2	28	2.33	79.5
27	1.4	21	1.65	51.6	86	1.0	21	1.72	55.8	145	0.1	32	2.63	93.0
28	1.5	18	1.32	41.8	87	0.7	28	2.27	77.5	146	0.5	28	2.13	70.2
29	1.7	9	0.65	20.1	88	1.3	16	1.12	36.2	147	1.0	18	1.45	45.9
30	1.3	2	0.05	0.8	89	1.5	6	0.37	12.6	148	1.0	14	0.95	31.5
31	1.8	3	0.12	4.1	90	1.5	5	0.27	8.5	149	1.2	9	0.52	17.5
32	1.5	5	0.46	15.0	91	1.5	4	0.07	2.3	150	1.4	3	0.30	10.3
33	1.4	12	1.01	35.1	92	1.2	7	0.55	18.1	151	1.7	1	0.02	0.6
34	1.2	25	2.10	70.2	93	1.1	12	0.97	31.5	152	2.1	1	0.02	0.1
35	1.1	34	2.60	88.8	94	1.1	10	0.90	29.9	153	1.4	1	0.02	0.6
36	1.0	34	2.52	86.8	95	1.2	5	0.45	14.4	154	1.4	2	0.15	5.7
37	1.0	34	2.42	83.7	96	1.7	2	0.05	1.0	155	1.2	9	1.65	20.1
38	0.8	35	2.35	78.5	97	1.7	6	0.42	14.7	156	0.8	18	1.55	50.6
39	0.8	37	2.35	78.5	98	1.4	16	1.20	41.3	157	0.6	31	2.30	78.0
40	0.6	38	2.42	80.6	99	1.5	17	1.27	43.9	158	1.0	23	1.60	50.6
41	0.6	29	1.97	64.1	100	1.7	23	1.70	58.9	159	1.3	12	1.07	25.3
42	1.1	16	1.12	37.2	101	2.1	32	2.42	85.7	160	1.8	6	0.35	11.1
43	1.2	14	0.90	29.9	102	2.3	36	2.52	88.8	161	1.7	2	0.10	2.5
44	1.4	7	0.45	14.4	103	1.9	34	2.38	83.7	162	1.5	2	0.05	0.7
45	2.4	3	0.02	0.5	104	1.1	33	2.35	82.6	163	2.1	1	0.02	0.1
46	1.5	5	0.15	5.4	105	0.6	32	2.40	86.3	164	1.4	1	0.05	0.8
47	1.4	11	0.65	21.2	106	0.6	34	2.42	84.7	165	1.4	5	0.26	8.3
48	0.8	23	1.75	57.8	107	0.5	36	2.42	80.6	166	1.1	13	0.82	27.1
49	0.5	32	2.45	83.7	108	0.7	25	1.65	52.7	167	0.6	21	1.55	49.6
50	0.4	32	2.50	86.8	109	1.2	28	1.01	32.0	168	0.6	18	1.35	42.0
51	0.5	36	2.50	86.8	110	1.5	10	0.45	13.9	169	1.1	8	0.51	16.5
52	0.5	37	2.53	86.8	111	2.6	3	0.01	0.5	170	1.3	3	0.10	2.7
53	0.6	36	2.45	83.7	112	1.4	4	0.12	4.1	171	1.5	1	0.02	0.2
54	0.8	33	2.30	77.5	113	1.2	7	0.46	14.4	172	2.1	1	0.02	0.1
55	0.8	18	1.55	50.1	114	1.1	8	0.50	16.0	173	1.8	3	0.20	6.9
56	1.3	9	0.65	21.7	115	0.8	34	0.97	31.5	174	1.5	6	0.42	13.9
57	1.1	5	0.32	10.8	116	0.2	23	1.87	61.0	175	1.2	6	0.42	13.4
58	1.8	1	0.10	3.2	117	0.1	31	2.43	82.6	176	1.4	3	0.15	5.0
59	1.6	1	0.02	0.9	118	0.1	33	2.45	84.7	177	2.3	1	0.02	0.2

$$t_T = \sum_{1}^{16} t = |t_1| + |t_2| + |t_3| \ . \ . \ . \ |t_{16}|$$

A probe configuration is a candidate for optimized fixed sample probe which represents a possible solution.

Families are sets of up to nine similar geometric configurations along with the data residue points not included in the members of the family. Each configuration of the family is mutually exclusive so that each of the 177 traverse points is associated with one and only one configuration.

A residue is the configuration belonging to each family which is made up of the unused points not belonging to any other configuration of the family.

A traverse grid with 177 traverse points is the sampling system for the engine exhaust (figure 1).

DESCRIPTION OF METHOD.

A special computer program was implemented to evaluate the frequency distribution of traverse emission measurements. Results in the form of histograms are presented in appendix A and show that the measurements are in a bimodal distribution rather than a normal distribution. The large number of low emission measurements located in the outer circumference of the plume (fan by-pass) was the first mode. The second mode consisted of the large number of high-emission measurements located at or near the center of the exhaust plume. The analysis techniques utilized in this report were selected based on the bimodal distributions.

The raw t ratio was the vehicle used to determine the relative merit of a probe configuration across the four gas groups and four throttle settings. When manually summed through all 16 combinations for a particular configuration, it was denoted as $\Sigma\ t_T$. The raw t ratio permitted comparison between and over all gas groups. This is important, because CO_2 was in units of percent, while the other gas groups were in units of parts per million. The numerator of the raw t ratio, $(\overline{X}_C - \overline{\overline{X}})$ was taken as an indication of a configurations accuracy. The denominator S_T was used as a means of normalizing the difference of the means to permit summation across gas groups and throttle settings. The square root of the sample size was not used in the raw t ratio to facilitate direct comparison of candidate probes with variable number of sample points.

The absolute value of the t_T quantity gave a single index to be used in ranking. A small magnitude was considered desirable.

PROCEDURE.

The analysis was divided into two parts, the determination of a representative traverse grid area, and the selection of the optimized probe configuration and location.

The representative area of the traverse grid was defined by processing several families of symmetrical probe configurations including cruciforms, annuluses, squares, diamonds, and hybrids. The t_T values were ranked for each traverse and gas specie. This practice was followed throughout the remainder of the analysis. Two lists were tabulated, each encompassing all 16 combinations. One list contained probe configurations associated with the three smallest t_T values for each condition. The other list contained configurations associated with the three largest t_T values for each condition. The configurations representing the smallest and largest t_T values of each condition were plotted, using a color code, on blank traverse grids. The areas of highest line density for the smallest and largest t_T values were declared representative or nonrepresentative, respectively. All 16 gas-throttle setting combinations were analyzed independently in order to get a detailed picture of the representative area for each traverse. The Σt_T value is a composite estimate of this area and is more easily implemented.

From this point on, probe families lost their significance, and individual probe configurations were considered. The representative area was redefined into a smaller area until one of practical size was found. Care was taken to avoid passing the optimum probe configuration and reducing the configuration to a point where the Σt_T values began to increase.

To determine the optimized fixed probe, configurations were fitted into the representative area, and the Σt_T values served to redefine the representative area. Two iterations of this procedure led to the ABCDE configuration of run 103. This probe configuration contained relatively few sampling points, 28 points sampled of 177 possibilities. The ABCDE configuration was broken into its components A, B, C, D, and E. All 31 possible combinations of these components were run against their residue. At this point the Σt_T quantities were supplemented by the ordered $(\bar{X}_C-\bar{\bar{X}})$ quantities, and the procedure became more subjective in order to comply with engineering requirements of simplicity and ease of fabrication. Color-coded overlays were drawn showing the best configurations associated with the three smallest $(\bar{X}_C-\bar{\bar{X}})$ values of each condition.

A configuration with a good Σt_T rating, in the area of high line density of the overlays just drawn, and meeting the engineering requirements was chosen as the final probe configuration.

RESULTS

ANNULAR AND CRUCIFORM PROBE FAMILIES.

Families of sample probes annular in geometric shape were compared with probe families of cruciform geometry. The annular probe family is shown in figure 2, and the cruciform probe family is depicted in figure 3. Because of the interest shown in these two families, the ranked Σt_T values have been tabulated in table 5. For the sake of completeness, all configurations

TABLE 5. SUMMATION OF t_T VALUES FOR ANNULAR AND CRUCIFORM PROBE FAMILIES

Configuration	N	$\Sigma\, t_T$
06	28	2.491
01 (RES)	21	2.972
+5	20	4.225
+4	20	4.232
+1 (RES)	89	6.252
+3	20	6.295
07	32	9.458
+2	28	9.917
05	20	13.529
08	40	15.282
02	8	20.327
04	16	20.695
03	12	21.849

NOTE:
1. Annular probes are designated 02 through 08 with 01 being residue.
2. Cruciform probes are designated +2 through +5 with +1 being residue.
3. Small magnitude of summation of t_T is desirable.
4. See appendix B for additional values supporting this table.

and residue have been included. As may be noted, the annular probes are designated 02 through 08, with the points that do not belong to any probe termed residue and assigned the 01 designation. The cruciform probes are designated +2 through +5, with the residue points designated +1. Table 5 compares the ordered raw t values representing all gas groups and throttle settings combined for the two probe families.

Performance of annular probe 06 (figure 4) was the best, with the lowest t_T value. The residue (01) from the annular probe was ranked second in performance. Cruciform probes +5 and +4 (figure 5) were third and fourth ranked in relative performance.

PROBE ANALYSIS.

To define the representative and nonrepresentative areas of the composite 16 traverses, the $\Sigma\, t_T$ magnitudes for members of families of symmetrical configurations were found. Composite traverse-grid plots were made showing the three best and three worst configurations of each rectangle, fragmented rectangle, diamond, cruciform, annulus, and hybrid configuration designed to investigate the effects of width, symmetry, and rotation used.

Rectangles encompassed the area bounded by lines drawn from points 43 to 79 and 27 to 66 (figure 1) in the first quadrant. This area is reflected in all four quadrants. Declared nonrepresentative were points along both the horizontal and vertical centerlines, points about the intersection of the centerlines, and points along the periphery of the grid-traverse area.

To select the optimized probe configuration, members of existing families were sampled predominantly in the representative area. New configurations were sampled entirely in the representative area and were subjected to a $\Sigma\, t_T$ analysis. This resulted in the configuration of run 30 (figure 6). Run 30 was then subjected to displacements, dismemberments, extensions, and all sorts of agonizing contortions. This resulted in the selection of run 103 (figure 7) which was an improvement.

The final solution was obtained by considering the 31 possible combinations of the 5 segments associated with one quadrant of run 103 (figure 7). This resulted in the final ABD configuration of run 104 (figure 8).

Table 6 lists the summation of t_T for the ABCDE configuration of run 103.

The THC-MAX traverse data are in error. Table 6 lists the $\sum_{1}^{15} t_T$, without the THC-MAX traverse, and $\sum_{1}^{16} t_T$, with the THC-MAX traverse. Configuration ABD had the best summation of t_T and it is therefore declared the optimized probe representing a solution. Table 7 compares the summation of the raw t_T of the final ABD configuration with the best annulus and cruciform configuration.

TABLE 6. SUMMATION OF t_T VALUES FOR ABCDE CONFIGURATIONS OF FIGURE 7

Rank	Configuration	$\sum_{1}^{15} t_T$	Configuration	$\sum_{1}^{16} t_T$
1	ABD	1.206	ABD	1.738
2	BD	1.391	ABC	1.887
3	ABDE	1.431	ABDE	1.920
4	ABC	1.462	BC	1.987
5	BDE	1.487	BD	2.010
6	BC	1.502	BDE	2.037
7	ABE	1.551	ABCE	2.069
8	AE	1.642	AE	2.084
9	ABCE	1.670	AD	2.099
10	AD	1.693	ABE	2.109
11	BE	1.700	BCE	2.227
12	BCE	1.785	ABCD	2.254
13	ABCD	1.855	ADE	2.298
14	A	1.901	BE	2.353
15	ADE	1.918	ABCDE	2.373
16	BCD	1.973	BCD	2.415
17	ABCDE	1.992	A	2.510
18	BCDE	2.162	BCDE	2.576
19	AC	3.044	AC	3.316
20	ACE	3.088	ACE	3.361
21	AB	3.203	ACD	3.560
22	ACD	3.288	ACDE	3.560
23	ACDE	3.288	AB	3.952
24	E	3.762	E	4.035
25	DE	4.339	DE	4.567
26	D	4.855	D	5.063
27	B	5.338	CDE	5.934
28	CDE	5.829	B	6.371
29	CE	6.351	CE	6.401
30	CD	6.354	CD	6.403
31	C	7.908	C	7.971

TABLE 7. SUMMATION OF t_T VALUES FOR THE BEST PROBE WITH THE BEST OF THE ANNULUS AND CRUCIFORM PROBE FAMILIES

	Best Probe (Figure 8)	Annular Probe-06	Cruciforms Probe +5	Cruciforms Probe +4
Σt_T	1.738	2.491	4.225	4.232

SUMMARY OF RESULTS

Emissions were measured at 177 sample locations on a 30-inch-diameter traverse grid encompassing the exhaust plume of mixed-flow JT8D-11 engine at each of four engine power settings from idle through maximum continuous power. The objective was to establish the average emission levels and to provide a data base as required to determine and evaluate fixed probe locations in the exhaust plume for acquiring representative emission samples. An analysis was conducted on the traverse-grid emission measurements to establish representative and nonrepresentative areas of the traverse.

The parameters used in this approach were those values associated with the evaluation across four gas groups, four throttle settings, and numerous families of probe configurations. A prime parameter utilized in this analysis was the raw t ratio defined as $(\overline{X}_C - \overline{\overline{X}}/S_T)$ the sample mean minus the grand mean divided by the standard deviation of the 177-point gas traverse.

Analysis included an investigation of numerous geometric configurations consisting of fragmented diamonds, rectangles, cruciforms, annuluses, and hybrid probes. The conclusion of this effort consisted of the selection of seven points in each of the quadrants, located on chords at three-fifths to two-thirds of the radius. The final solution was obtained by considering all the possible combinations of the points previously selected. This resulted in a probe configuration consisting of five points in each of the quadrants located on chords at three-fifths to two-thirds of the radius.

CONCLUSIONS

Based upon the results reported herein, it is concluded that:

1. There is an area of the JT8D exhaust plume suitable for acquiring representative emission samples with fixed probes.

2. The best probe configuration consisted of five points in each quadrant (20 total sample points) located on chords at 56.5 percent and 65.9 percent of the radius.

REFERENCES

1. Clean Air Amendments of 1970, Public Law 91-604, 91st Congress, H.R. 17255, December 31, 1970.

2. McAdams, H. T., Analysis of Aircraft Exhaust Emission Measurements Statistics, EPA Technical Report NA-5007-K-2.

3. Souza, Anthony F. and Reckner, Louis K., Variability in Aircraft Turbine Engine Emission Measurements, Technical Report EPA 460/3-74-006.

4. Klueg, Eugene P. and Slusher, Gerald R., Exhaust Emission Probe Investigation of a Mixed Flow Turbofan Engine, Paper Presented Before the Instrument Society of America, October 1974.

5. Rules and Regulations, Part 87, Control of Air Pollution From Aircraft and Aircraft Engines, Federal Register, Volume 38, NO137, July 17, 1973.

6. Croxton, Frederick E., Elementary Statistics, Dover, 1953.

7. Dixon, Wilfrid J., and Massey, Frank J., Introduction to Statistical Analysis, McGraw-Hill, 1957.

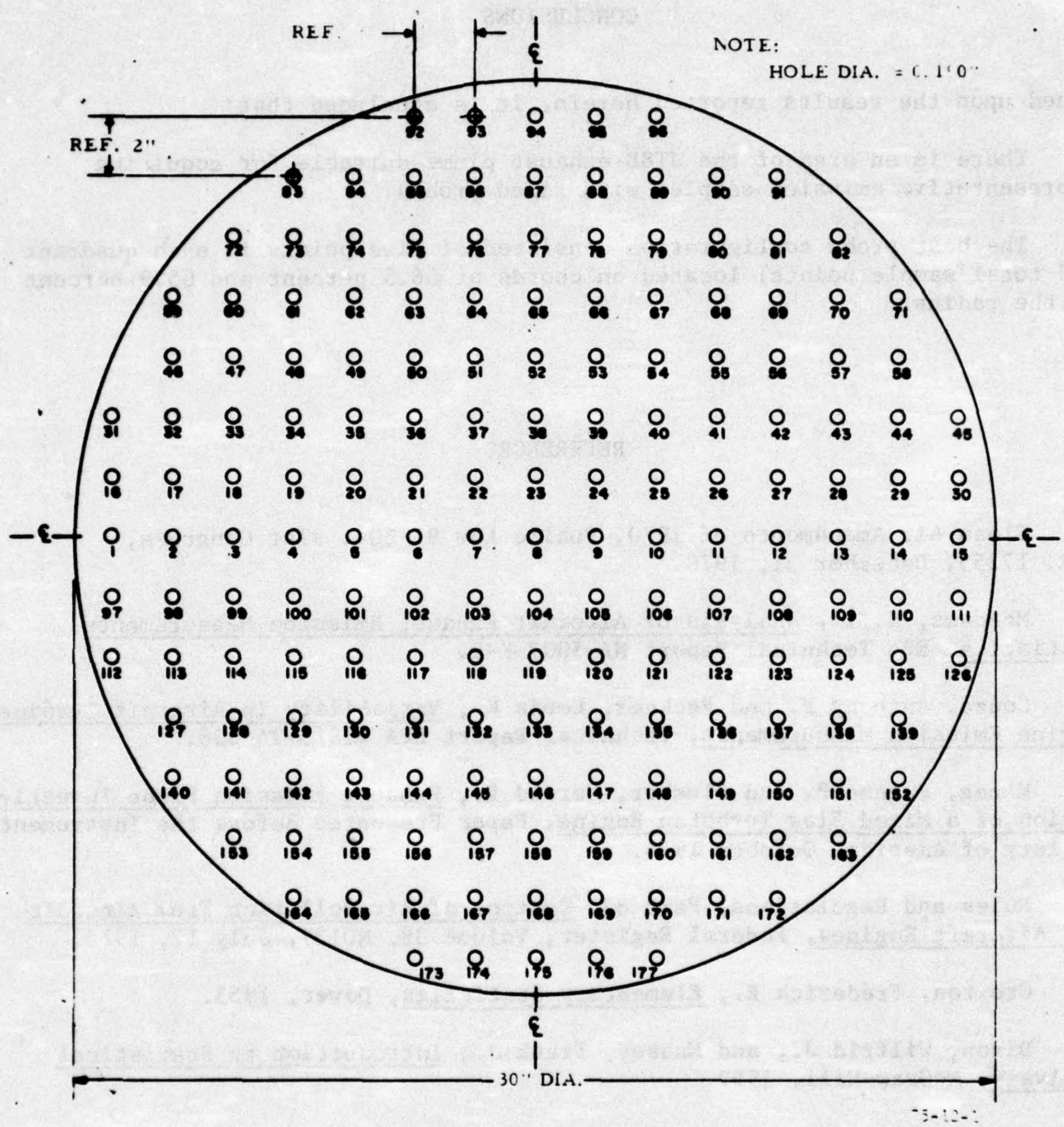

FIGURE 1. TRAVERSE EMISSION SAMPLING POINTS (177)

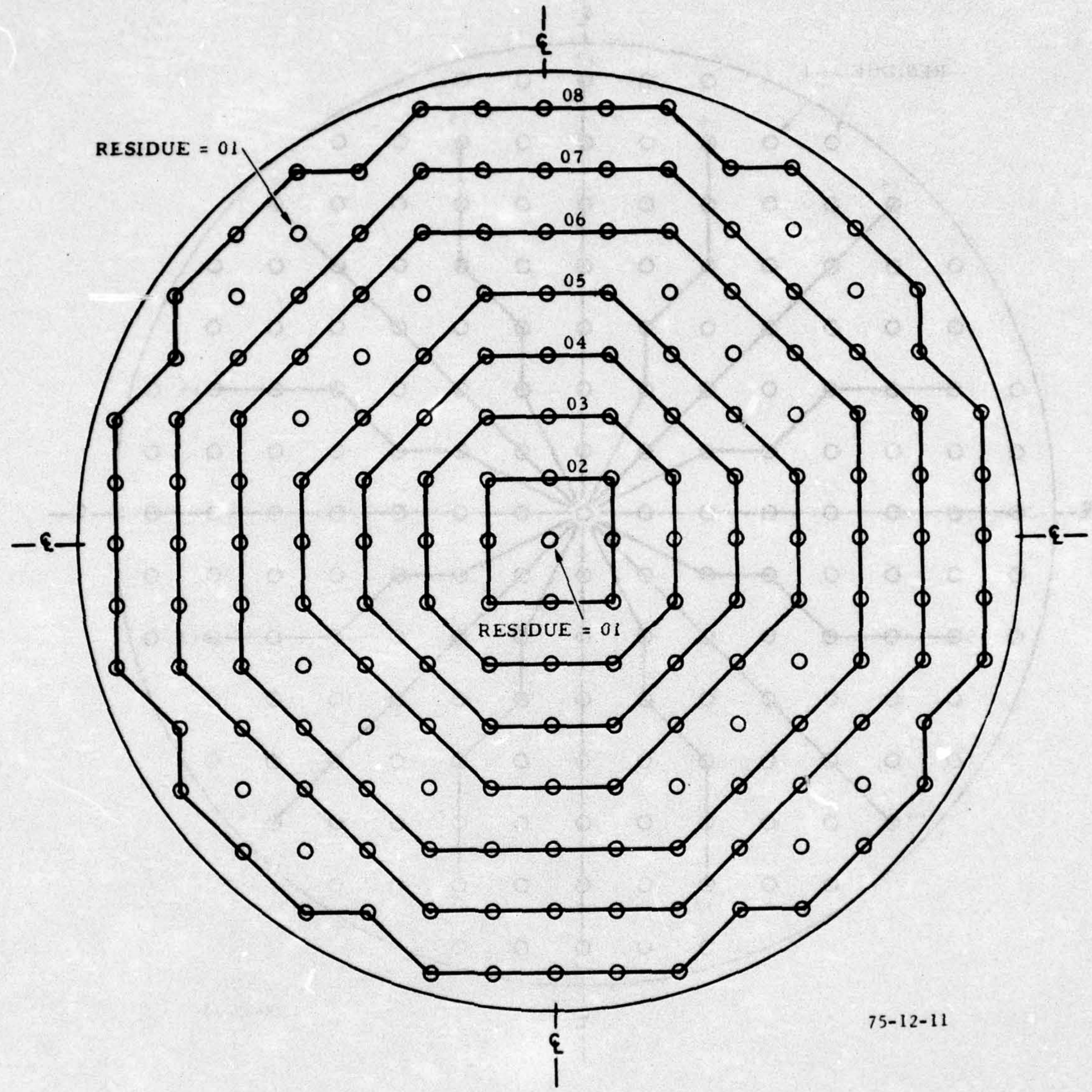

FIGURE 2. ANNULUS FAMILY OF PROBES (RUN 1)

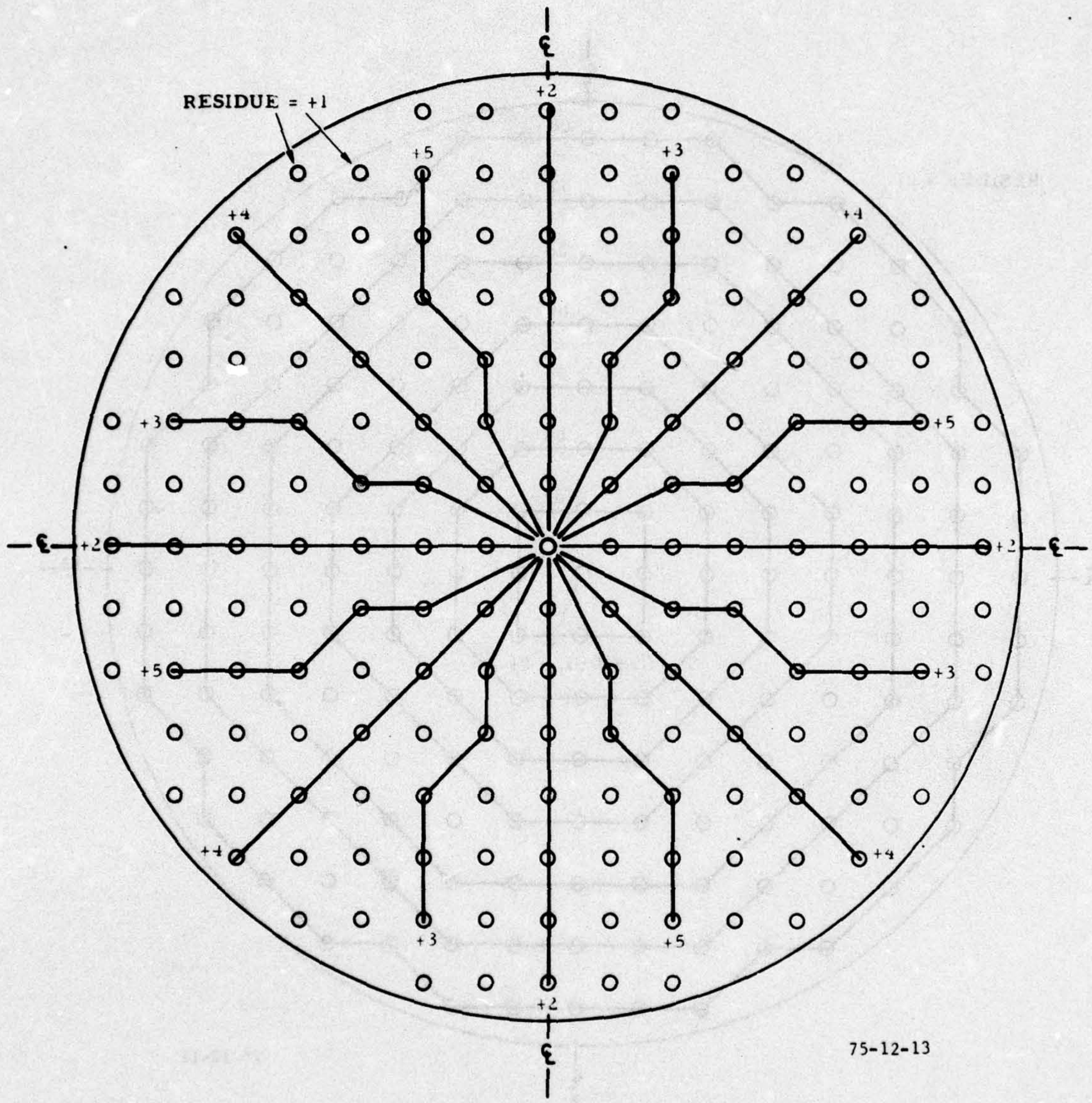

FIGURE 3. CRUCIFORM FAMILY OF PROBES (RUN 2)

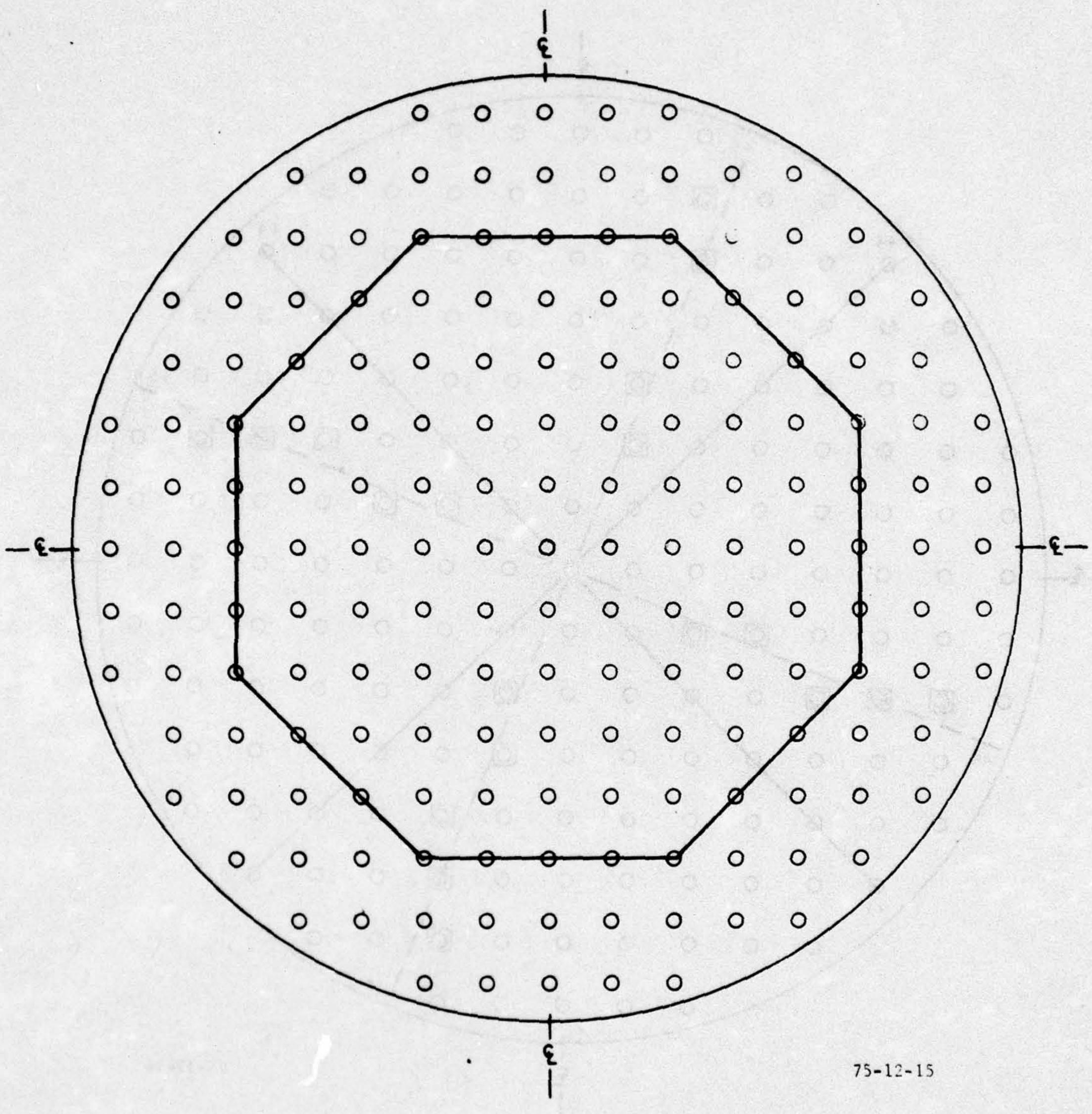

FIGURE 4. ANNULUS 06 ONLY

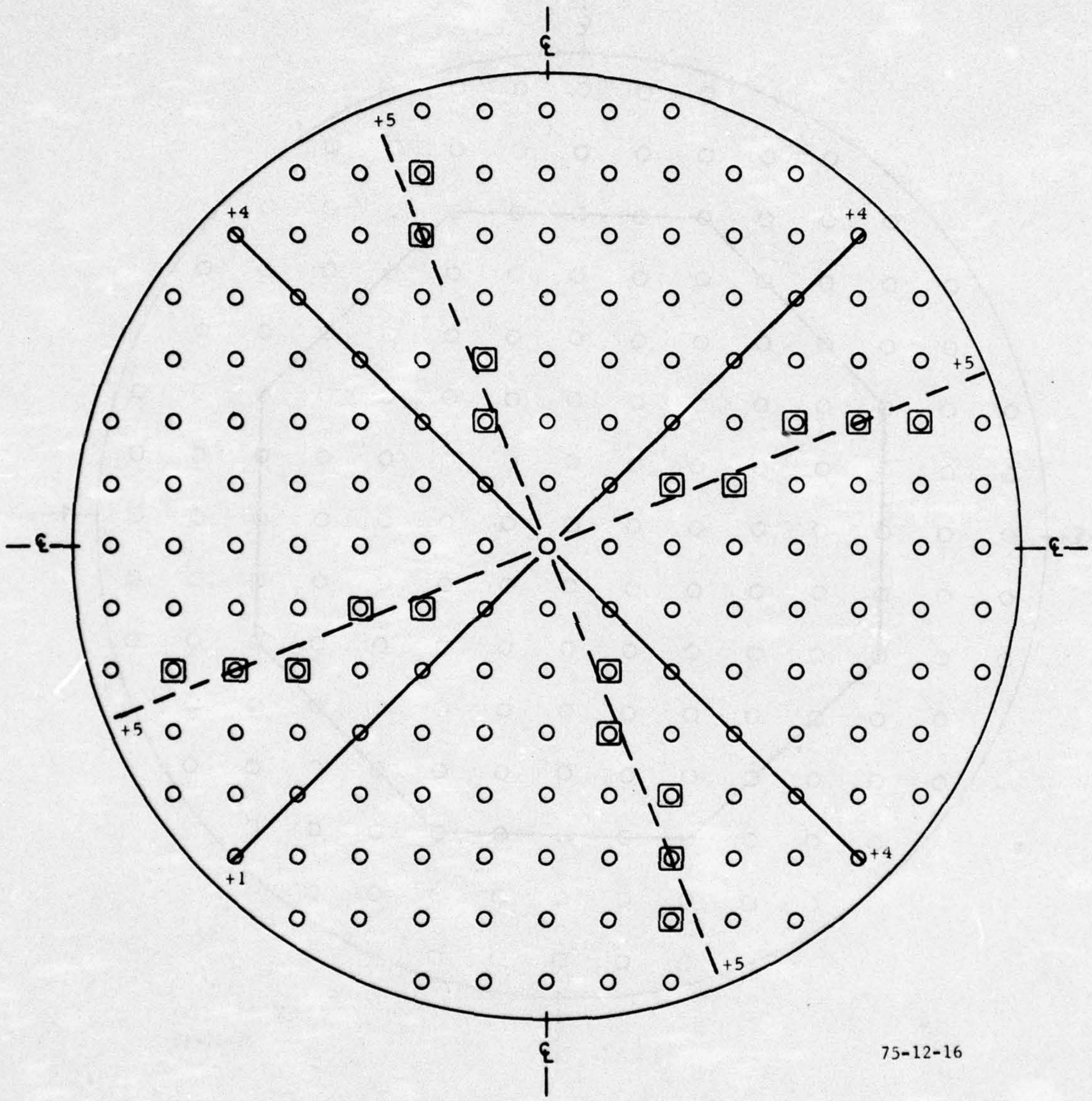

FIGURE 5. CRUCIFORMS +4 AND +5 ONLY

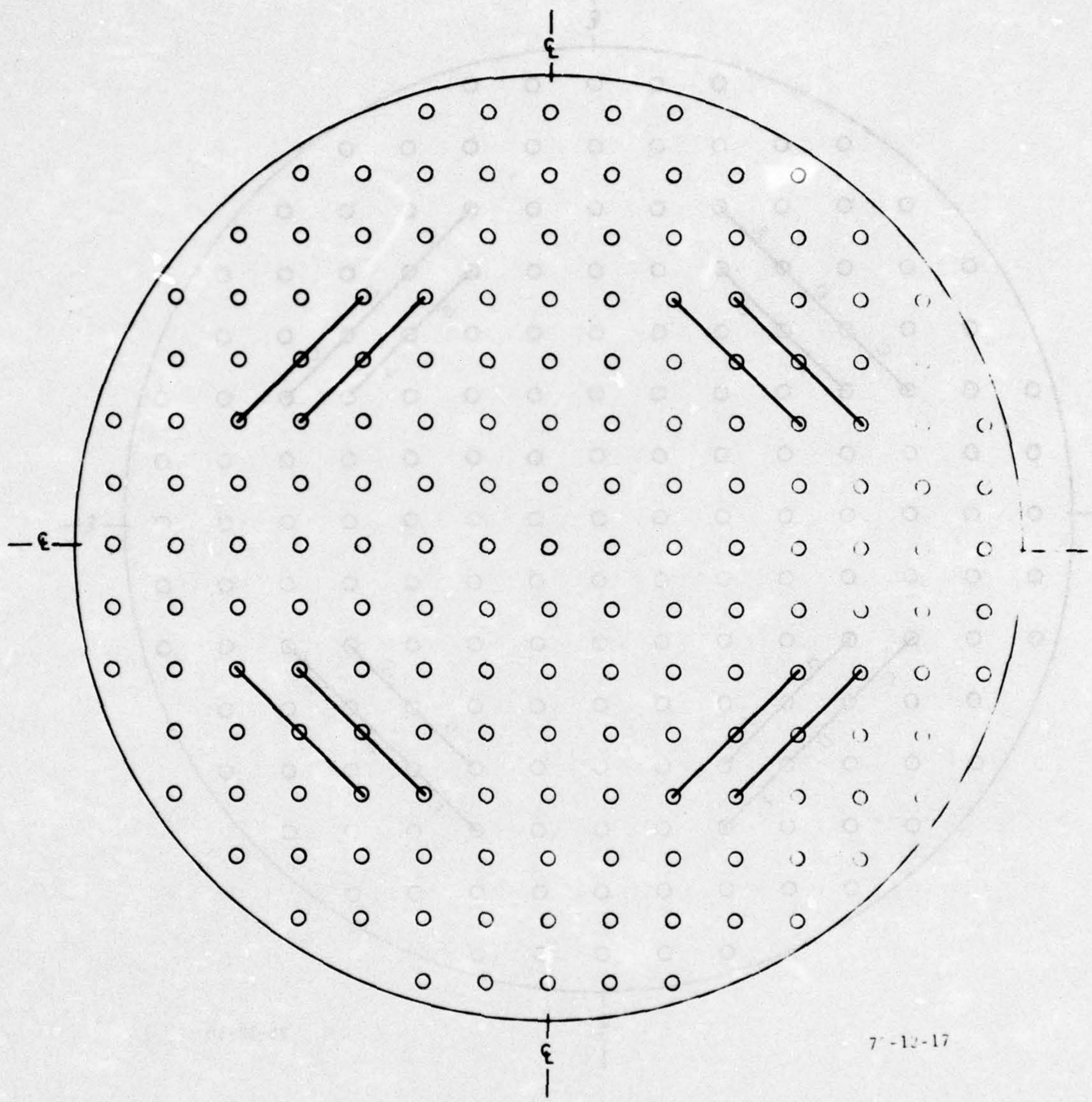

FIGURE 6. A GOOD PROBE CONFIGURATION (RUN 30)

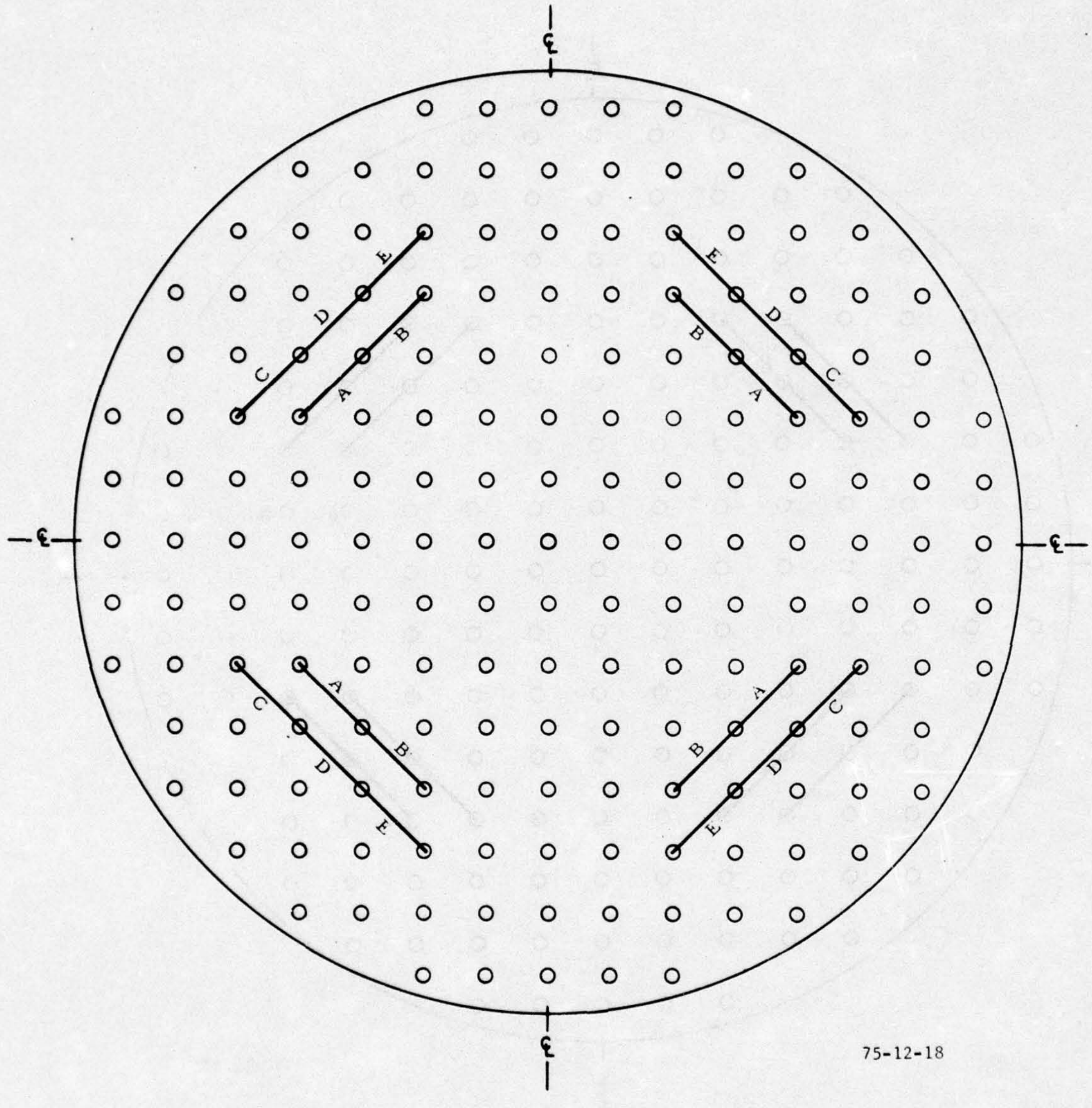

FIGURE 7. A BETTER PROBE CONFIGURATION (RUN 103)

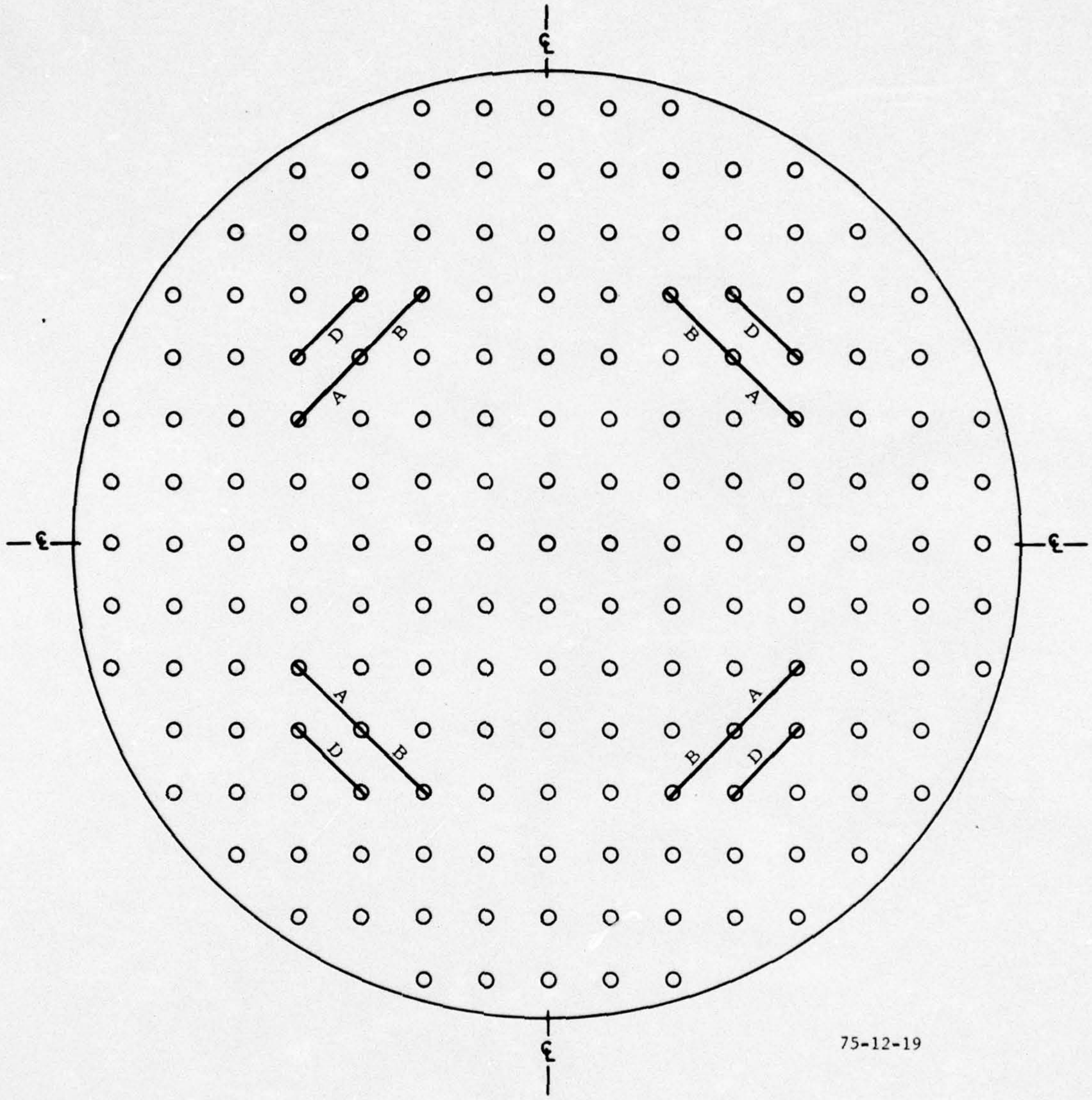

FIGURE 8. THE BEST PROBE CONFIGURATION (RUN 104)

APPENDIX A

TRAVERSE HISTOGRAMS

Histograms were calculated for each gas traverse using a special computer program. The histogram consists of 12 columns each 1/2 S wide. The first and last columns are somewhat wider, extending from $-\infty$ to -5/2 S and 5/2 S to $+\infty$, respectively. The frequency values (ordinates) of the columns were normalized upon the column with the maximum frequency value. The ordinate units are 1/10 the maximum frequency value and may assume values of 0, 1/10, 2/10, 3/10, through 10/10.

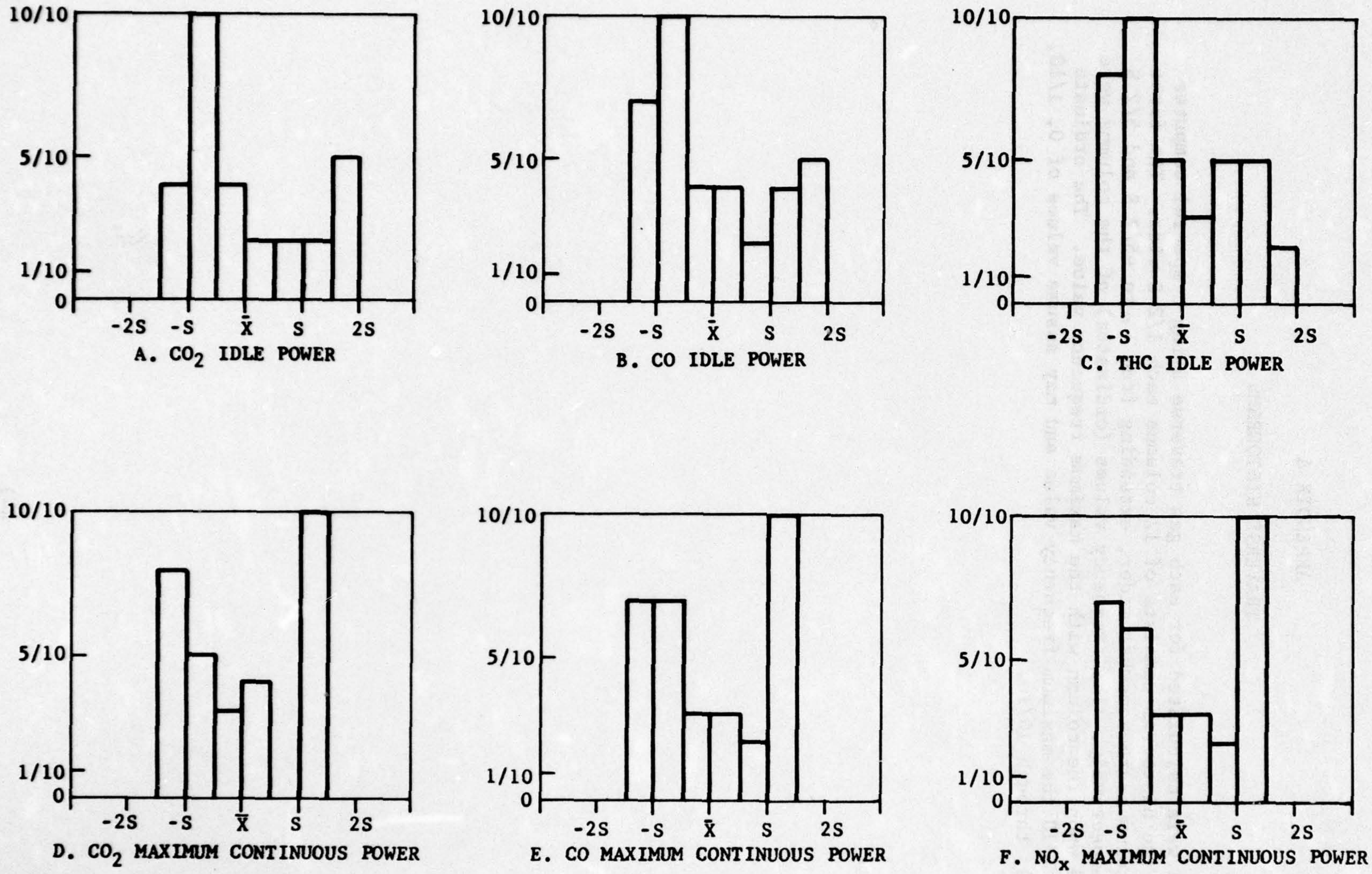

FIGURE A-1. TRAVERSE EXHAUST PLUME HISTOGRAMS

APPENDIX B

TRAVERSE STANDARD DEVIATIONS AND DIFFERENCE OF THE MEANS FOR GASES AND THROTTLE SETTINGS--ANNULAR AND CRUCIFORM PROBE FAMILIES

TABLE B-1. STANDARD DEVIATION FOR THE TRAVERSES

Gas Power	S_T
THC-IDLE	88.181
HOLD	22.078
MAX	0.559
APP	0.670
CO2-IDLE	0.655
HOLD	0.691
MAX	0.984
APP	0.762
CO-IDLE	203.838
HOLD	131.590
MAX	12.858
APP	31.616
NO_X-IDLE	5.271
HOLD	6.510
MAX	33.729
APP	13.094

TABLE B-2. DIFFERENCE BETWEEN SAMPLE MEAN AND THE GRAND 177-POINT TRAVERSE MEAN FOR ANNULAR AND CRUCIFORM PROBE FAMILIES (QUALIFYING DATA IN SUPPORT OF TABLE 5)

Configuration	01	02	03	04	05	06	07	08
THC-IDLE	-13.487	106.791	122.041	117.329	78.241	-5.673	-53.703	-90.009
HOLD	-3.496	22.143	28.864	30.518	19.150	-0.809	-13.039	-22.037
MAX	-0.083	0.185	-0.244	-0.421	-0.412	-0.084	-0.104	0.430
APP	-0.198	0.597	0.681	0.550	0.365	-0.111	-0.264	-0.334
CO2-IDLE	-0.121	1.055	1.059	0.921	0.521	-0.172	-0.444	-0.619
HOLD	-0.130	1.113	1.107	0.989	0.542	-0.192	-0.451	-0.658
MAX	-0.164	1.101	1.197	1.193	0.951	0.081	-0.512	-1.093
APP	-0.172	1.014	1.134	1.102	0.750	-0.122	-0.517	-0.770
CO -IDLE	-31.880	306.644	318.894	277.707	168.644	-38.106	-134.450	-201.431
HOLD	-21.548	188.160	207.369	183.973	108.035	-25.715	-86.590	-128.865
MAX	-1.609	14.778	15.986	16.715	12.103	0.617	-7.129	-14.372
APP	-5.589	37.845	43.304	44.033	30.620	-0.958	-21.998	-32.280
NOX-IDLE	-0.968	9.096	8.758	7.308	3.953	-1.613	-3.563	-4.859
HOLD	-1.228	10.959	10.722	9.034	4.972	-1.746	-4.359	-6.153
MAX	-5.905	39.992	41.475	41.610	32.307	1.745	-18.065	-36.908
APP	-3.673	17.604	19.516	18.985	12.186	-2.680	-9.171	-11.921

Configuration	+1	+2	+3	+4	+5
THC-IDLE	-35.270	43.570	36.921	29.551	29.481
HOLD	-8.878	12.084	9.070	6.185	6.930
MAX	0.100	0.066	-0.297	-0.142	-0.097
APP	-0.171	0.594	-0.085	-0.078	0.092
CO2-IDLE	-0.279	0.390	0.318	0.209	0.170
HOLD	-0.296	0.421	0.309	0.249	0.172
MAX	-0.391	0.717	0.379	0.126	0.230
APP	-0.323	0.543	0.252	0.213	0.213
CO -IDLE	-86.547	120.573	95.844	66.294	54.194
HOLD	-55.653	81.000	60.785	38.385	35.085
MAX	-5.308	8.795	4.453	2.353	4.503
APP	-12.454	20.363	8.370	7.370	11.170
NOX-IDLE	-2.261	3.133	2.478	1.793	1.403
HOLD	-2.827	4.029	3.007	2.197	1.737
MAX	-13.884	25.045	12.907	5.907	7.907
APP	-5.423	9.616	3.941	3.576	3.151

APPENDIX C

RAW t AND DIFFERENCE OF THE MEANS FOR GASES AND THROTTLE SETTINGS--ABCDE CONFIGURATIONS

TABLE C-1. RAW t VALUES FOR A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($|t|$ and Σt_T)

	A	B	C	D	E	AB	AC	AD
N	8	8	8	8	8	12	16	16
#1 CO APP	0.264	0.367	0.566	0.432	0.333	0.279	0.151	0.084
#2 HOLD	0.084	0.339	0.539	0.311	0.204	0.196	0.228	0.113
#3 IDLE	0.068	0.369	0.565	0.298	0.167	0.216	0.241	0.113
#4 MAX	0.352	0.517	0.493	0.231	0.143	0.440	0.071	0.060
#5 CO2 APP	0.127	0.349	0.584	0.434	0.341	0.166	0.228	0.162
#6 HOLD	0.020	0.271	0.569	0.381	0.298	0.136	0.275	0.181
#7 IDLE	0.020	0.283	0.584	0.380	0.252	0.135	0.302	0.200
#8 MAX	0.244	0.605	0.507	0.207	0.506	0.385	0.131	0.018
#9 NOX APP	0.030	0.294	0.667	0.461	0.370	0.091	0.318	0.215
#10 HOLD	0.005	0.251	0.505	0.369	0.311	0.126	0.250	0.182
#11 IDLE	0.027	0.260	0.567	0.378	0.302	0.122	0.297	0.202
#12 MAX	0.202	0.571	0.504	0.230	0.093	0.354	0.151	0.014
#13 THC APP	0.113	0.036	0.278	0.258	0.707	0.013	0.082	0.072
#14 HOLD	0.195	0.395	0.463	0.251	0.119	0.268	0.134	0.028
#15 IDLE	0.147	0.430	0.514	0.236	0.070	0.275	0.183	0.044
#16 MAX	0.608	1.033	0.063	0.205	0.272	0.749	0.272	0.406
$\sum_{1}^{15}$	1.901	5.338	7.908	4.858	3.762	3.203	3.044	1.693
$\sum_{1}^{16}$	2.510	6.371	7.971	5.063	4.035	3.952	3.316	2.099

TABLE C-1. RAW t VALUES FOR A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS (|t| and Σt_T) (continued)

	AE	BC	BD	BE	CD	CE	DE	ABC
N	16	16	16	16	12	12	12	20
#1 CO APP	0.034	0.100	0.032	0.017	0.339	0.465	0.375	0.059
#2 HOLD	0.060	0.100	0.140	0.068	0.455	0.400	0.248	0.098
#3 IDLE	0.049	0.091	0.035	0.101	0.451	0.395	0.227	0.091
#4 MAX	0.104	0.012	0.143	0.187	0.363	0.390	0.215	0.066
#5 CO2 APP	0.107	0.117	0.051	0.004	0.528	0.479	0.391	0.134
#6 HOLD	0.139	0.149	0.055	0.013	0.339	0.463	0.337	0.146
#7 IDLE	0.136	0.150	0.048	0.016	0.500	0.446	0.310	0.152
#8 MAX	0.097	0.049	0.199	0.277	0.358	0.351	0.152	0.028
#9 NOX APP	0.170	0.186	0.083	0.038	0.586	0.550	0.412	0.212
#10 HOLD	0.153	0.127	0.059	0.030	0.455	0.427	0.336	0.127
#11 IDLE	0.164	0.154	0.059	0.021	0.492	0.466	0.340	0.154
#12 MAX	0.055	0.335	0.170	0.239	0.368	0.366	0.183	0.011
#13 THC APP	0.297	0.157	0.147	0.371	0.339	0.503	0.490	0.119
#14 HOLD	0.038	0.034	0.072	0.138	0.384	0.312	0.171	0.024
#15 IDLE	0.038	0.042	0.097	0.180	0.396	0.337	0.152	0.041
#16 MAX	0.440	0.485	0.619	0.652	0.049	0.049	0.228	0.424
$\sum_{1}^{15}$	1.644	1.502	1.391	1.700	6.354	6.351	4.339	1.462
$\sum_{1}^{16}$	2.084	1.987	2.010	2.353	6.403	6.401	4.567	1.887

TABLE C-1. RAW t VALUES FOR A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS (|t| and Σt_T) (continued)

N	ABD	ABE	ACD	ACE	ADE	BCD	BCE	BDE
	20	20	20	20	20	20	20	20
#1 CO APP	0.006	0.034	0.202	0.173	0.120	0.161	0.132	0.078
#2 HOLD	0.006	0.036	0.240	0.206	0.115	0.137	0.104	0.013
#3 IDLE	0.010	0.063	0.243	0.210	0.109	0.123	0.090	0.011
#4 MAX	0.171	0.206	0.078	0.093	0.012	0.011	0.027	0.078
#5 CO2 APP	0.081	0.037	0.265	0.237	0.183	0.177	0.148	0.095
#6 HOLD	0.071	0.038	0.289	0.270	0.194	0.189	0.169	0.094
#7 IDLE	0.071	0.019	0.308	0.276	0.194	0.187	0.155	0.073
#8 MAX	0.148	0.210	0.117	0.113	0.007	0.027	0.031	0.151
#9 NOX APP	0.130	0.093	0.340	0.318	0.235	0.234	0.212	0.130
#10 HOLD	0.072	0.049	0.271	0.254	0.199	0.173	0.156	0.101
#11 IDLE	0.078	0.048	0.306	0.291	0.215	0.191	0.176	0.100
#12 MAX	0.121	0.175	0.140	0.139	0.029	0.008	0.009	0.118
#13 THC APP	0.111	0.291	0.159	0.257	0.248	0.218	0.316	0.308
#14 HOLD	0.060	0.113	0.153	0.109	0.024	0.073	0.028	0.055
#15 IDLE	0.070	0.137	0.178	0.143	0.032	0.065	0.030	0.081
#16 MAX	0.532	0.559	0.277	0.272	0.380	0.442	0.442	0.550
$\sum_{1}^{15}$	1.206	1.551	3.288	3.088	1.918	1.973	1.785	1.487
$\sum_{1}^{16}$	1.738	2.109	3.560	3.361	2.298	2.415	2.227	2.037

TABLE C-1. RAW t VALUES FOR A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($|t|$ and Σt_T) (continued)

	CDE	ABCD	ABCE	ABDE	ACDE	BCDE	ABCDE
N	16	24	24	24	24	24	28
#1 CO APP	0.450	0.117	0.093	0.048	0.212	0.178	0.138
#2 HOLD	0.372	0.129	0.102	0.026	0.220	0.135	0.128
#3 IDLE	0.359	0.117	0.090	0.006	0.217	0.116	0.113
#4 MAX	0.319	0.038	0.025	0.112	0.095	0.040	0.006
#5 CO2 APP	0.463	0.181	0.157	0.112	0.266	0.192	0.193
#6 HOLD	0.434	0.180	0.163	0.101	0.282	0.199	0.189
#7 IDLE	0.418	0.182	0.155	0.087	0.285	0.184	0.181
#8 MAX	0.279	0.013	0.016	0.117	0.104	0.016	0.005
#9 NOX APP	0.518	0.247	0.229	0.161	0.336	0.248	0.257
#10 HOLD	0.408	0.164	0.150	0.105	0.271	0.189	0.179
#11 IDLE	0.435	0.185	0.172	0.109	0.299	0.203	0.196
#12 MAX	0.298	0.007	0.006	0.085	0.135	0.009	0.018
#13 THC APP	0.493	0.176	0.258	0.251	0.291	0.340	0.287
#14 HOLD	0.291	0.058	0.022	0.049	0.129	0.062	0.051
#15 IDLE	0.292	0.060	0.031	0.062	0.146	0.051	0.049
#16 MAX	0.105	0.399	0.399	0.488	0.272	0.414	0.381
$\sum_{1}^{15}$	5.829	1.855	1.670	1.431	3.288	2.162	1.992
$\sum_{1}^{16}$	5.934	2.254	2.069	1.920	3.560	2.576	2.373

TABLE C-2. DIFFERENCE BETWEEN SAMPLE MEAN AND GRAND MEAN FOR THE A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($\bar{X}_C-\bar{\bar{X}}$)

	A	B	C	D	E	AB	AC	AD
N	8	8	8	8	8	12	16	16
#1 CO APP	8.345	11.595	-17.905	-13.665	-10.530	8.804	-4.780	-2.655
#2 HOLD	11.035	44.660	-70.965	-40.965	-26.840	25.869	-29.965	-14.965
#3 IDLE	13.894	75.144	-112.356	-60.856	-33.981	43.977	-49.231	-23.481
#4 MAX	4.528	6.653	-6.374	-2.292	-1.847	5.653	-0.910	0.778
#5 CO2 APP	0.097	0.266	-0.445	-0.344	-0.260	0.126	-0.174	-0.123
#6 HOLD	0.014	0.188	-0.394	-0.264	-0.206	0.094	-0.190	-0.125
#7 IDLE	-0.014	0.185	-0.382	-0.249	-0.165	0.089	-0.198	-0.131
#8 MAX	0.240	0.595	-0.499	-0.204	-0.050	0.378	-0.129	0.018
#9 NOX APP	0.391	3.584	-8.734	-6.034	-4.846	1.191	-4.171	-2.821
#10 HOLD	0.034	1.634	-3.291	-2.403	-2.028	0.822	-1.628	-1.184
#11 IDLE	-0.142	1.371	-2.992	-1.992	-1.592	0.642	-1.567	-1.067
#12 MAX	6.829	19.254	-16.996	-7.758	-3.133	11.958	-5.083	-0.465
#13 THC APP	0.076	-0.024	-0.186	-0.173	-0.474	-0.009	-0.055	-0.048
#14 HOLD	4.318	8.718	-10.220	-5.545	-2.620	5.922	-2.951	-0.614
#15 IDLE	12.991	37.996	-45.371	-20.859	-6.209	24.258	-16.190	-3.934
#16 MAX	-0.340	-0.577	0.035	-0.115	-0.152	-0.419	-0.152	-0.227

TABLE C-2. DIFFERENCE BETWEEN SAMPLE MEAN AND GRAND MEAN FOR THE A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($\overline{X}_C-\overline{\overline{X}}$) (continued)

	AE	BC	BD	BE	CD	CE	DE	ABC
N	16	16	16	16	12	12	12	20
#1 CO APP	-1.092	-3.155	-1.030	0.533	-16.196	-14.696	-11.863	-1.880
#2 HOLD	-7.902	-13.152	1.848	8.910	-59.881	-52.631	-32.631	-12.865
#3 IDLE	-10.043	-18.606	7.144	20.582	-91.856	-80.606	-46.243	-18.556
#4 MAX	1.340	0.153	1.840	2.403	-4.681	-5.014	-2.764	0.853
#5 CO2 APP	-0.081	-0.090	-0.039	-0.003	-0.402	-0.365	-0.298	-0.102
#6 HOLD	-0.096	-0.103	-0.038	-0.009	-0.342	-0.320	-0.233	-0.101
#7 IDLE	-0.089	-0.099	-0.032	0.010	-0.327	-0.292	-0.203	-0.100
#8 MAX	0.095	0.048	0.196	0.273	-0.352	-0.346	-0.149	0.028
#9 NOX APP	-2.228	-2.440	-1.090	-0.496	-7.675	-7.200	-5.400	-2.799
#10 HOLD	-0.997	-0.828	-0.384	-0.197	-2.962	-2.778	-2.187	-0.823
#11 IDLE	-0.867	-0.810	-0.310	-0.110	-2.592	-2.458	-1.792	-0.812
#12 MAX	1.848	1.129	5.748	8.060	-12.408	-12.342	-6.183	0.377
#13 THC APP	-0.199	-0.105	-0.098	-0.249	-0.227	-0.337	-0.328	-0.080
#14 HOLD	0.849	-0.751	1.586	3.049	-8.486	-6.886	-3.770	-0.535
#15 IDLE	3.391	-3.703	8.554	15.879	-34.900	-29.734	-13.392	-3.594
#16 MAX	-0.246	-0.271	-0.346	-0.365	-0.027	-0.027	-0.127	-0.237

TABLE C-2. DIFFERENCE BETWEEN SAMPLE MEAN AND GRAND MEAN FOR THE A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($\overline{X}_C-\overline{X}$) (continued)

	ABD	ABE	ACD	ACE	ADE	BCD	BCE	BDE
N	20	20	20	20	20	20	20	20
#1 CO APP	-0.180	1.070	-6.380	-5.480	-3.780	-5.080	-4.180	-2.480
#2 HOLD	-0.865	4.785	-31.515	-27.165	-15.165	-18.065	-13.715	-1.715
#3 IDLE	2.044	12.794	-49.556	-42.806	-22.206	-25.056	-18.306	2.294
#4 MAX	2.203	2.653	1.000	-1.197	0.153	-0.147	-0.347	1.003
#5 CO2 APP	-0.062	-0.028	-0.202	-0.180	-0.140	-0.135	-0.113	-0.072
#6 HOLD	-0.049	-0.026	-0.200	-0.186	-0.134	-0.130	-0.177	-0.065
#7 IDLE	-0.046	-0.013	-0.202	-0.181	-0.127	-0.122	-0.101	-0.048
#8 MAX	0.146	0.207	-0.115	-0.111	0.007	0.027	0.031	0.149
#9 NOX APP	-1.699	-1.224	-4.449	-4.164	-3.084	-3.064	-2.779	-1.669
#10 HOLD	-0.468	-0.318	-1.763	-1.653	-1.298	-1.123	-1.013	-0.658
#11 IDLE	-0.412	-0.252	-1.612	-1.532	-1.132	-1.007	-0.927	-0.527
#12 MAX	4.072	5.922	-4.713	-4.673	-0.987	-0.257	-0.297	3.992
#13 THC APP	-0.074	-0.195	-0.106	-0.172	-0.166	-0.146	-0.212	-0.206
#14 HOLD	1.335	2.505	-3.365	-2.405	-0.535	-1.605	-0.645	1.225
#15 IDLE	6.211	12.071	-15.744	-12.644	-2.839	-5.754	-2.654	7.151
#16 MAX	-0.297	-0.312	-0.152	-0.152	-0.212	-0.247	-0.247	-0.307

TABLE C-2. DIFFERENCE BETWEEN SAMPLE MEAN AND GRAND MEAN FOR THE A B C D E CONFIGURATION FOR GASES AND THROTTLE SETTINGS ($\overline{X}_C-\overline{\overline{X}}$) (continued)

	CDE	ABCD	ABCE	ABDE	ACDE	BCDE	ABCDE
N	16	24	24	24	24	24	28
#1 CO APP	-14.217	-3.696	-2.946	-1.530	-6.696	6.454	-4.351
#2 HOLD	-48.902	-17.006	-13.381	-3.381	-28.923	-17.715	-16.858
#3 IDLE	-73.168	-23.929	-18.314	-1.148	-44.148	-23.731	-22.963
#4 MAX	-4.097	0.486	0.319	1.444	-1.222	-0.514	0.081
#5 CO2 APP	-0.353	-0.138	-0.119	-0.086	-0.203	-0.146	-0.147
#6 HOLD	-0.300	-0.124	-0.113	-0.070	-0.195	-0.137	-0.131
#7 IDLE	-0.274	-0.119	-0.102	-0.057	-0.187	-0.121	-0.118
#8 MAX	-0.274	-0.013	-0.016	-0.115	-0.103	0.016	0.005
#9 NOX APP	-6.790	-3.242	-3.005	-2.105	-4.396	-3.242	-3.369
#10 HOLD	-2.659	-1.070	-0.978	-0.682	-1.762	-1.228	-1.168
#11 IDLE	-2.292	-0.975	-0.908	-0.575	-1.575	-1.071	-1.034
#12 MAX	-10.065	-0.225	-0.192	2.888	-4.433	-0.292	-0.626
#13 THC APP	-0.330	-0.118	-0.173	-0.168	-0.195	-0.228	-0.192
#14 HOLD	-6.420	-1.202	-0.482	1.076	-2.841	-1.374	-1.130
#15 IDLE	-25.970	-5.321	-2.738	5.433	-12.863	-4.538	-4.341
#16 MAX	-0.059	-0.223	-0.223	-0.273	-0.152	-0.231	-0.213

APPENDIX D

COMPARISON OF RAW t FOR THE BEST PROBE CONFIGURATION WITH THE BEST OF THE ANNULAR AND CRUCIFORM PROBE FAMILIES

TABLE D-1. RAW t VALUES FOR A FINAL PROBE CONFIGURATION

	ABD	06	+5	+4
N	20	28	20	20
#1 CO APP	0.006	0.030	0.353	0.233
#2 HOLD	0.006	0.195	0.266	0.292
#3 IDLE	0.010	0.187	0.266	0.325
#4 MAX	0.171	0.048	0.350	0.183
#5 CO2 APP	0.081	0.160	0.280	0.280
#6 HOLD	0.071	0.277	0.248	0.360
#7 IDLE	0.071	0.263	0.260	0.319
#8 MAX	0.148	0.083	0.233	0.128
#9 NOX APP	0.130	0.205	0.241	0.273
#10 HOLD	0.072	0.268	0.267	0.337
#11 IDLE	0.078	0.306	0.266	0.347
#12 MAX	0.121	0.052	0.234	0.175
#13 THC APP	0.111	0.165	0.137	0.116
#14 HOLD	0.060	0.036	0.314	0.280
#15 IDLE	0.070	0.064	0.334	0.335
#16 MAX	0.532	0.151	0.174	0.254
$\sum_{1}^{16}$	1.738	2.491	4.224	4.234