AD A952972

TECHNICAL MEMORANDUM NO. CAL-42

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH IN JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY
AND THE
OFFICE OF AIR RESEARCH, DEPARTMENT OF THE AIR FORCE
Contract N6ori-119, Task Order 1
NR 220-041
Report No. DD-420-A-37

SUMMARY REPORT ON VALVELESS PULSEJET INVESTIGATION

By

J.G. Logan, Jr.

October 1951

CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, New York

SUMMARY

The investigations conducted at Cornell Aeronautical Laboratory with valveless pulsejet engines from October 1948 to September 1951 and the whirling arm tests of 6-inch valveless pulsejets conducted at the Chesapeake Bay Annex of the Naval Research Laboratory between January 1951 and September 1951 are described.

INTRODUCTION

In 1948 studies of wave phenomena in pulsejet engines and acoustic jets indicated the possibility of building valveless jet engines utilizing intermittent combustion. Experimental investigations with small models demonstrated that intermittent operation could be obtained with continuous air and fuel injection. Tests of models with combustion chamber diameters up to 6 inches showed that resonant operation could also be achieved in large size models. It was also observed during these tests that resonant operation could be achieved at inlet pressures corresponding to relatively low Mach numbers.

An extensive experimental program was undertaken with small-scale models to determine the influence of tube geometry upon thrust and specific impulse. In conjunction with these experiments, schlieren investigations of two-dimensional glass walled models were conducted in order to obtain some insight into the operating mechanism.

From the early investigations, it appeared that the valveless pulsejet was, potentially, a more efficient power plant than either the conventional pulsejet or the ramjet for certain specific applications. One of the more interesting of these applications appeared to be the use of the valveless pulsejet as a power plant for the jet-propelled helicopter. In September 1950, at the request of the Office of Naval Research, a joint program was established with the Naval Research Laboratory to determine the possibility of employing valveless pulsejet engines as propulsion units for helicopter rotors. Six inch diameter valveless pulsejet engines developed at C.A.L. were supplied to N.R.L. for whirl testing on the 41.2 foot diameter whirling arm at the Chesapeake Bay Annex. This memorandum summarizes the results of the theoretical and experimental investigations conducted at C.A.L. with valveless pulsejet engines from October 1948 to September 1951 and whirling arm tests conducted by the Naval Research Laboratory at Chesapeake Bay Annex from January 1951 to September 1951 (1).

TESTS OF SMALL SCALE MODELS

After it had been established (2) that valveless configurations would resonate when air and fuel are injected continuously, a series of experiments were undertaken with small-scale models to determine to what extent thrust and specific impulse values are influenced by tube geometry and fuel characteristics (3).

These models were made up of a number of units which could be assembled to give various configurations. The combustion chamber diameter was varied from 2-1/2 to 4 inches with a fixed length of 4 inches. The length of the tailpipe could be varied continuously between 12 and 16 inches. Both propane and methane were used as fuels and air and fuel were injected into the side of the combustion chamber. Fuel consumption was measured by means of a small rotameter and thrust was determined on a small thrust stand with the aid of a spring balance. The highest mean values of specific impulse which could be obtained were about 2400 lbs. thrust per lb. fuel per sec. for thrusts, corrected for the momentum of the incoming air, of the order of 3 lbs. Significant differences in performance were observed in some cases for operation with propane and methane. Fig. 1 shows the results of a series of experiments performed with a model having a combustion chamber of 3 inches. When methane was used as a fuel the specific impulse values increased as the tailpipe length was increased, with propane, however, the specific impulse values decreased. At a tailpipe length of 17 inches, methane yielded twice the specific impulse values obtained with propane.

The operating frequency of these jets depended not only on the configuration but also on the air-fuel ratio. The highest values of specific impulse were obtained at frequencies which were lower than those at which an ordinary dynajet of the same shape would operate. It was observed during these tests that slight changes in tube geometry, air-fuel ratio or fuel injection methods also exerted appreciable influence upon the specific impulse values. In one instance, the specific impulse and thrust changed by 30 percent when the tailpipe length was changed by one-quarter inch. Still larger changes were observed for changes in air-fuel ratio.

In these early investigations[3] the tailpipe diameters were restricted to 1.5 inch (Appendix A Models 1-18). Later investigations were conducted with engines having tailpipe diameters of 2.5 and 3.0 inches (Appendix A - Models 20,21) in order to obtain larger thrust values. The thrust obtained with the 2.5 inch tailpipe, was approximately 11 pounds (1.5 lbs. per square inch of combustion chamber area). The corresponding fuel specific impulse was approximately 2500 seconds. With the straight tube model, maximum thrusts obtained were of the order of 13.2 lbs. (about 1.9 lbs. per square in.) but the specific impulse was only 1850 seconds.

In these experiments with small-scale models, two stable operating frequencies were observed, one occurring near the lean limit and the other near the stoichiometric ratio. In order to determine the operating frequencies and investigate pressure variations in the combustion chamber and tailpipe, pressure records were made using a FM condenser-type pressure gauge[4]. Frequency measurements obtained from the pressure records showed that at the lean limit of operation (at which maximum performance occurred), the frequency was approximately 70 percent of the frequency for operation near the stoichiometric ratio. The pressure curves showed also that the time of rise to peak pressure was approximately the same for both frequencies of operation (3).

Fig. 2 shows typical pressure records obtained in the combustion chamber and tailpipe of a 3.0 inch diameter straight tube jet, 28 inches long. Measurements of the oscillation amplitudes indicated that the amplitude of the combustion chamber and tailpipe pressures were of approximately the same order of magnitude. Measured amplitudes were of the order of 35 inches Hg.

To determine the thrust developed per lb. air per second (air specific impulse), measurements of mass flow were made using a calibrated orifice plate. Total pressure measurements were also made at the air inlet with a standard pitot tube. A standard 3/8 inch pipe was used as an air inlet. Inlet-exit area ratios were of the order of 1/18. Measurements indicated that air specific impulse values varied from 35 to 60 lbs. thrust/lb. air per sec. Air-fuel mixtures for maximum specific impulse were much greater than stoichiometric, peak performance occurring at an air-fuel ratio of 32. The corresponding total inlet air pressures for maximum performance were approximately 2.5 lbs. per sq. in. gauge.

Both theoretical and experimental attempts were made to obtain a better insight into the mechanism of valveless pulsejets. A two-dimensional model of a valveless pulsejet with vicor glass* sidewalls was constructed for observation by means of high speed motion pictures. Initial attempts to obtain resonant operation were not successful and it appeared that the rectangular cross section of this model had some effect on the combustion phenomena.

*Manufactured by The Corning Glass Company.

However, no difficulties were encountered with a similar model built entirely of steel. It was then suspected that the observed difficulties had been due to leakage or lack of sufficient rigidity. Another more rigid model was constructed with operated satisfactorily. Flash photographs and high-speed schlieren pictures (up to 4000 frames per sec) were taken. The high speed pictures indicated then an intermittent fuel-air injection process occurred. These film speeds, however, were not great enough to yield details of the combustion phenomena.

Attempts were made to determine theoretically values of thrust and specific impulse based on a quasi-steady flow assumption. These investigations were discontinued because of the difficulty of treating the scavenging phase. Later, a general analysis of valveless pulsejet engines, based on entropy considerations was made by J. Foa[5]. This analysis, however, did not permit the determination of jet thrust. By means of the method of characteristics, G. Rudinger[6] found that it was possible to obtain agreement with experimental results with regard to thrust, specific impulse and operating frequency on the basis of reasonable assumptions concerning the initial conditions. Unfortunately, the same results could apparently be obtained by different sets of initial conditions. Therefore no definite conclusions regarding the mechanism of the engine could be drawn.

In all of these investigations, a long inlet tube was employed which approximated an infinite inlet duct, eliminating the influence of reflected waves from a finite inlet. Since under some conditions, a finite inlet tube may be required, some thought was given to designs which would utilize the experimentally observed tendency of flows to follow a convex curvature of a wall on one side, without a constraining wall on the other (Coanda effect[7]).

If such a scheme were successful, inflow into the combustion chamber of the pulsejet could take place through a practically open inlet tube while the reverse flow would be deflected by the Coanda effect and exhausted downstream.

A preliminary series of experiments on the Coanda effect was undertaken with a two-dimensional model. Carbon dioxide was added to the airstream to enable flow visualization. A strong deflection was observed without the use of a constraining wall both in steady and in pulsating flow (3).

WHIRLING ARM TESTS OF THE VALVELESS PULSEJET

In September 1951, at the request of the Office of Naval Research, a joint program was established with the Naval Research Laboratory to determine the feasibility of employing valveless pulsejets as propulsion units for helicopter rotors. This program comprised the whirl testing of valveless engines, developed at C.A.L., at the Chesapeake Bay Annex of the Naval Research Laboratory.

Preliminary static tests of 6 inch diameter models were undertaken at C.A.L. to obtain a model suitable for whirl testing. These valvelsss engines, Fig. 3, varied in length from 32 to 56 inches. A low pressure blower which delivered air at a dynamic head of about 3.5 inch of Hg corresponding to a flight Mach number of approximately 0.4 was used in these tests.

In these tests (Appendix A - Model 22) gasoline was used as fuel and the model selected for whirl testing produced 38 lbs. total thrust with a specific impulse (based on total thrust) of 1500 seconds.

Since the initial phase of the joint program consisted of tests using air supplied by centrifugal compression, a special hollow rotor arm, Fig. 4, was constructed at the Chesapeake Bay Annex for the whirl tests. This arm did not have a mechanical drive and air from an auxiliary blowdown high-pressure supply fed through the rotor arm was used for starting the engines. During the initial tests with one valveless jet mounted at each rotor tip (Fig. 4) it was found that the arm could not be accelerated to a speed at which adequate air could be supplied for operation by means of centrifugal compression. Measurements of the available blowdown air supply revealed that a maximum air flow of 0.25 lbs/sec. was available for only 0.9 minutes which proved to be insufficient to accelerate the arm to the desired speeds.

Tests were then conducted with one valveless pulsejet mounted on the arm and the second replaced by a 8.0 inch diameter NRL conventional pulsejet. This engine alone accelerated the arm to a tip speed of 320 fps and when the valveless pulsejet was started with the auxiliary air supply, a tip speed of 160 rpm was obtained. Although the valveless jet resonated using only the air supplied by centrifugal compression, the thrust obtained was not sufficient to increase the speed of the arm by more than a few rpm.

Two additional air compressors were then installed which when used in conjunction with the original supply yielded a steady flow of 0.75 lbs/sec. at 150 psig. Tests were then continued with one six-inch valveless engine mounted at each rotor tip. Using these engines a maximum tip speed of approximately 240 fps was obtained. It was observed during these tests that small changes in inlet area and exit configuration had a noticeable effect on the maximum rpm obtained. A straight exit proved to be superior to the original flared exit used in static testing, even at the relatively low tip speeds of 150 fps.

Drag measurements based on deceleration tests indicated that two six-inch valveless engines would not yield sufficient thrust to accelerate the arm to the desired rotor tip speeds. The rotating arm was then modified to permit the installation of two engines at each blade tip and the maximum tip speed was then increased to approximately 350 fps.

It was noted that at tip speeds of the order of 280 fps the thrust suddenly started to increase rapidly and it is believed that the performance increase was due to an increase in air supply as a result of centrifugal compression. In these tests, however, it was not possible to shut-off the compressor supply and obtain operation entirely under centrifugal compression.

During this test period, a compressor failure occurred. In order to furnish power for the arm, two 8.0 inch pulsejet engines were mounted at a distance of seven feet from the hub (Fig. 4). Since the characteristics of these engines were approximately known from tests, new estimates of the arm drag with the dual jet mountings were obtained. These new estimates indicated that due to internal blade losses and large external drag, even four six-inch valveless jets would not furnish sufficient thrust to operate the arm in the desired test range 400-600 fps. Upon completion of the compressor repairs, tests were continued using the auxiliary pulsejet power. Although maximum tip speeds of approximately 440 fps were obtained, it was observed that appreciable interference occurred between the valveless jets and the pulsejets. This interference appeared to effect the operation of the valveless engines.

As a result of failure to obtain self operation which was believed due to excessive arm drag, plans were made to construct a small aerodynamically clean rotor arm which could be powered by a single six-inch valveless engine. The preliminary investigations of the effect of external configuration, air inlet geometry and location of fuel inlets on the performance of the six-inch valveless engines which were initiated on the 41.2 foot diameter rotor will be continued on the small rotor arm. Tests on the existing rotor will be limited to larger engine sizes (7-1/2 - 8-1/2 inches diameter). A detailed report of the report of the investigations conducted so far on the 41.2 foot diameter rotor is being prepared and will be issued by the Naval Research Laboratory(1).

In parallel with these tests, a program of large scale static experimentation with six-inch diameter engines was undertaken (Appendix A). The primary purpose was to investigate the effects of changes on engine geometry upon thrust since, at the present time, the effects of such changes cannot be determined theoretically. These tests have shown that thrust is appreciably affected by changes of size and/or location of the side air inlet. Best performance was obtained with a 2-1/4 inch diameter air inlet approximately 8 inches downstream of the nose. Total thrust values of 44 lbs. were obtained with an inlet air velocity of 300 mph.

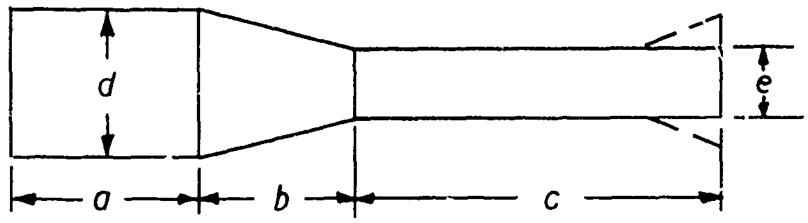
Tests were also undertaken to determine if inlets of elliptical cross section could be used without decreasing the engine performance. The use of inlets with this geometry would then allow the rotor sections to be employed at the tip of the whirling arm which would appreciably reduce the rotor drag. At the present time, although satisfactory operation has been obtained with the elliptical sections of approximately 3.5 by 1.25 inches the maximum thrust obtained was less than the optimum observed for circular inlets.

REFERENCES

1. Porter, C., Performance and Developmental Studies of 6" Valveless Pulsejet on Rotor Tips. NRL Report (to be published).
2. Project SQUID Annual Program Report, January 1, 1949.
3. Logan, J., Projec. SQUID Technical Memorandum No. CAL-27, 1 May 1949.
4. Project SQUID Annual Program Report, January 1, 1948, p. 18.
5. Foa, J.V., Performance of Single Flow Jet Engines, Project SQUID Technical Report No. 20, 1 May 1950.
6. Project SQUID Annual Program Report, January 1, 1950, pp. 27-30.
7. Sproule, R. The Coanda Effect.Report No. 327, Office of the Publication Board, Department of Commerce, Washington, D.C.
8. Project SQUID Quarterly Report, 1 April 1950, pp. 6-7.
9. Project SQUID Quarterly Report, 1 October 1950, pp. 4-5.
10. Project SQUID Semi-Annual Report, 1 April 1951.
11. Project SQUID Semi-Annual Report, 1 October 1951.
12. Project SQUID Semi-Annual Report, 1 April 1951.

APPENDIX A
SUMMARY OF VALVELESS PULSEJET INVESTIGATIONS

TABLE I



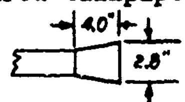
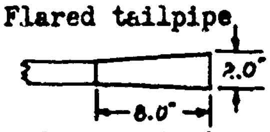
Model	a	b	c	d	e	Thrust lbs.	Is Seconds	Remarks
		inches						
1	4.0	3.0	8.0	3.0	1.5	0.699	548	Straight exit Fuel-gasoline Single side injection
2	4.0	3.0	16.0	3.0	1.5	0.839	692	Same as 1
3	4.0	3.0	19.0	3.0	1.5	0.791	580	Same as 1
4	4.0	3.0	22.0	3.0	1.5	0.663	563	Same as 1
5	3.0	1.5	14.5	2.5	1.25	0.67	1300	Dynajet no valves Flared exit Single injection Fuel Propane
6	3.0	1.5	14.5	2.5	1.25	0.68	949	Separate air-propane injection
7(a)	4.0	3.0	8.0	3.0	1.5	1	865	Single propane air injection
(b)	4.0	3.0	8.0	3.0	1.5	1.94	1112	Separate air propane injection
(c)	4.0	3.0	9.5	3.0	1.5	1.31	1040	Same as 7(b)
(d)	4.0	3.0	14.0	3.0	1.5	2.68	1110	" " "
(e)	4.0	3.0	16.0	3.0	1.5	2.96	1554	" " "
(f)	4.0	3.0	21.5	3.0	1.5	2.0	945	" " "
8	4.0	3.0	16.0	3.5	1.5	2.76	1300	Separate air propane; straight tailpipe
9	4.0	3.0	16.0	3.5	1.5	2.75	2120	Flared tailpipe  and separate injection-propane-air
10	4.0	3.0	16.0	3.5	1.5	3.20	1555	Flared tailpipe  and separate injection-propane-air

TABLE I (Cont)

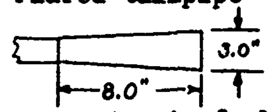
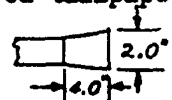
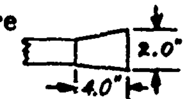
Model	a	b	c	d	e	Thrust	Is	Remarks
		inches				lbs.	Seconds	
11	4.0	3.0	16.0	3.0	1.5	3.25	1350	Flared tailpipe  separate air fuel injection-propane-air
12	4.0	3.0	16.0	3.0	1.5	3.25	1350	Flared tailpipe  separate air-propane injection
13(a)	4.0	3.0	13.75	2.5	1.5	2.4	1670	Flare 
(b)	4.0	3.0	14.0	2.5	1.5	2.5	1880	
(c)	4.0	3.0	15.0	2.5	1.5	1.3	840	
(d)	4.0	3.0	16.0	2.5	1.5	2.0	1319	separate air-fuel injection
(e)	4.0	3.0	16.75	2.5	1.5	1.1	1100	Fuel propane (typical values)
14(a)	4.0	3.0	13.5	3.0	1.5	4.0	1270	
(b)	4.0	3.0	14.0	3.0	1.5	3.75	1480	Fuel propane
(c)	4.0	3.0	14.75	3.0	1.5	2.5	1610	(typical values)
(d)	4.0	3.0	16.5	3.0	1.5	3.0	1290	
15(a)	4.0	3.0	13.5	3.0	1.5	1.9	1480	
(b)	4.0	3.0	14.0	3.0	1.5	3.0	1690	Fuel methane
(c)	4.0	3.0	14.75	3.0	1.5	2.5	1600	(typical values)
(d)	4.0	3.0	16.5	3.0	1.5	3.0	2120	Same exit and injection as 13
16(a)	4.0	3.0	13.25	3.5	1.5	3.0	1380	
(b)	4.0	3.0	14.25	3.5	1.5	3.0	1690	Fuel propane
(c)	4.0	3.0	16.0	3.5	1.5	3.5	1970	(typical values)
(d)	4.0	3.0	17.25	3.5	1.5	3.5	1900	Same exit and injection as 13
17(a)	4.0	3.0	13.25	3.5	1.5	1.75	1250	
(b)	4.0	3.0	14.25	3.5	1.5	2.75	1910	Fuel methane
(c)	4.0	3.0	16.0	3.5	1.5	3.42	2150	(typical values)
(d)	4.0	3.0	17.25	3.5	1.5	2.75	1940	Same exit and injection as 13
18(a)	4.0	3.0	13.25	4.0	1.5	2.75	1080	
(b)	4.0	3.0	14.25	4.0	1.5	2.75	1250	Fuel propane
(c)	4.0	3.0	15.25	4.0	1.5	3.25	1390	(typical values)
(d)	4.0	3.0	17.0	4.0	1.5	2.85	1440	Same exit and injection as 13

TABLE I (Cont.)

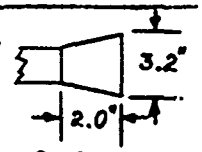
Model	a	b	c	d	e	Thrust lbs	Is Seconds	Remarks
	inches							
19				2.5				Inverted pulsejet; over-all dimensions 8.75 in., combustion chamber diameter 2.5 in. No thrust measurements. Model resonated and produced some thrust.
20(a)	6.0	3.5	16.75	3.0	2.5	11.0	2430	Flared exit 
(b)	6.0	3.5	18.5	3.0	2.5	10.5	2560	
(c)	6.0	3.5	19.5	3.0	2.5	10.5	2270	
(d)	6.0	3.5	20.5	3.0	2.5	9.0	2230	Separate air fuel injection. Three point fuel injection system
21	-	-	L_0=26	3.0	3.0	13.0	1710	Straight tube
			L_0=27	3.0	3.0	13.25	1850	Conditions same as 20
			L_0=28	3.0	3.0	11.5	1460	

TABLE II

Model 22-6.0 (Figure 3)

Investigation of Effect of Tailpipe Length

Configuration	Overall Length	Tailpipe Length	Thrust	Specific Impulse	Airspeed Tested	Remarks
	Inches	Inches	Lbs.	Sec.	MPH	
(1) Flat nose. 2 Fuel injectors in 2.0" dia.inlet	50	27	36	1408	280	
(2) Flat nose 4 Fuel Nozzles in 3.0" dia.air inlet	50	27	37	1560	290	
(3) Conical nose	56	27	36	1560	290	Length increased to app.56.0 inches by addition of conical nose.
(4) Conical nose 4 Fuel nozzles in 3.0" dia.air inlet	52	23	38	1600	300	
(5) Conical nose 4 Fuel nozzles in 3.0" dia.air inlet	44	15	-	-	290	Model would resonate but not produce steady thrust.
(6) Conical Nose 2.0" dia.air inlet with 3 fuel nozzles	48	19	38	1530	290	Very stable operation. Easy to start. Thrust controlled from zero to max.by fuel control. A third fuel nozzle added upstream of air intake.
(7) Conical nose 2.0" dia.air inlet with 3 fuel nozzles	42	10	10-15	-	290	Combustion chamber reduced to 10.0" real resonance achieved.
(8) Conical nose. 2.0" dia.air inlet with 3 fuel nozzles	42	15	33	1800	290	One fuel nozzle upstream of air intake. Runs fairly stable. Good operation over range of fuels Best operation appears to occur when a separate nozzle is used outside of air intake

TABLE II (Cont.)

Model 22-6.0

Configuration	Overall Length	Tailpipe Length	Thrust	Specific Impulse	Airspeed Tested	Remarks
	Inches	Inches	Lbs.	Sec.	MPH	
(9) Conical nose. 2.0" diameter air inlet with 3 fuel nozzles.	32.0	5.0	-	-	290	Tests initiated on model temporarily suspended. Indications are that model will resonate. No thrust measurement. Test conducted to determine if ignition can be obtained at maximum air intake velocities. With a small "flame holder" surrounding the spark, the jet could be ignited at the maximum air intake velocity.

TABLE III

Model 22-6.0
Investigation of Effect of Air Inlet Location

Configuration			Thrust lbs.	Specific Impulse Sec.	Airspeed mph.	Comments
Overall Length inches	Tailpipe Length inches	Air Inlet Position inches				2.0 inch dia.air inlet All tests run with 2 fuel nozzles in air inlet. One auxiliary nozzle 6.0" from nose.Examination of jet after tests indicated puddling from auxiliary nozzle. (Nozzles in air inlet projecting 1/2" into jet)
58	33	8.0	35	1750	300	
			23	1730	250	One fuel nozzle burned off. Performance erratic.
54	29	8.0	38	1520	300	Thrust plate distance 15" from tailpipe.
			34	1260	250	Thrust plate distance 11".
50	25	8.0	23	850	290	East starting at 1/2 air.Stops resonating full open.Runs best with 1/2 air.
			25	930	250	Sensitive to air valve setting. Runs best with 1/2 air.
			13	560	180	
46	21	8.0	20	740	290	Noise level of resonance low. Will not resonate thru entire air valve range.
42	17	8.0	14	520	300	
58	33	10.0	34	1100	290	Operation very erratic. Did not run steadily.
54	29	10.0	26	820	290	
50	25	10.0	25	730	300	
46	21	10.0	14	520	300	
42	17	10.0	10	550	300	
58	33	15.0	24	960	300	
54	29	15.0	17	780	300	
			14	840	250	
			14	650	200	
50	25	15.0	16	600	300	
			15	600	250	
			14	520	200	
46	21	15.0	14	600	300	
			9	390	250	Fuel supply fluctuating.
			11	920	200	
42	17	15.0	14	560	300	
			12	540	250	

TABLE IV

Model 22-6.0

Investigation of fuel injection location and air inlet area

Configuration	Thrust lbs	Fuel Flow gal/hour	Specific Impulse Sec.	Airspeed mph	Comments
(1) Overall length	18	12.35	870	300	Fuel nozzles 1.0" behind wall of jet.
	18	12.15	890	300	Difficult to start, intermittent resonance.
(2) 2-3/8"dia. air inlet (standard pipe fitting)	34	16.1	1270	300	
	20	14.05	850	300	
	36	15.0	1440	300	
(1) Auxiliary fuel nozzle 2.0" downstream of air inlet. Straight entry	26	19.0	820	300	Did not operate on full air. Runs only rich.
	16*	12.55	760	300	
	30	18.8	960	300	*without auxiliary nozzle
(2) 2-3/8" dia.air inlet	31	20.25	920	300	
(1) Auxiliary fuel nozzle 3.0" downstream of air inlet. Straight entry.	22	17.5	750	300	Did not run steadily.
	24	16.7	860	300	
(2) 2-3/8" dia. air inlet	28	17.85	940	300	
(1) Auxiliary fuel nozzle 3.0 inches downstream of air inlet. Nozzle pointed at angle toward nose	28	19.0	880	300	Somewhat increased stability
	20*	12.5	960	300	*Air inlet nozzles only
	28	18.6	900	300	
	28	18.25	920	300	
(2) 2-3/8" dia. air inlet					
(1) 2-3/8" dia.air inlet	32	12.0	1600	300	Performance not steady
(2) Two fuel nozzles in air inlet 1.0" behind jet wall					

TABLE IV (Cont.)

Configuration	Thrust lbs.	Fuel Flow gal/hour	Specific Impulse Sec.	Airspeed mph	Comments
(1) Larger fuel nozzles (2) 2-3/8" dia. air inlet	28	15.2	1100	300	Does not resonate with full air. Performance not steady
(1) 2-3/8" dia. air inlet	37	16.7	1330	300	Steady performance
(2) Fuel nozzles flush with jet wall	38	18.4	1240	300	
	38	15.4	1480	300	
(3) Auxiliary nozzle 1.0" upstream of air inlet	24	14.05	1020	200	
	20	13.5	890	200	
	5	12.5	240	100	
(1) 2-1/4" dia.air inlet	44	18.4	1440	300	Steady performance
(2) Fuel nozzles flush with jet wall	43.5	17.5	1490	300	
	43	16.3	1580	300	
(3) Auxiliary nozzle 1.0" upstream of air inlet	32	15.2	1270	250	
	32	14.25	1350	250	
	16	12.9	745	200	
(1) 2-5/16" dia. air inlet	41	19	1300	300	Steady
(2) Fuel nozzles flush with jet wall	40.5	16.5	1470	300	
	40	18.4	1300	300	
(3) Auxiliary nozzle 1.0" upstream of air inlet	39.5	15.4	1540	300	
(1) Edges of 2-3/8" diameter air inlet squared.	30	10.8	1670	300	Improved steady performance

TABLE V

Model 22-6.0

Investigation of air inlets of elliptical cross section

Configuration	Thrust lbs.	Fuel Flow gal/hour	Specific Impulse Sec.	Airspeed mph	Comments
(1) Inlet dimensions 3-1/8 x 1-1/4 inches	36	17.0	1270	300	Air inlet 8.0 inches downstream of nose
	31	13.0	1430	300	
	20	7.5	1600	300	Fuel nozzles in air inlet 1-3/8" from combustion chamber wall
	32	14.5	1280	300	
	34	14.5	1400	300	Fuel nozzles flush with combustion chamber wall
	30	16.0	1120	300	
(2) Inlet dimensions 3-1/2 x 1-1/4 inches	18	21	510	300	Fuel nozzles flush with combustion chamber wall
	20	21.5	560	300	
	20	11.5	1050	300	Fuel nozzles 1-3/8" from combustion chamber wall
	22	12.5	1050	300	
	26	12.2	1280	300	
	28	19.5	860	300	
	32	16	1200	300	Fuel nozzles 2-1/8" from combustion chamber wall

VARIATION OF SPECIFIC IMPULSE WITH TAILPIPE LENGTH

COMBUSTION CHAMBER DIAMETER ~ 3.0 INCHES

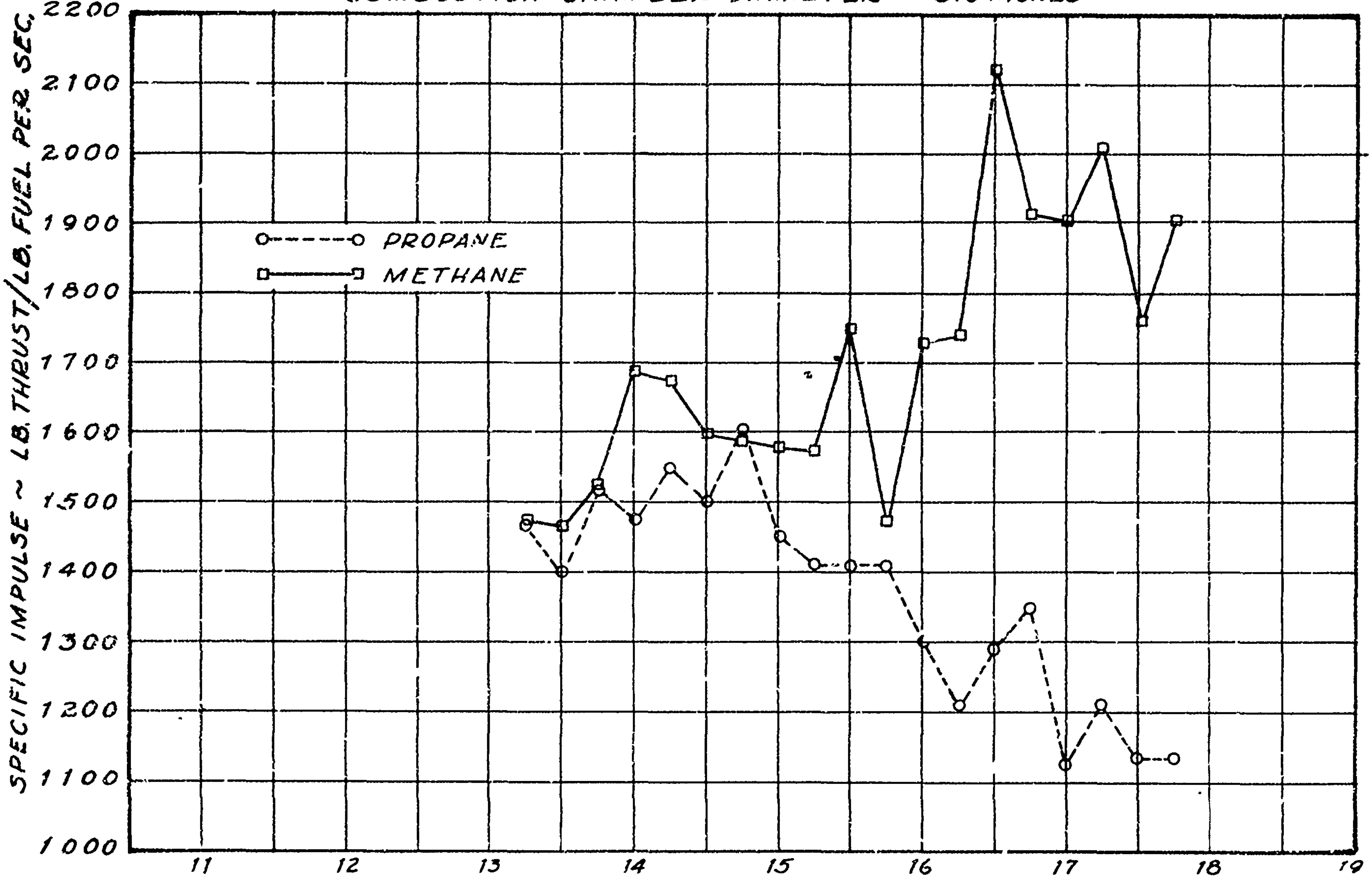
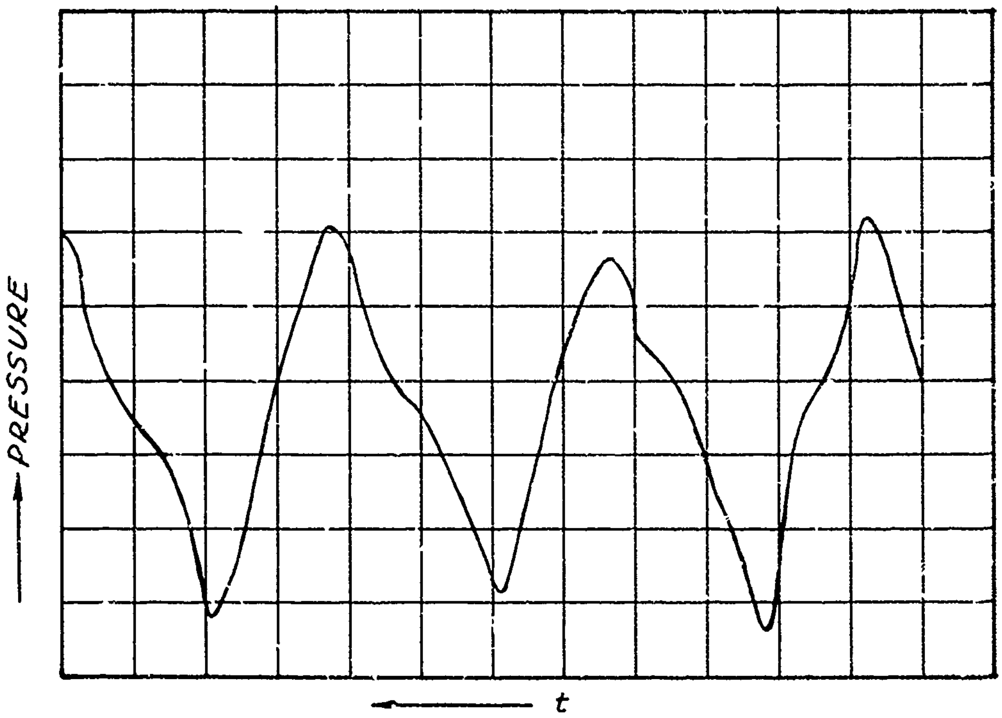
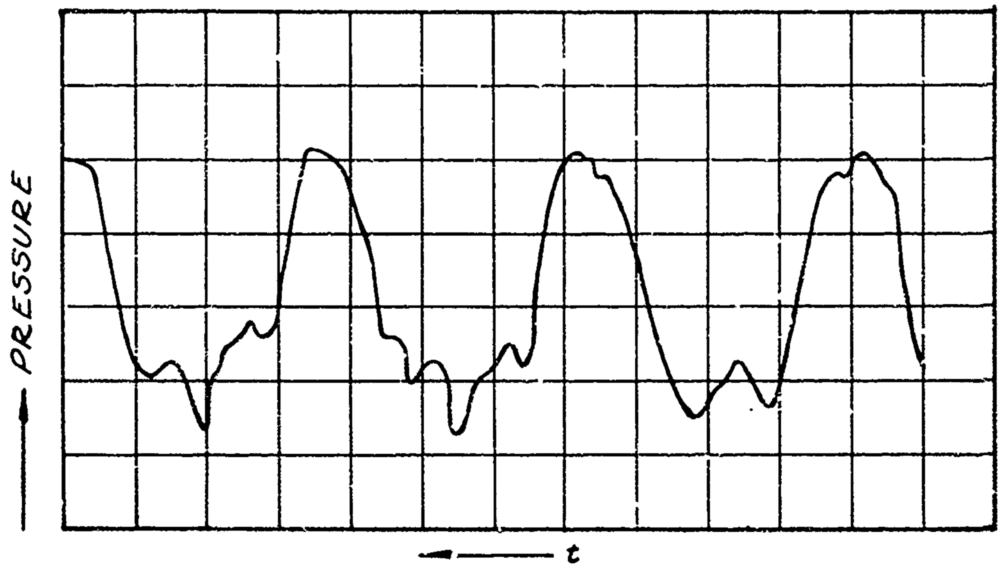


Fig. 1

PRESSURE MEASUREMENTS ~
VALVELESS PULSEJET
MODEL 21 [3.0" DIAMETER, 28" LENGTH]

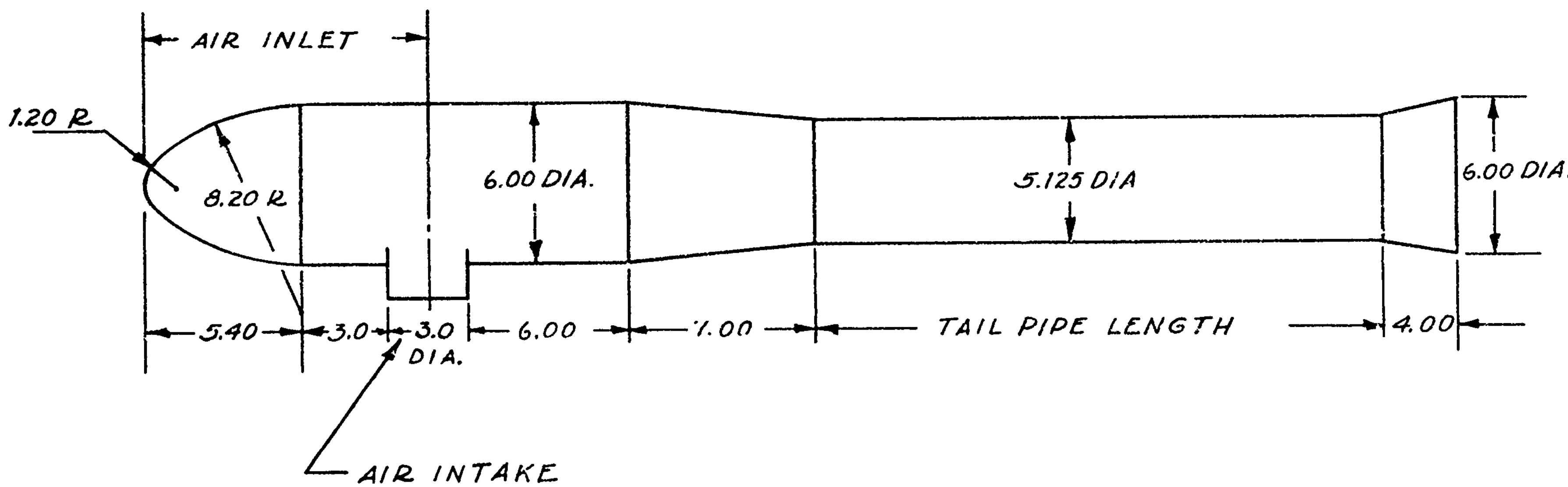


COMBUSTION CHAMBER PRESSURE RECORD FOR STRAIGHT TUBE VALVELESS JET WITH FLARED EXIT (TOTAL AMPLITUDE 35" Hg)



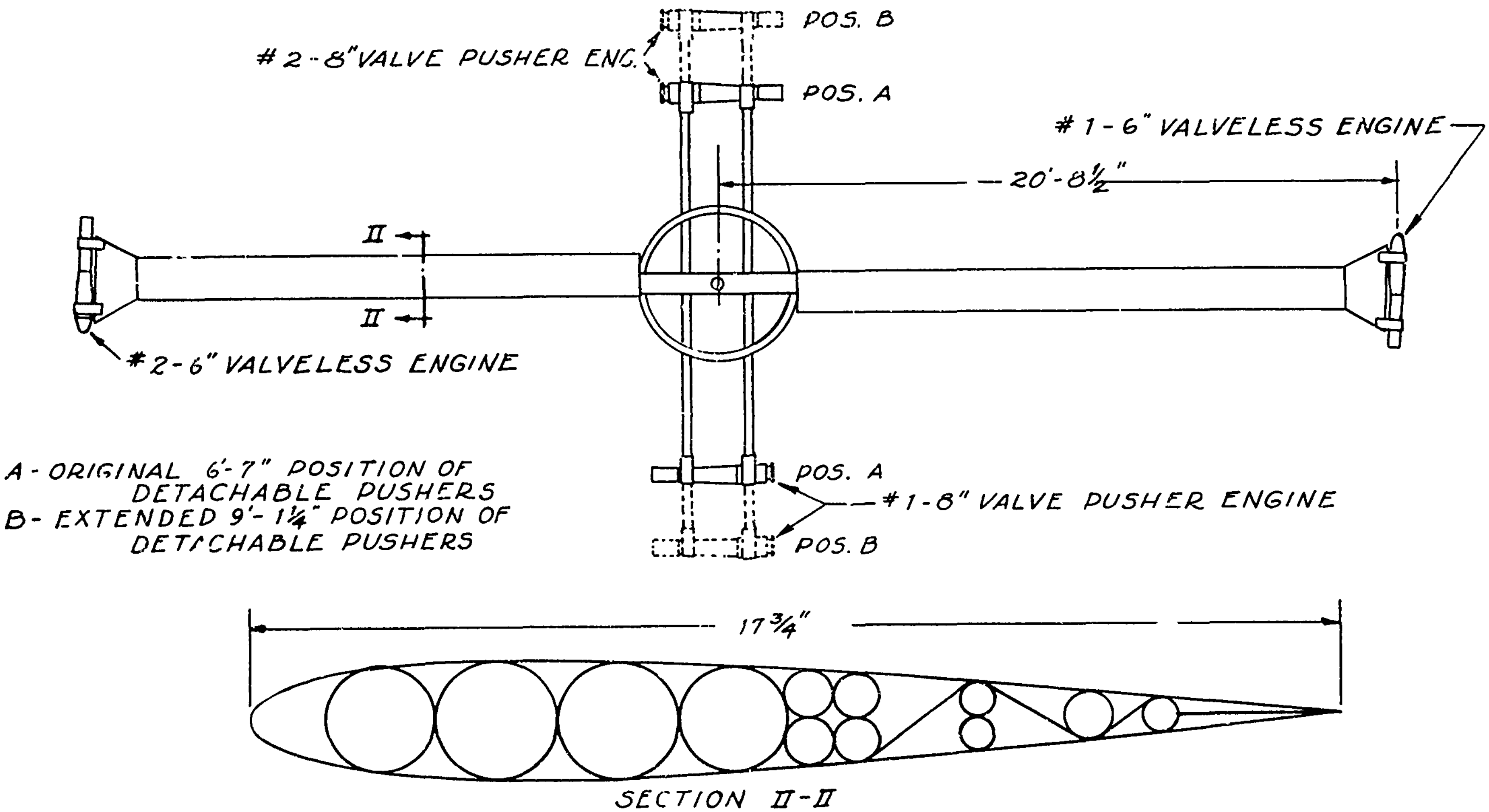
TAILPIPE PRESSURE RECORD FOR STRAIGHT TUBE VALVELESS JET WITH FLARED EXIT (TOTAL AMPLITUDE 35" Hg.)

Fig. 2



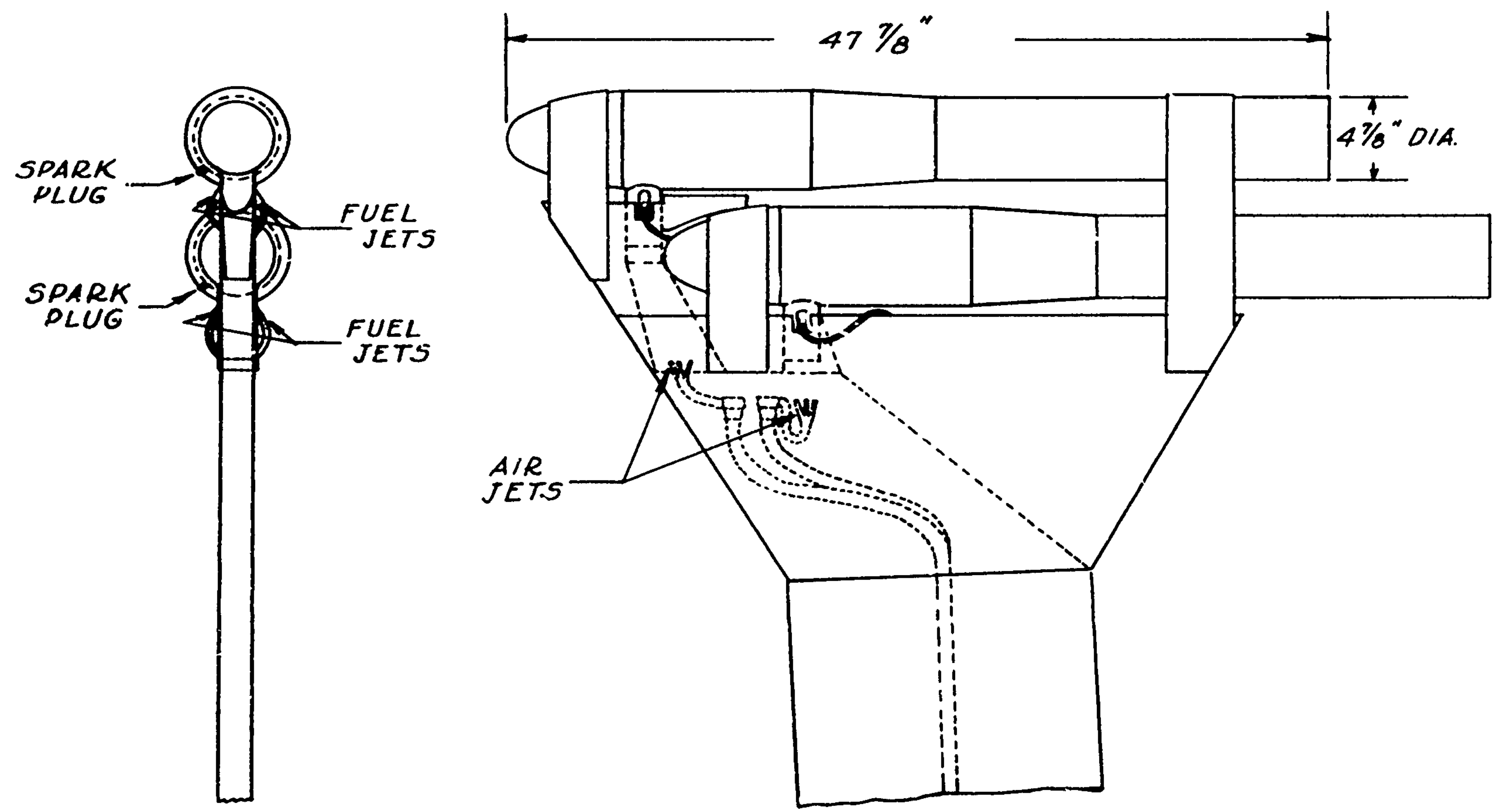
VALVELESS JET MODEL 22 - 6.0 DIA

Fig. 3



41'-5" AIR INDUCTION ROTATING ARM (1)
6" SINGLE VALVELESS & 8" PUSHER ENGINES

Fig. 4



6" VALVELESS SINGLE THROAT P.J. ENGINE
DUAL MOUNTING (1)

Fig. 5

DISTRIBUTION LIST

PARTS A,B,C, and DP of the A.N.A.F.G.M. Mailing List, July 1951

1. H.S.Taylor, Princeton University
2. J.V.Charyk, Princeton University
3. F. Clauser, Johns Hopkins University
4. J.V.Foa, Cornell Aeronautical Laboratory
5. N.J.Hoff, Polytechnic Institute of Brooklyn
6. M.J.Zucrow, Purdue University
7. K. Wohl, University of Delaware
8. G.Markstein, Cornell Aeronautical Laboratory
9. R.N.Pease, Princeton University
10. P.Libby, Polytechnic Institute of Brooklyn
11. S.A.Guerrieri, University of Delaware
12. L. Lees, Princeton University
13. G.Rudinger, Cornell Aeronautical Laboratory
14. S.W.Yuan, Polytechnic Institute of Brooklyn
15. P.K.Porter, Cornell Aeronautical Laboratory
16. H.J.Shafer, Princeton University
17. A.P.Colburn, University of Delaware
18. G.S.Meikle, Purdue University
19. J.J.O'Neil, Cornell Aeronautical Laboratory
20. R.J.Woodrow, Princeton University
21. F.A.Parker, Princeton University
22. M.Summerfield, Princeton University
23. W.J.Barr, Princeton University
24. J.H.Wakelin, Textile Research Foundation

25/37. Chief of Naval Research, Code 429, Washington, D.C.(13cc)

38. Commanding Officer, O.N.R., New York, New York
39. Commanding Officer, O.N.R., Chicago, Illinois
40. Commanding Officer, O.N.R., Boston, Mass.
41. Commanding Officer, O.N.R., San Francisco, Calif.
42. Commanding Officer, O.N.R., Pasadena, Calif.

43/45. Chief, Bureau of Aeronautics, Power Plant Div., Exp.Engines Branch (3)

46. Chief, Bureau of Aeronautics, Power Plant Div., Fuels and Lubricants Branch
47. Chief, Bureau of Aeronautics, Ship Installations Div.
48. P.Kratz, O.N.R. Reg.Representative, Philadelphia, Penna.
49. Commander R.W.Pickard, BuAer Representative, Cornell Aeronautical Laboratory, Buffalo, New York
50. D.G.Samaras, Office of Air Research, Wright-Patterson Air Force Base

51/52. F.Tanczos, Bureau of Ordnance, Guided Missiles Division, Washington, (2)

53. W.Worth, Power Plant Laboratory, Engineering Div., Wright Field
54. C.F.Yost, Directorate of Research and Development, USAF, Pentagon

55/56. Chief of Naval Research, Navy Research Section, Library of Congress(2)

57. W.Tenney, Aeromarine Company
58. R.Folsom, University of California, Mechanical Engineering Department
59. Engineering Librarian, Columbia University Library
60. C.Millikan, Guggenheim Aeronautical Laboratory, California Institute of Tech.
61. B.L.Crawford, Department of Chemistry, University of Minnesota
62. Officer in Charge, Naval Ordnance Test Station, Pasadena, Calif.
63. J. Moriarty, Purdue University Library
64. B. Lewis, Bureau of Mines, Pittsburgh, Penna.
65. L.Crocco, Princeton University
66. Manson Benedict, Hydrocarbon Research, Inc., New York City

67. Gerhard Dieke, Johns Hopkins University
68. M.W.Evans, 3115 Western Avenue, Park Forest, Chicago Heights, Illinois
69. K.F.Hertzfeld, Department of Physics, Catholic University of America
70. Arnold Kuethe, University of Michigan, Ann Arbor, Michigan
71. C.C.Lin, Dept. of Aero. Eng., Massachusetts Institute of Technology
72. A.J.Narad, Consulting Engineering Lab., General Electric, Schenectady
73. W.R.Sears, Graduate School of Aeronautical Engineering, Cornell University
74. Guenther von Elbe, U.S.Bureau of Mines, Central Exp. Station, Pittsburgh
75. G. Henning, Aerojet Engineering Corp., Azusa, California
76. J.B.Henry, Allegheny Ludlum Steel Corp., Breckenridge, Penna.
77. L.N.K. Boelter, University of California, Los Angeles, Calif.
78. Committee on Undersea Warfare, National Research Council, Wash.
79. P.A.Lagerstrom, Guggenheim Aero.Lab., California Institute of Technology
80. J.Keenan, Massachusetts Institute of Technology, Cambridge, Mass.
81. J.D.Akerman, University of Minnesota, Minneapolis, Minn.
82. W.A.Wildhack, National Bureau of Standards, Washington, D.C.
83. Buffalo-Electro Chemical Corporation, Buffalo, New York
84. R. Ladenburg, Princeton University, Physics Department
85. D.H.Hill Library, University of North Carolina, Raleigh, North Carolina
86. I.T.E.-Circuit Breaker Company, Special Products Div., Philadelphia, Pa.
87. Aircooled Motors, Inc., Syracuse, New York
88. AiResearch Manufacturing Company, Los Angeles, Calif.
89. Allison Division, General Motors Corporation, Indianapolis, Indiana
90. B.G.Corporation, New York
91. Champion Spark Plug Company, Toledo, Ohio
92. Fredric Flader, Inc., North Tonawanda, New York
93. General Electric Company, Aircraft Gas Turbines Div., West Lynn, Mass.
94. General Laboratory Associates, Inc., Norwich, New York
95. Lycoming-Spencer Div., Avco Manufacturing Corporation, Williamsport, Pa.
96. McCulloch Motors Corporation, Los Angeles, California
97. Pratt and Whitney Aircraft Division, U.A.C., East Hartford, Conn.
98. Stalker Development Company, Bay City, Michigan
99. Stanford University, Stanford, Calif.
100. Thompson Products Inc., Cleveland, Ohio
101. University of Southern California, Los Angeles, Calif.
102. Westinghouse Electric Corporation, A.G.T. Division, Essington, Pa.
103. Kenneth Razak, Acting Dean, College of Business Administration and Industry, University of Wichita, Wichita, Kansas
104/106. Cornell Aeronautical Library, 4455 Genesee Street, Buffalo, N.Y. (3)
107. Georgia Institute of Tech., Dept.of Mechanical Eng., Atlanta, G. Attn: Prof. M.J.Goglia
108. Dr. R.B.Dow, BuOrd, Navy Dept. (Re9a)
109. Dr. R.M.Robertson, O.N.R., Washington, D.C.
110. Dr. Ralph Zirkind, BuAer, Navy Department, Washington, D.C.
111. Lt.Col.J.H.Clayton, AFDRD-RE-1, A/F, Director Research and Development Pentagon, Washington, D.C.
112. Dr. A.M.Rothrock, N.A.C.A.
113. Atlantic Research, 812 N. Fairfax Street, Alexandria, Va.
114. Chief, Bureau of Aero.Ships Installation Div.Rocket Branch, Navy Dept. Washington, D.C.
115. Dr. R.H.Wilhelm, Chemical Eng. Building, Princeton University
116. Mr. J.P.Layton, Princeton University
117. Dr. Mark M. Mills, Princeton University

118. Mr. J.A.Browning, Dartmouth University, Hanover, N.H.
119. Professor G.C.Lamb, Northwestern University, Evantons, Illinois
120. Dr. A. Ferri, N.A.C.A. Langley Field, Virginia
121. Professor W.M.Rohsenow, M.I.T., Cambridge, Mass.
122. Mr. H. Hottel, M.I.T. Cambridge, Mass.
123. Professor F.G.Keyes, M.I.T. Cambridge, Mass.
124. Professor E. Johnson, Princeton University