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MODEL INDUCTION TEST FACILITY CAPABILITY FOR TESTING TURBOFAN ENGINES

James W. Hale

ARO, Inc.

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ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was done by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65802F. The research was conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC. The work was accomplished from July 6, 1971 to June 30, 1972 under ARO Project No. BE2256, and the manuscript was submitted for publication on November 30, 1972.

This technical report has been reviewed and is approved.

ROBERT O. DIETZ
Director of Technology

ABSTRACT

The objective of this model study was to determine the potential for testing very large thrust, high-bypass-ratio, turbofan engines at conditions simulating flight Mach numbers of 0.4 to 0.6, sea level, by use of a jet pumped air supply system. The simulation of low altitude, subsonic operation of a large, high-bypass-ratio, turbofan engine in ground test facilities requires extremely large airflows. This airflow, even at relatively low pressure, cannot be provided by existing test facilities for engines having thrust levels of 60,000 to 100,000 lbf. The jet pumped air supply is therefore a very attractive potential facility. The purpose of this study is to determine the maximum jet pump mass ratio at which the pressure rise corresponding to sea-level flight at M = 0.4 to 0.6 can be obtained and the resulting motive airflow rate and state conditions required to test engines in the thrust class of 60,000 to 100,000 lbf.

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NOMENCLATURE

A	Area, in.^{2}
C_p	Specific heat at constant pressure, Btu/lbm-°R
D	Diameter
F	Force, lbf
I. D.	Inside diameter
J	Mechanical equivalent of heat, ft-lbf/Btu
M	Mach number
$\dot{m}$	Mass flow rate, lbm/sec
P	Static pressure, psia
P_t	Total pressure, psia
R	Specific gas constant, ft-lbf/lbm-°R
T	Static temperature, °R
T_t	Total temperature, °R
γ	Ratio of specific heats at constant pressure
η	Subsonic diffuser efficiency

SUBSCRIPTS

2, 3, 4, 5, and 16	Station location

a	Annular
d	Diffuser
e	Ejector
ex	Exit
i	Inlet
nex	Nozzle exit
p	Plenum
t	Total
s	Static

SUPERSCRIPTS

'	Primary fluid
''	Secondary fluid
*	Nozzle throat

SECTION I
INTRODUCTION

Environmental simulation testing of aerospace propulsion devices and systems requires that the simulation capabilities of ground test facilities cover a range of test conditions comparable to those to which vehicles will be subjected during flight. Advancements in aerospace technologies have placed more stringent requirements on performance capabilities of ground environmental simulation facilities. High altitude simulation requirements have increased to the point where existing conventional mechanical exhaust gas pumping systems are not capable of providing the test conditions required in the development and testing of large full-scale propulsion systems.

Problems associated with ground test facilities to enable simulation of flight conditions for aerospace propulsion systems have led to the application of ejectors-diffusers to pump exhaust gases from test cells to the atmosphere. The simplicity of construction and installation of ejectors-diffusers plus their performance capabilities provides an economical and feasible means for pumping large quantities of gases at the low pressures required to simulate flight conditions.

The airflow rate for large-bypass-ratio, subsonic turbofan engines operating at altitudes below 15,000 to 20,000 ft places very stringent requirements on ground test facilities designed primarily for testing turbojet and small-bypass-ratio turbofan engines. A facility which uses the compressor-generated air supply to drive a jet pump which induces air from the atmosphere, compresses it to the required level of pressure, and delivers it to the turbofan inlet plenum might be used to meet the low altitude test requirement of these engines. The feasibility of this approach has been verified theoretically.

SECTION II
APPARATUS

2.1 TEST ARTICLE

A model annular ejector was designed to use a standard 8-in. pipe as the mixing section. The ejector as-built parameters and dimensions are shown in Fig. 1 (Appendix I). A subsonic diffuser with a half-angle of approximately 3.65 deg connected the standard 8-in. pipe to a standard 16-in. pipe. The ejector nozzle throat area was $A^* = 1.94$ in.^{2}. The ejector secondary airflow inlet pipe was an 8-in. schedule 80 pipe (see Fig. 1).

The ejector was equipped with an inlet plenum section made from a standard 16-in. pipe inside of which a 6-in.-diam baffle was installed (Fig. 2). A secondary air plenum and airflow measuring nozzle with a throat diameter of 1.50 in. were attached to the inlet plenum. A number 8 mesh 0.016-in.-diam wire screen was selected for installation between the subsonic diffuser exit and the exhaust plenum section. The screen has approximately 75 percent open area. This size screen was available and is the size normally used in the Engine Test Facility (ETF), AEDC, for flow straightening in ducts equal to or less than 6 ft in diameter. The exhaust plenum section was made from a standard 16-in. pipe. Provision was made near the downstream end of the plenum for installation of a 9-probe total pressure rake. A typical high thrust, high-bypass-ratio, simulated turbofan engine made from a standard 6-in. pipe connected the exhaust plenum to the exhaust ducting in the R-2C-1 test area of the Engine Test Facility, AEDC. The high pressure air supply was connected to the secondary air plenum and the annular ejector nozzle plenum. This installation is presented in Figs. 2 and 3.

Air from the von Kármán Gas Dynamics Facility (VKF), AEDC, 4000-psi storage tank provided the primary air or driving medium for the annular ejector and the secondary air.

2.2 INSTRUMENTATION

The parameters of primary interest were the ejector driving fluid total pressure and temperature, ejector inlet pressure, simulated engine inlet total and static pressure, and simulated engine exhaust pressure. The location of these parameters are shown in Fig. 2. The type of measuring instruments and the maximum deviation within the measured range of each of the manually recorded parameters is presented in Table I (Appendix II).

The rake total pressure parameters were measured on a 120-in. manometer board filled with tetrabromoethane (TBE) and recorded by a 70-mm camera. The TBE had a specific gravity of approximately 2.94 at 70°F. The accuracy of the manometer board is believed to be excellent because of the following factors which were used in gathering data:

1. The tubes containing TBE were referenced to atmosphere, and the data taken from the barometer were used in reducing the manometer data.
2. A vacuum check was taken before testing and at an interval during testing to ensure that the pressure lines and manometer board contained no leaks.

SECTION III
TEST PROCEDURE

The preoperational procedures for the test components were completed and the ETF exhaust ducting was opened to atmospheric pressure. Then the ejector driving pressure was set and maintained constant at 50, 65, and 70 psia while the secondary air plenum pressure was varied over a range of values for each of the set ejector driving pressure levels. Steady-state data were recorded for each set condition. Pressures and temperatures indicated by gages were recorded manually, and the manometer board was photographed.

SECTION IV
RESULTS AND DISCUSSION

The model tests of the jet pump air supply facility were conducted with ejector driving pressures of 50, 65, and 70 psia. At each of these ejector driving pressures, several secondary airflow rate values were set for steady-state data points while the simulated engine exhaust pressure was maintained at atmospheric conditions. The results of the test are presented in Figs. 4, 5, and 6. A listing of the tabulated data taken during the test is presented in Table II. The ratios of ejector inlet pressure to ejector driving pressure (P_{ei}/P_{te}), secondary-to-primary mass flow ($\dot{m}''/\dot{m}'$), and engine inlet static to total pressure ($P_{s_{16}}/P_{t_{16}}$, avg) are shown as varying with engine inlet total pressure ($P_{t_{16}}$, avg). The engine inlet total pressure ($P_{t_{16}}$, avg) is the average of 8 probes (not including the center probe) of the 9-probe rake. The probes were located on centroids of equal areas in the 16-in. duct shown in Fig. 1.

The 9-probe-rake total pressure profile for the ejector driving pressures of 50, 65, and 70 psia at the maximum secondary airflow is shown in Fig. 7 and Table II.

In order to use these curves to predict engine performance, atmospheric pressure of 14.7 psia (secondary inlet total pressure) is divided by the ejector driving pressure and the result indicated on each of the ejector driving curves (50, 65, and 70 psia) in Fig. 4. The corresponding values of secondary-to-primary mass flow ratios, $\dot{m}''/\dot{m}'$, versus ejector exit total pressure, $P_{t_{16}}$, avg, determined from Fig. 4 are presented in Fig. 5. These results are also shown in the following table:

P_{te}, psia	P_{ei}, psia	P_{ei}/P_{te}	$P_{t_{16}}$, avg, psia (from Fig. 4)	$\dot{m}''/\dot{m}'$ (from Fig. 5)
50	14.7	0.294	16.55	1.65
65	14.7	0.226	17.275	1.40
70	14.7	0.210	17.375	1.175

The largest secondary-to-primary mass flow rate, $\dot{m}''/\dot{m}'$, was obtained with the smaller of the three ejector driving pressures. A mass ratio, $\dot{m}''/\dot{m}'$, of 1.65 resulted from the P_{te} of 50 psia (see above table). Since $\dot{m}'' + \dot{m}' = \dot{m}_T$ and $\dot{m}''/\dot{m}' = 1.65$, then $\dot{m}_T = 2.65\ \dot{m}'$ or $\dot{m}' = \dot{m}_T/2.65$. The sea-level airflow requirements for the corresponding flight Mach number for different thrust level typical turbofan engines is shown in the following table:

Engine Thrust, lbf	Bypass Ratio	Sea-Level Airflow Requirement at Flight Mach No.
40,000	8:1	1800 at $M_o = 0.40$
45,000	5:1	1800 at $M_o = 0.40$
60,000	8:1	2700 at $M_o = 0.40$
67,000	5:1	2700 at $M_o = 0.40$
89,000	8:1	4000 at $M_o = 0.45$
100,000	5:1	4000 at $M_o = 0.45$

The sea-level airflow requirement for a 100, 000-lbf-thrust 5:1 or 89, 000-lbf-thrust 8:1 bypass ratio turbofan engine operating at a flight Mach number of 0. 45 is 4000 lbm/sec. For a total mass flow $\dot{m}_T$ = 4000 lbm/sec, the required primary mass flow would be $\dot{m}' = \dot{m}_T/2.65$ = 4000/2. 65 = 1509 lbm/sec. The engine inlet total pressure for the flight Mach number of 0. 45 would be 16. 89 psia. Figure 6 shows the engine inlet plenum Mach number variation with inlet total pressure.

Theoretical performance calculations for the model induction test facility were made by using the equations for constant area mixing ejector design as shown in Appendix III and Ref. 1 for comparison with experimental performance. The calculations were made for jet pump secondary flow inlet Mach numbers (M_3'') of 0. 10, 0. 15, 0. 20, 0. 30, and 0. 40 at ejector driving pressures (P_{te}) of 30, 50, and 70 psia as shown in Table III. These theoretical data for P_{te} of 50 and 70 psia are shown in Fig. 5 as the points marked "predicted by theory". The theoretical engine inlet total pressure or ejector exit total pressure (listed as P_{s_5} in Table III) was based on an assumed value of subsonic diffuser efficiency of 60 percent (η = 0. 60). A more accurate efficiency for the subsonic diffuser may have resulted in a closer prediction of the experimental performance.

SECTION V
CONCLUSIONS

An ejector sized for 1509 lbm/sec of driving air at 50 psia could induce 2500 lbm/sec of atmospheric air, thus delivering 4000 lbm/sec of air at 16. 55 psia which corresponds to the airflow requirement of a 100,000 lbf 5:1 or a 89,000 lbf 8:1 bypass ratio turbofan engine operating at M_o = 0.45, sea-level flight condition.

REFERENCES

1. Lewis, G. W. G. and Drabble, J. S. "Ejector Experiments." National Gas Turbine Establishment, Pystock, Hants (Great Britain), Report No. R. 151, 1954.

APPENDIXES

I. ILLUSTRATIONS
II. TABLES
III. EJECTOR DESIGN CONSTANT AREA MIXING

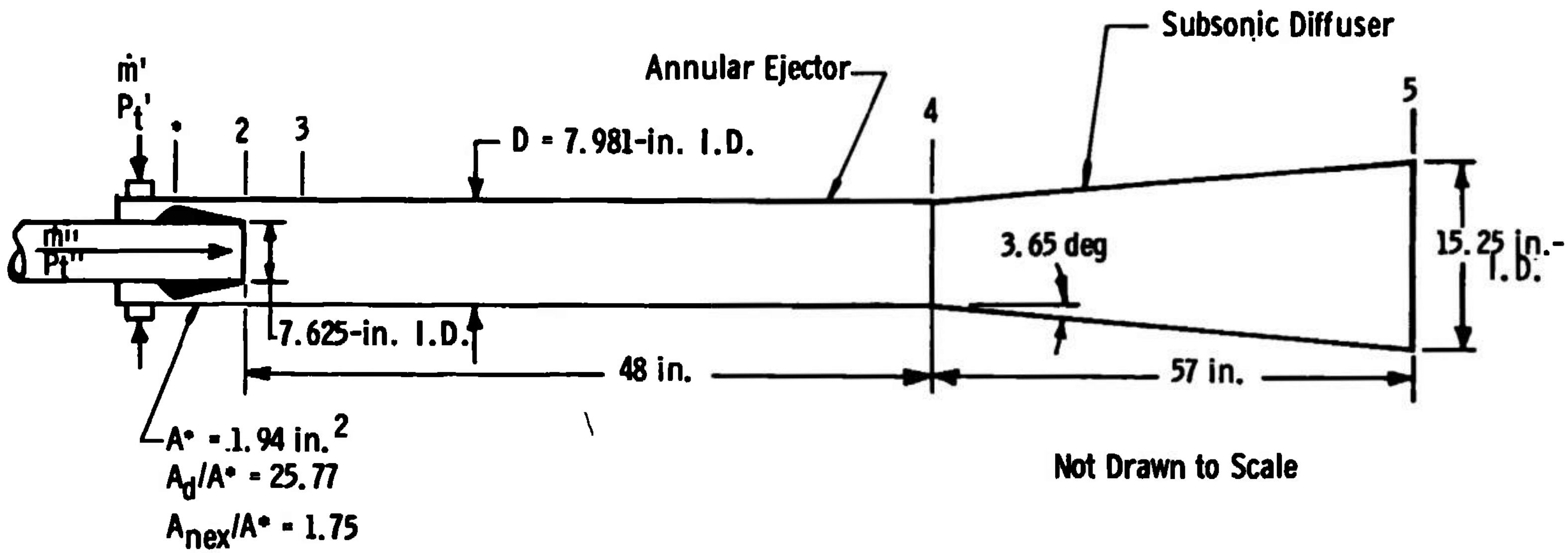


Fig. 1 Model Air-Driven Annular Ejector

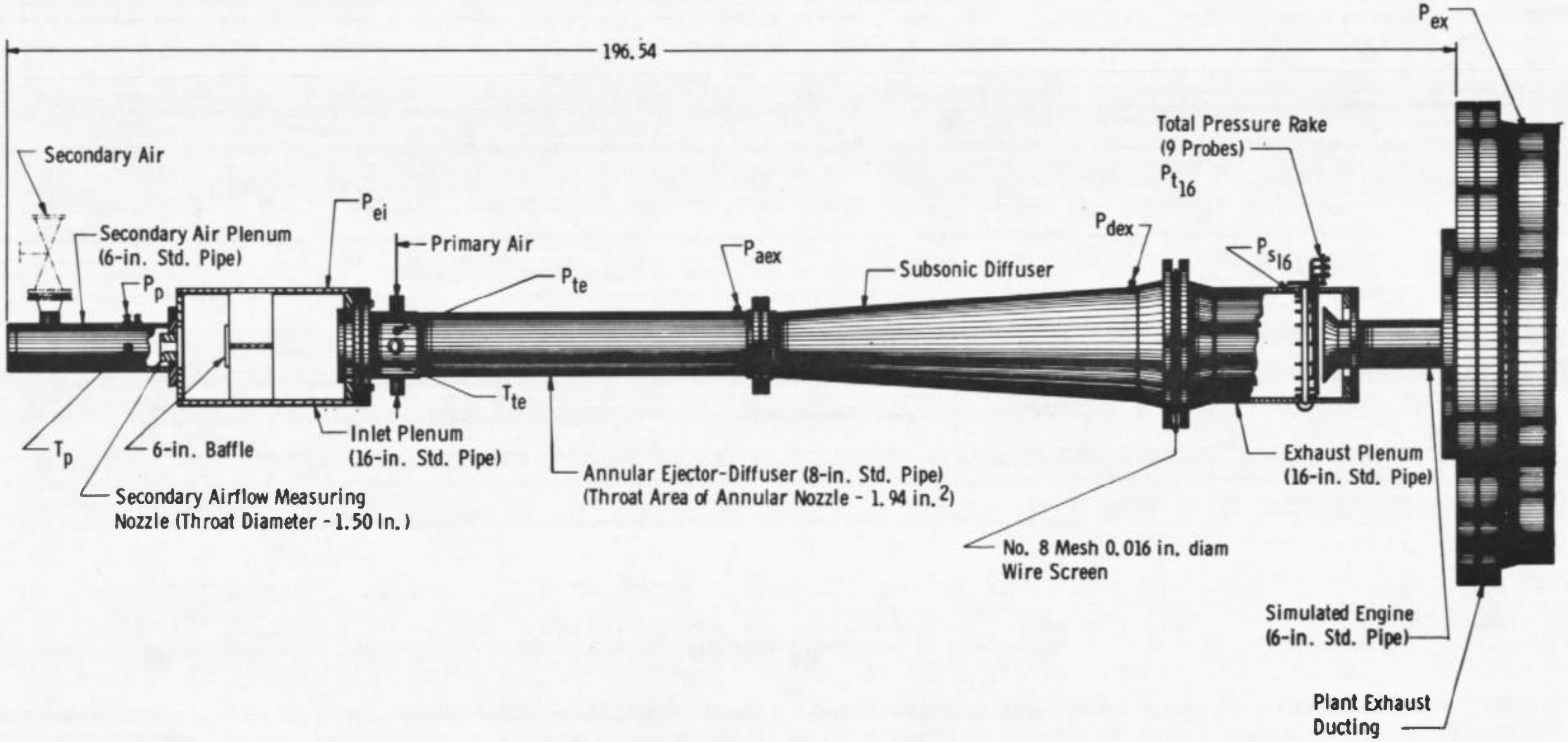


Fig. 2 Model Induction Test Facility for Turbofan Engines

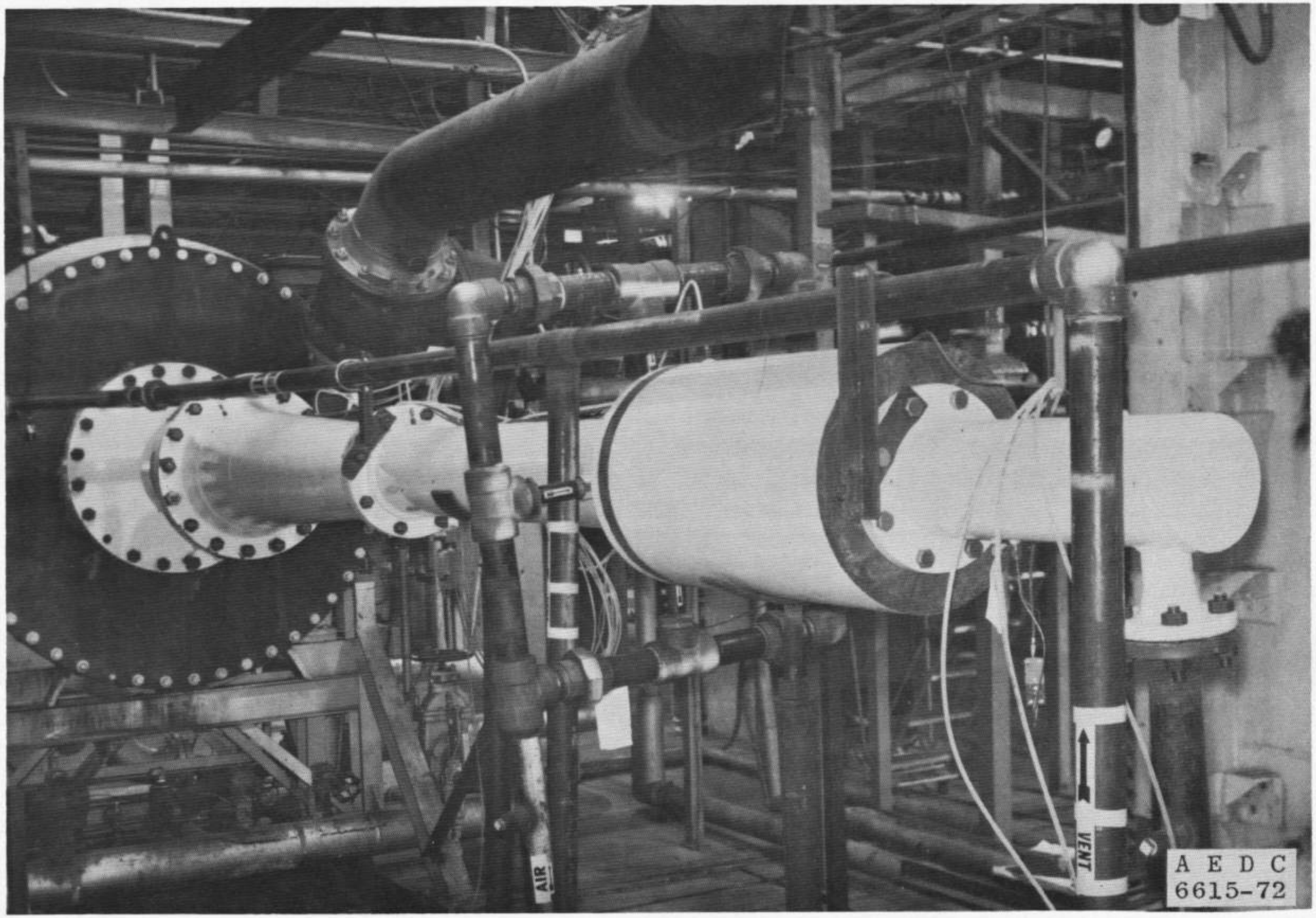


Fig. 3 Photograph of Model Induction Test Facility for Turbofan Engines

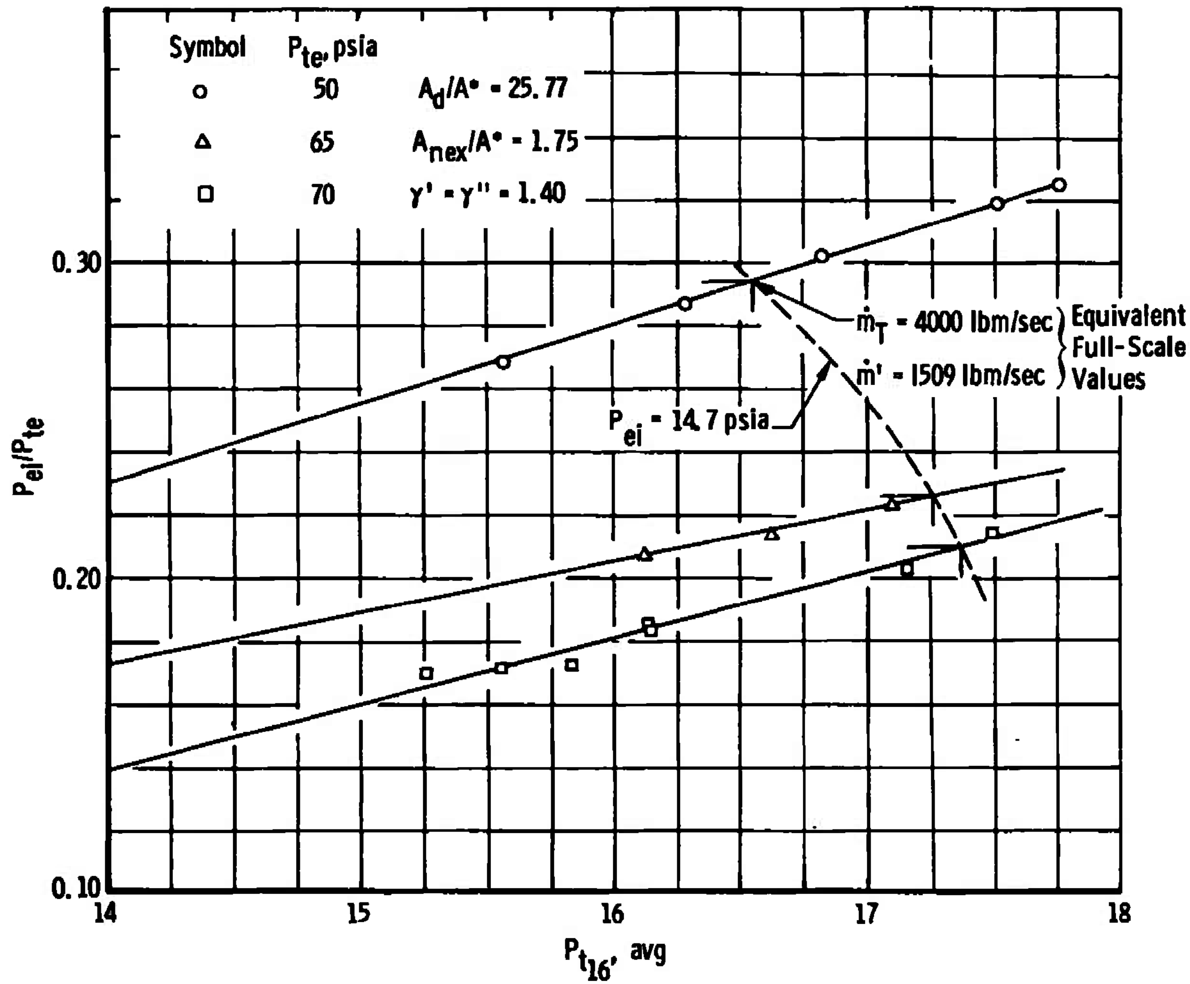


Fig. 4 Variation of Ratio of Ejector Inlet to Ejector Driving Pressure (P_{ei}/P_{te}) with Ejector Exit Total Pressure ($P_{t_{16}}$, avg)

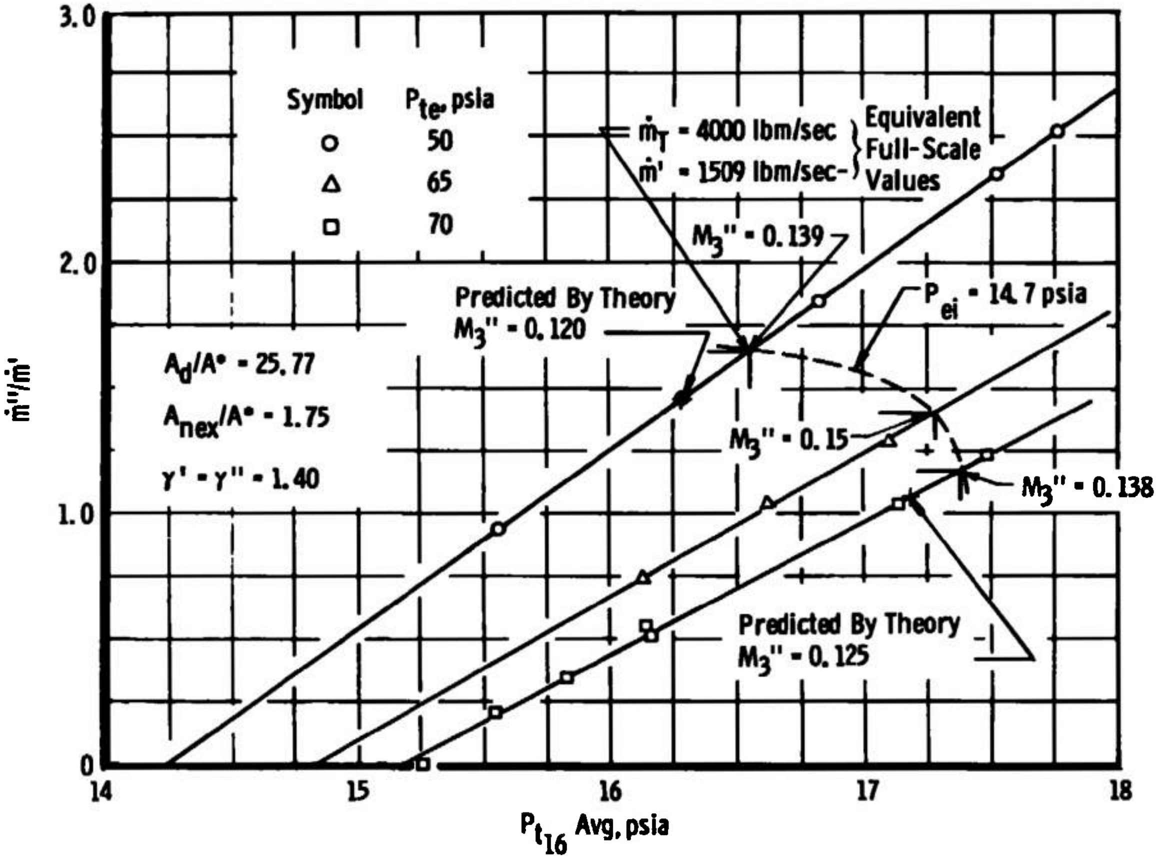


Fig. 5 Variation of Secondary-to-Primary Mass Flow Ratio (m″/m′) with Ejector Exit Total Pressure ($P_{t_{16}}$, avg)

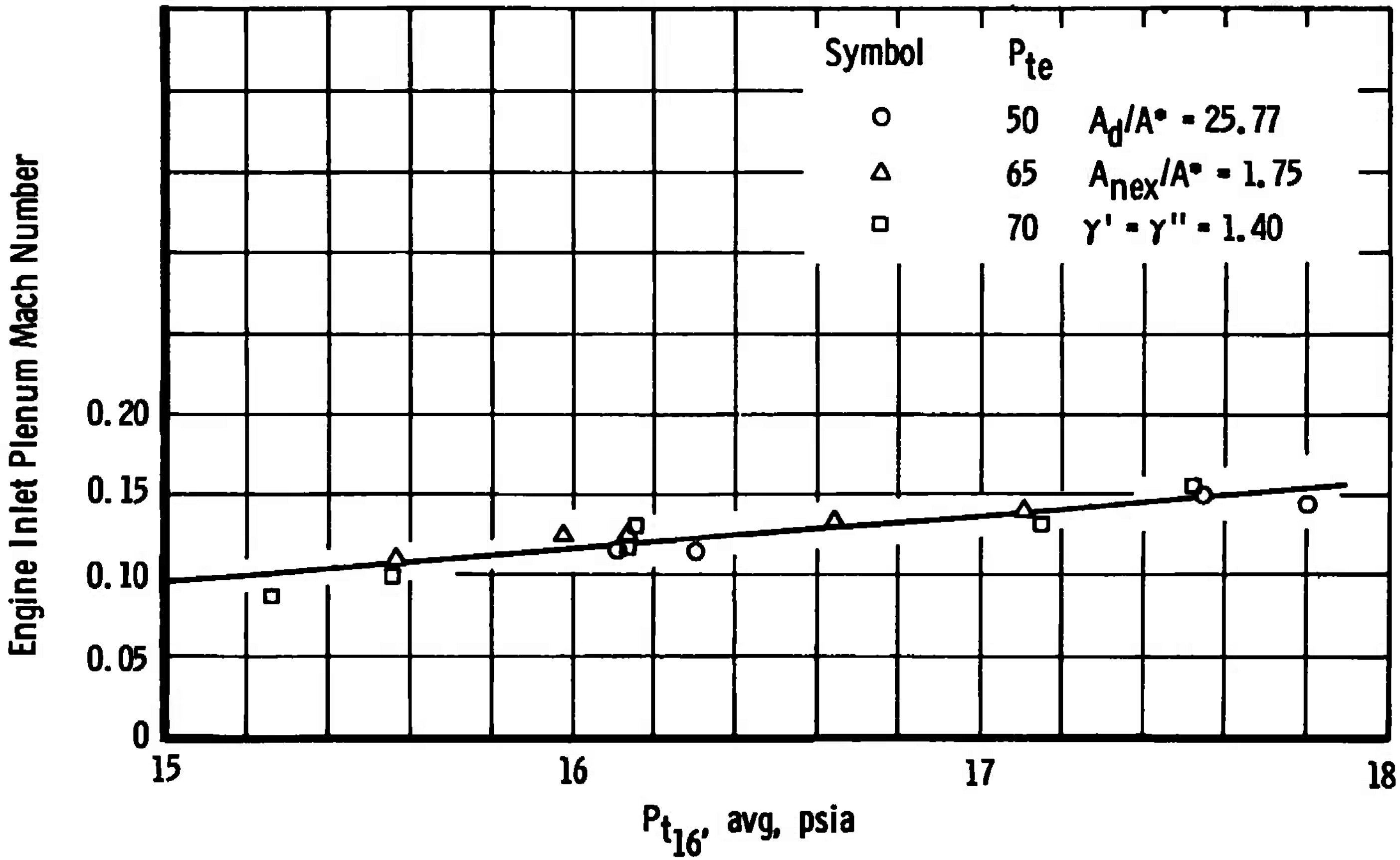


Fig. 6 Variation of Simulated Turbofan Engine Inlet Mach Number with Turbofan Engine Inlet Total Pressure ($P_{t_{16}}$, avg)

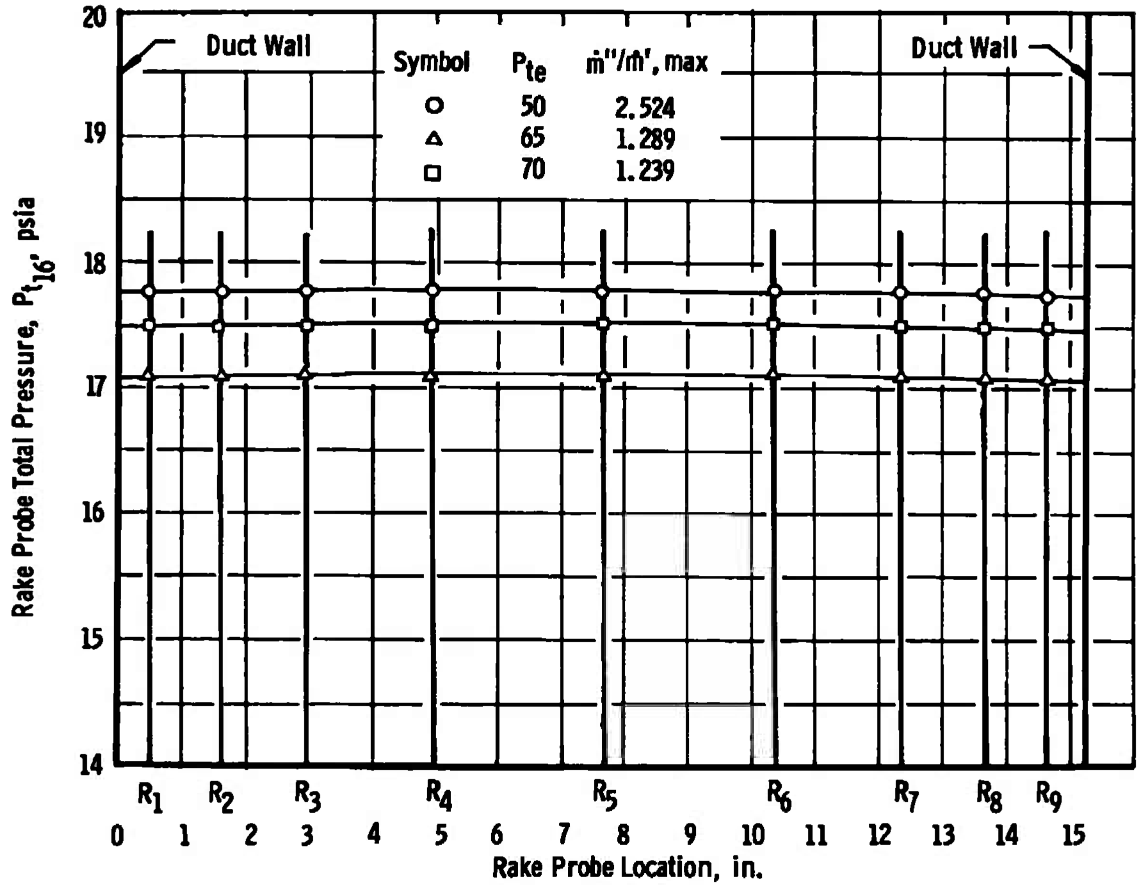


Fig. 7 Simulated Turbofan Engine Inlet Total Pressure Profile

TABLE I
MAXIMUM DEVIATION OF MEASURING INSTRUMENTS

Parameter	Range Measured	Type of Instrument	Instrument Full Range	Maximum Deviation
P_{ei}	11.00 to 16.25 psia	Bourdon Tube Type Gage	0 to 30 psia	±0.02 psia
P_{dex}	15.00 to 18.00 psia		0 to 50 psia	±0.06 psia
P_{ex}	14.20 to 14.41 psia		0 to 30 psia	±0.01 psia
P_{aex}	14.00 to 17.00 psia		0 to 30 psia	±0.01 psia
P_{s16}	15.15 to 17.70 psia		0 to 30 psia	±0.022 psia
P_p	16.00 to 14.00 psia		0 to 500 psia	±0.50 psia
P_{te}	36.00 to 75.00 psia		0 to 500 psia	±0.75 psia
Barometer	28 to 31 in. HgA		28 to 31 in. HgA	-0.009 in. HgA
T_p	40 to 60°F	Copper-Constantan Thermocouple	-100 to +400°F	±5.0°F
T_{te}	40 to 62°F	Copper-Constantan Thermocouple	-100 to +400°F	±5.0°F

TABLE II
EJECTOR TABULATED TEST DATA

Run Pt No.	$P_{t_{16}}$, psia								
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9
1	17.756	17.765	17.765	17.777	17.793	17.784	17.771	17.762	17.743
2	17.506	17.519	17.519	17.528	17.541	17.534	17.525	17.513	17.506
3	16.797	16.821	16.821	16.850	16.843	16.837	16.831	16.821	16.809
4	16.090	16.090	16.096	16.102	16.112	16.112	16.105	16.102	16.090
5	15.561	15.561	15.561	15.573	15.573	15.573	15.561	15.561	15.551
6	16.613	16.613	16.613	16.625	16.641	16.635	16.625	16.619	16.600
7	17.080	17.086	17.086	17.095	17.114	17.114	17.100	17.092	17.074
8	15.965	15.978	15.978	15.978	15.984	15.978	15.978	15.965	15.956

	$P_{t_{16}}$ avg., psia	$P_{t_{16}}$ Center	P_{ei}/P_{te}	$P_{s_{16}}/P_{t_{16}}$ Avg.
1	17.765	17.793	0.3250	0.9851
2	17.519	17.541	0.3190	0.9846
3	16.823	16.843	0.3020	0.9659
4	16.098	16.112	0.2918	0.9908
5	15.563	15.573	0.2689	0.9915
6	16.618	16.641	0.2135	0.9875
7	17.091	17.114	0.2231	0.9871
8	15.973	15.984	0.2189	0.9892

TABLE II (Continued)

Run Pt. No.	P_p, psia	P_{te}, psia	P_{ei}, psia	P_{aex}, psia	P_{dex}, psia	$P_{s_{16}}$, psia	P_{ex}, psia	T_p, °F	T_{te}, °F
1	140	50	16.25	17.00	17.50	17.50	14.20	50	40
2	130	50	15.95	16.75	17.25	17.25	14.30	55	50
3	103	50.5	15.25	16.15	16.60	16.25	14.25	58	52
4	80	49	14.30	15.60	15.95	15.95	14.20	58	52
5	52.5	50.5	13.58	15.18	15.40	15.43	14.21	58	55
6	74	65	13.88	16.00	15.60	16.41	14.21	55	62
7	92	65	14.50	16.90	15.10	16.87	14.22	55	55
8	55	61	13.35	15.50	15.80	15.80	14.24	60	55

	$\dot{m}''$, lbm/sec	$\dot{m}'$ lbm/sec	$\dot{m}''/\dot{m}'$ lbm/sec	$\dot{m}_t$, lbm/sec	T_p, °R	T_{te}, °R	$\sqrt{T_p}$	$\sqrt{T_{te}}$	$P_{t_{16}}$ Avg. (8probes)
1	5.825	2.308	2.524	8.133	510	500	22.583	22.361	17.765
2	5.383	2.285	2.356	7.668	515	510	22.694	22.583	17.519
3	4.253	2.304	1.846	6.557	518	512	22.760	22.627	16.823
4	3.303	2.235	1.478	5.538	518	512	22.760	22.627	16.098
5	2.168	2.297	0.944	4.465	518	515	22.760	22.694	15.563
6	3.064	2.937	1.043	6.001	515	522	22.694	22.847	16.618
7	3.809	2.956	1.289	6.765	515	515	22.694	22.694	17.091
8	2.266	2.775	0.817	5.041	520	515	22.804	22.694	15.973

TABLE II (Continued)

Run Pt. No.	$P_{t_{16}}$, psia								
	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9
1	17.482	17.493	17.493	17.505	17.521	17.521	17.505	17.493	17.482
2	16.121	16.132	16.132	16.132	16.144	16.138	16.132	16.121	16.110
3	15.829	15.829	15.829	15.829	15.840	15.829	15.829	15.817	15.812
4	15.553	15.559	15.559	15.559	15.559	15.559	15.553	15.547	15.542
5	15.249	15.255	15.255	15.255	15.261	15.255	15.299	15.249	15.238
6	16.279	16.284	16.279	16.290	16.301	16.301	16.290	16.289	16.273
7	17.122	17.128	17.128	17.139	17.156	17.150	17.145	17.133	17.117
8	17.735	17.746	17.746	17.746	17.769	17.769	17.758	17.746	17.724
9	16.121	16.127	16.127	16.132	16.132	16.132	16.127	16.121	16.110
10	16.144	16.144	16.144	16.144	16.155	16.155	16.144	16.138	16.127

	$P_{t_{16}}$ avg., psia	$P_{t_{16}}$ Center	P_{ei}/P_{te}	$P_{s_{16}}/P_{t_{16}}$ Avg.
1	17.497	17.521	0.2142	0.9830
2	16.127	16.144	0.1859	0.9906
3	15.825	15.840	0.1736	1.1185
4	15.554	15.559	0.1716	0.9933
5	15.251	15.261	0.1699	0.9950
6	16.286	16.301	0.2866	0.9910
7	17.133	17.156	0.2024	0.9879
8	17.746	17.769	0.1966	0.9974
9	16.125	16.132	0.2070	0.9891
10	16.143	16.155	0.1839	0.9880

TABLE II (Concluded)

Run Pt. No.	P_p, psia	P_{te}, psia	P_{ei}, psia	P_{aex}, psia	P_{dex}, psia	$P_{s_{16}}$, psia	P_{ex}, psia	T_p, °F	T_{te}, °F
1	94	68.5	14.675	16.75	17.30	17.20	14.30	48	40
2	44	70	12.975	15.725	16.10	15.975	14.31	48	40
3	27	71	12.325	15.450	15.80	17.70	14.31	50	40
4	16	70.5	12.1	15.25	15.50	15.45	14.31	50	45
5	--	69	11.725	15.05	15.20	15.175	14.41	52	45
6	82	50.5	14.475	15.825	16.15	16.14	14.30	50	40
7	80.1	70.05	14.175	16.50	16.95	16.925	14.30	50	45
8	95	74.9	14.725	17.00	17.50	17.70	14.30	48	45
9	53	64.5	13.35	15.675	16.00	15.95	14.31	50	45
10	40	70.0	12.875	15.70	16.00	15.95	14.31	50	45

	$\dot{m}''$, lbm/sec	$\dot{m}'$ lbm/sec	$\dot{m}''/\dot{m}'$ lbm/sec	$\dot{m}_t$, lbm/sec	T_p, °R	T_{te}, °R	$\sqrt{T_p}$	$\sqrt{T_{te}}$	$P_{t_{16}}$ Avg. (8probes)
1	3.919	3.162	1.239	7.081	508	500	22.539	22.361	17.497
2	1.834	3.231	0.568	5.065	508	500	22.539	22.361	16.127
3	1.123	3.277	0.343	4.400	510	500	22.583	22.361	15.825
4	0.666	3.238	0.206	3.904	510	505	22.583	22.472	15.554
5	-----	3.169	0	3.169	512	505	22.627	22.472	15.251
6	3.412	2.331	1.464	5.743	510	500	22.583	22.361	16.286
7	3.333	3.218	1.036	6.551	510	505	22.583	22.472	17.133
8	3.961	3.440	1.151	7.401	508	505	22.539	22.472	17.746
9	2.205	2.962	0.744	5.167	510	505	22.583	22.472	16.125
10	1.664	3.215	0.518	4.879	510	505	22.583	22.472	16.143

TABLE III
EJECTOR TABULATED CALCULATED PERFORMANCE DATA

EJECTOR DESIGN

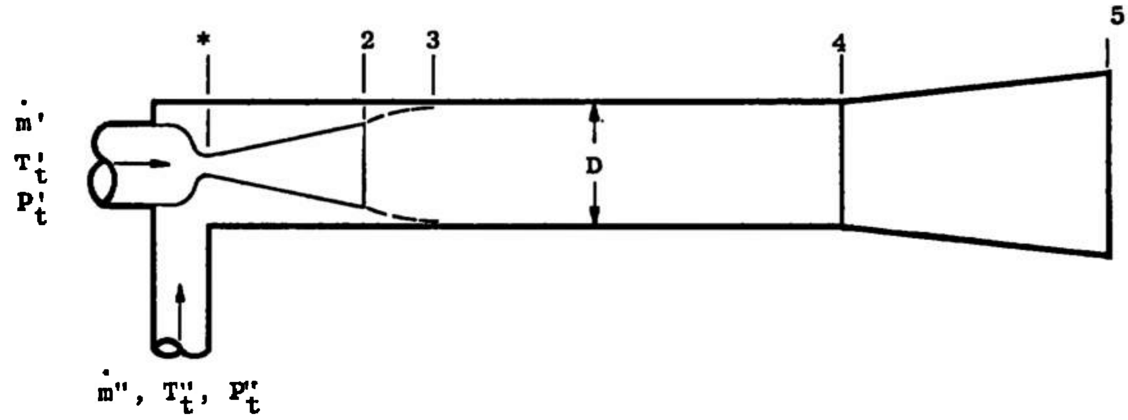
• • • CONSTANT AREA MIXING NO 1 • • •

DATE 8/14/72

TIME 1036.29

γ'	γ''	T_t'	T_t''	R'	R''	P_t'	P_t''	$\dot{m}''$	$\dot{m}'$	$\dot{m}_3''$	N	$\dot{m}''/\dot{m}'$
1.400	1.400	510.0000	510.0000	53.3400	53.3400	30.0000	14.7000	2.858	1.371	.100	.600	2.085
1.400	1.400	510.0000	510.0000	53.3400	53.3400	30.0000	14.7000	4.255	1.371	.150	.600	3.104
1.400	1.400	510.0000	510.0000	53.3400	53.3400	30.0000	14.7000	5.614	1.371	.200	.600	4.095
1.400	1.400	510.0000	510.0000	53.3400	53.3400	30.0000	14.7000	8.173	1.371	.300	.600	5.961
1.400	1.400	510.0000	510.0000	53.3400	53.3400	30.0000	14.7000	10.457	1.371	.400	.600	7.627
1.400	1.400	510.0000	510.0000	53.3400	53.3400	50.0000	14.7000	2.842	2.285	.100	.600	1.244
1.400	1.400	510.0000	510.0000	53.3400	53.3400	50.0000	14.7000	4.230	2.285	.150	.600	1.851
1.400	1.400	510.0000	510.0000	53.3400	53.3400	50.0000	14.7000	5.580	2.285	.200	.600	2.442
1.400	1.400	510.0000	510.0000	53.3400	53.3400	50.0000	14.7000	8.121	2.285	.300	.600	3.554
1.400	1.400	510.0000	510.0000	53.3400	53.3400	50.0000	14.7000	10.383	2.285	.400	.600	4.544
1.400	1.400	510.0000	510.0000	53.3400	53.3400	70.0000	14.7000	2.822	3.200	.100	.600	0.882
1.400	1.400	510.0000	510.0000	53.3400	53.3400	70.0000	14.7000	4.201	3.200	.150	.600	1.313
1.400	1.400	510.0000	510.0000	53.3400	53.3400	70.0000	14.7000	5.541	3.200	.200	.600	1.732
1.400	1.400	510.0000	510.0000	53.3400	53.3400	70.0000	14.7000	8.062	3.200	.300	.600	2.519
1.400	1.400	510.0000	510.0000	53.3400	53.3400	70.0000	14.7000	10.305	3.200	.400	.600	3.220

APPENDIX III
EJECTOR DESIGN
CONSTANT AREA MIXING



2. COMPUTER INPUTS:

Program No. 1	Program No. 2
γ'	γ'
γ''	γ''
T_t'	T_t'
T_t''	T_t''
R'	R'
R''	R''
P_t'	P_t'
P_t''	P_t''
$\dot{m}''$	$\dot{m}''$
A_d/A^*	$\dot{m}'$
M_3''	M_3''
η	η

3. Equations used in computer programs No. 1 and 2:

$$P_t''/P_3 = \left[1 + \frac{\gamma'' - 1}{2} (M_3'')^2\right]^{\frac{\gamma''}{\gamma'' - 1}}$$

$$P_t'/P_3 = (P_t''/P_3)\ (P_t'/P_t''$$

$$M_3' = \left[\frac{(P_t'/P_3)^{\frac{\gamma' - 1}{\gamma'}} - 1}{\frac{\gamma' - 1}{2}}\right]^{1/2}$$

$$A_3'/A^* = \frac{1}{M_3'}\left[\frac{2}{\gamma' + 1}\left\{1 + \frac{\gamma' - 1}{2} (M_3')^2\right\}\right]^{\frac{\gamma' + 1}{2(\gamma' - 1)}}$$

$$A_3''/A_3' = \frac{A_d/A^*}{A_3'/A^*} - 1$$

$$\dot{m}''/\dot{m}' = \left(\frac{A_3''}{A_3'}\right)\left(\frac{M_3''}{M_3'}\right)\left[\frac{\gamma''\ R'\ T_t'\left\{1 + \frac{\gamma'' - 1}{2} (M_3'')^2\right\}}{\gamma'\ R''T_t''\left\{1 + \frac{\gamma' - 1}{2} (M_3')^2\right\}}\right]^{1/2}$$

$$m' = \frac{\dot{m}''}{(\dot{m}''/\dot{m}')}$$

$$\left(\frac{P}{P_t}\dot{m}\right)'_{M=1} = \sqrt{\frac{\gamma' g}{R'}}\left[\frac{2}{\gamma' + 1}\right]^{\frac{\gamma' + 1}{2(\gamma' - 1)}}$$

$$A^* = \frac{\dot{m}\sqrt{T_t'}}{P_t'\left(\frac{P}{P_t}\dot{m}\right)'_{M=1}}$$

$$A_3' = (A_3'/A^*)\ A^*$$

$$A_3'' = (A_3''/A_3')\ A_3'$$

$$P_3 = P_t'/(P_t'/P_3)$$

$$F_4 = P_3 \left[A_3' \left\{ 1 + \gamma' (M_3')^2 \right\} + A_3'' \left\{ 1 + \gamma'' (M_3'')^2 \right\} \right]$$

$$\dot{m}_4 = \dot{m}' + \dot{m}''$$

$$R_4 = \frac{\dot{m}' R' + \dot{m}'' R''}{\dot{m}_4}$$

$$C_p' = \frac{R'}{J} \frac{\gamma'}{\gamma' - 1}$$

$$C_p'' = \frac{R''}{J} \frac{\gamma''}{\gamma'' - 1}$$

$$\dot{m}_4 C_{p_4} = \dot{m}' C_p' + \dot{m}'' C_p''$$

$$T_{t_4} = \frac{\dot{m}' C_p' T_t' + \dot{m}'' C_p'' T_t''}{\dot{m}_4 C_{p_4}}$$

$$\gamma_4 = \left[1 - \frac{R_4}{JC_{p4}} \right]^{-1}$$

Let

$$G = (m_4/F_4)^2 \frac{R_4 T_{t_4}}{\gamma_4 g} \quad \text{and } K = 1 - 2\gamma_4 G$$

$$M_4 = \left[\frac{K - \sqrt{K - 2G}}{1 - \gamma_4 K} \right]^{1/2}$$

$$(P_t/P)_4 = \left[1 + \frac{\gamma - 1}{2} M_4{}^2 \right]^{\frac{\gamma_4}{\gamma_4 - 1}}$$

$$P_4 = \frac{F_4}{(A_d/A^*) A^* (1 + \gamma_4 M_4^2)}$$

$$P_{s5}/P_4 = 1 + \eta \left[(P_t/P)_4 - 1 \right]$$

$$P_{s_5} = (P_{s_5}/P_4) P_4$$

$$A_d/A^* = \frac{(A_3' + A_3'')}{A^*}$$

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13 ABSTRACT

The objective of this model study was to determine the potential for testing very large thrust, high-bypass-ratio, turbofan engines at conditions simulating flight Mach numbers of 0.4 to 0.6, sea level, by use of a jet pumped air supply system. The simulation of low altitude, subsonic operation of a large, high-bypass-ratio, turbofan engine in ground test facilities requires extremely large airflows. This airflow, even at relatively low pressure, cannot be provided by existing test facilities for engines having thrust levels of 60,000 to 100,000 lbf. The jet pumped air supply is therefore a very attractive potential facility. The purpose of this study is to determine the maximum jet pump mass ratio at which the pressure rise corresponding to sea-level flight at M = 0.4 to 0.6 can be obtained and the resulting motive air-flow rate and state conditions required to test engines in the thrust class of 60,000 to 100,000 lbf.

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