U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 64-20

SUMMARY REPORT ON INVESTIGATION OF MINIATURE VALVELESS PULSEJETS

Task 1D010501A01405
(Formerly Task 9R99-20-001-05)
Contract DA 44-177-TC-688

February 1964

102 p $4.00 hc
$0.75 mf

prepared by:

HILLER AIRCRAFT COMPANY
Advanced Research Division
Palo Alto, California

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This report describes certain research undertaken in connection with miniature valveless pulse jets and the results therefrom. As such, the report is offered for the stimulation and exchange of ideas. In addition, the contractor has included descriptions of potential or ultimate uses of the individual pulse jet which were not fundamental requirements of the contract and as such were not therefore required to be substantiated as was the basic valveless pulse jet research mentioned above.

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Report No. ARD-307

Prepared by:

Hiller Aircraft Company
Advanced Research Division
Palo Alto, California

for

U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

FOREWORD

This report fulfills the requirements of U. S. Army Transportation Research Command Contract DA 44-177-TC-688.

The work was performed in the Advanced Research Division of Hiller Aircraft Company in the Propulsion Research Department (Mr. E. R. Sargent, Dept. Mgr.) under the direction of R. M. Lockwood, Principal Investigator with assistance from W. G. Patterson and J. E. Beckett, Research Engineers and D. A. Graber, Head Propulsion Lab Technician. Editing assistance by Harry W. Sander is acknowledged. This investigation of multiple miniature valveless pulsejets was started in July of 1960 and completed in June of 1962.

Acknowledgement is made of the support and guidance of Mr. J. R. Cloyd and Lt. David L. Overman of the former Engineering Sciences Division of the Transportation Research Command for whom the work was performed.

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SUMMARY

Miniature valveless pulsejets have several intriguing characteristics such as simplicity (no moving parts), low cost, high combustion efficiency and a high rate of heat transfer due to the unsteady nature of the flow. This project was established because there was a dearth of reliable basic information. Eleven sizes and types of miniature valveless pulsejets were constructed and tested. Three different basic sizes representing the best configuration were tested extensively as straight-tube combustors, singly and in clusters, for thrust, fuel flow rates, thrust augmentation capability, and other performance characteristics, with key results as tabulated below:

VALVELESS PULSEJETS Designation	COMBUSTOR Dia. max.	COMBUSTOR Total Length inches	TOTAL THRUST pounds	① Tsfc min. $\frac{\text{lb}}{\text{hr}\cdot\text{lb}}$	FUEL FLOW RATE pph	AUGMENTATION RATIO	TOTAL THRUST max., pounds	① Tsfc min. $\frac{\text{lb}}{\text{hr}\cdot\text{lb}}$	FUEL FLOW RATE pph
			SINGLE ENGINES						
	COMBUSTOR ONLY					AUGMENTED			
HC-1 (straight)	2.40	26.87	2.6	5.8	15.9	1.8	4.6	3.3	15.2
HC-1 ④ (U-shaped)	(with modified fuel system) 2.40	26.87	2.2	5.2	10.7	-	-	-	-
HH-M1 (straight)	2.75	46.25	10.0	3.2	32.0	1.9	17.0	1.8	31.2
HH-M2 (straight)	3.25	51.13	12.5	3.4	42.5	1.8	23.0	1.9	13.7
			MULTIPLE ENGINES						
HC-1 straight 6-in-line	2.40	26.87	11.5	6.3	72	1.9	② 13.5	5.0	67.5
HC-1 straight 6 rectangular cluster	2.40	26.87	9.2	7.8	72	-	-	-	-
HH-M1 straight (3-in-line)	2.75	46.25	23.0	3.3	76	1.8	② 36.0	1.9	68.5
HH-M2 straight (3-in-line)	3.25	51.13	31.0	3.4	103	1.6	② 47.5	2.2	102

① Minimum Tsfc is usually near, but not at, fuel flow rate for maximum thrust (see referenced figures and text).

② Total thrust was not maximum available due to fuel system supply limitation.

③ Accuracy of test data approximately ± 5%.

④ A special dual thrust-plate test stand was used to measure thrust from each end of straight-tube engines and to measure direct thrust from U-shaped engines.

⑤ Most of testing was with gaseous propane fuel; check runs with 80-90 octane gasoline gave essentially same performance as with propane.

Operation of multiple pulsejets when arranged as close as combustor dimensions will allow in a single line or "train" of six pulsejets, did not show loss of thrust and Tsfc performance, but the operating range was narrow. However, a rectangular array of six combustors, when spaced this closely, showed a performance loss of about 20%.

Limited testing with interconnecting tubes showed that it is feasible, (1) to start adjacent pulsejets in a cluster from one operating pulsejet without the usual spark plug and jet of starting air and (2) to at least partically reduce interference effects due to close proximity.

The engines would not start on liquid fuels during most of the program. Development in the Hiller Propulsion Research Lab of a new miniature flat spray fuel nozzle, near the end of the program, permitted successful operation on liquid fuel (80-90 octane gasoline) with all three of the best configurations, HC-1, HH-M1 and HH-M2, with essentially the same performance as on gaseous propane fuel.

Operational problems were primarily (1) noise (as is typical of jet engines, 124-130 decibels range overall level at 25 feet from jet outlets, but without significant increase due to multi-engine operation), (2) vibration (operating cycle frequency range 180-320 cps) and (3) combustor shell temperatures up to 1850°F, which can be handled satisfactorily for most applications by (a) shrouding with relatively lightweight heat-insulating and noise-absorbing material, (b) alternate, i.e., out-of-phase, timing of combustors, and (c) shock mounting of combustors to isolate vibration and permit thermal expansion of the combustor shells with minimum thermal stress.

A major obstacle to improvement lies in the lack of a suitable engine cycle performance prediction analysis to give some indication of (a) ultimate possible performance and (b) guide designers by predicting the effect of design changes, but this situation is somewhat alleviated by the basic simplicity of the engine structure which permits relatively rapid changes in test configuration. On the other hand, measurement of "instantaneous" gas pressures, temperatures and velocities, etc., are difficult and expensive, whereas simple measurements are limited to average thrusts, combustion chamber pressures, fuel flow rates, shell temperatures, operating frequencies, and overall noise levels.

It is concluded that miniature valveless pulsejets seem to be well suited for heater-blower applications as well as having some potential for thrust applications.

I. INTRODUCTION

A contract was awarded to Hiller Aircraft Company by the United States Army Transportation Research Command in June 1960, to conduct an investigation into the characteristics of multiple miniature valveless pulsejet engines. It had been previously observed that the thrust-to-volume ratio increased as pulsejet volume was decreased, somewhat like the well-known 2/3 scaling law that is applied to turbojet and ramjet engines. It was desired to make a more precise determination of a valveless pulsejet scaling rule, and to determine practical limits to miniaturization of the engines. It was also desired to explore the general characteristics of miniature pulsejets when operated in multiples.

Valveless pulsejets seem to offer valuable potential as extremely simple devices for lift and propulsion, for the creation of an air cushion beneath vehicles, and for heaters and heater-blower combinations. By using large numbers of small engines, they may be fitted into a wide variety of configurations. When used in conjunction with intermittent jet thrust augmenters of the Contractor's special design, they also offer very interesting possibilities as jet pumps. It has been shown in tests on other projects (References 3 and 4) that the presence of the augmenter increases the pumping rate by a factor as great as twenty times that of the pumping rate of the basic combustor or valveless pulsejet alone (Figure 40).

One of the main attractions of the intermittent jet devices is the high thrust augmentation which has been achieved with relatively compact augmenters. Comparison with steady flow ejector-type thrust augmenters emphasizes this outstanding performance (References 1-4 incl.). For example, an augmenter with a throat area-to-primary jet area ratio of 4 and a length-to-throat diameter ratio (L/D) of 1½, when used with an intermittent jet, can produce a thrust increase equal to anywhere between 60% and 140% of the primary jet thrust, depending on the augmenter configuration and the intermittent jet wave form and velocity. The same augmenter and primary jet relationship for the case of steady flow would produce less than 20% thrust augmentation. Making use of this high thrust augmentation, the full-size Pulse Reactor (valveless combustor with thrust augmenters) system with no moving parts has achieved a static or low-speed performance which is competitive with that of turbojet lift engines (i.e., thrust-specific fuel consumption of better than one pound of fuel per hour per pound of thrust and component thrust-to-weight ratios which indicate that an overall ratio of ten-to-one is within the "state of the art" as indicated in References 1, 2 and 13).

Additional characteristics of the Pulse Reactor engine which make it attractive are low exhaust temperatures and velocities on the order of 200°F and 200 feet per second, an engine operating cycle which repels foreign particles from the combustor inlets, extreme simplicity and low cost. Another interesting characteristic of unsteady flow is that the heat transfer rate can be much higher than for comparable steady flow conditions as indicated in References 8-12 inclusive. This has obvious implications for possible heating and drying applications.

Miniaturization of these valveless pulsejets and thrust augmenters extends the scope of potential applications. Operation of the small engines in clusters and trains increases their versatility and furnishes additional information concerning their operational characteristics. For the foregoing reasons, and because of the limited knowledge concerning the performance of miniature valveless engines, particularly when operating in clusters or trains, it was deemed worthwhile to make this investigation.

The project guidelines set for the Contractor were to make a broad survey of sufficient depth using essentially current designs only to determine and report general characteristics, and their implications, without attempting to make large improvements, but recognizing that adjustments and modifications would be necessary to start scaled-down engines and to get a sufficient range of operational data.

The first phase of the contract included design and assembly of the necessary test equipment, collection of results of previously constructed engines, construction and performance testing of several different sizes of miniature pulsejet clusters, and investigation into such areas as fuels and fuel injection, starting, cyclical rates, thrust and fuel flow rates, thrust augmentation ratios and methods, noise and vibration, and the like. The second phase continued the investigation into the areas mentioned above.

Eleven sizes and types of engines, essentially in the five to ten pound thrust range, were built and tested. Numerous modifications and alterations were made to these in order to achieve satisfactory operation and to determine their characteristics more fully. The most outstanding ones were tested in multiples and the representative data are reported. Some problem areas which appeared were not completely resolved, although considerable insight was gained.

In this investigation, full advantage has been taken of other work reported in the literature, or in the Contractor's files and experience, so as to avoid unnecessary duplication, and this work is referenced wherever used in this report in discussing performance and basic characteristics. Particular advantage has been taken of the full-scale Pulse Reactor lift-propulsion system development (References 1, 2 and 13) which is concerned with the development of valveless pulsejets with augmenters for aircraft use. Recent designs of combustors and augmenters developed on these were found to be superior and programs were scaled down for use on the subject contract. The performance of the larger engines has provided important inputs for the establishment of scaling trends. Insight concerning the novel method of energy transfer by pressure wave action from intermittent jets to secondary air flow in ejector-type thrust augmenters and jet pumps has been gained from the separate study reported in References 3 and 4.

The research technique has consisted essentially of the application of the combination of prior and current knowledge of the state of the art as represented by the literature and by other active projects in this field (most of which are being conducted by this contractor), miniaturization of the best designs of larger engines in successive steps, and the associated testing of the best combinations of resultant miniature engines.

A major obstacle to improvement lies in the lack of a suitable engine cycle performance prediction analysis to give some indication of (a) ultimate possible performance and (b) guide designers by predicting the effect of design changes, but this situation is somewhat alleviated by the basic simplicity of the engine structure which permits relatively rapid changes in test configuration. On the other hand, measurement of "instantaneous" gas pressures, temperatures and velocities, etc. are difficult and expensive, whereas simple measurements are limited to average thrusts, combustion chamber pressures, fuel flow rates, shell temperatures, operating frequencies, and overall noise levels.

There are two general approaches to the handling of such problems of analysis. One is generally called one-dimensional non-steady flow gas dynamic analysis using the "method of characteristics" or by the reasoning of Riemann. Unfortunately, the fundamental partial differential equations that describe the unsteady flow of compressible fluids are much too complicated to be dealt with directly. Instead, solutions are generally obtained by graphical-numerical iteration procedures using finite-difference equations as described in references 14 and 15. This is an exceedingly tedious process which for example typically required as much as 50 hours for construction of the wave diagrams for a single cycle in even the limited cases of the intermittent jet and thrust augmenter combinations described in References 3 and 4, in the simplified case of analysis of the relationship of a pulsating jet driving a turbine as described in Reference 16.

The question arises then concerning the practicability of using high-speed machine computer techniques. The preceding reference is also pertinent because it contains the only example that the Contractor has discovered of the somewhat extensive use of a digital computer (IBM 704 - Fortran program) on a problem of this general nature using the general approach of the "method of characteristics". This is reported to have reduced the cycle calculating time to only 1-1/2 minutes for the simplest cases and to about 4 minutes for a more precise calculation in contrast to the approximately 50 hours per cycle as required by the manually plotted wave diagram technique. However, a recent search indicates that the card decks and the detailed description of the method of programming are no longer available.

The extension of the research program described in References 3 and 4 under Navy Contract Nonr 3082(00) is aimed at applying high-speed digital computer techniques to the intermittent jet-augmenter relationship, using either the method of characteristics approach somewhat akin to that described in Reference 16 or to what may be a more flexible and powerful technique that is called the artificial viscosity method ("Q" Method) of von Neumann and Richtmyer (Reference 17).

This situation is even more complicated by the fact that the pulsejet (particularly valveless) state of the art is quite unlike the situation for other kinds of engines (reciprocating engines, ramjets, gas turbines) wherein there are detailed and well-written textbooks, handbooks and periodicals, etc., that both summarize characteristics, give complete and detailed theory and provide extensive tabulations of actual engine performance, manufacturer's specifications, etc. Instead, although there have been many research and development projects conducted in this country and abroad, much of the work was originally classified. A fairly complete, accurate and extensive survey covering the historical development up to this date has never been conducted. Reference 19 is the most useful summary of the U. S. work up to 1948, and Dr. J. V. Foa's "Elements of Flight Propulsion" (Reference 15) is the only textbook which deals with nonsteady flow processes at considerable length and also provides an excellent dissertation on the classical methods of analysis and their limitations.

Dr. Foa has also given some indication that within certain limits the overall potential performance of valveless pulsejet engines might be determined by modifications of his analytical techniques using his "entropy method" as described in Chapter 15 of Reference 15 entitled "Nonsteady-Flow Thrust Generators". This technique, however, does not provide detailed analysis of nonsteady thrust generation.

2. VALVELESS PULSEJET DESIGN, FABRICATION AND TEST EQUIPMENT

2.1 Pulsejet Sizes and Fabrication

2.1.1 Straight-Tube Combustors

As an initial guide for scaling down the size of pulsejet engines, the combustor of the Contractor's full size Pulse Reactor engine, the 9.1-inch diameter HS-1 model, was used. The scaled-down versions are designated as HS-1 (size), the "size" being the squared ratio of the combustion chamber diameters of the scaled version to original version. When combustor geometry has changed significantly, a different designation is used (Example HC-1, for conical combustion chamber).

Extrapolating the trend of thrust versus Pulse Reactor size established in previous tests on large engines, several engines were scaled in the thrust range of less than 10 lbs. Scaled engine drawings were completed as represented by the sketches in Figures 1 and 2. For example, Figure 1 shows the HS-1(.024), which, unfortunately, would not run properly. Modification to this size resulted in the HC-1 configuration as shown in Figure 3. Figure 4 illustrates the changes in the HS-1(.075) combustor dimensions from Figure 2 which were necessary to produce good resonant performance, the modification being designated HS-1(.075)-3.

Another small engine was scaled down from the HS-type combustor with shape generally like that illustrated in Figures 1 and 2 and designated as HS-1(.0189). Major dimensions are given in Table I. This combustor could be operated only by simultaneously injecting an acetylene and oxygen fuel mixture, and its performance was very poor.

The very smallest size valveless pulsejet that this Contractor tested was designated HS-1(.0068) and was supposedly the smallest size on record of this general type. It was also scaled down from the HS-type with major dimensions as given in Table I. It was tested prior to this contract. This combustor also did not resonate except when a combination as reactive as acetylene and oxygen was injected separately but simultaneously. The thrust of this combustor was roughly one pound. This does not rule out the possibility that pre-mixed fuel and air might not resonate, but such a combination was not considered to be of practical value within the scope of the program, and thus no tests of such nature were conducted.

TABLE 1

PRELIMINARY GEOMETRY OF

SCALED-DOWN VALVELESS PULSEJET COMBUSTORS

VALVELESS PULSEJETS	COMBUSTION CHAMBER		TRANSITION Comb. chbr. to tailpipe,	INLET		TAILPIPE		
Designation	dia.	length	length	dia.	length	length	min. dia.	overall length
HS-1	9.10	20.00	21.00	5.00	20.00	108.00	4.50	169.60
HS-1(.075)	2.50	5.49	5.49	1.56	5.49	29.25	1.18	45.72
HS-1(.075)-3	2.65	5.50	5.50	1.35	5.25	30.00	1.20	51.75
*HS-1(.075)-T	2.50	3.50	5.50	1.50	3.75	10.00	1.20	22.50
HS-1(.024)	1.39	3.05	3.05	.87	3.05	16.10	.66	25.25
HS-1(.0189)	1.25	2.25	2.00	.75	2.25	13.00	.75	21.00
HS-1(.0068)	.75	1.75	1.50	.44	1.68	7.10	.44	12.00

All measurements in inches.

Tailpipe taper for all combustors 2° 18' included angle.

* Overall dimensions shortened by use of tapered inlet.

The maximum possible reduction of the length of the valveless pulsejet combustor was determined on a company-sponsored program separate from this contract, but the information was used to advantage on this contract. The effect of reduction of tailpipe length was investigated on a combustor of 2-1/2-inch combustion chamber diameter, designated HS-1(.075)-3. It was possible to shorten the tailpipe only a few inches and still maintain operation. However, a surprising discovery was made. It was discovered that when an inlet with a slight taper of only about 2° included angle, convergent in the direction of efflux, was substituted for the cylindrical inlet, the tailpipe could be drastically shortened. The combustor was finally shortened to a tailpipe length of only 10 inches with 22-1/2 inches length over-all (1-3/4 inches tailpipe exit diameter and 1-1/2 inches inlet diameter). At this extremely short length it was necessary to put a 1/8 inch radius flare at the end of the tailpipe in order to get the combustor to resonate. However, at this very short length, its operating range was so limited that no data were taken. The favorable effect of such a slight taper to the inlet is still not fully understood, but it has been shown to improve the ease of engine starting, operating stability, and throttling range. In the case of full-scale engines the use of the tapered inlet has been an important contributor to improved performance (References 2 and 13).

Under Bureau of Naval Weapons Contract NOw 61-0226-c, a new 5-1/4 inch (combustion chamber diameter) combustor shell geometry was developed which provided 50% more thrust per unit engine volume than the previous 5-1/4 inch diameter HS-1 type geometry (References 2 and 13). The main features of this new configuration were 45° conical bulkheads at both ends of the combustion chamber and a shorter combustion chamber and tailpipe. It was decided to take advantage of these improvements, so two additional sizes of combustors were scaled down from this new basic geometry. Figures 5 and 6 are sketches of these combustors, the first one designated as HH-M1 with a 2-3/4 inch diameter combustion chamber, and the second as HH-M2 with a 3-1/4 inch diameter combustion chamber. While the largest of these combustors is somewhat on the high side of the range of thrust specified for this investigation, its performance and characteristics were important from the standpoint of experiments in conversion from gaseous to liquid fuels.

For initial tests, all of the aforementioned combustors were built in the straight configuration for simplicity and economy of manufacture. No effort was made to minimize their weight since sufficient durability for testing was desired without requiring special attention to shell construction. In order to control a reasonably close tolerance on dimensions, a conical steel forming mandrel was fabricated. The forming mandrel is 48 inches long and has an included angle of 2° - 18'. The small end is 0.625 inches in diameter.

This mandrel was used to form the exhaust tailpipe sections on all engines throughout this investigation. No. 316 stainless steel sheets of 0.050 inch, 0.032 inch, and 0.020 inch thickness were used in conjunction with heli-arc welding to fabricate the various sizes of pulsejets.

Techniques, other than manual, for forming and welding the combustor shells are numerous and are prescribed by the economics and applications involved. One interesting method which was investigated is electroplating. Figure 7 shows an HC-1 type combustor which was formed entirely by electroplating.

2.1.2 Thrust Augmenters

Thrust augmenters were scaled down to match combustor size. The "rules of thumb" on the augmenter dimensions are length-to-diameter ratio of 2 for the exhaust augmenter and 3 for the inlet augmenter, eight degrees of divergence (included angle), and an augmenter throat diameter to primary jet diameter ratio of 2. Pyrex glass has proven to be the cheapest test material for the smallest of the miniaturized test augmenters as it is easily formed and satisfactorily withstands the operating temperatures, which are as high as 300°F. Figure 8 shows the key dimensions of augmenters for the HC-1 combustor and Figure 9 shows actual pyrex augmenters. The extra length is trimmed during the tuning process. The flared inlets of the larger augmenters were formed from mild steel by metal spinning and then welded to the conical sections. Augmenters of extremely light weight (12:1 thrust-to-weight ratio) have been built for the full scale Pulse Reactors using honeycomb or high temperature "stafoam" covered with Fiberglas skin and high temperature resin as indicated in References 1, 2 and 13.

2.1.3 U-Shaped Combustors

In order to serve as a thrust device, in most cases the pulsejet combustor must be bent into a U-shape so that the tailpipe and inlet point in the same direction (the inlet end of the combustor produces almost as much thrust as the tailpipe). Simple dies as illustrated in Figure 10 were made for the U-turn tailpipe sections on the HC-1 and the HH-M1 combustors. A tapered steel mandrel conforming to the tailpipe inside dimensions was heated and bent into the U-shape of desired radius. Its outline was then scribed onto a thick steel plate, which was cut through and filed to a satisfactory clearance. Using the bent tailpipe mandrel, the left and right sides of the U-turn were pressed out using first one side and then the other side of the steel plate die. These two halves were then welded together. Figure 11 shows the mandrel and die along with the right and left hand pressing plates that were necessary to compensate for the taper of the mandrel.

Figure 12 is a comparison of the HO-1 and the HH-M1 U-shaped combustors. The flat combustion chamber bulkhead for the HO-1 has been replaced with a 45° conical combustion chamber bulkhead for ease of fabrication as well as improvement in structural durability. It has been determined that this type of bulkhead does not adversely affect combustor performance and, in fact, may even improve it.

Figure 13 shows a combustor of the HO-1 type which has been bent into the U-shape with a smaller radius than usual. There is no apparent adverse effect on resonant performance; however, the inlet and tailpipe are so close together that individual thrust augmenters cannot be used. A common thrust augmenter cannot be expected to produce the desired augmentation ratios.

Several lightweight U-shaped combustors were constructed. A HO-1 pulsejet made of 0.020 inch stainless steel weighed 0.67 lb for a maximum thrust-to-weight ratio of 3.3:1. An HH-M1 combustor of 0.012 inch Haynes alloy weighed 1.18 lb giving a maximum thrust-to-weight ratio of 8.5:1. Several hours of testing have been accumulated on the HH-M1 with no evidence of structural failure. For comparison, the commercially available valved pulsejets, Dynajet and Tigerjet, weigh 0.95 lb and 0.43 lb for thrust-to-weight ratios of 4.2:1 and 4.6:1 respectively. Combustor shells of significantly thinner material require circumferential stiffeners to prevent resonant ovalizing or collapse of the tubular sections, as well as damage due to handling.

An attempt to manufacture an HH-M1 combustor from Haynes alloy of 0.005 inch thickness was made with the previously described simple tooling. The estimated maximum thrust-to-weight ratio was greater than 12:1. This engine was not completed due to difficulty in pressing out the U-turn half sections. The thin sheet material would not draw into the die in one pressing operation without splitting. Manual heli-arc welding of this very thin material is also difficult, but is done successfully. More practical techniques would be resistance lap welding or burn-down flange welding. Manufacturers of the small valved pulsejets use both techniques on thin gage material; for example the Tigerjet and Dynajet are welded by melting-down flanges left from half-shells while the Minnesota Engine Works M.E.W. 307 is resistance lap-welded.

2.2 Fuel and Fuel Injection Systems

Gaseous propane has proven to be a satisfactory fuel for operation of miniaturized Pulse Reactors. Some effort has been expended to devise a successful liquid fuel system for small engines, and partial success in this regard has been achieved using gasoline.

The fuel nozzles, even with gaseous fuels, have been a problem with the miniature valveless pulsejet engines. Commercial sources were investigated for fuel nozzles of appropriate size and properties without success. Several Hiller-designed systems were then tried. Good operation with a moderately wide throttling range using propane has been achieved for three types of fuel systems. The first consists of inserting the fuel line into the combustion chamber inlet along the longitudinal axis. Fuel injection was accomplished through four holes from which jets spray at right angles to the longitudinal axis of the engine inlet. The best position for the fuel injection with this drilled tube type system was at a plane parallel to and only about 1/4 inch upstream from the combustion chamber bulkhead (Fig. 14). The second successful type of fuel system (Fig. 15) consisted of four tubes inserted through the forward bulkhead of the combustion chamber shell; that is, they were approximately perpendicular to radial lines that extend outward from the longitudinal axis of the combustor. The HC-1 combustor was fitted with the first type of fuel nozzle. The primary disadvantage noted with these nozzles was a tendency to choke and clog after a few hours of operation.

The third and most successful type of fuel nozzle was an impingement type nozzle called Graber's* "Question Mark" nozzle (Fig. 16). It caused two jets of fuel to strike each other head-on and form a thin disc-shaped spray pattern. This nozzle has the characteristic of variable jet outlet area as a function of fuel pressure, which is believed at this time to be desirable in Pulse Reactor combustor operation. Also, the jet outlet area was easily preset to provide the required fuel flow rates for a range of fuel pressures.

The high cyclic operating rate of the miniature combustors, as compared to the larger combustors, was thought to cause the majority of the fuel system difficulties, and necessitate a high mixing rate with the incoming air charge. For good performance (Tsfc), the fuel jet outlet area must be of a size to optimize fuel jet velocity, penetration, and mixing with the air charge. The HS-1(.075)-3 and the HH-M1 combustors were each fitted with two of the "Question Mark" nozzles for testing, whereas the HH-M2 combustor used four.

The HH-M2 combustor was made to operate satisfactorily on gasoline when fitted with two "lorgnette" fuel nozzles as shown in Figure 17. These nozzles were similar in operation to the "Question Mark" nozzle, but of a different shape and tube size.

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The smaller HC-1 combustor was fitted with several different types of fuel nozzles designed for operation with gasoline. The first nozzle to be tried was the lorgnette type of the size which was successful in the HH-M2 combustor tests. With one nozzle located in the combustion chamber, the HC-1 combustor started and resonated strongly for a few seconds until the shell and nozzle began to heat up. At this point the fuel in the nozzle vaporized and resonant combustion ceased, due to the restricted fuel flow rate. Three solutions to this problem were posed:

(1) To make the fuel nozzle inside diameter large enough to pass the required amount of vaporized gasoline;

(2) To make the fuel nozzle small enough to reduce the amount of heat transfer and to prevent vaporization of the fuel inside the nozzle;

(3) To place the nozzle in the inlet passage where its operating temperature would be lower due to the intermittent flow of hot and cool gases.

Sketches (1) and (2) of Figure 18 show two types of nozzles tried in the HC-1 combustor. These were located in the inlet and were of relatively large size. Resonant performance, thrust, and throttling range were satisfactory, but poor Tsfc associated with this nozzle location was demonstrated. In this position, distribution and mixing with the inflowing airstream were good; however, the nozzle outlets could not sense the cyclic combustion chamber pressure rise and accordingly, there was no intermittent stoppage of fuel flow. Fuel was, therefore, being injected into the jet blowdown, resulting in the poor Tsfc.

Relocation into the combustion chamber was accomplished successfully by reducing the size of the lorgnette nozzle. In this way, the heat transfer and vaporization problems were controlled and effective penetration into the incoming air stream was retained. Sketches (3) and (4) of Figure 18 show the lorgnette nozzle position in the combustion chamber and the nozzle dimensions. Tsfc improved considerably with this injection setup (see Section 4. TEST RESULTS).

2.3 Ignition Systems

Each pulsejet was equipped with a small model airplane type spark plug located in the combustion chamber. Any conventional spark supply was satisfactory. For multiple engine ignition, a 7-cylinder aircraft magneto driven by a 1/4 horsepower electric motor was used.

The Clevite Corporation has developed a piezoelectric "spark pump" of compact and rugged design and has successfully demonstrated its use on a small, single cylinder, reciprocating engine

(Reference 5). A version which can be actuated by hand squeezing is available and is attractive for pulsejet ignition systems where compactness and portability are required.

Once a combustor was operating, adjacent interconnected combustors could be started without a spark. These interconnected engines and their characteristics are described in section 4.5.

The possibility of using pyrotechnics as starting devices for the pulsejets was investigated. Several tests were made using squibs and short duration miniature rockets as a means for providing the initial disturbance and ignition in the engine, thus replacing the starting air jet and spark plug. The limited tests were not successful. No conclusion was reached as to the possibility of ultimate success of this technique.

2.4 Pulsejet Tuning and Operation

In scaling down the HS-1 combustor (225 lb thrust) to a miniaturized version, thrust, general performance, and even resonant operation can be lost. In preliminary testing, the miniature combustors had to be tuned to a strongly resonant condition by variations in the fuel system and shell geometry. Shell geometry changes as a result of tuning are shown by comparing Figure 1 with Figure 3 and in a comparison of Figure 2 with Figure 4, as well as Table 1. The HH-M1 and HH-M2, scaled from the new combustor geometry developed under Bureau of Naval Weapons Contract NOw 61-0226-c, did not perform well in their original dimensions and were also modified. In general, the miniature combustors required proportionately a larger combustion chamber diameter and a longer tailpipe than their larger sized predecessors.

The ability to observe the pulsejet performance and prescribe a change in fuel system or shell geometry to improve its operation has been developed as a result of many hours of testing and experimenting. Still, there are occasions when the relationships between these changes and performance are very puzzling. The presence of thrust augmenters sometimes increases the basic performance of the combustor (e.g., see References 1, 2 and 13). However, at other times the performance is affected adversely. The fuel nozzle position has proven to be very sensitive, not so much for resonant operation as for optimization of thrust and specific fuel consumption.

The thrust augmenters frequently exhibit a tuning effect with changes in their length and diameter. Their thrust output, in terms of percent of primary jet thrust, also varies with combustor output and appears to depend on the jet pulse velocity and configuration (see also References 3 and 4). In the several instances where poor augmentation could not be improved by changes in the augmenter diameter or L/D, the jet pulse velocity and wave form are thought to be at fault.

The fuel injection problem has proven to be more critical with the smaller pulsejets. This was apparently due to the increased cyclic rate with reduced size which requires close attention to fuel nozzle design and location to insure maximum fuel penetration and dispersion into the incoming air charge. Attempts to convert from propane gaseous fuel to liquid gasoline fuel were tedious. However, this area of investigation received much attention. The advantages and desirability of liquid fuels were apparent and greatly simplified combustor testing and data processing as well as providing a more versatile miniature Pulse Reactor. Preliminary experience under Contract NOw 61-0226-c (References [illegible] and 13) with two intermediate sized combustors of 5-1/4 inch and 4 inch combustion chamber diameters indicated that the 4-1/4 inch size was the smallest at that time which could be operated over a wide throttling range without noticeable starting and performance problems. However, by the end of the project described herein, liquid fuel supply techniques had progressed to the point where even the small HC-1 combustors were operated successfully on gasoline (see section 4.1).

The qualitative Pulse Reactor cycle of operation may be described briefly with reference to Figure 19. Starting is accomplished by simultaneously turning on the ignition, fuel, and starting air. (Replacement of the starting air stream by a small jet of propane has proven to be successful in some configurations.) The resulting combustion causes a pressure build-up, and the air and combustion products expend out both ends of the combustor, introducing the exhaust phase. In this phase, the ignition and starting air are turned off, and as the pressure in the combustion chamber is higher than the fuel pressure, the fuel flow ceases momentarily. The momentum of the exhaust gases causes an over-expansion in the combustion chamber and flow reverses in the inlet and tailpipe. During this inflow phase, as the combustion chamber pressure is substantially below the fuel manifold pressure, the fuel again flows into the chamber. The air flows which enter from both ends of the combustor collide in the combustion chamber and there is a vigorous mixing of the incoming air-charge and fuel. The hot products of combustion which didn't quite escape from the tailpipe during the previous phases are thoroughly mixed with the fresh charge and furnish multiple points of ignition for the next combustion phase. Starting air and spark are not needed for the following cycles, which are repeated at a frequency determined by the size of the combustor. The vigorous mixing and multiple-point ignition explains why the resonant combustor may be operated on a wide variety of fuels. The performance (at sea level) does not, in general, depend on the use of fuels with high flame speeds, but only on the heating value and the mixing efficiency. Of additional importance is the very rapid thrust response to changes in fuel flow rate. It is estimated that the Pulse Reactor's throttle response is complete within three to four combustion cycles, a small fraction of a second.

The intermittent jets from the ends of the combustor can be compared to pistons as they travel through the augmenters, forcing air out ahead and drawing ambient air in over the curved augmenter entrance. With optimum geometry relationships between the augmenters and combustor, the thrust of the combustor can usually be more than doubled. Because it has been discovered that the presence of augmenters affects the performance of the basic combustor, the augmentation ratio is defined as the total thrust (combustor and augmenter combination) divided by the thrust of the combustor when operated alone.

2.5 Test Rig

It was decided to use the thrust plate technique for the initial performance tests of the straight combustors. This was done for the following reasons: First, it is easier to build the engine in the straight configuration. Second, when the straight engines are tested on a more conventional thrust bed, one can measure only the difference between the thrust from the inlet and outlet. With two thrust plates, inlet and exhaust thrust can be measured separately.

Concerning design of the thrust plate type mechanism for measurement of jet reaction thrust, reference was made to an English study by P. N. Rowe (Ref. 6). The essence of the problem of accurate measurement with thrust plates lies in the necessity of turning the jet efflux precisely 90°. Otherwise, the small angle by which the jet is not orthogonal to its original axis represents a significant error. In order to increase the accuracy, it was decided that the thrust plate should have thin, parallel plates mounted on the edge of the thrust plate, which act as flow straighteners. Figure 20 shows the thrust plate construction.

Each thrust plate was provided with a Hagan pneumatic null-balance thrust cell. A variable mechanical multiplier linkage was installed which allows the full range of the thrust cell to be used for any size combustor within the 5 to 15-lb thrust range. A thrust cell was installed on the engine support structure to provide a direct measurement of thrust for tests of U-shaped Pulse Reactors. The thrust was indicated on a pressure gage in psig and converted to pounds thrust by means of a calibration test. Estimated accuracy of the thrust measurement was within + 5%. A later comparison made between the thrust indication of the thrust plate and the direct thrust indication of a U-shaped combustor verified this estimated accuracy.

Propane fuel supply for tests on the HO-1 combustors consisted of three 25-gallon liquid propane storage tanks connected to a fuel manifold. A larger propane supply system (a 500-gallon storage tank with a 2 inch diameter feed line) was later installed in order to test the larger sizes of miniature engines.

Figure 21 shows the thrust stand and control console, which contains all controls necessary for operation as well as gages providing readings of thrust, fuel flow rate, fuel pressure, fuel temperature and combustion chamber average pressure. Propane fuel flow rate measurement was estimated to be accurate usually to about ±5%. However, difficulty was occasionally encountered in the form of (1) fluctuations of the floats of the tapered-tube flow meters (Brooks SHO-RATE "150" Rotameters) and (2) the occasional presence of both liquid and gaseous phases in the metering system, which reduced the accuracy of measurement to an estimated ±10% and required adjustments to the fuel supply and metering system.

Gasoline fuel supply to the thrust stand was furnished by a small Vickers positive displacement pump, with a pressure by-pass valve, driven by a 1/4 horsepower motor. Starting air source was a conventional air compressor supplying air at 80 to 100 psig.

3. TEST PROCEDURES

Each combuster of a particular size was given an individual performance test to insure that all have comparable performance characteristics. The combustors were then arranged in the desired cluster configuration. Augmenters were usually tuned to the combustors for maximum performance by varying the augmenter length and the spacing between the augmenter and the combustor. Performance was noted for the individual combustor, the individual Pulse Reactor (combustor and augmenters), and the Pulse Reactor cluster. Frequency of resonant combustion was usually determined by comparing and synchronizing aurally the signal from an audio oscillator with the noise from the pulsejets.

The acoustic over-all near noise level of these combustors is in the neighborhood of 130 db (decibels) at the resonating frequency and ranged from 124 to 130 db. Mounting of gages and instruments in control consoles and panels without acoustic treatment is poor practice as the panels are forced into vibration, and gage life, as well as the accuracy of the readings, is affected. As an example, we have been using Brooks SHO-RATE "150" Rotameters with a tapered tube and spherical float for our fuel flow measurements. This flow meter set-up was particularly sensitive to vibration in that certain conditions will cause the float to roll around the inside circumference of the tapered tube. Under this condition, the flow meter will not indicate the actual flow as calibrated. In addition, the "buzzing" of the float may be so rapid as to be undetectable except under the closest scrutiny. In general, instrumentation and systems which are affected by vibration should receive acoustical and mechanical insulation from vibration if used in the Pulse Reactor environment.

It has been observed that the trend of combustion chamber average pressure of valveless pulsejets follows the trend of thrust for various fuel flow rates, as it does for valved pulsejets (Ref. 7). For a fixed engine configuration, the combustion chamber average pressure is then a good indicator of thrust performance. Since this is such a simple parameter to measure, it is very useful for automatic control devices and as a continuous operational indicator of internal performance which can be calibrated in terms of thrust (Reference 13), and has been so demonstrated on larger size equipment than tested in this project. It was used in the gasoline fuel tests with the miniature HH-M2, HH-M1 and HC-1 models as a rough indication of performance improvement as changes in the fuel system were tried.

4. TEST RESULTS

4.1 HC-1 Pulse Reactor

Initial tests were performed with six C-1 combustors, with drilled tube type nozzles (Fig. 14 and 15), arranged first in two rows with spacing of 2½ inches between centers vertically and 3 inches between centers horizontally, which was about as close together as they could be placed (Fig. 22), and then in line or "train" with about 2½ inches between combustor centerlines. Figure 23 shows the general arrangement for the line or "train", although the spacing pictured is greater because augmenters are also shown in that photograph.

Using propane fuel, each combustor started easily alone and ran at a resonant frequency of approximately 320 cps. When operating in a single row of three, the engines seemed to lock in phase and run smoothly. With all six combustors operating at once, there was a noticeable beat which indicated a difference in resonant frequency between two or more engines. This effect was more noticeable in the case of the in-line arrangement as compared to the rectangular array. Fuel flow rate versus thrust for both the rectangular array tests and the in-line tests is shown in Figure 24. Data points indicate unaugmented pulsejets operation with 1,2,3,4,5 and 6 combustors running in the combinations shown with a fuel flow rate of 12 lb/hr each. It was difficult to get all six combustors to operate simultaneously at any other fuel flow rate. Furthermore, interpretation of these results was complicated by the fact that this was also approximately the maximum rate at[*] which the storage tanks could supply propane to all six combustors. Thrust-specific fuel consumption was then in the range of 6 to 8 pounds of fuel per hour per pound of thrust. With the rectangular cluster array there was a definite and increasing drop in thrust when the number of engines operating simultaneously was increased to five and then six (Fig. 24), with a loss of about 20% for the latter.

"Sniffer" tests, using the Johnson-Williams No. 1201, Model G Sniffer, indicated that some unburned propane was being blown back out of the inlet. However, in the case of in-line operation of as many as six engines, although the operating thrust range was still very narrow, there was no loss of thrust due to proximity even though the adjacent combustion chambers were so close as to be in direct contact.

Subsequent improvement in design and location of the fuel injection system improved thrust and Tsfc, but again insufficient fuel flow rate prevented maximum cluster performance from being

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[*] Fuel system improvement was planned for succeeding phase

reached. It was expected that direct tubular interconnection between the adjacent combustors would broaden the operating range of thrust and reduce interference due to acoustic coupling, particularly in the rectangular array, but such direct interconnection experimentation was restricted to the later tests of the improved valveless pulsejet combustors, models HH-M2 and HH-M1 (see section 4.5).

Figure 26 shows thrust versus fuel flow rate for one HO-1 combustor, augmented and unaugmented. Comparison with Figure 24 points out the limitations of the small propane fuel supply system in that flow rates were insufficient to reach maximum performance with all six combustors operating. In fact, it is doubtful whether maximum performance with just one combustor was quite reached, as the unaugmented thrust curve does not show the most characteristic "peaking" or at least flattening out at maximum flow rates (References 1 and 2). Nevertheless, cluster performance can be compared with individual Pulse Reactor performance at mid-range flow rates. From Figure 25, cluster thrust of 13.5 lbs augmented at a flow rate of 67 pph compares almost identically with 6 times the single Pulse Reactor performance of Figure 26 of 2.3 lb thrust augmented at 11.1 pph. Therefore, it may be concluded that there is very little effect of combustor interaction on total thrust and thrust-specific fuel consumption (Tsfc) at this particular flow rate. This is probably also the case for the entire thrust range in the rectangular array. That is, they may either cease operation entirely or, if they operate at all, then operate without loss due to close proximity. Maximum thrust per unit engine volume for the single pulsejet of Figure 26, unaugmented, was 150 lb/ft³ with a combustor volume of 0.018 ft³.

Two HO-1 U-shaped combustors were performance-tested on gasoline. Simultaneous operation with the tailpipes almost touching showed effects of interference in that it was difficult to get them both to resonate over the complete fuel flow range, but individual performance was good. Figure 27 presents the thrust versus fuel flow rate data for one unaugmented HO-1 U-shaped combustor. The Tsfc of 5.2 is significantly better than the 5.8 figure for the straight HO-1 combustor operated on gaseous propane, due mainly to the improved nozzle location. However, maximum thrust was not as great.

At this point in the program a comparison of thrust measuring methods was accomplished by measuring the direct thrust of the U-shaped HO-1 combustor in a support arrangement like that shown in Figure 37 and comparing it with the thrust measured by use of a thrust plate as shown in Figure 20. The correlation was within the general accuracy of thrust measurement of about ± 5%.

4.2 HS-1(.075)-3 Pulse Reactor

Only one HS-1(.075)-3 Pulse Reactor was tested. The designation was used to indicate that the HS-1 configuration, that is described in References 1 and 2, was scaled down by the ratio of 0.075 to 1, and the -3 referred to the third modification of this basic design. Its performance was not attractive in view of the superior performance of the new HH- type geometry which was scaled down from a 5.25-inch diameter combustor that was developed under the program described in References 2 and 13. However, it started easily and was characterized by smooth and stable operation, especially at the lower fuel flow rates. The test set-up and dimensions are shown in Figure 4. Figure 28 presents data on thrust and average combustion chamber pressure vs. fuel flow rate for the combustor, augmented and unaugmented. Unaugmented, the combustor produced a maximum thrust of 8.5 lbs and a Tsfc of 4.0 pph/lb at 7.5 lb thrust. Augmented, maximum thrust was 11 lb and best Tsfc was 2.6 pph/lb, but richout occurred at a lower fuel flow rate than for the unaugmented combustor. The performance curves are terminated at the upper ends by combustor richout which indicates that there was sufficient fuel flow rate to give maximum thrust for this particular engine and fuel system.

It is apparent that the augmentation ratio of 1.5 at maximum thrust is far below what can be expected. For analysis, Figure 29 shows the thrust of the exhaust and inlet ends of the Pulse Reactor separately. Augmentation ratio of the exhaust is low but starts to increase at the maximum fuel flow rate, while inlet augmentation starts high and drops as fuel flow increases. Performance of this type is caused by either poor matching and tuning of the augmenters to combustor or perhaps a combustor geometry which does not perform well when augmented. Several hours, however, were spent in trying to tune augmenters to this combustor with no improvement in augmentation ratio. Also, the effect of the proximity of thrust plates on combustor and augmenter performance had not yet been precisely determined. Thrust per unit engine volume, unaugmented, was 97 lb/ft^3 and engine volume was 0.088 ft^3.

4.3 HH-M1 Pulse Reactor

The HH-M1 geometry and test set-up is illustrated in Figure 5. Figures 30 and 31 present thrust, average combustion chamber pressure, and augmentation ratio vs. fuel flow rate for one HH-M1 Pulse Reactor. Maximum thrust, unaugmented, was approximately 10 lbs with a Tsfc of 3.2 pph/lb. Augmented, maximum thrust was 17 lb with a Tsfc of 1.8 pph/lb. Combustor richout did not occur and fuel flow rate could not be increased beyond that shown even though the large 500 gal. fuel supply was being used. It is suspected that another 3 to 4 lbs thrust could be achieved for the augmented combuster by increasing the flow rate another 10 to 15 pph.

Augmentation ratio of 1.9 is representative of what should be expected for this size Pulse Reactor. Resonant combustion frequency was 210 cps. Maximum thrust/volume for the combustor was 140 lb/ft^3.

Three straight HH-M1 Pulse Reactors were arranged in a row with a spacing of 9 inches between centers, which was as close as the augmenters would permit. Figure 32 shows their performance in terms of thrust and augmentation ratio vs. fuel flow rate. Maximum cluster thrust, unaugmented, was 22.5 lbs with a Tsfc of 3.3 pph/lb. Augmented, maximum thrust was 36 lb, but at a lower fuel flow rate than when unaugmented and with a Tsfc of 1.9 pph/lb. Augmentation ratio was 1.8. Again, fuel flow rate was insufficient to reach the highest possible performance.

Sound level readings were taken using a General Radio Co. sound level meter, Type 1551 A. The C weighting scale was used to provide a relatively flat frequency response at the 130 db level and the readings were taken at a distance of 25 ft. As the test stand was located under a shelter which caused some echo and sound reflection, the sound level readings should not be considered quantitatively as very reliable. They do, however, represent the effect of multiple engine operation. Table I presents readings with 1, 2, and 3 engines operating, each with the same fuel flow rate. Two readings represent the extremes of the indicating needle fluctuation and the third, the average observed value.

TABLE 2

SOUND LEVEL READINGS

No. of Engines Operating	1	2	3
Maximum db	128	129	130
Minimum db	124	124	126
Average db	127	127	128

The pulsejets were not interconnected and the audible beat indicated that they would not stay in synchronization.

4.4 HH-M2 Pulse Reactor

Three straight HH-M2 combustors, with dimensions as shown in Figure 6, were set up on the thrust stand with 9" spacing between centers. Each combustor was fitted with four "lorgnette" type fuel nozzles. Augmenters were the same as those used for the HH-M1 tests. Fuel flow for each combustor was furnished through two flow meters and supply lines in parallel connection, and thus higher fuel flow rates than those for the HH-M1 tests were obtained.

The performance of one combustor is shown in Figures 33 and 34. Unaugmented, maximum thrust was 12.5 lb with a Tsfc of 3.6 pph/lb. Augmented, maximum thrust was 23.5 lb with a Tsfc of 2.0 pph/lb giving an augmentation ratio of 1.8. It is of interest to note how nearly constant is the thrust-specific fuel consumption (Tsfc) in each case.

In the single combustor test, the rich-out point was reached. Augmenters were slightly undersized as they were built to match the HH-M1 combustor, and accordingly, the augmentation was below that of the HH-M1. Note that the trends of thrust augmentation are quite different at inlet and at tailpipe ends of the combustor as indicated in the upper curves on Figure 34.

Resonant combustion frequency was 188 cps. Combustor maximum thrust/volume ratio was calculated to be 125 lb/ft^3. With all three combustors operating, fuel flow rate was again below that required for full performance and the rich-out point was not reached. From Figure 35 maximum thrust, unaugmented, was 30 lb with a Tsfc of 3.5 pph/lb. Augmented, maximum thrust was 47.5 lb with a Tsfc of 2.2 and an augmentation ratio of 1.6. It is believed that higher thrust augmentation can be achieved through better matching of augmenters and combustors. Support for this belief comes from noting (from Figure 33) that the average combustion chamber pressure is lower in the presence of thrust augmenters than without them. In tests with larger Pulse Reactors (References 1, 2 and 3), the highest thrust augmentation was achieved in conjunction with increased average combustion chamber pressure.

The majority of gains in liquid fuel injection techniques were made with the HH-M2 engine fitted with two of the small lorgnette fuel nozzles.

The liquid fuel check-out tests with 80-90 octane gasoline were surprising in that the combustor started easily the first time and resonated over a fuel flow range of 20%. Combustion chamber average pressure reached a maximum of 1.0 psig before rich-out.

Based on its rough operating characteristics, it was concluded that the inlet tube dimensions were too large; accordingly, the inlet diameter and length were reduced from 1-1/2" diameter by 5-3/4" length to 1-3/8" diameter by 5-1/2" length. With the same fuel nozzles and location, the combustor then resonated over a 50% fuel flow range and the combustion chamber average pressure reached 1.5 psig. Note that with propane, maximum combustion chamber average pressure approached 2.0 psig. This corresponds to about 9.5 lbs thrust with an estimated propane fuel flow rate of 35 pounds per hour. Success with liquid fuel injection depends, first of all, on combustor shell geometry which must be favorable to strong resonance. Then the fuel nozzle size, spray pattern and location requirements must be met.

4.5 Pulsejet Interconnecting and Synchronization

Three straight HH-M2 combustors were connected together at the combustion chamber with 5-3/4" lengths of 3/8" i.d. tubing as illustrated in Figure 36. The combustion chamber of the center combustor thus had two interconnecting tubes and its individual operation was affected slightly. It tended to be hard starting and would not resonate at low fuel flow rates. The outer two combustors appeared to operate normally.

With one combustor running, the other two could be started in sequence using only the jet of starting air while opening the fuel valve. No spark was necessary. The apparent effect of the interconnecting tubes on cluster operation was to synchrozine the combustors. The customary "beat", caused when each of the combustors resonates with slight differences in frequency, was not heard.

Two HH-M1 U-shaped engines were also manufactured for testing as shown in Figure 37. With this setup, by careful adjustment of the fuel flow rates to each combustor, the two combustors could be synchronized as determined by the lack of an audible beat or differences between the two resonant frequencies. There were no direct combustor interconnections.

In order to determine more accurately the combustion frequencies and synchronization, two war-surplus voice-powered microphones were used in conjunction with a dual beam oscilloscope (Tektronix Type 502). The microphones were shrouded so that 3/16" i.d. nylon tubing could be connected to them. The tubes were then connected to the pulsejet combustion chamber pressure taps. The tubing lengths to each combustor were the same in order to prevent phase lag. It was also necessary to have the tube length-to-diameter ratio, L/D, rather large to damp out second order pressure wave effects and to have the tube length such that its natural acoustic frequency was not in resonance with the pulsejet combustion frequency.

Figures 38 and 39 are Polaroid photographs of single-sweep oscilloscope traces. Figure 38 trace (1) shows the cyclic frequency of one combustor operated at full throttle, while trace (2) is the same combustor at idle. The CRT grid is measured in centimeters and the sweep speed was 5 milliseconds per centimeter. Full throttle indicates 228 cps while idle indicates 233 cps, an increase in resonant combustion frequency as fuel flow is decreased.

Oscilloscope operation in the pulsejet acoustic environment is affected by microphonics at high amplifier gain settings. However, acoustical insulation was not needed because the voice-powered microphones produced plenty of voltage for the acoustic signal supplied, as evidenced by the 0.5 volt per centimeter vertical gain setting on the scope.

Figure 39 compares the cyclic frequency of each combustor when operated together. In this case the combustors were audibly synchronized without interconnection tubes. The scope traces substantiated this and also indicated that they were synchronized approximately 180° out of phase. It became apparent from watching the traces that the combustors "preferred" this mode of operation. An audible beat occurred when the frequencies became different due to different rates of fuel flow. With one combustor at idle and the other at full throttle, a beat frequency as high as 10 cps was obtained.

A 5-1/2" by 1/2" i.d. tube connecting the two HH-M1 combustion chambers caused the combustors to operate synchronized in phase (i.e., fire simultaneously) as observed on the scope. With this arrangement, after starting one combuster, the other could be started without the use of starting air or spark. Other methods of interconnection tried thus far have not produced the desired strong synchronization out of phase. The out-of-phase mode of operation is associated with reduced noise level, and it is suspected and indicated from preliminary observations that maximum thrust will be achieved in this way also. Further investigation of synchronization control, starting, and combustor interaction was planned for this pair of combustors for a later phase, but was not conducted. Shrouding and noise control is also an area of interest which was not conclusively studied.

4.6 Schlieren Analysis

A high speed schlieren motion picture of the exhaust gases has been taken showing the operation of the engine illustrated in Figure 13. The engine was observed to be operating at approximately 280 cycles per second from examination of the motion pictures taken at 5600 frames per second. These pictures represent the first time that we have taken high speed schlieren motion pictures that simultaneously show the flow at both inlet and tailpipe of a valveless pulsejet engine. Preliminary examination of the motion pictures indicates that efflux from the tailpipe lasts for approximately 12/20 of the engine cycle compared to only about 7/20 for the efflux from the inlet. By contrast it should be noted that the efflux velocity from the inlet is much higher than the efflux velocity from the tailpipe. Since these pictures were taken, the schlieren system was modified to a color system by the addition of a multicolored filter which greatly improves flow visualization. Full use of the schlieren visualization is being made in the previously noted investigation of the energy transfer process from an intermittent jet to secondary fluid in thrust augmenterr (References 3 and 4).

5. CONCLUSIONS

The experience gained in constructing and testing the miniature valveless pulsejets and thrust augmenters to date has led to a broader understanding of their parameters, characteristics and problems. The fact that the original scaled-down versions would not run satisfactorily emphasizes the importance of combustor shell geometry on performance and points out the nature of the problems created through miniaturization. Four sizes tested extensively represented the best configurations developed after many hours of tuning and experiments (see Table 3). The HS-1(.075)-3 combustor which was characterized by a 5-1/2 inch straight section between the combustion chamber and the tailpipe was noted for its easy starting and smooth performance especially at the low fuel flow rates. However, the augmentation ratio was not as high as the HC-1 or the HH type Pulse Reactors. The HC-1 Pulse Reactor performed well even though its very small size led to complications in designing a satisfactory fuel system which would give easy starting and wide range performance. The HH-M1 and the HH-M2 Pulse Reactors performed better, although this may be attributed to their larger size.

Figure 41 presents the trends of thrust per unit combustor volume as a function of combustor volume. These data are based on the unaugmented performance and show the complete range of valveless pulsejet combustors from the 9.1 inch diameter HS-1B to the HC-1 miniature combustor which have been tested at Hiller. The thrust-to-volume ratio increases with decreasing combustor size at a rate somewhat less than represented by the "2/3 law" as sometimes referred to in gas turbine scaling. In view of thrust-to-volume, Tsfc, and augmentation performance, the HH-M1 represented the best of the miniature Pulse Reactors tested on the contract.

Figure 42 shows combustion frequency versus combustor volume. The trend closely follows the $1/V^{3}$ slope. Since the length-to-volume (L/D) relationship for the valveless combustors is fairly rigidly prescribed by resonant combustion requirements, the frequency also closely follows the 1/L slope.

The "lorgnette impingement" type fuel nozzle proved to be successful in these tests of miniature valveless pulsejets using gaseous propane and liquid gasoline of 80-90 octane; however, further improvements in Tsfc should follow from additional effort and research in this area.

No adverse effect on performance (thrust and Tsfc) of multiple engines in close proximity due to pressure wave interaction was observed for a single train or line. However, the close rectangular array of six unaugmented HC-1 combustors did show a performance drop when more than four combustors were operating. Pulse Reactor interaction appeared to affect the stability and frequency of resonant combustion and, during tests of compact clusters, showed up as a difficulty in keeping all the combustors resonating over the complete fuel flow range. Further investigation of combustor interconnections should provide the solution for this difficulty.

Operational problems were primarily (1) noise (as is typical of jet engines, 124-130 decibels range overall level at 25 feet from jet outlets, but without significant increase due to multi-engine operation), (2) vibration (operating cycle frequency range 180-320 cps) and (3) combustor shell temperatures up to 1850°F, which can be handled satisfactorily for most applications by (a) shrouding with relatively lightweight heat-insulating and noise-absorbing material, (b) alternate, i.e., out-of-phase, timing of combustors, and (c) shock-mounting of combustors to isolate vibration and permit thermal expansion of the combustor shells with minimum thermal stress.

A major obstacle to improvement lies in the lack of a suitable engine cycle performance prediction analysis to give some indication of (a) ultimate possible performance and (b) guide designers by predicting the effect of design changes, but this situation is somewhat alleviated by the basic simplicity of the engine structure which permits relatively rapid changes in test configuration. On the other hand, measurement of "instantaneous" gas pressures, temperatures and velocities, etc., are difficult and expensive, whereas simple measurements are limited to average thrust, combustion chamber pressures, fuel flow rates, shell temperatures, operating frequencies, and overall noise levels.

Although it has no moving parts, the combination of valveless pulsejets with ejector type jet pumps provides a device with large air-handling capacity which can in many cases be substituted for the combination of an engine or motor driving a fan or blower and combustor or furnace. Such tests as the "Sniffer" gas analyzer tests reveal excellent combustion efficiency, and the unsteady flow provides a higher heat transfer rate than may be expected for steady flow. These characteristics all point towards the use of valveless pulsejets with ejectors as simple, efficient, low-cost heater-blowers. It is also concluded that the same characteristics, in general, indicate that the units may have merit as ultra-simple thrust devices.

6. REFERENCES

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TABLE 3

MAJOR TEST RESULTS

PULSEJET	COMBUSTOR MAX. DIA. inches	COMBUSTOR TOTAL LENGTH inches	TOTAL THRUST pounds	① Tsfc MINIMUM lb/hr/lb	FUEL FLOW RATE pph	AUGMENTATION RATIO	TOTAL THRUST MAXIMUM pounds	① Tsfc MINIMUM lb/hr/lb	FUEL FLOW RATE pph	FIGURE REF. NO.
SINGLE ENGINES										
	COMBUSTOR ONLY					AUGMENTED				
HS-1(.024)	1.35	25.25	-	-	-	-	-	-	-	1
HC-1 (Straight)	2.40	26.87	2.6	5.8	15.9	1.8	4.6	3.3	15.2	3, 26
HC-1 (U-shaped)	2.40	26.87	2.2	5.2	10.7	-	-	-	-	12,27
HS-1(.075)	2.50	45.72	-	-	-	-	-	-	-	2
HS-1(.075)-3	2.65	51.75	8.2	4.0	32.2	1.5	11.0	2.6	28.6	4, 28
HH-M1 (Straight)	2.75	46.25	10.0	3.2	32.0	1.9	17.0	1.8	31.2	5, 12, 30
HH-M2 (Straight)	3.25	51.13	12.5	3.4	42.5	1.8	23.0	1.9	13.7	6, 33
MULTIPLE ENGINES										
HC-1 (Straight) Six In-Line	2.40	26.87	11.5	6.3	72.0	1.9	13.5	5.0	67.5	24,25
HC-1 (Straight) Six In Rectangular cluster	2.40	26.87	9.2	7.8	72.0	-	-	-	-	24,25
HH-M1 (Straight) Three In-Line	2.75	46.25	23.0	3.3	75.9	1.8	② 36.0	1.9	68.5	32
HH-M2 (Straight) Three In-Line	3.25	51.13	31.0	3.4	102	1.6	② 47.5	2.2	102	35

① Minimum Tsfc is usually near, but not at, fuel flow rate for maximum thrust (Ref. text).
② Total thrust not maximum here due to fuel supply system limitation (see Figures and text).
③ Most of testing was with gaseous propane fuel; HC-1(U-shaped), HH-M1, HH-M2 brief check runs gave essentially same performance as with propane (ex. Fig. 27 and text).

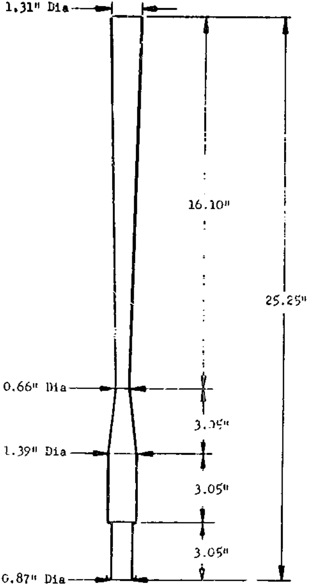


FIGURE 1: SKETCH SHOWING DIMENSIONS OF HS-1(.024) COMBUSTOR

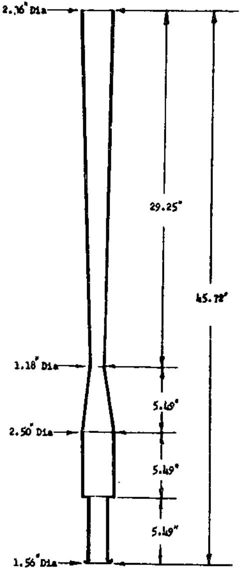


FIGURE 8: SKETCH SHOWING DIMENSIONS OF HS-1(.075) COMBUSTOR

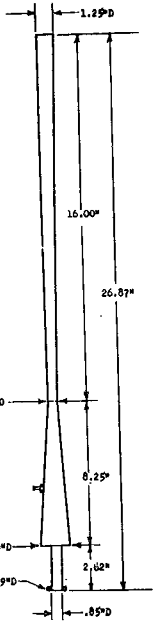
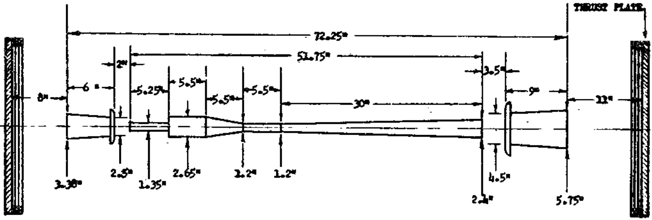


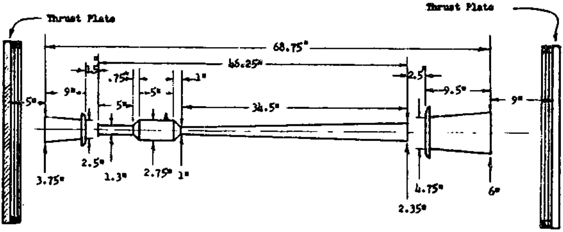
FIGURE 3: DIMENSIONS OF CONFIGURATION C-1 VALVELESS PULSEJET COMBUSTOR WITH CONICAL COMBUSTION CHAMBER



HS-1(.075)-3 PULSE REACTOR

PERFORMANCE: 11 lb MAX. THRUST; TSFC 2.6 pph/lb (PROPANE)

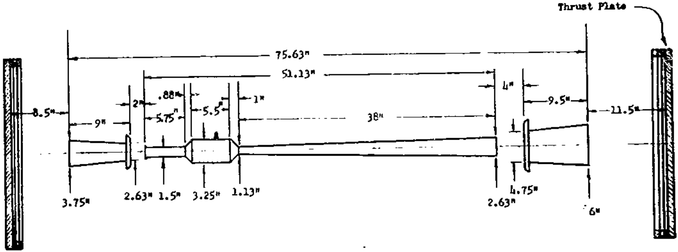
FIGURE 4: SKETCH OF HS-1(.075)-3 TEST SETUP WITH AUGMENTERS



HS-M1 PULSE REACTOR

PERFORMANCE: 17 lb MAX. THRUST; TSFC 1.8 pph/lb (PROPANE)

FIGURE 5: SKETCH AND DIMENSIONS OF HS-M1 COMBUSTOR TEST SETUP WITH AUGMENTERS



HH-M2 PULSE REACTOR

PERFORMANCE: 23½ lb MAX. THRUST; TSFC 1.9 pph/lb (PROPANE)

FIGURE 6: SKETCH AND DIMENSIONS OF HH-M2 COMBUSTOR SETUP WITH AUGMENTERS

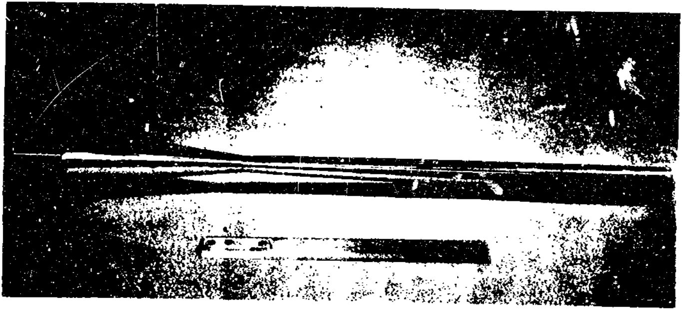


FIGURE 7: A C-1 COMBUSTOR FORMED ENTIRELY BY ELECTROPLATING

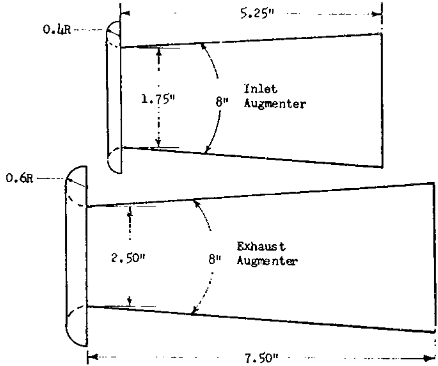
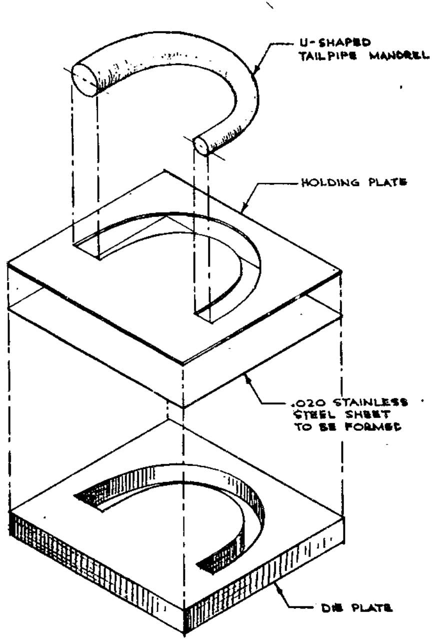


FIGURE 8: PULSE REACTOR C-1 AUGMENTERS

FIGURE 9: PYREX AUGMENTERS FOR C-1 COMBUSTOR



FORMING DIE FOR U-TURN TAILPIPE SECTIONS

FIGURE 10

FIGURE 11: FORMING DIE AND MANDREL WITH LEFT AND RIGHT HAND PRESS PLATES FOR C-1 COMBUSTOR U-TURN

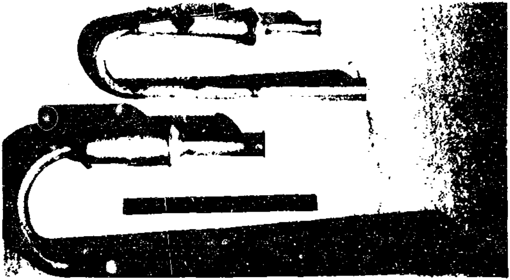


FIGURE 12: COMPARISON OF C-1 AND HN-M1 U-SHAPED COMBUSTORS

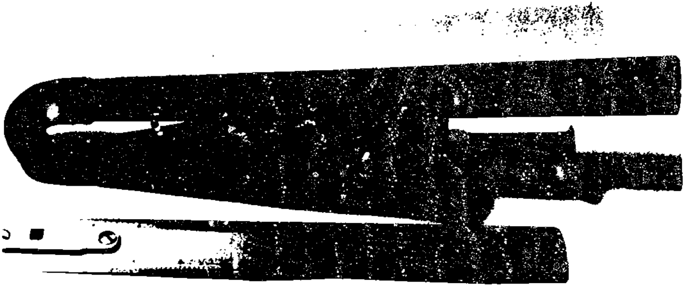


FIGURE 13: SMALL U-SHAPED COMBUSTOR WITH CONICAL INDENTED COMBUSTION CHAMBER

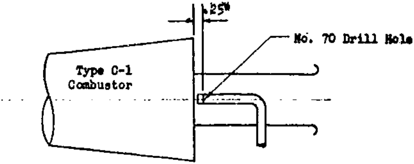


FIGURE 14: INLET FUEL NOZZLE WITH MULTIPLE FUEL JETS

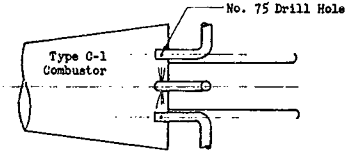


FIGURE 15: COMBUSTION CHAMBER FUEL NOZZLE WITH MULTIPLE JETS

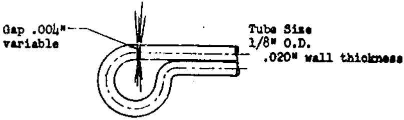
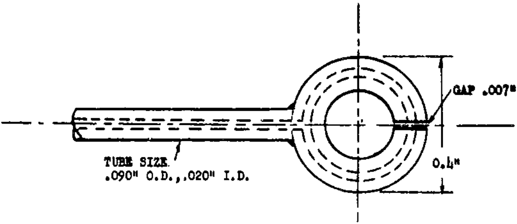
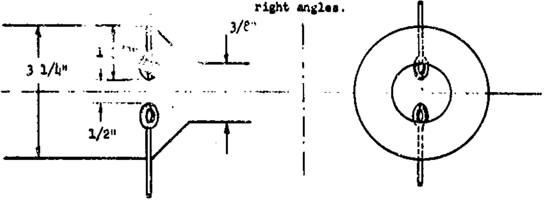


FIGURE 16: GRABER'S "QUESTION MARK" FUEL NOZZLE



"LORONETTE" FUEL NOZZLE



Nozzles are oriented so that their spray planes intersect each other at right angles.

FUEL NOZZLE POSITION

FIGURE 17: FUEL NOZZLES AND LOCATION FOR OPERATION OF NH-42 COMBUSTOR WITH GASOLINE

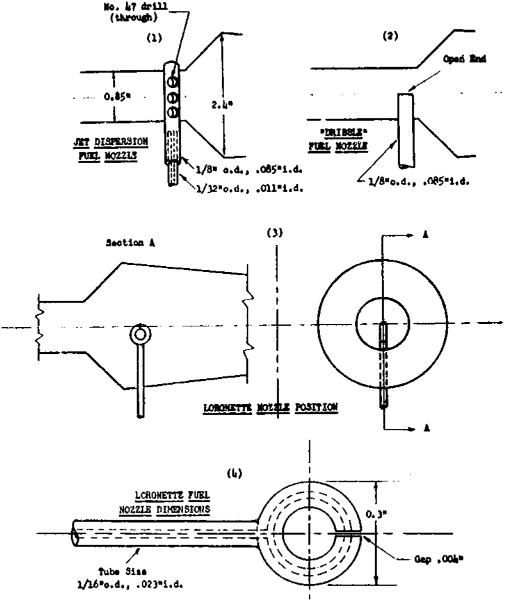


FIGURE 18: FUEL NOZZLES AND LOCATIONS FOR OPERATION OF C-1 COMBUSTOR WITH GASOLINE

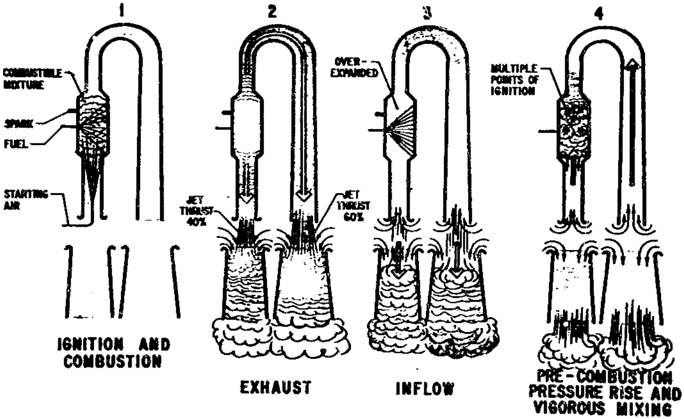


FIGURE 19: PULSE REACTOR CYCLE DIAGRAM

[illegible] JET THRUST PLATE CLOSE-UP

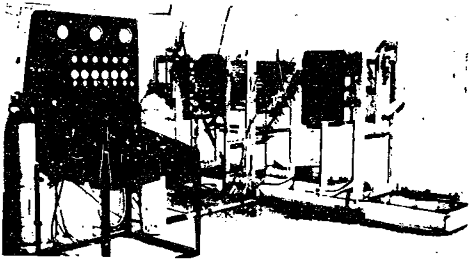


FIGURE [illegible] MINIATURE CLUSTERED PULSE REACTOR TEST RIG

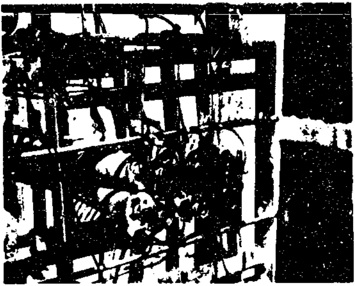


FIGURE 22: CLUSTER OF SIX C-1 COMBUSTORS
IN CLOSE RECTANGULAR ARRAY

FIGURE 23: SIX C-1 COMBUSTORS IN LINE (OR "TRAIN"), AUGMENTED

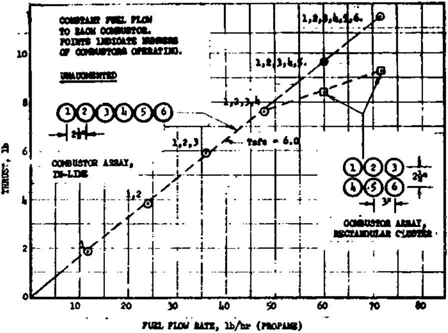


FIGURE 24: C-1 COMBUSTORS UNAUGMENTED, IN-LINE AND RECTANGULAR ARRAYS

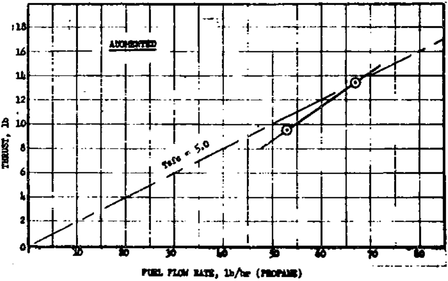


FIGURE 25: SIX IN-LINE C-1 COMBUSTORS WITH AUGMENTORS

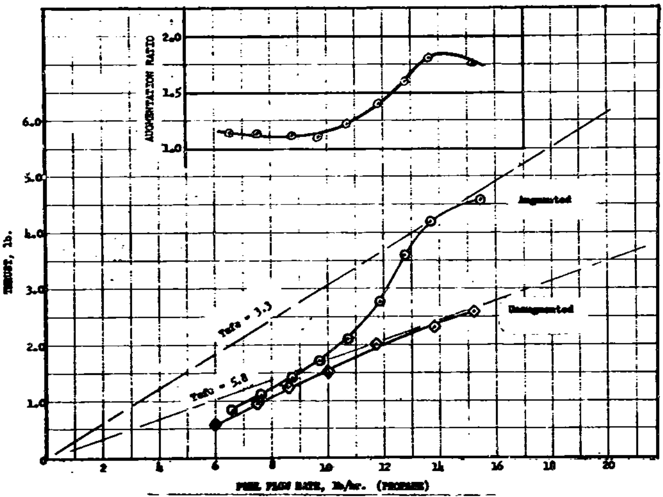


FIGURE 26c GHR G-1 COMBUSTOR, AUGMENTED AND UNAUGMENTED

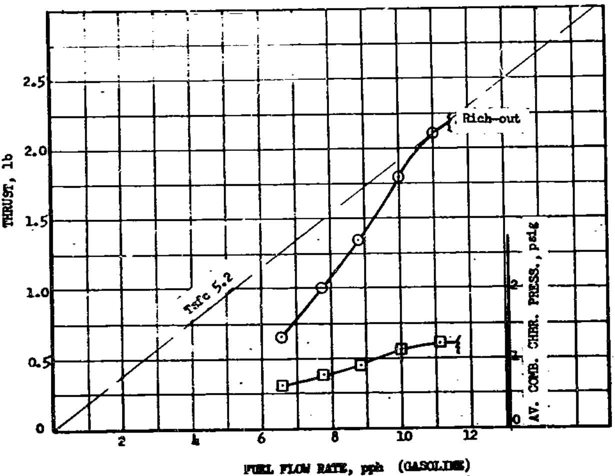


FIGURE 27a ONE C-1 U-SHAPED COMBUSTOR, UNAUGMENTED, WITH LONGSETTE NOZZLES - GASOLINE FUEL

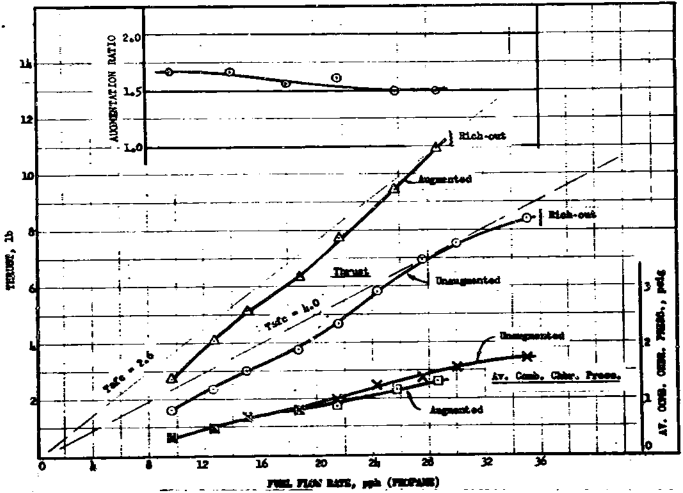


FIGURE 28. THRUST AND AVERAGE COMBUSTION CHAMBER PRESSURE OF ONE RB-1 (0.075)-3 PULSE REACTOR, AUGMENTED AND UN-AUGMENTED

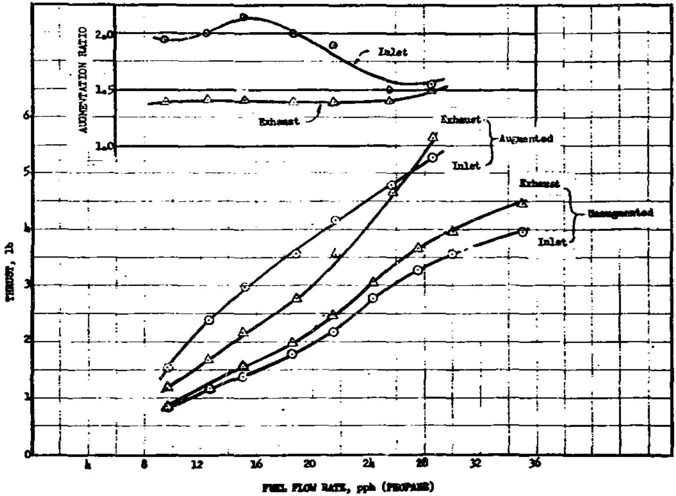


FIGURE 29: AUGMENTED AND UNAUGMENTED THRUST FOR EXHAUST AND INLET ENDS OF ONE RS-1 (0.075)-3 PULSE REACTOR

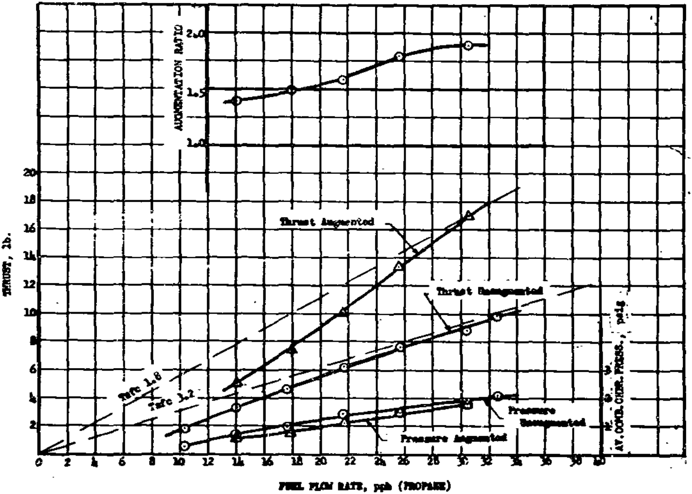


FIGURE 30: [illegible] COMBUSTOR, AUGMENTED AND UNAUGMENTED

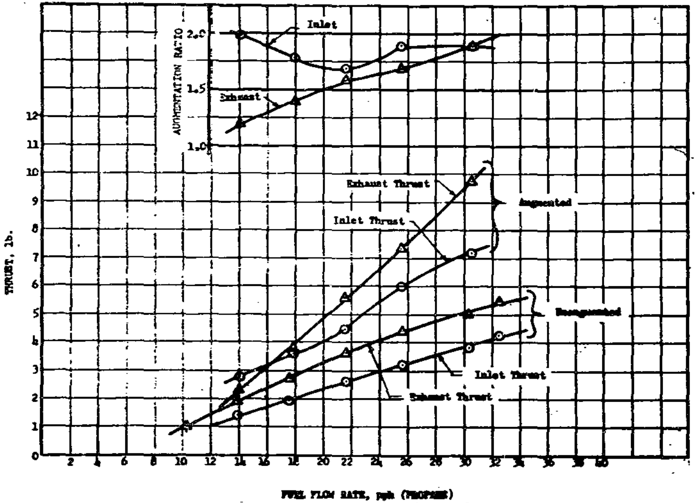


FIGURE 31. ONE [illegible] COMBUSTOR, AUGMENTED AND UNAUGMENTED

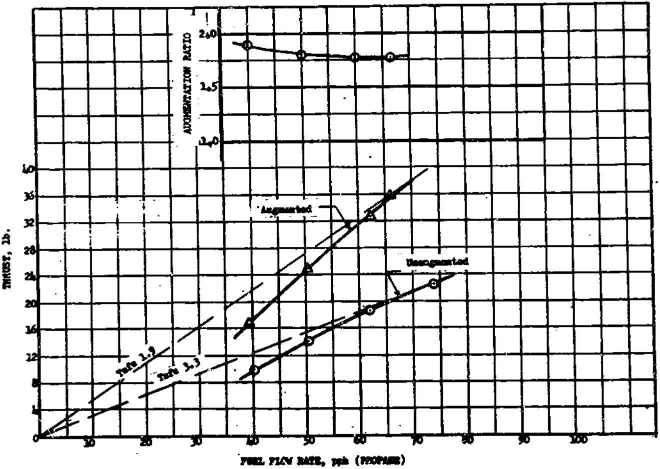


FIGURE 32: THREE [illegible] COMBUSTORS, AUGMENTED AND UNAUGMENTED

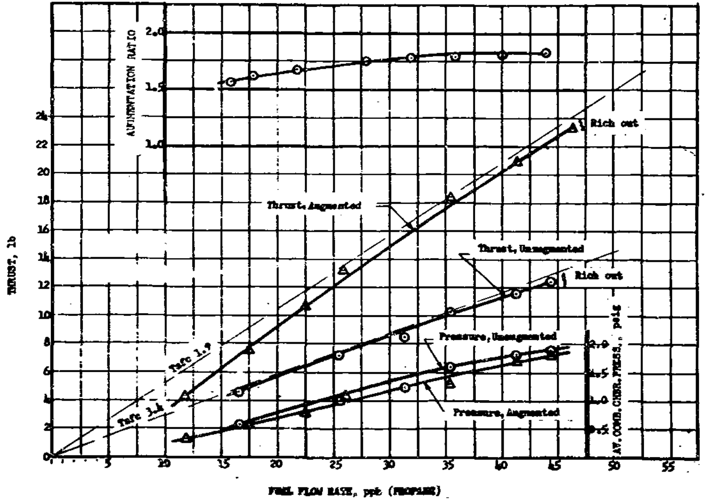


FIGURE 33c ONE [illegible] COMBUSTOR, AUGMENTED AND UNAUGMENTED

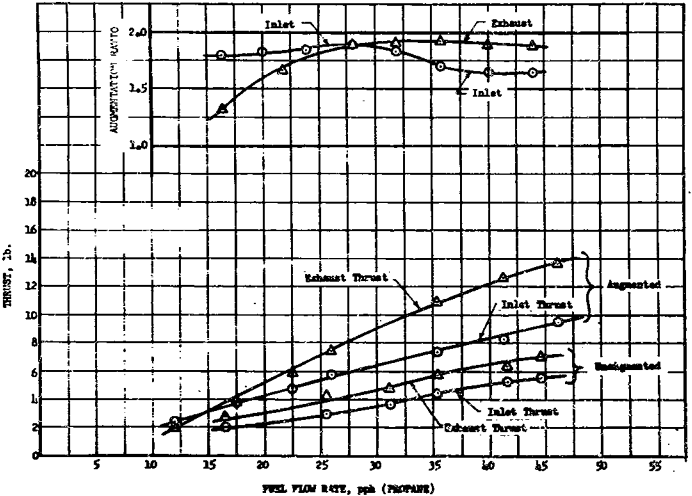


FIGURE 34e ONE [illegible] [illegible], AUGMENTED AND UNAUGMENTED

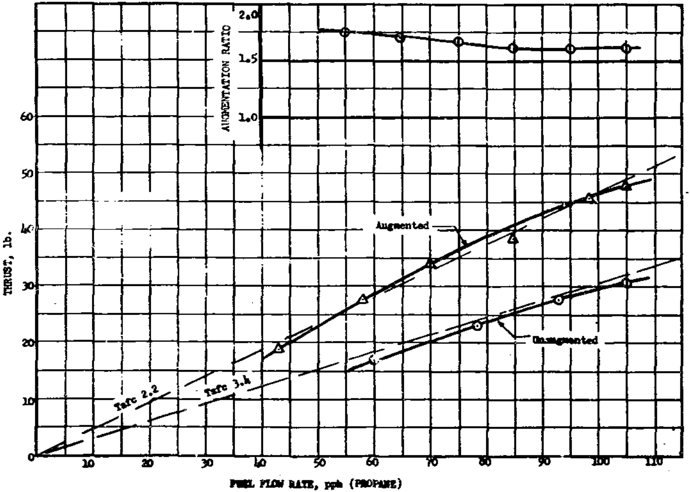


FIGURE 35: THREE [illegible] COMBUSTORS, AUGMENTED AND UNAUGMENTED

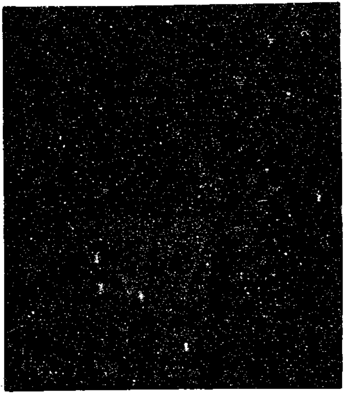


FIGURE 36: HH-M2 COMBUSTORS WITH INTERCONNECTING TUBES BETWEEN COMBUSTION CHAMBERS

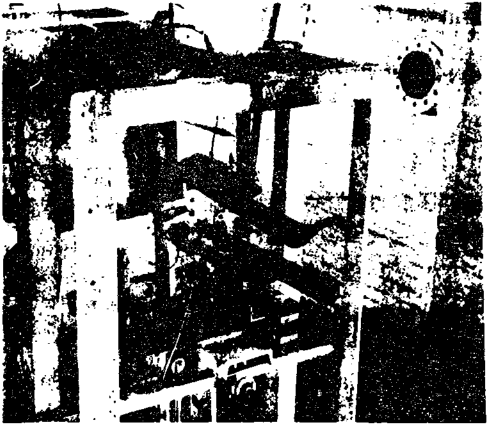


FIGURE 37: TWO HH-M1 U-SHAPED COMBUSTORS ON THRUST STAND

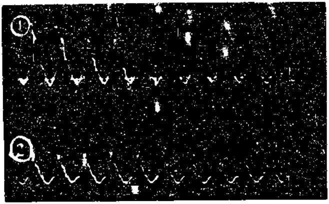


FIGURE 38: OSCILLOSCOPE PHOTOGRAPH, SWEEP 5 msec/cm. TRACE (1) HH-M1 COMBUSTOR AT FULL THROTTLE (228 cps); TRACE (2) **SAME COMBUSTOR** AT IDLE (233 cps). NOTE APPROXIMATELY 5 cps **DIFFERENCE**

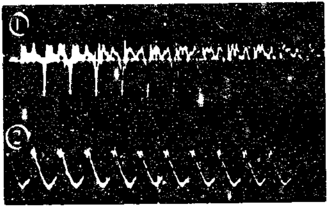
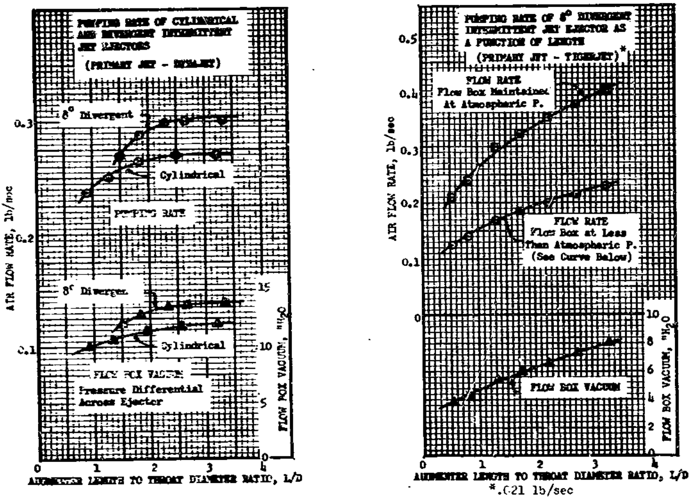


FIGURE 39: OSCILLOSCOPE PHOTOGRAPH, SWEEP 5 msec/cm. **TRACES (1) and (2)** FROM A PAIR OF HH-M1 COMBUSTORS ILLUSTRATE **PAIRED COMBUSTOR** SYNCHRONIZATION APPROXIMATELY 180° OUT OF **PHASE. NO** COMBUSTOR INTERCONNECTION



*.021 lb/sec

FIGURE 40a PUMPING RATES OF INTERMITTENT JET EJECTORS

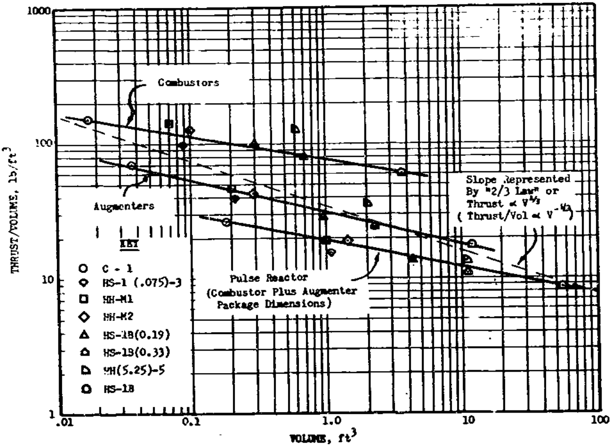


FIGURE 41: TRENDS OF THRUST/VOLUME VERSUS VOLUME FOR COMBUSTORS AUGMENTERS, AND PULSE REACTORS

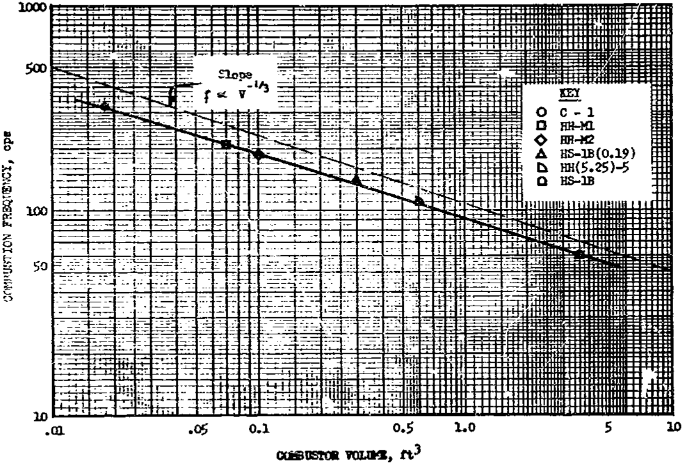


FIGURE 42: COMBUSTION FREQUENCY VERSUS COMBUSTOR VOLUME FOR PULSE REACTOR COMBUSTORS

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