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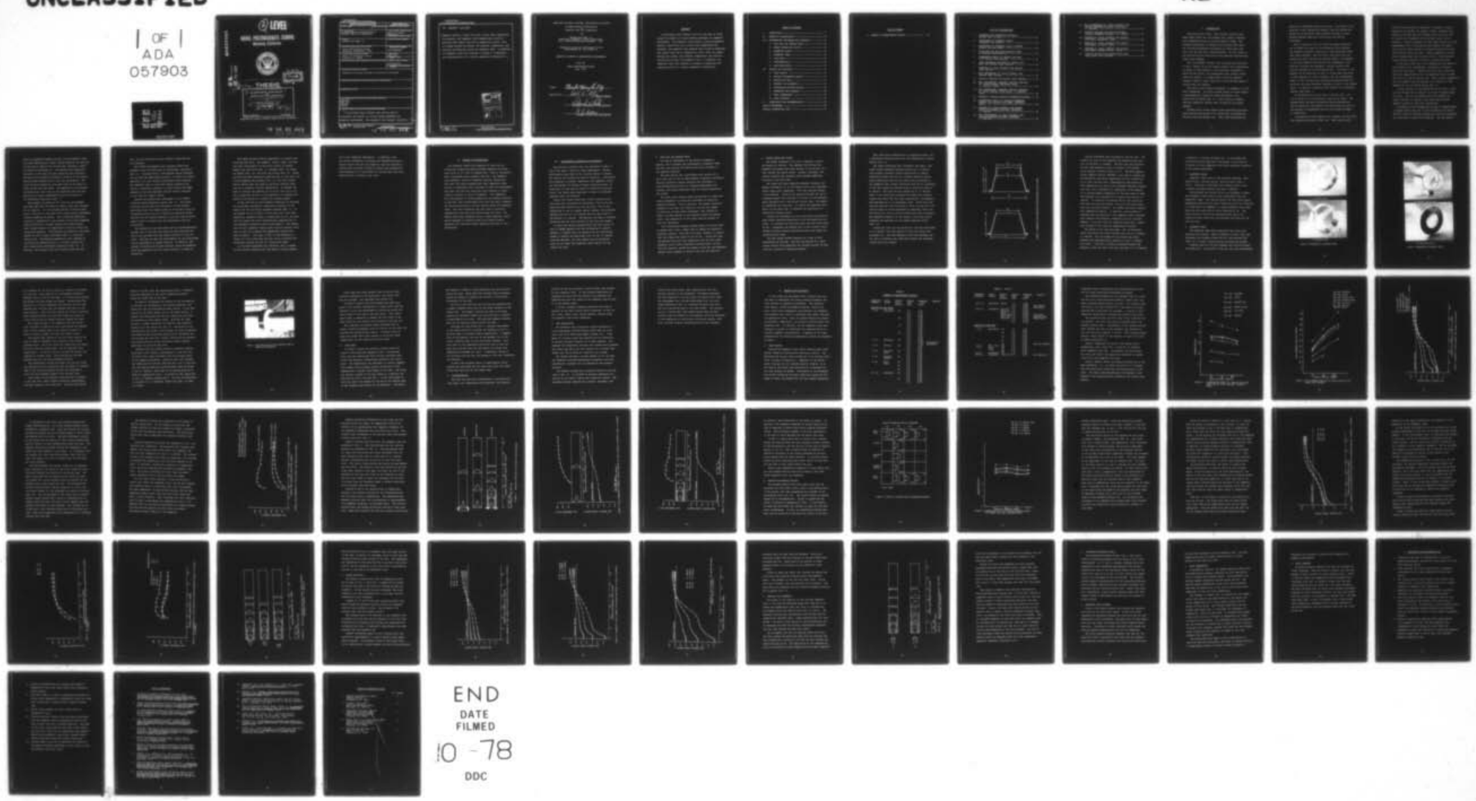

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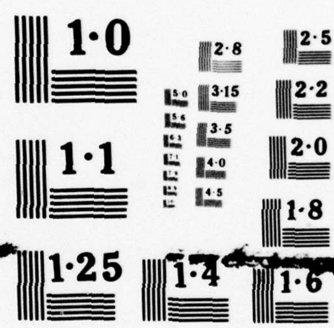
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

Masters THESIS

AN EXPERIMENTAL INVESTIGATION
OF
TURBOJET TEST CELL AUGMENTORS

by

Charles Nim Sapp, Jr.

June 1978

71 p.

Thesis Advisor: D. Netzer

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An Experimental Investigation of Turbojet Test Cell Augmentors

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

A one-eighth scale turbojet test cell was used to investigate the effects of various design parameters on augmentor performance. The augmentor inlet design, nozzle-to-augmentor spacing, engine flow rate, nozzle total temperature and pressure, and augmentor tube diameter were varied to determine what effect they had on augmentation ratio, total air pumped through the system, and pressure, temperature, and velocity distributions within the augmentor tube. In addition, two augmentor tubes were combined in tandem to investigate the characteristics of a tertiary augmentor configuration.

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I. INTRODUCTION

During the early 1950's, when turbojet engines first began making their way into general use, typical combustor exit temperatures were in the 1500 degree F range. The problems encountered in designing and building test cells for the post-maintenance calibration of those early jets were, for the most part, straightforward. In fact, many of the facilities were nothing more than modified reciprocating-engine test chambers.

Over the decades, however, the jet engine has continued to grow. Modern units now produce turbine inlet temperatures in excess of 2500 degrees F, with attendant increases in mass flow and thrust, and afterburners have further complicated the problem. To combat these increasing demands industry turned to water injection as the principal means of cooling test cell exhaust.

The typical water quench arrangement is composed of three basic subsystems: an electric power system for water supply, a hydromechanical system for water application, and a safety monitor system [Ref. 4]. Such a setup is complex, and that complexity implies lower reliability and higher expense.

Although water offers superior heat absorbing qualities, spray devices have proved to be inefficient at penetrating the high velocity exhaust core. Thus, huge quantities are required to accomplish effective cooling. Since much of the moisture is lost through the exhaust stack the problem has become one of providing large supplies of water in often drought plagued areas such as San Diego and Oakland, California.

Also of concern is the fact that the spray mechanisms act to quench the flame of the afterburner which arrests the combustion process, resulting in some afterburner feed fuel being unburned. This raw fuel, along with such substances as sulfur dioxide and unburned carbon, is suspended in the water droplets and settles onto landscaping, automobiles, buildings and equipment, causing corrosion and soiling problems for the surrounding area. The water in the exhaust can be beneficial in that it causes small particles to lump together for ease of removal, but the contaminated water is also corrosive and increases maintenance costs for pollution and noise abatement equipment located in the exhaust stack. In addition, quenching often results in an unsightly exhaust plume [Ref. 1].

An alternative to the wet cell is the dry cell, i.e., one in which all of the cooling is done by air alone. Dry systems offer increased reliability and maintainability, ease of operation, and reduced life cycle costs, as well as the promise of independence from an ever dwindling supply of fresh water.

As promising as they appear to be, however, the dry cells have numerous problems of their own. They receive their cooling from entrained or augmented air pumped in ejector fashion by the primary jet exhaust stream. Excessive augmentation can pump down the pressure within the test cell to the point of exceeding the structural limits of the building. Excessive pumping can also induce errors in thrust measurements due to the pressure drop between the engine inlet and the engine exhaust or through distortions in the flow patterns within the cell. Higher augmentation ratios mean increased mass flow through the cell, which requires larger and more expensive pollution treatment devices.

On the other hand, too little augmentation can result in recirculation and, consequently, reingestion of exhaust gases into the engine. Reduced cooling airflow could also cause the temperatures within the augmentor tube to exceed the limit for that particular tube. This limiting temperature can run anywhere from 400 degrees F for concrete to 1000 degrees for the new Coanda system [Ref. 4].

A major obstacle in the designing of test cells is that one cell design must be used for a variety of engine types and sizes. This is unavoidable when one considers the large inventory of engines in use today and the great expense involved in test cell construction.

An example of this dilemma may be seen at numerous Naval Air Rework Facilities, due to the introduction of the TF-30/TF-41 class of turbofan engines into test cells designed for relatively low mass flow turbojets. The fan engines tend to overpump the system and many of the augmentor tubes have been modified with "choke" plates placed at the entrance of the tube to restrict the airflow and, therefore, reduce the amount of entrained air. The problem with these modifications is that they are made locally by test engineers who have little guidance available to them as to the various effects these changes have on test cell performance. The trial and error method has long been known to be costly in terms of both time and money. The magnitude of the problem is brought more into focus by the prediction that dry augmentors will require augmentation ratios as high as 6:1 for afterburner operations [Ref. 7].

This problem is certainly not a new one and attempts have been made over the years to design a test cell suitable for all engines. A.V. Roe Canada Limited of Toronto began using a test cell in the early 1950's which used an adjustable tertiary augmentation system. This introduced additional cooling air downstream of the entrance of the first augmentor tube and featured a colander device with sliding covers which allowed control of augmentation ratios by varying the system back pressure. The mechanism was effective, but being exposed to such a harsh environment made it a high maintenance item. The maximum augmentation ratio achieved by the system was something over 3:1, so water cooling was still required for afterburner operations [Ref. 11]. In addition, the tertiary inlet was located inside the test cell, so the increased flow also tended to pump down the cell pressure.

More recent developments have centered around such systems as the F-14 Hush House at NAS Miramar, California [Ref. 1]. Patterned after a 1966 Swedish design developed for use with the SAAB Draken aircraft, it offers air cooled operation up to and including afterburner power settings. The augmentor tube is lined with acoustic material and offers a significant reduction in noise without the added expense of the noise abatement devices usually contained in the test cell exhaust stacks.

Another new system under development is the Coanda/ Refraction Noise Suppressor System [Ref. 4]. The Coanda principle involves gas flow following a curved surface, which means that the exhaust gases can be turned as much as 90 degrees without the use of baffles or deflector plates. Coupled with the acoustic material lining the tube as above, great savings in construction and maintenance costs are anticipated.

The problem with the Hush House and the Coanda/Refraction systems lies in the fact that they have been developed for use as run up stands with the engine installed in the air-frame. They may not meet the requirements for out-of-airframe runs as performed at a rework facility. In addition, the concept of putting the acoustic material along the augmentor walls has apparently met with some difficulty in terms of durability.

Some modeling work directly applicable to turbojet test cells has been done. For example: Bailey, Tower, and Fuhs and their investigation of pollution control of airport engine test facilities [Ref. 7], Hasinger [Ref. 13], Hayes and Netzer [Ref. 14], and Croft and Lilley [Ref. 15]. Deleo and Wood did some significant modeling work in 1952 [Ref. 10], as did Lemmerman and Lockwood [Ref. 11], but their experimental results were all based on miniature ejectors using hot gas to simulate turbojet temperatures. No attempt was made to simulate the geometry of an actual test cell or to burn liquid fuel and mix it with bypass air to simulate the exhaust flow pattern of a mixed flow turbofan engine.

In May 1973 the Air Force Weapons Laboratory at Kirtland Air Force Base, New Mexico, completed an analysis of jet engine test cell pollution abatement methods [Ref. 3]. It was brought out as a result of this study that "with some exceptions, augmentor design is essentially an art, and test facility people have never systematically measured any of the parameters concerning ejector performance". The usefulness of their augmentor design model would be limited "until data on test cell pressure and temperature profiles are made available". This type of data is very expensive to obtain in a full scale test cell but can be collected very efficiently through the use of a scaled down model.

As the above discussion has indicated, work is needed to more exactly determine what the design variable effects are on dry augmentor performance. In addition, more definitive information on pressure and temperature distributions within the cell and augmentor tube are required to provide data for model validation efforts and guidance for test engineers as to the effects of various major and minor modifications to existing test cells.

II. METHOD OF INVESTIGATION

Dry augmentor tubes with diameters of eight and ten inches were constructed which provided augmentor-to-nozzle area ratios of 16.7 and 26 respectively. Used in conjunction with a one-eighth scale turbojet test cell, the augmentor inlet geometry, nozzle to augmentor spacing, engine mass flow rate, and nozzle pressure and total temperature were varied to investigate their influence on test cell performance. The eight- and ten-inch tubes were also combined to investigate a tertiary air type of augmentor. All augmentors were instrumented to record temperature and pressure profiles at the wall, and a seven-probe pitot rake was used to measure the velocity profiles at various stations along the augmentor tubes. The rake information was also used to calculate augmentation ratio and total exhaust mass flow rate. Hot exhaust tests were conducted using a sudden expansion ramjet burner designed to simulate mixed flow turbofan engine operation over the entire power spectrum from idle to full afterburner.

III. EXPERIMENTAL PROCEDURES AND APPARATUS

The sub-scale turbojet test cell described in Refs. 9 and 12 was used to carry out these experiments. Certain modifications were made to the original design to enhance the results and increase the ease of operation. Since extensive changing of nozzles, augmentors, and augmentor inlets was anticipated, the design of those items was driven, in large part, by the need for ease of installation and durability, the latter being important in order to withstand repeated tests and handling.

Engine flow rates scaled down 1/64th of actual TF-41 flow rates were envisioned as providing a look at the full operating power spectrum for the test cell. Due to the limitations on the air supply system, however, the available maximum flow rate of 2.19 lbm/sec was only about half of the desired 4.11 lbm/sec. The decision was made to continue, exploring only the lower portion of the flow rate regime.

As data were being analyzed during the first series of runs it became apparent that the differences in results between 2.0 lbm/sec and 2.19 lbm/sec were not significant enough to justify the additional runs, so the 2.0 lbm/sec runs were deleted. For this reason only the bellmouth inlet on the eight-inch augmentor shows results for the latter flow rate.

A. TEST CELL AND EXHAUST STACK

For ease of adjustment of the nozzle-to-augmentor spacing, and to enhance the interchange of augmentor tubes, the cell test section and exhaust stack were retained in two separate sections.

The test section was a one-eighth scale version of a TF-41 test cell in use at NARF Alameda in Oakland, California. Features included a square aluminum inlet bellmouth, a flow-straightening section of aluminum honeycombing and screens, and hinged plexiglass sides for engine observation and access.

The plate steel exhaust stack was mounted on a wheel and track arrangement to allow easy adjustment of nozzle-to-augmentor spacing. Once in position, the exhaust stack was anchored to the test cell frame by a tie bar and clamps. To allow for variable stack resistance, four lengths of angle iron were mounted in grid fashion inside the exhaust stack. Any combination of the slats could be removed to vary the resistance.

The track-mounted exhaust system proved to be quite easy to manage and it was a simple task to change the nozzle-to-augmentor spacing. Care had to be taken, however, to ensure that the clamps were tight on the tie bar. During hot runs and maximum flow cold runs (especially with the flat plate augmentor inlet) heavy vibrations occurred which, on more than one occasion, caused the clamps to slip and the augmentor/exhaust stack assembly to slide to the full aft position.

B. RAMJET ENGINE AND PIPING

The ramjet consisted of an inlet, combustor, nozzle, and bypass air ducting. The combined flow through the combustor and bypass duct were matched to the suction airflow through the engine intake. Primary, secondary, and suction airflows were measured using standard ASME-type orifices in the feed lines.

Two three-inch pipes supplied combustor (primary) and bypass (secondary) air to the ramjet from an Allis-Chalmers twelve stage axial compressor. Fuel was injected through a ring manifold. Ignition was supplied through the use of a methane-oxygen torch mounted in the wall of the combustor, which was made from a thin-walled inconel tube. The bypass air performed two functions. It cooled the combustor walls while, at the same time, it enhanced the simulation of a mixed-flow turbofan engine.

Primary and secondary air flow rates were controlled by hand valves installed downstream of the flow-measuring orifices. To increase the ease with which the flow rates could be set, a manometer was mounted next to each control valve, thereby avoiding numerous preliminary data runs simply for adjusting flow rates.

The fuel supply system consisted of a tank of JP-4 pressurized by nitrogen. The fuel was metered by a cavitating venturi which permitted the accurate control of fuel flow as a function of upstream pressure.

Most tests were conducted with a converging nozzle, but a converging-diverging nozzle was also employed for limited testing (Fig. 1).

The ramjet functioned well throughout the tests. The higher nozzle pressures produced during the 1.5 lbm/sec runs yielded a smoothly running engine able to sustain combustion without the use of a constant ignition source. During operations with the flat plate inlet installed on the augmentor tube, severe vibrations from the air turbulence in the tube caused the pressure data at high flow rates to be erratic. The flow rate was backed off to 1.0 lbm/sec where it was found that, although the ramjet ran slightly rougher and would lose the flame occasionally, the pressure data smoothed out to an acceptable level. Since this flow rate was used for only one series of data, the use of a continuous ignition source guaranteed an operating ramjet for the entire run, and its use was hardly more than a nuisance. The combustion behavior of the engine at the lower nozzle pressures was expected for the sudden expansion burner [Ref. 12].

During the cold runs the primary air flow was maintained at 0.5 lbm/sec, with the balance of the flow coming from secondary air. The only departure from this procedure was for the 2.19 lbm/sec runs, when both primary and secondary valves were fully opened.

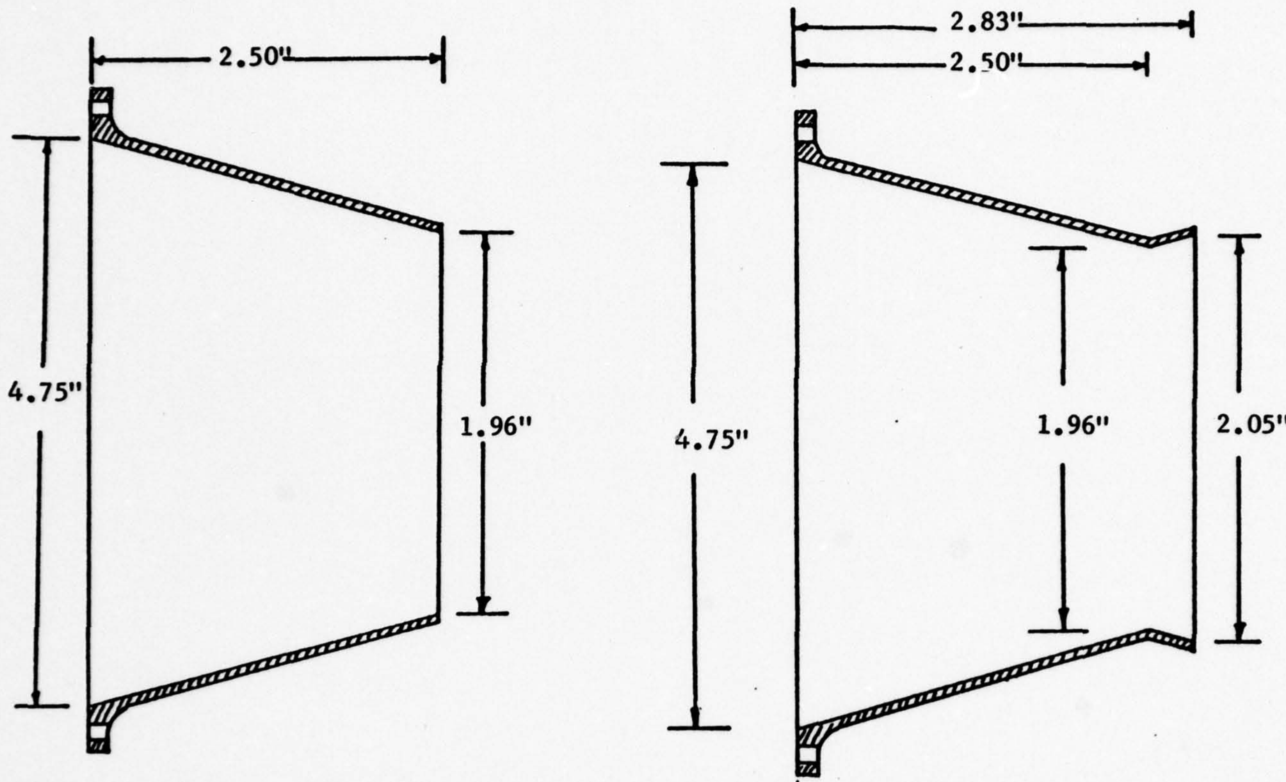


FIGURE 1. CONVERGING AND CONVERGING-DIVERGING NOZZLES USED IN TESTS.

Similar procedures were followed for the hot runs. The primary air flow to the combustor was adjusted after ignition to maintain 0.5 lbm/sec. The fuel flow was regulated by fuel tank pressure to give a constant 0.035 lbm/sec, which yielded a fuel/air ratio of 0.07. The Naval Weapons Center computer routine (PEPCODE 2) was used to compute the stoichiometric combustion temperature for JP-4 burned with air at that fuel/air ratio (approximately 4200 degrees R). This temperature was used as the estimated combustor temperature and, with a secondary air temperature of 562 degrees R, an average exhaust temperature at the exit plane of some 2400 degrees R was computed for an engine flow rate of 1.5 lbm/sec. In actuality the exhaust was not well mixed and the inner core was much hotter, the outer core much cooler, than the calculated average. No attempt was made to measure this temperature profile. In addition, some evidence of unburned fuel was observed in the combustor which indicated that complete stoichiometric combustion had not occurred. However, it was felt that the computed values gave a reasonable estimate of the range of temperatures involved.

Two series of hot runs were made. One, as described above, maintained the overall engine flow rate at a constant 1.5 lbm/sec. For the second hot run series the nozzle pressure was readjusted after ignition to the 2.0 lbm/sec cold value. This gave a slightly increased average temperature, since the total flow rate came down to 1.33 lbm/sec, a reduction in cooling secondary air. It was hoped that this would provide additional information on the relative influence of total temperature and nozzle pressure variations on the system performance.

C. AUGMENTOR INLETS

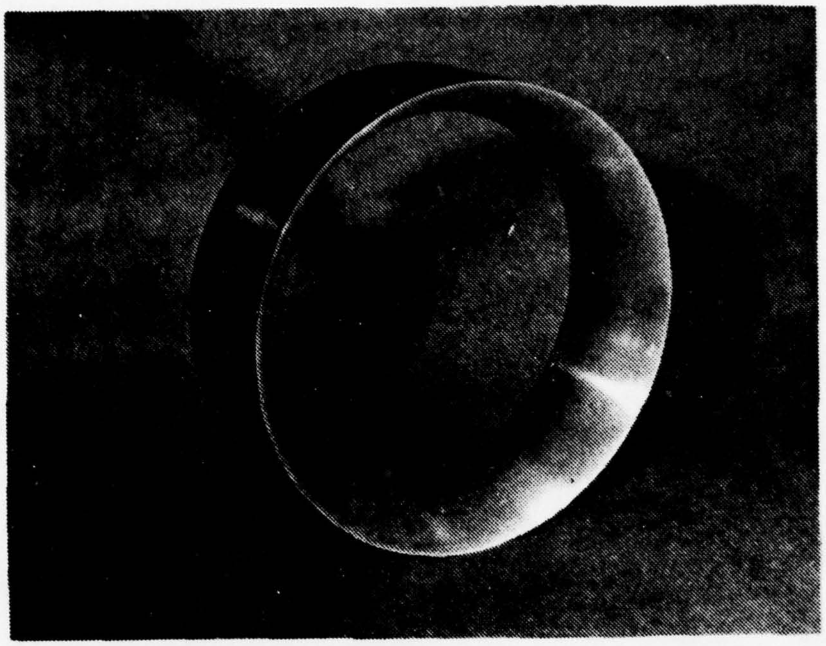
Augmentor inlets were of four different designs: bell-mouth, conical, reverse conical, and flat plate (Figs. 2 and 3). They were constructed from aluminum since it was a readily available material and easy to machine.

The bellmouth and conical inlets were designed to represent standard inlets found on many operational test cell augmentors today. The reverse conical and flat plate inlets represented modifications used on some test cells to "throttle" or "choke down" the augmentor to reduce excessive flow rates. Runs were also made with no inlet installed at all. The entire series of inlets was constructed for use on the eight-inch tube, while only the bellmouth was used with the ten-inch tube.

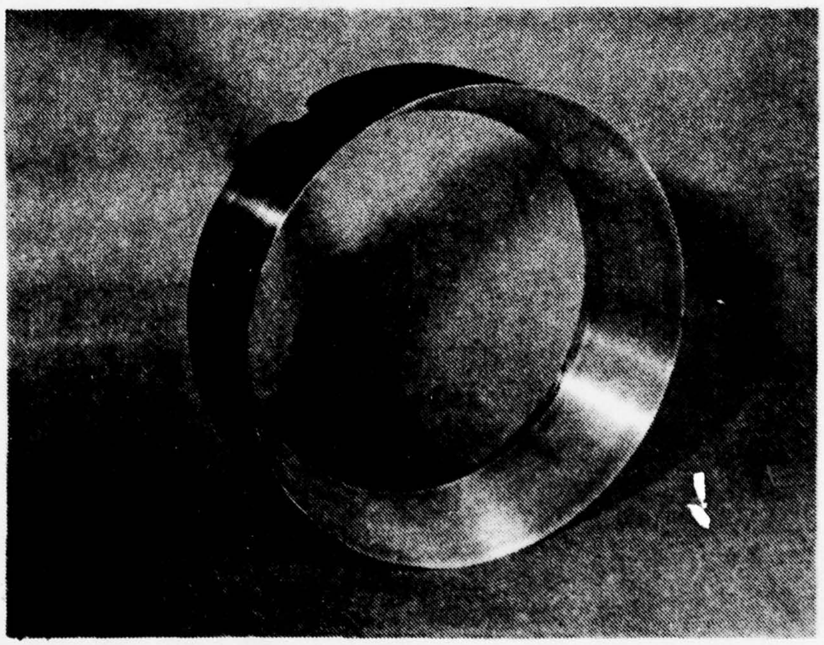
D. AUGMENTOR TUBES

The augmentor tubes were constructed from scrap pipe obtained from salvage. Made of schedule 40 steel, they were thoroughly grit blasted inside and out, then treated with light oil to inhibit rusting during the machining process.

Pressure taps of 1/32-inch diameter were drilled through the upper wall. The outside of the wall was then counterbored

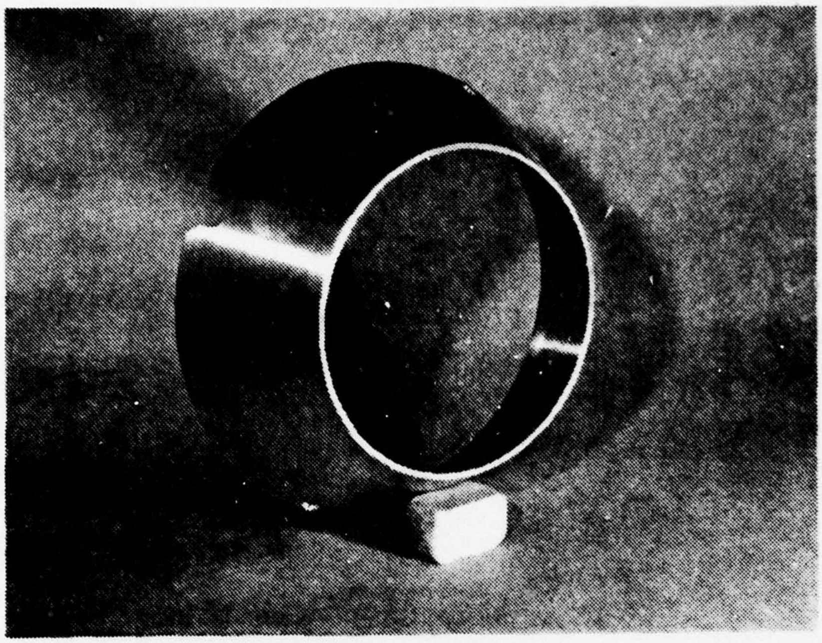


(a) BELLMOUTH INLET

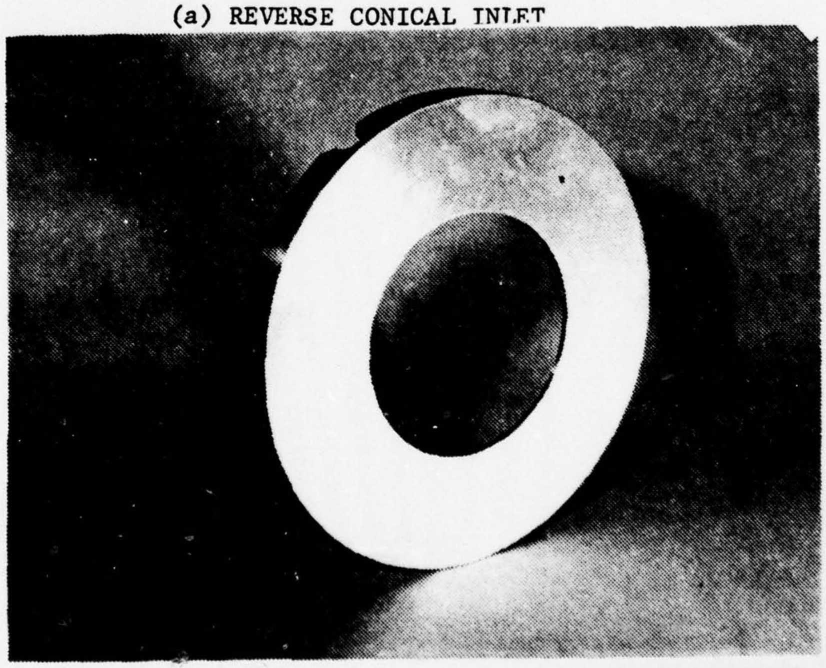


(b) CONICAL INLET

FIGURE 2. PHOTOGRAPHS OF AUGMENTOR INLETS



(a) REVERSE CONICAL INLET



(b) FLAT PLATE INLET

FIGURE 3. PHOTOGRAPHS OF AUGMENTOR INLETS

to a diameter of 1/4 inch at each tap, leaving a tap length of 3/16 inch. This resulted in a recommended length-to-diameter ratio of six for the taps. A 1/4-inch pipe coupling was placed into each recess and welded. Thread sealer was applied to a 1/8-inch Swedgelok tube fitting, one for each pressure tap, and then each was screwed into place in the pipe coupling. After two-inch lengths of 1/8-inch stainless steel tubing had been cut, each was locked into place in a tube fitting and the system pressure checked for leaks.

The inside surface of the augmentor tube was worked with a grinder to remove any burrs from around the pressure taps, and the leading edge of the tube was turned on a lathe to ensure a proper fit with the various inlets.

The presure taps started at the very front edge of the pipe in order to determine the location of the minimum pressure point. The first seven were spaced one inch apart, the next three two inches apart, and the remainder four inches apart. At the exit end of the pipe the pattern was repeated in reverse order. This distribution provided adequate data for the entire pressure profile.

The construction of both the eight- and ten-inch tubes was identical with the exception that the number of pressure taps in the four-inch spacing section was increased to allow for the increased length of the ten-inch tube.

Once either of the augmentor tubes had been installed in the test cell, twelve copper-constantan thermocouples were spot welded to its outer wall. With the thin-walled tubes it was felt that the thermocouples gave a reasonably accurate indication of the static temperature profile along the inside wall of the tube.

In order to investigate the effects of the introduction of tertiary air downstream of the primary augmentor, the eight-inch tube was shortened by seven inches. It was then mounted in the usual fashion aft of the engine nozzle. A support was constructed and the full length ten-inch tube was mounted onto the exhaust stack. With the two tubes mounted in tandem (coaxially) the smaller tube exhausted directly into the larger one (Fig. 4). The object of the investigation was to see if the exhaust air from the smaller tube would entrain sufficient quantities of additional air from outside the test cell, further cooling the hot exhaust gas and diluting the visual pollutants without drawing additional air from the test cell.

Assuming that the primary nozzle-to-augmentor spacing would have little effect on performance, it was set with the nozzle exit plane coincident with the entrance plane of the augmentor bellmouth. Since the area ratio between the eight-inch and ten-inch tube was only 1.56, it was felt that the spacing should be varied between those two tubes to see if, perhaps, there might be an optimum position in terms of augmentation ratio. It turned out that there was, in fact, an apparent optimum point. For this configuration, it occurred at 0.15 diameters (eight-inch pipe), or about 1.2 inches.

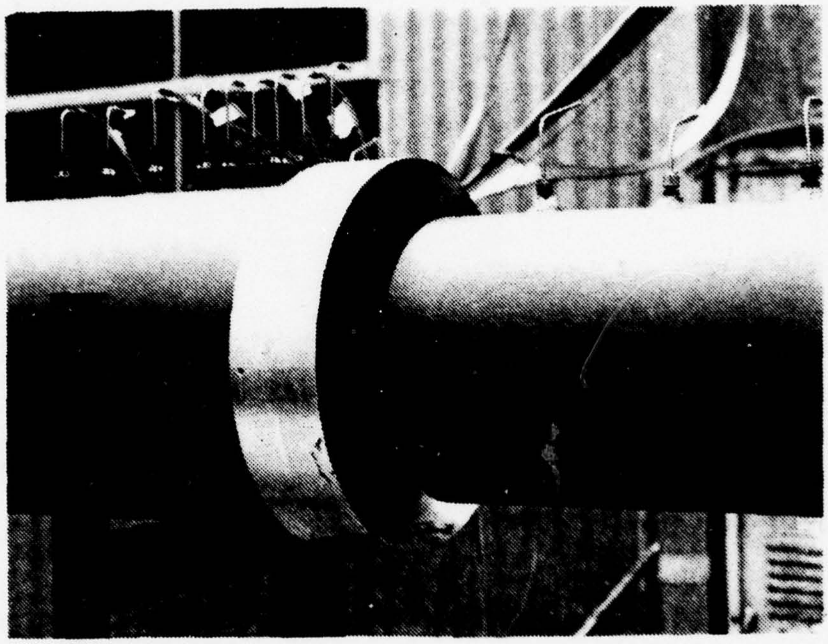


FIGURE 4. EIGHT-INCH AND TEN-INCH AUGMENTOR TUBES IN TERTIARY CONFIGURATION.

Since there were more pressure taps to monitor than positions available on the Scanivalve, only every other tap was recorded. The remainder were sealed off.

In order to monitor the flow through the eight-inch pipe in the tertiary configuration a single pitot tube was mounted to allow the measurement of velocities across the entire width of the tube at the exit plane. This information made it possible to compare the flow rates in the small tube with and without the influence of tertiary air.

The literature on ejector design indicated that an ejector length-to-diameter ratio of from six to ten [Ref. 10] provided the optimum mixing length. A nominal ratio of eight was chosen which gave lengths of 64 and 80 inches respectively for the eight and ten-inch tubes.

E. PITOT RAKE

In order to survey the velocity profiles along the length of the eight-inch augmentor tube, a seven-probe pitot rake was constructed from 1/8-inch stainless steel tubing and featured a thermocouple mounted on the center probe. The thermocouple was attached to a digital temperature readout which allowed constant monitoring of rake temperatures to prevent heat damage to the rake. The tubing ran through a length of 3/4-inch tubing to a position outside the aft end of the test cell. It was long enough to allow the rake to be pushed all the way to the leading edge of the constant area section of the augmentor. The handle was marked in inches to allow monitoring the rake position within the tube. Marks were also scribed every 90 degrees around the handle to indicate the vertical or horizontal orientation of the rake.

For use in the ten-inch tube the rake was modified with a support assembly which took up the excess diameter of the larger tube. The support centered the rake in the tube, holding the outermost probes away from the wall a distance of approximately one inch. This provided adequate measurement for the velocity profile within the tube.

Although the rake worked well, a possible improvement to the system would be to modify the assembly so that it would be able to withstand higher temperatures. A temperature of 800 degrees F was set as the maximum, due to the silver soldering used to bond the probes together. With this limit it was impossible during hot runs to move any more than half-way down the tube before the center core temperatures exceeded the limit. A meaningful survey of hot velocity profiles near the augmentor inlet was, therefore, not possible.

A pitot rake blockage factor of approximately three percent was calculated for the eight-inch tube, with something less than that for the larger tube.

F. INSTRUMENTATION

The test cell was fully instrumented to calculate air flow rates, cell temperatures and pressures, and velocity profiles at the cell entrance, engine outlet, and throughout the augmentor tube. It also allowed computation of augmentation ratios and the recording of pressures and temperatures along the length of the augmentor tube as well as in the exhaust stack.

A 48-port automatic stepping Scanivalve was used to measure the air-flow orifice static pressures, as well as cell inlet, engine inlet, engine exhaust, exhaust stack and augmentor tube static pressures.

G. DATA ACQUISITION

The automatic data acquisition system consisted of a fully programmable Hewlett-Packard 9830A desk top calculator with an HP 9867B mass memory storage unit. A B&F Model SY 133 data logger was coupled with the Scanivalve to provide automatic scanning of 75 data channels. The pressure and temperature raw data were automatically punched onto paper tape which was then entered via a digital tape reader into the HP 9830A for reduction and storage.

The system included a printed readout of all raw data and numerous calculated performance parameters, and also provided for a graphic plot of temperature and pressure profiles.

The computer program was a modified version of the one used in Ref. 12. It included an optional bypassing of a portion of the rather lengthy data reduction routine. The shortened program computed only primary, secondary, and suction flow rates which, when combined with the flow-setting accuracy of the manometers, noticeably shortened the time required to set and verify the desired flow rates. The arrangement was a decided improvement over the technique described in Ref. 12, although the paper tape still had to be carried by hand to the tape reader. The installation of a direct data input system which feeds raw data directly from the sensors to the computer was being installed at the completion of this project and should improve, even more, the data handling characteristics of the equipment.

IV. RESULTS AND DISCUSSION

In this study the one-eighth scale turbojet test cell was used to investigate the various design parameters and their effects on augmentor performance. The augmentor inlet design, nozzle-to-augmentor spacing, engine flow rate, nozzle total temperature and pressure, and augmentor tube diameter were varied to determine what effect they had on augmentation ratio, total air pumped through the system, and pressure, temperature, and velocity profiles within the augmentor tube. In addition, the two augmentor tubes were combined in tandem to investigate the characteristics of a tertiary augmentor configuration. A summary of the tests conducted and the resulting augmentation ratios are presented in Table I.

A. INLET DESIGN

Varying the augmentor inlet design produced some interesting, though not particularly startling, results. The bellmouth and conical inlets turned out to be the most efficient in terms of pumping air. Depending on the design goals, that may not be a desired quality, however, as in the case of the inlets used specifically to decrease the air flow through the system. Performance of the bellmouth and conical inlets was virtually identical across the full range of tests, and showed that the more complex production

TABLE I

SUMMARY OF EXPERIMENTAL RESULTS

Augmentor Diameter	Inlet Design	Nozzle-Inlet Spacing	Engine Flow Rate	Augmentation Ratio	Remarks
RESULTS OF COLD RUNS:					
8 in.	Bellmouth	-1D	1.0	3.49	
			1.5	3.36	
			2.0	3.16	
			2.2	3.06	
		OD	1.0	3.56	
			1.5	3.52	
			2.0	3.28	
			2.2	3.14	
		1D	1.0	3.44	
			1.5	3.35	
			2.0	3.04	
			2.2	3.04	
		2D	1.0	3.41	
			1.5	3.34	
			2.0	3.08	
			2.2	3.06	
8 in.	Bellmouth	OD	1.0	3.42	Converging-Diverging
			1.5	3.34	
			2.2	3.18	
8 in.	Conical	OD	1.0	3.50	
			1.5	3.47	
			2.2	3.14	
8 in.	Straight Pipe	OD	1.0	3.26	
			1.5	3.12	
			2.2	2.89	
8 in.	Reverse Conical	OD	1.0	2.22	
			1.5	2.06	
			2.2	1.94	
8 in.	Flat Plate	OD	1.0	1.26	
			1.5	1.18	
		1D	1.0	1.52	
			1.5	1.29	
		2D	1.0	1.55	
			1.5	1.40	
10. in.	Bellmouth	OD	1.0	3.10	
			1.5	3.09	
			2.2	2.80	
		1D	1.0	3.09	
			1.5	2.99	
			2.2	2.75	

TABLE I (CON'T.)

Augmentor Diameter	Inlet Design	Nozzle-Inlet Spacing	Engine Flow Rate	Augmentation Ratio	Remarks
8/10 in.	Bellmouth	OD/CD	1.0	3.29	
			1.5	3.09	Full Stack Resistance
			2.2	2.80	
8/10 in.	Bellmouth	OD/0.5D	1.0	4.71	
		OD/0.25D	1.0	4.92	
		OD/OD	1.0	4.89	
		OD/0.125D	1.0	5.08	Two Slats Removed From Stack Grid.
		OD/0.375D	1.0	4.92	
		OD/0.15D	1.5	4.51	
			1.0	4.97	
			2.2	4.19	

<u>RESULTS OF HOT RUNS:</u>

Augmentor Diameter	Inlet Design	Nozzle-Inlet Spacing	Engine Flow Rate	Augmentation Ratio	Remarks
8 in.	Bellmouth	-1D	1.3	3.99	
			1.5	3.83	
		OD	1.3	4.03	
			1.5	3.87	
		1D	1.3	3.98	
			1.5	3.70	
		2D	1.3	4.16	
			1.5	3.80	
		OD	1.5	3.81	Conv-Div Nozzle
8 in.	Rev. Cone	OD	1.5	2.61	
8 in.	Flat Plate	OD	1.0	2.20	
		1D	1.0	2.45	
		2D	1.0	2.56	
10 in.	Bellmouth	OD	1.5	3.43	
8/10 in.	Bellmouth	OD/0.15D	1.5	5.36	Two Slats Out

techniques used to manufacture the curved bellmouth inlet did not yield significant performance dividends.

The reduced performance of the straight tube (no inlet) was due to air flow which was allowed to "spill over" the sharp cornered leading edge of the pipe. Air entering from the areas in the cell located off to the side of the tube entrance had a high angle of incidence. A region of flow separation formed which increased the losses at the inlet.

The reverse conical and flat plate inlets suffered from two effects: the inlet loss factor discussed above, and reduced entrance area. The geometry of the reversed conical inlet reduced the area of the augmentor tube entrance by 34%, the flat plate reduced it by 61%. This blockage mechanism was a major factor in the tendency of those two inlets to reduce entrained air.

Figure 5 summarizes the effect inlet design had on augmentation ratio, while Fig. 6 shows how it affected total augmentor flow rate. As expected, the more severe the inlet loss factor the greater the reduction in augmentation ratio and augmentor flow rate.

Figure 7 shows a series of pressure profiles run at the same conditions, i.e., an engine flow rate of 1.5 lbm/sec with the nozzle exit flush with the entrance plane of the inlet. The figure shows dramatically the changes in the augmentor flow characteristics induced by the various inlet designs.

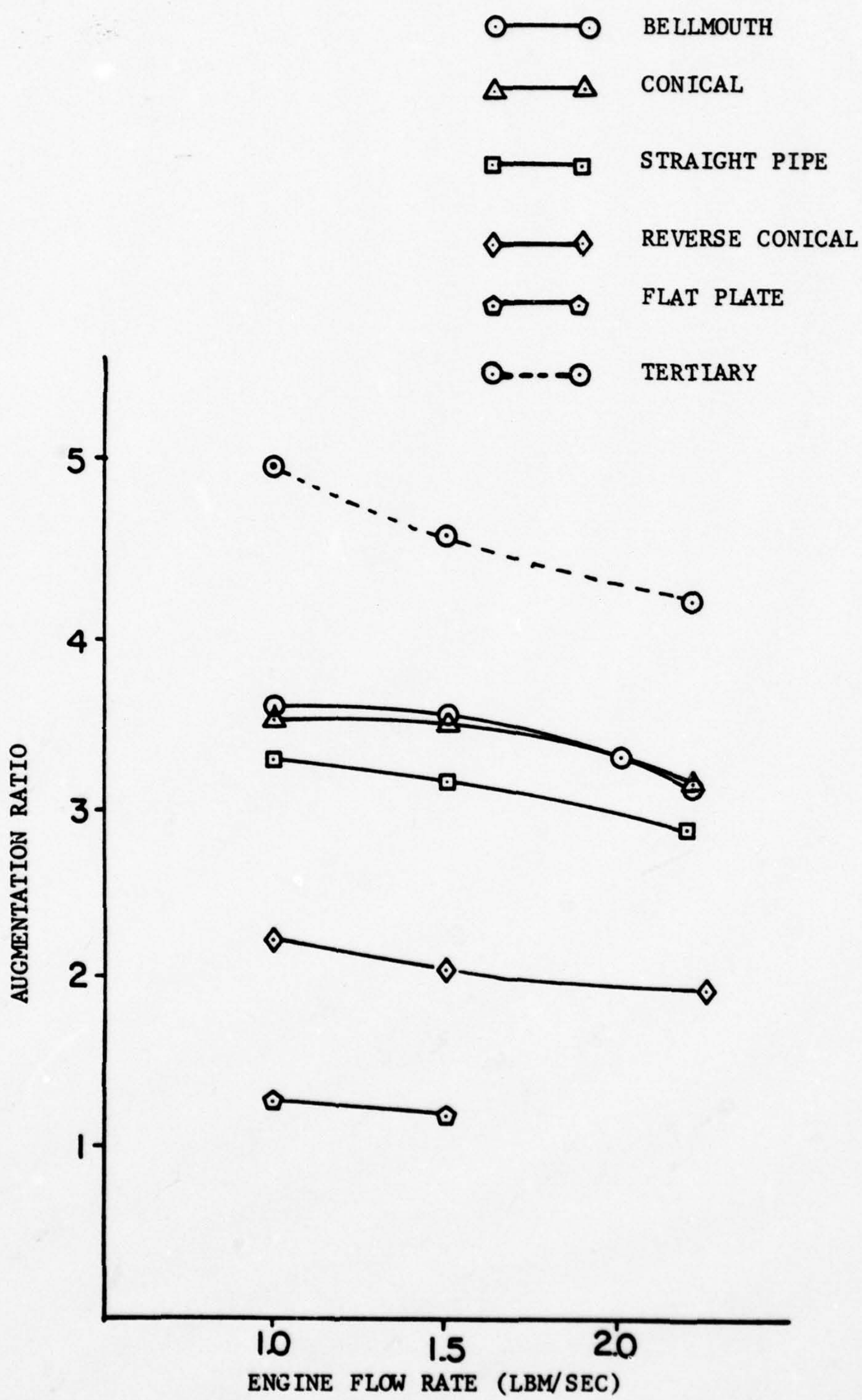


FIGURE 5. AUGMENTATION RATIO VS. ENGINE FLOW RATE (FOR VARIOUS INLET DESIGNS) SPACING: FLUSH.

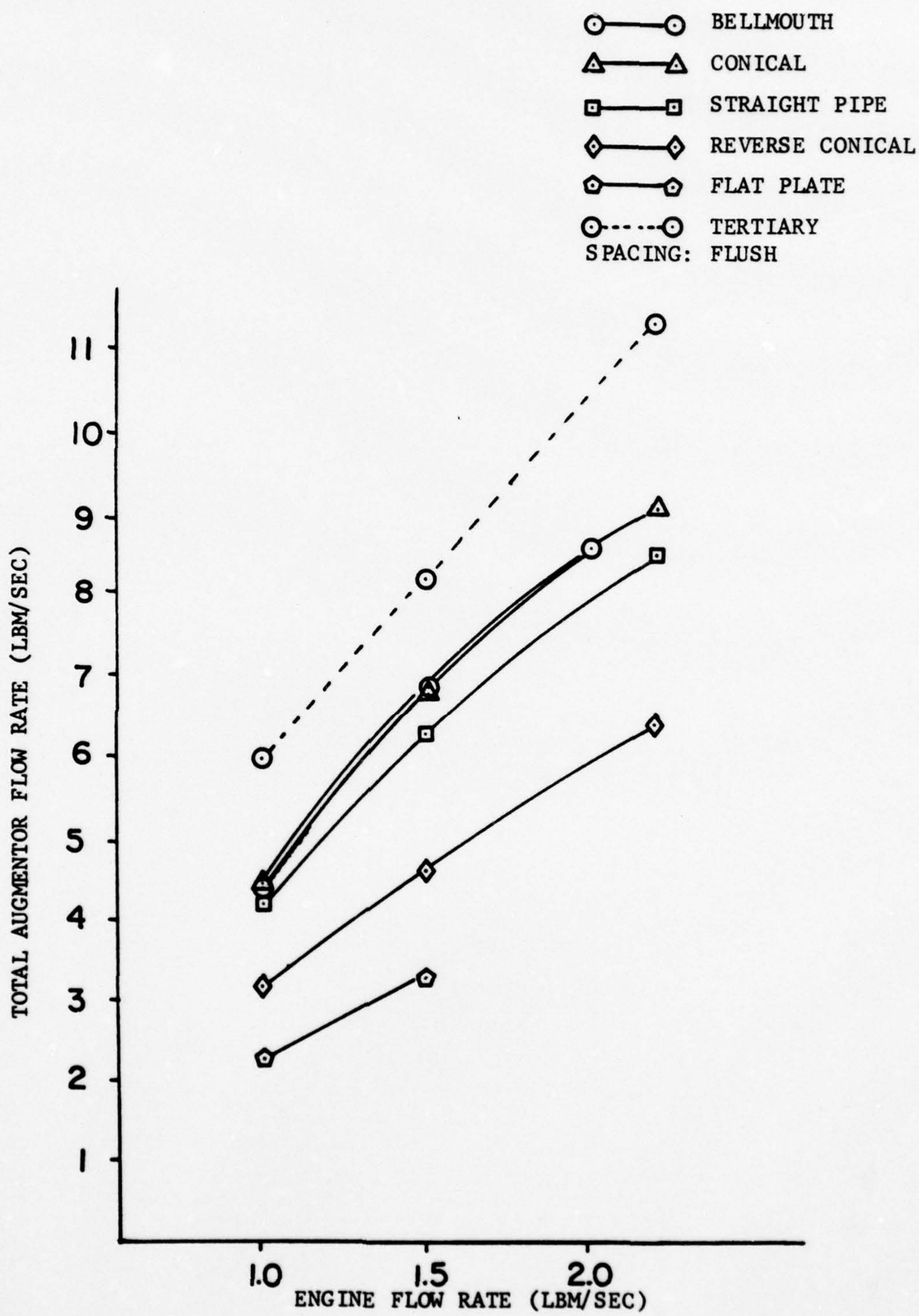


FIGURE 6. TOTAL AUGMENTOR FLOW RATE VS. ENGINE FLOW RATE (FOR VARIOUS INLET DESIGNS).

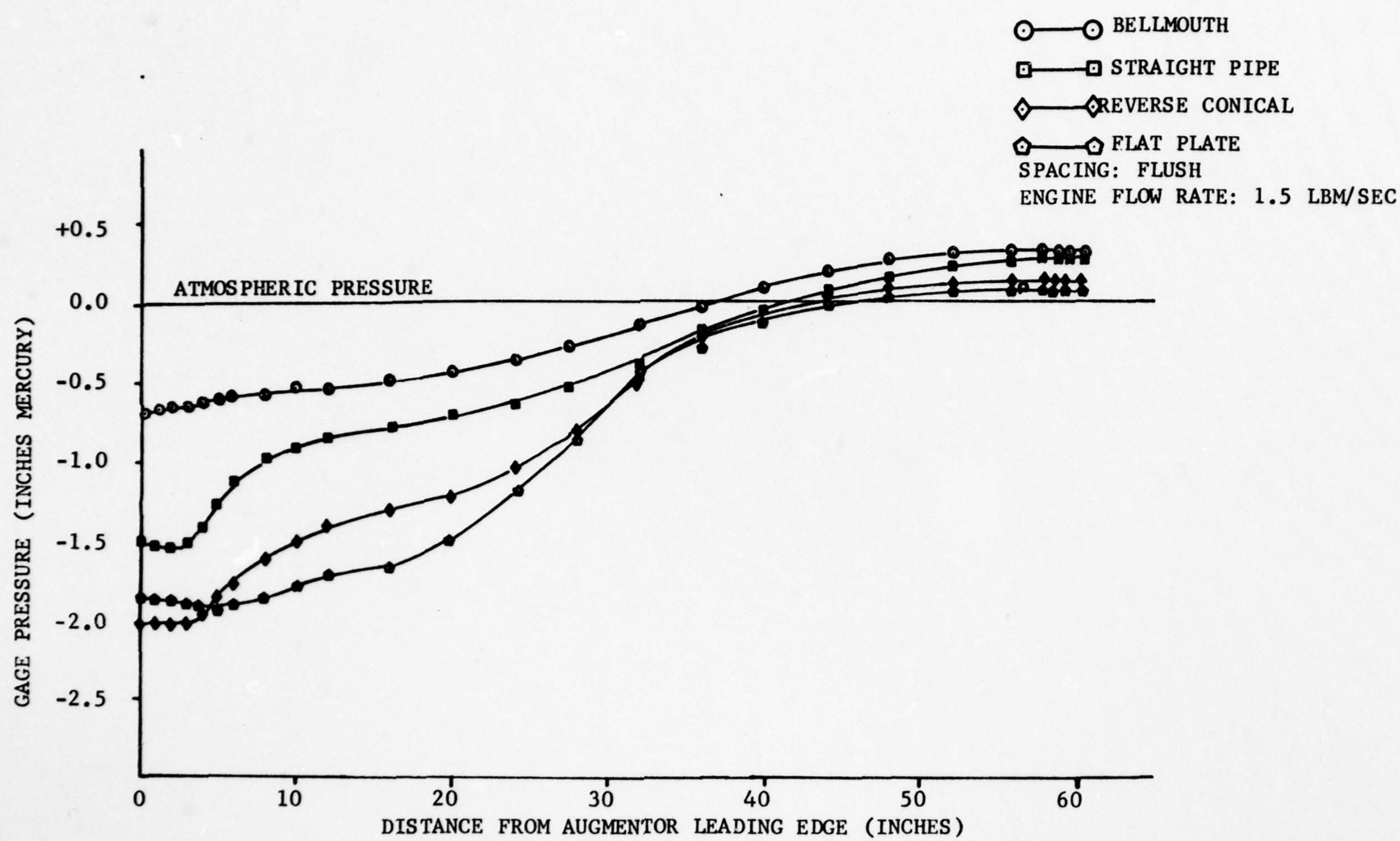


FIGURE 7. PRESSURE VS. AXIAL DISTANCE (FOR VARIOUS INLET DESIGNS)

As different as they were, the profiles showed some common characteristics: an initial minimum pressure point followed by a pressure rise. This rise leveled off and was followed by another rise which finally began to level toward the exhaust end of the tube. The major difference induced by the inlets was the severity of the initial pressure drop and the location of that minimum point within the tube. The pressure profiles all passed through the atmospheric line within one tube diameter of each other. It is apparent that the greater the inlet loss/flow blockage (less total air flow) the greater the initial pressure drop and the lower the final pressure.

For the bellmouth and conical inlets the low pressure point occurred at the throat of the inlet, where the inlet joins the constant area portion of the mixing tube. The other inlets had the low pressure point inside the tube. The greater the initial pressure drop the further the low pressure point moved inside the tube. The bellmouth and conical inlets provide a smooth transition to axial flow (low inlet losses) for the augmented air coming in from the test cell. For the remainder of the inlets the air enters sharply around corners and a region of separated flow is formed inside the tube, the size of which depends upon the geometry and extent of area blockage. The incoming air is forced into a vena contracta which acts to accelerate the flow. Each inlet experiences this phenomenon for a different distance into the tube.

The pressure profiles are indicative of the degree of mixing taking place. As the slower air mixes with the higher velocity air from the primary jet nozzle, variations in the rate of pressure rise take place. Once mixing has fairly well been accomplished the pressure profiles level off.

Typical temperature profiles are presented in Fig. 8 for reacting flow conditions. The bellmouth data indicate that smooth, even mixing takes place within the augmentor and that the wall temperature is kept to a minimum. The reversed conical inlet produced only about an eleven per cent increase in maximum wall temperature, and rose more rapidly to its peak. It provides a significant reduction in augmentation ratio, while not significantly sacrificing augmentor tube life. The profile indicates that this inlet provides a higher spreading rate of the hot center core gases.

The flat plate inlet produces a large recirculation region just inside the augmentor inlet, and the wall temperature rapidly rises to a peak value near flow reattachment. The peak temperature is significantly greater than the mean temperature which occurs when the flow is well mixed and axial in flow direction. Thus, although this inlet certainly does its part in decreasing the augmentation ratio, it is apparent that its use must be approached with caution because the flow patterns behind that flat plate can produce detrimental thermal effects on the augmentor.

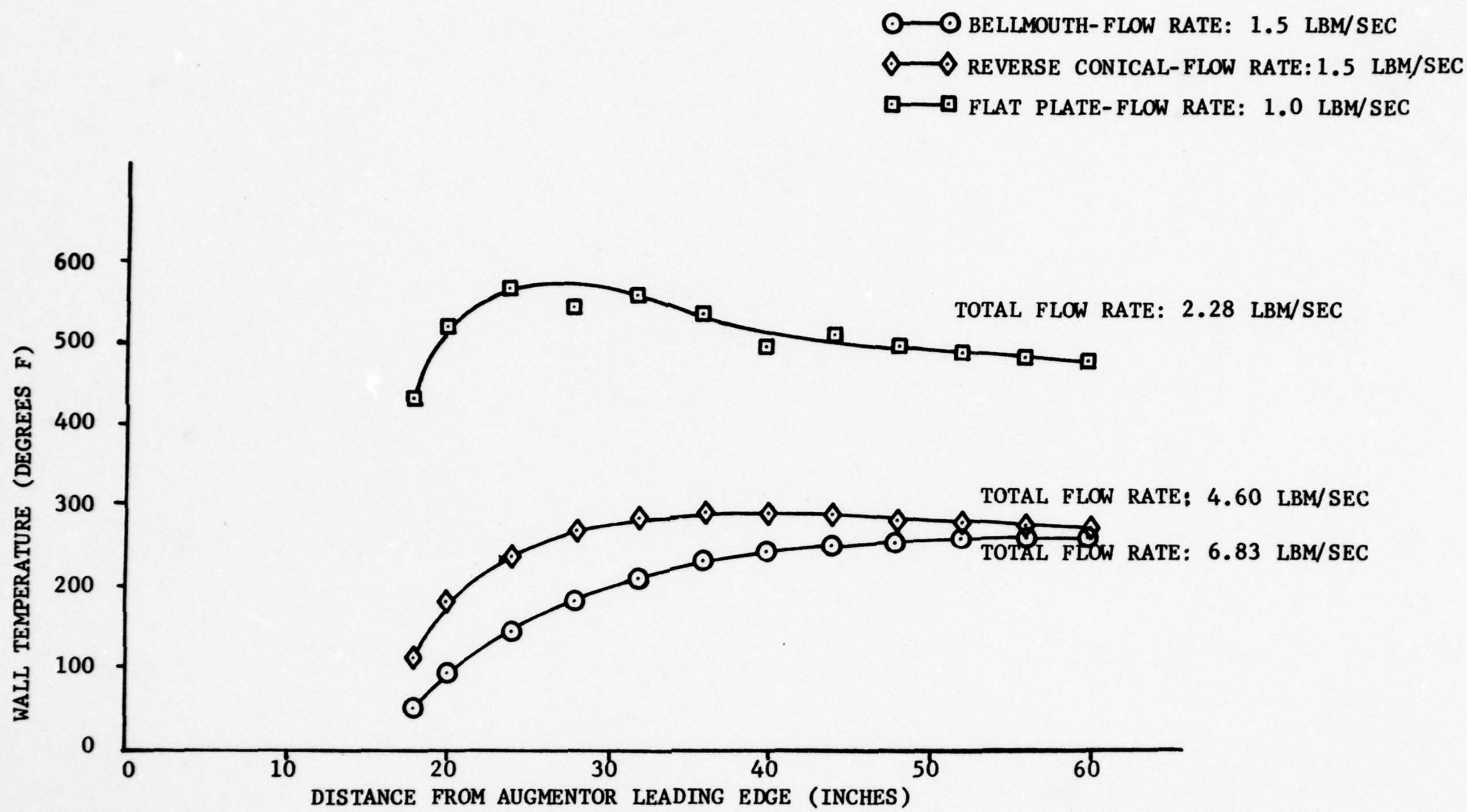


FIGURE 8. WALL TEMPERATURE VS. AXIAL DISTANCE (FOR VARIOUS INLET DESIGNS)

Despite signficant differences in flow rates and flow patterns within the tubes, the temperature profiles all leveled off at approximately five augmentor diameters (20 jet diameters) downstream from the engine exit plane. This location also corresponds to the position where the pressure profiles level off (Fig. 7).

Typical velocity profiles within the augmentor tube are presented in Fig. 9. More detailed data for the velocity profiles are presented in Ref. 16. The measurements were all taken with the nozzle exit plane coincident with the inlet entrance plane, and at a flow rate of 1.5 lbm/sec. The most informative plot is the one for the flat plate inlet. The zone of recirculation may readily be seen behind the flat plate. The bulges in the lower portion of the profiles, most visible in the upper two tubes, are due to the influence of the test cell floor on the incoming air flow. The cell floor tends to direct the secondary flow so that it is more axial and therefore tends to achieve covelocity with the engine flow much sooner.

Figures 10 and 11 are typical plots of temperature, pressure, and velocity profiles for the bellmouth/conical and flat plate inlets, respectively. The temperature and pressure profiles level off coincidentally at approximately five augmentor diameters, as discussed above. The velocity profiles have also become practically uniform at this location. These data indicate that the wall pressure profile can

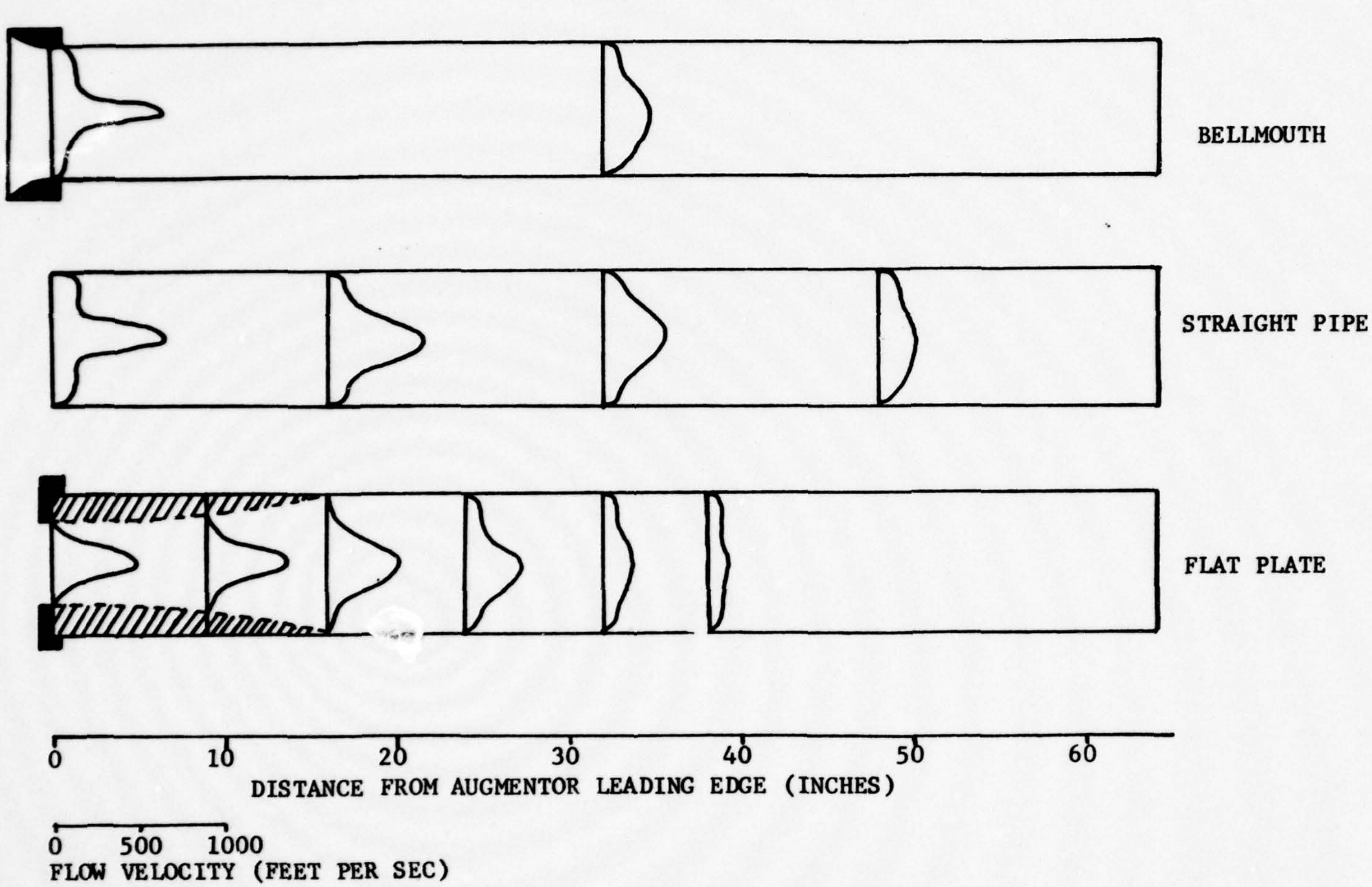


FIGURE 9. VELOCITY PROFILES FOR VARIOUS INLET DESIGNS.

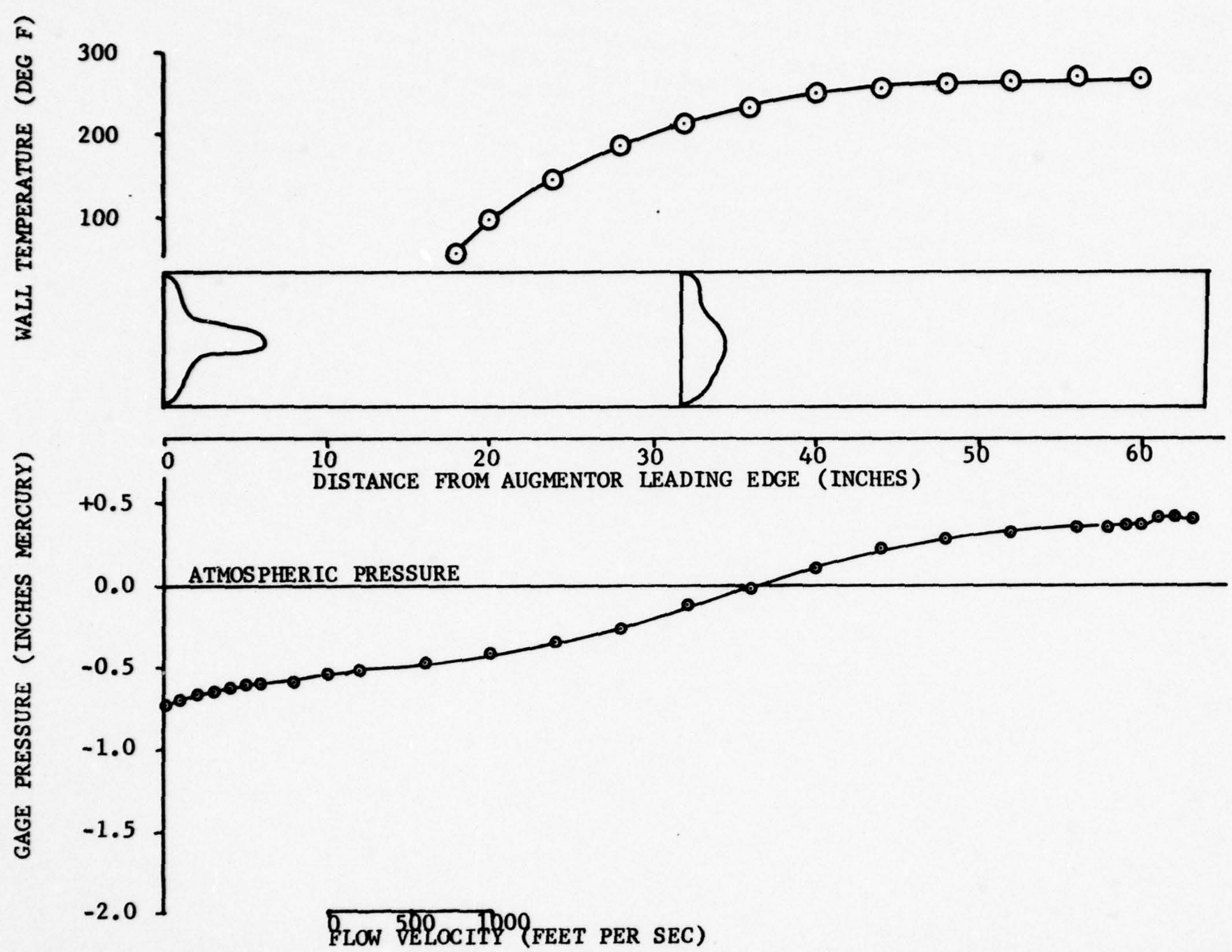


FIGURE 10. WALL TEMPERATURE, PRESSURE, VELOCITY PROFILES VS. AXIAL DISTANCE (BELLMOUTH, FLUSH, 1.5 LBM/SEC)

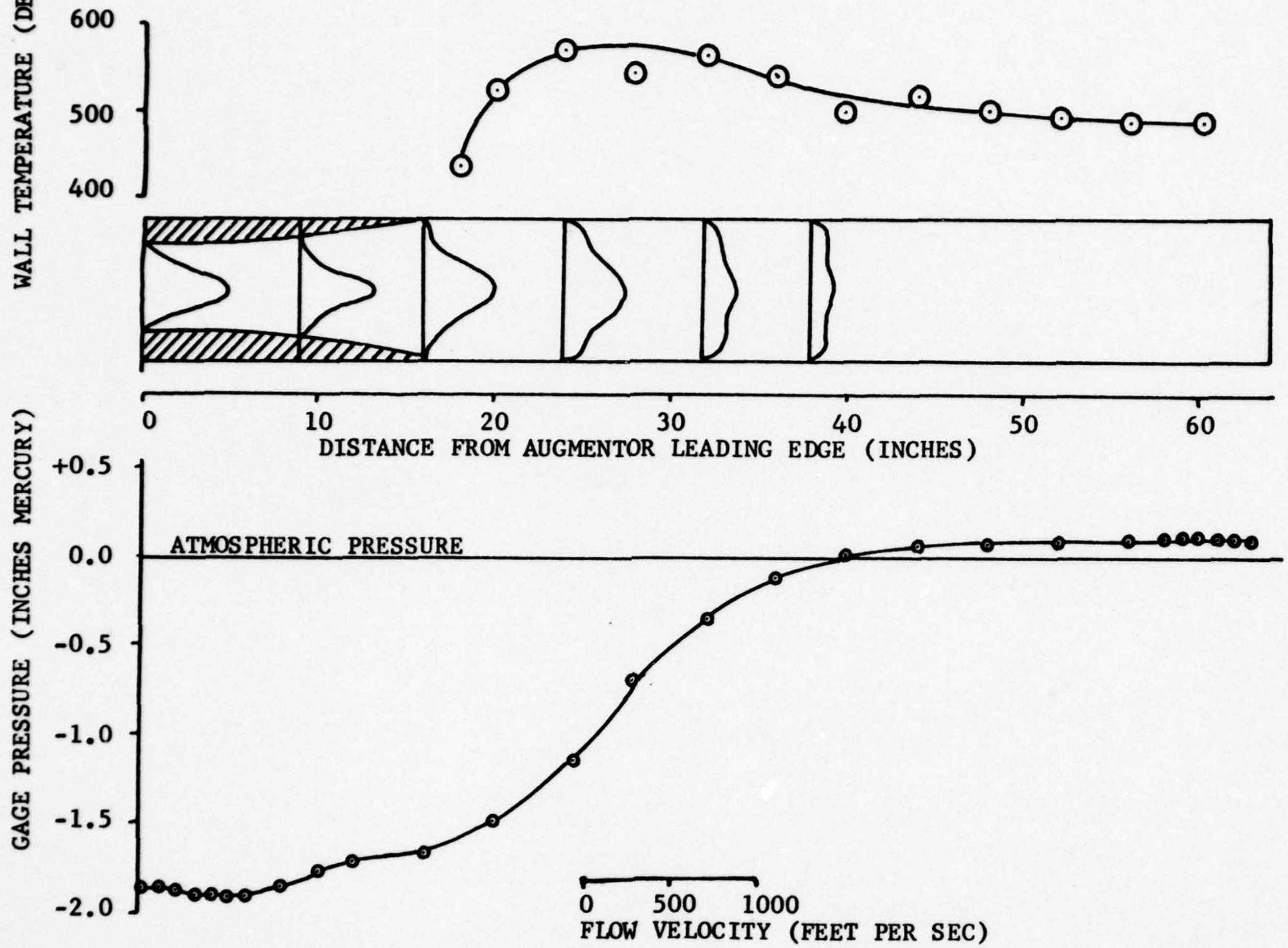


FIGURE 11. WALL TEMPERATURE, PRESSURE, VELOCITY PROFILES VS. AXIAL DISTANCE (FLAT PLATE, FLUSH, 1.0 LBM/SEC)

be used as a good indication of the extent of mixing. In addition, five augmentor diameters of length should be all that is required to obtain good ejector pumping characteristics. This conclusion appears to be quite insensitive to the type of inlet employed and the engine flow rate.

In Ref. 17, Engel notes that in ejector flow, optimum mixing has occurred when the ratio between the mean velocity of the entrained air and the velocity of the core is approximately 0.7 to 0.8. That location would be difficult to determine accurately on the figure presented but qualitatively agrees with the above findings. To continue mixing beyond the point mentioned above would result in less overall gain due to flow losses within the pipe.

From a noise suppression standpoint it would appear that jet core breakup devices should be located at less than three diameters within the augmentor.

B. NOZZLE-TO-AUGMENTOR SPACING

The variable spacing data were taken using only the bellmouth and flat plate inlets, since it was obvious early in the project that they represented the extremes in the performance scale (Fig. 12). The overall effect of spacing seemed to be inconsequential. Figure 13 summarizes the effect of spacing on augmentation ratio. It can readily be seen that the effect was limited, at least for the flow rates investigated. In fact, an uncertainty analysis was done and the variation of the data fell within in the five

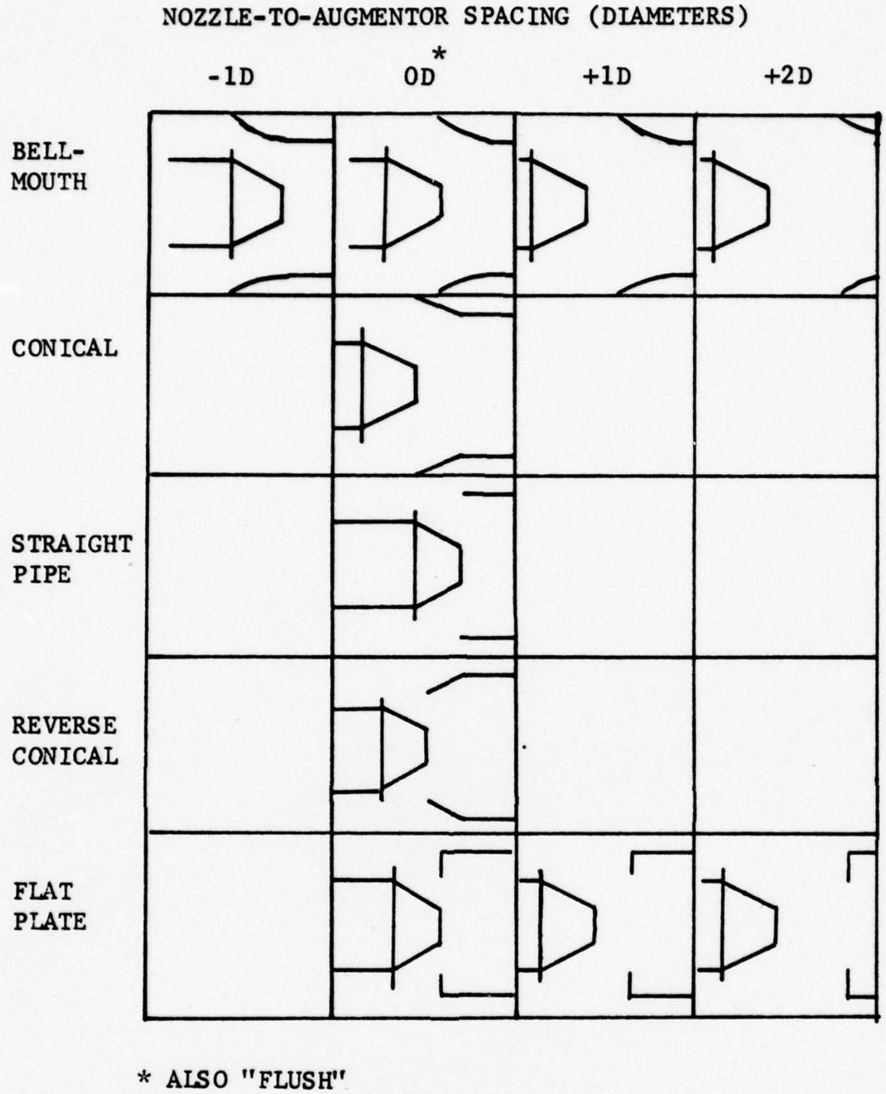


FIGURE 12. SUMMARY OF VARIOUS NOZZLE-TO-AUGMENTOR SPACINGS.

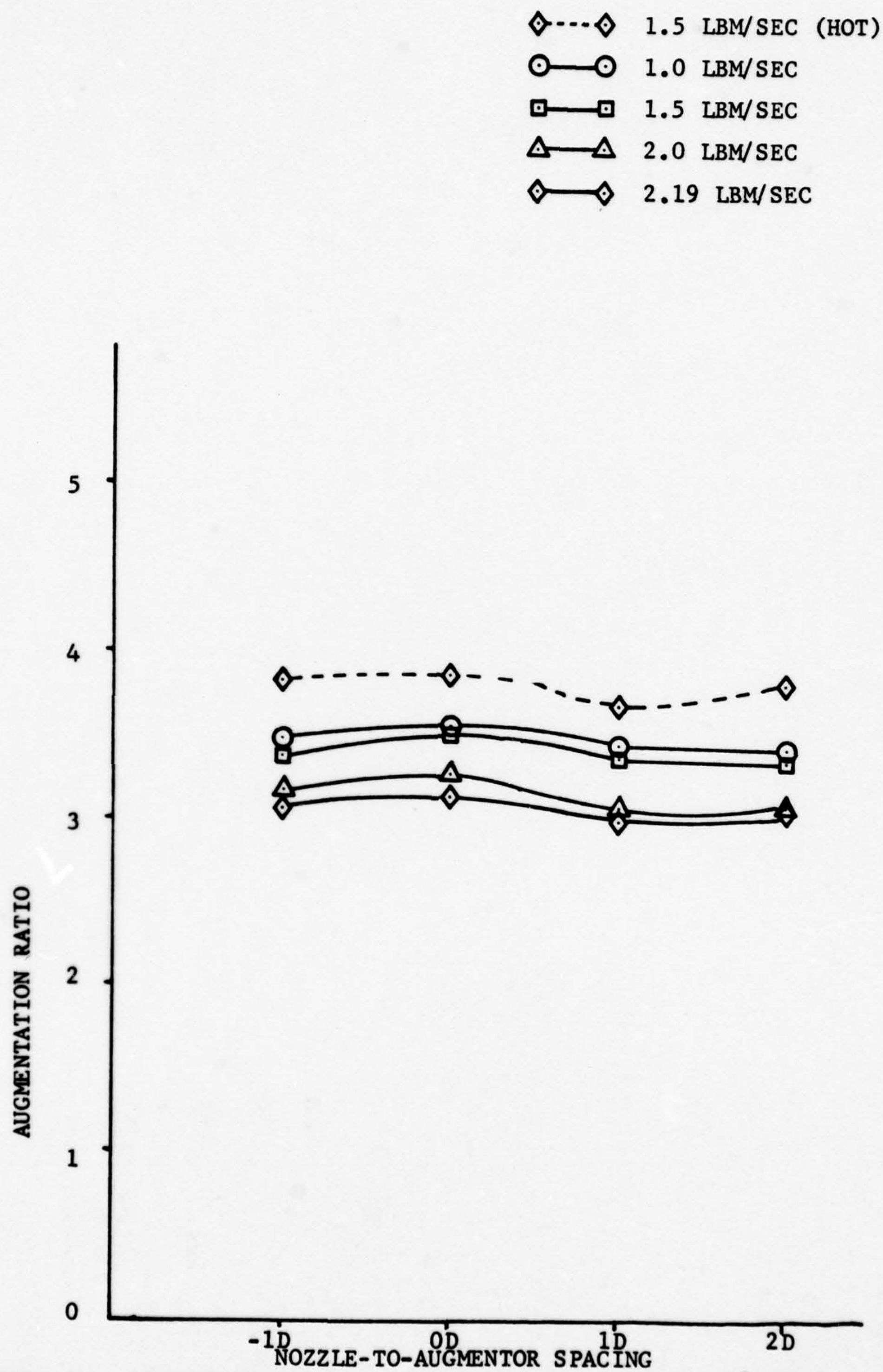


FIGURE 13. AUGMENTATION RATIO VS. NOZZLE-TO-AUGMENTOR SPACING (FOR VARIOUS FLOW RATES, BELLMOUTH INLET)

percent uncertainty band. Since the oscillatory pattern repeated itself at various flow rates, however, it was felt that the response was, in fact, a real one and not just due to random fluctuations in the data.

The oscillatory nature of the response was also noted by Keenan, Neumann, and Lusterwerk [Ref. 8]. They found that, for a choked nozzle, the augmentation ratio variations with changes in spacing showed "oscillations independent of the inlet type corresponding to the expansion pattern of the primary stream which repeatedly diverges and converges as it approaches the inlet of the tube". The same argument is not applicable in the case of unchoked flow. In Figure 13, the flow rates of 1.0 and 1.5 lbm/sec are both unchoked, while 2.0 and 2.19 lbm/sec are choked. All four curves indicate that a rise in augmentation ratio was experienced as the nozzle was moved from the throat of the bellmouth to a position flush with the entrance plane of the augmentor. That rise in augmentation ratio was due primarily to the reduction in blockage from the engine being placed into the inlet. As the spacing was increased to one diameter the ratio began to decrease, probably due in most part to the blockage effect of the spreading exhaust jet. As the spacing was increased to two diameters the unchoked flow curves leveled off while the choked flow curves exhibited a tendency to rise again.

Since the nozzle is choked at a flow rate of 1.5 lbm/sec when the engine is operating in the hot mode, the very top curve was plotted to see if the same rise in augmentation ratio would occur for that flow rate simply by choking the nozzle. As the spacing was increased from one to two diameters the augmentation did increase indicating that there was some effect from the shock expansion pattern on augmentation ratio. In addition, as engine-augmentor spacing is increased, entrance losses should be less important, since the pumped air enters the augmentor in a more axial direction. This investigation should be carried further to greater spacings and higher engine flow rates to verify these observations.

As previously mentioned, the effect of changing the spacing was minimal, at least at the flow rates investigated. Since the majority of the noise generated by a jet engine is from the shear layer between the jet exhaust stream and the low velocity pumped air, it would seem that to increase nozzle distance beyond the entrance to the augmentor tube would cause far greater noise problems within the test cell than would be worth the small change in augmentation ratio.

From Fig. 14 the effect of spacing on the pressure profile can be seen. All three plots were for nearly equal total flow rates since augmentation ratio did not change appreciably. With the nozzle exit even with the front lip of the constant area tube the blockage effect was high,

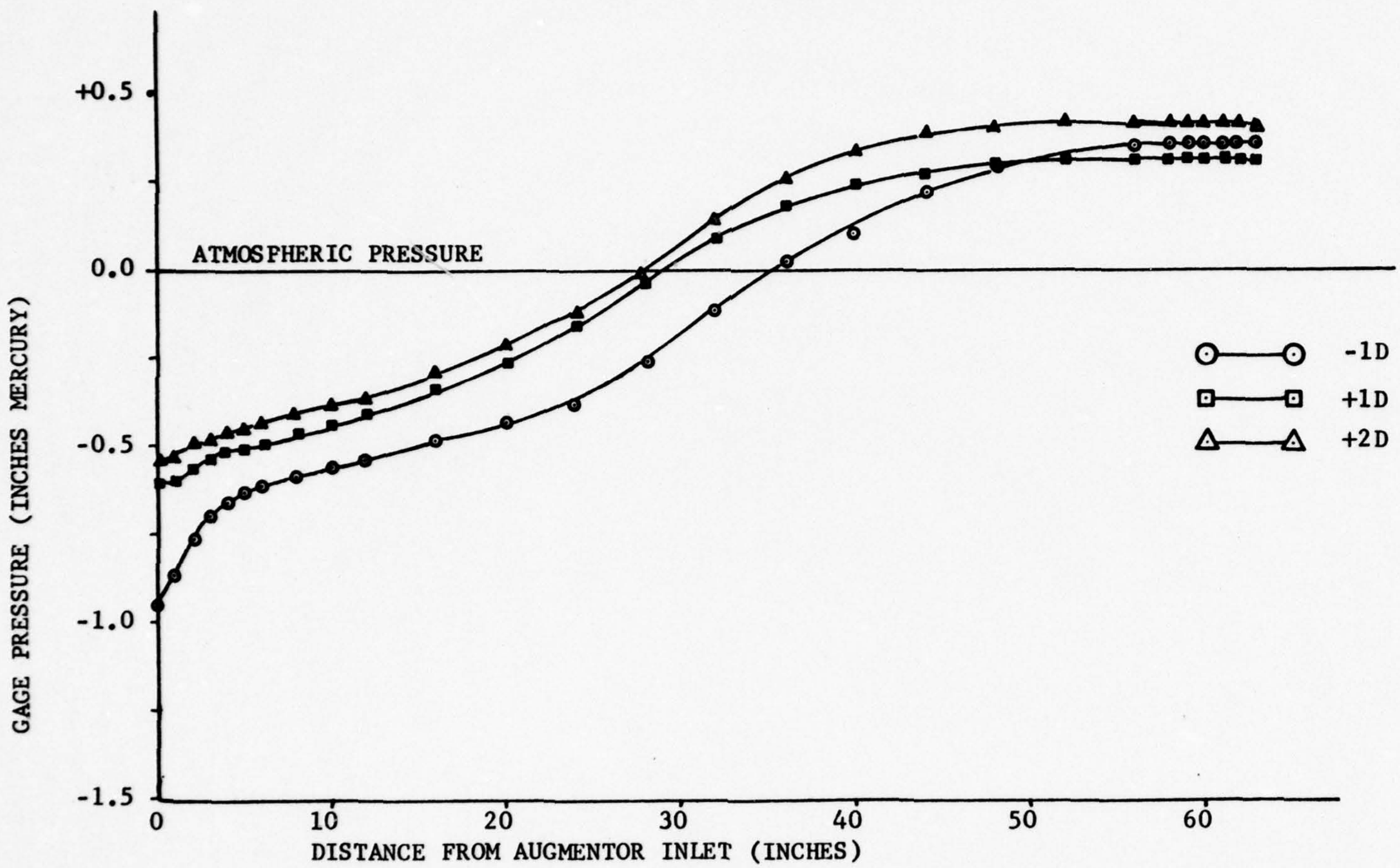


FIGURE 14. PRESSURE VS. AXIAL DISTANCE (FOR VARIOUS NOZZLE-TO-AUGMENTOR SPACINGS, BELLMOUTH, 1.5 LBM/SEC)

resulting in the rapid acceleration (low pressure) of the pumped air at the augmentor inlet.

As the nozzle was backed out of the bellmouth the initial pressure measurement in the tube was further from the nozzle exhaust. If the two-diameter curve is translated one diameter to the right, the plots correspond to distances from the nozzle exhaust. The two curves are virtually identical out to a distance of five augmentor diameters. The jet spreading rate appears to be dominated by the jet itself, not by the extent of unconfined jet mixing (unless physical flow blockage occurs from the nozzle).

The temperature profiles in Fig. 15 show that, for the bellmouth, the maximum temperature decreased slightly as the spacing increased. Since the engine flow rate was held constant, and it has been shown that the augmentation ratio varied little with spacing, it can be concluded that the temperature difference was due to changes in the mixing process. Again, if the curves were plotted in terms of distance from the jet exhaust the temperature profiles would be identical out to distances of about five augmentor diameters.

Figure 16 shows that the effect of spacing on the flat plate inlet profiles was much the same except for the zero spacing case, where physical flow blockage reduced the augmentation ratio.

Figure 17 shows the effect of nozzle spacing on the velocity profiles within the tube for the flat plate inlet.

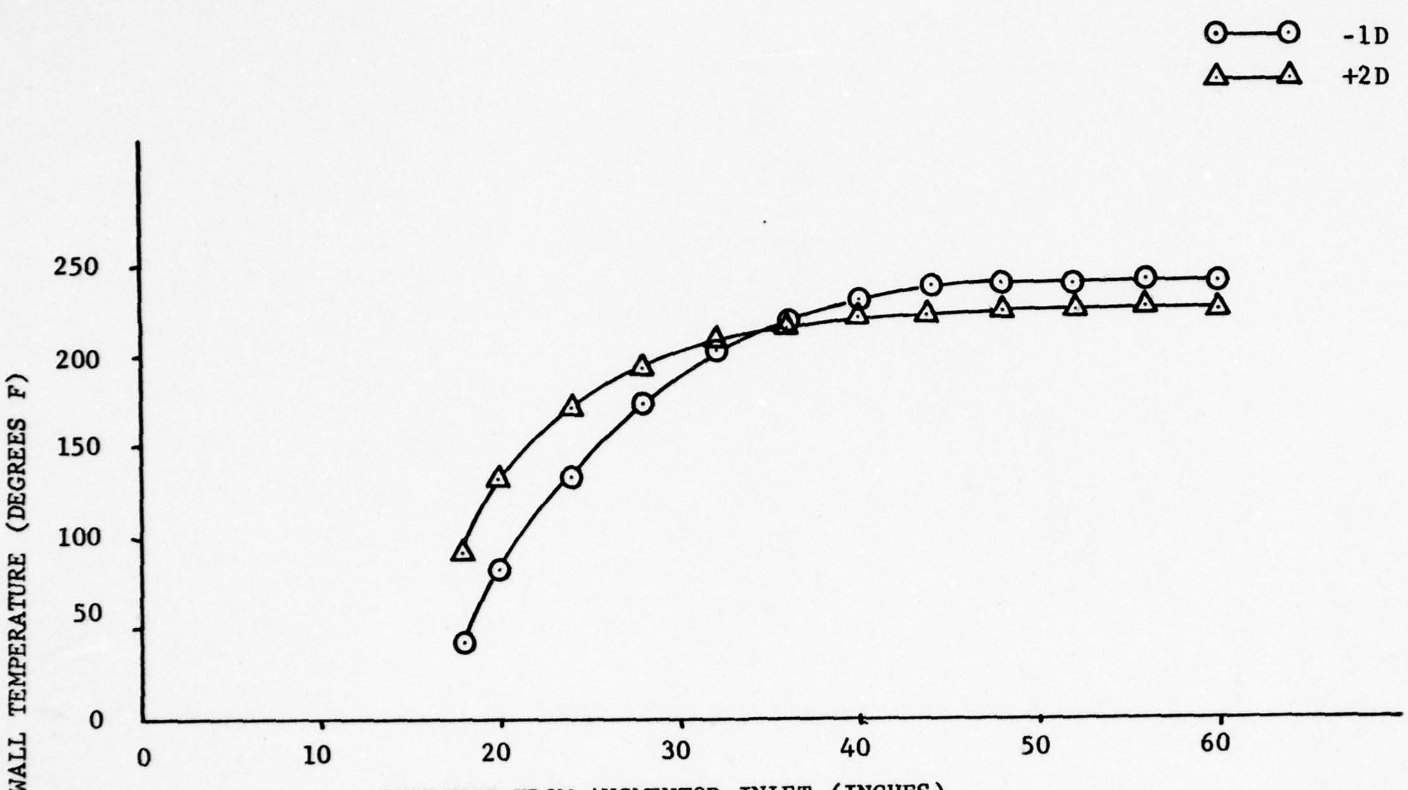


FIGURE 15. WALL TEMPERATURES VS. AXIAL DISTANCE (FOR VARIOUS AUGMENTOR SPACINGS, BELLMOUTH, 1.5 LBM/SEC).

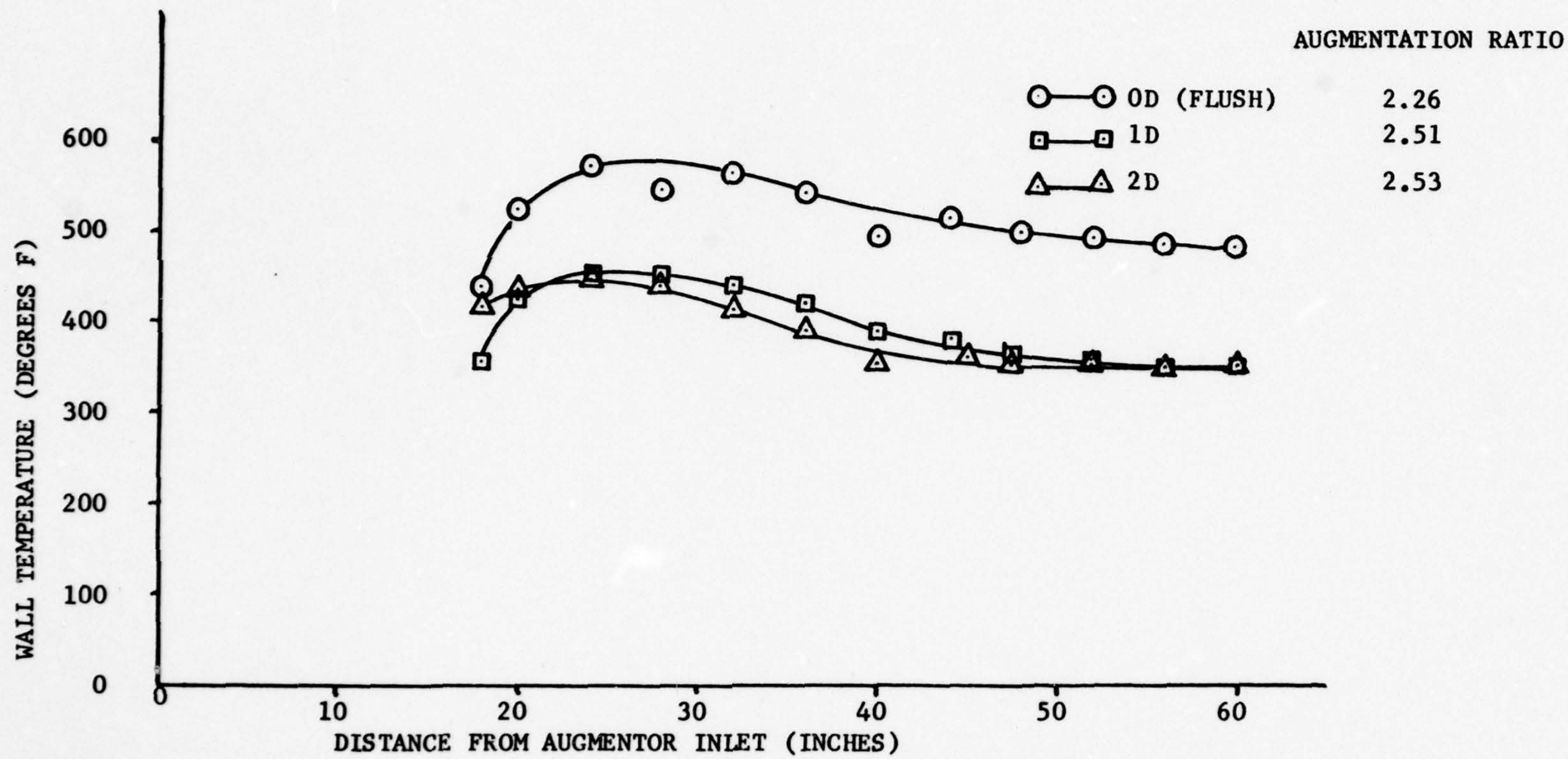


FIGURE 16. WALL TEMPERATURES VS. AXIAL DISTANCE (FOR VARIOUS AUGMENTOR SPACINGS, FLAT PLATE, 1.0 LBM/SEC)

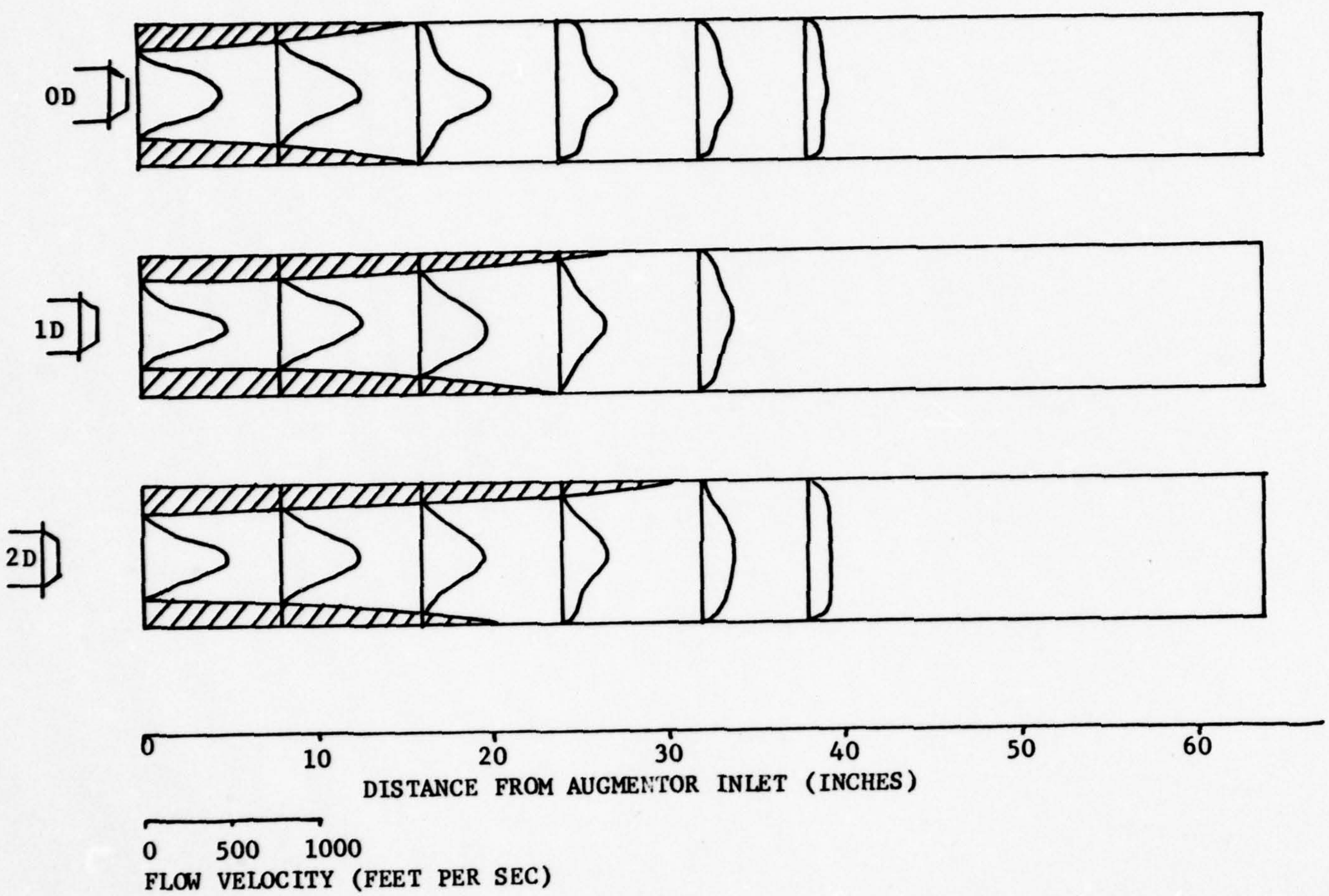


FIGURE 17. VELOCITY PROFILES FOR FLAT PLATE INLET (VARIOUS AUGMENTOR SPACINGS, 1.0 LBM/SEC).

The recirculation zone is elongated along the upper surface of the tube, as spacing is increased, while it grew and then receded along the lower surface of the tube. The unsymmetrical appearance of the zones was felt to be due to the influence of the cell geometry on the inlet flow, as pointed out earlier in the case of the bellmouth inlet.

C. ENGINE FLOW RATE

The effect of engine flow rate on augmentation ratio may be seen in Fig. 5, while Fig. 6 summarizes the effect of engine flow rate on the total air flowing through the augmentor. As the engine flow rate increased, the total augmentor flow rate increased while at the same time the augmentation ratio decreased.

Figures 18, 19 and 20 show how increasing engine flow rates altered the pressure profiles within the augmentor tube for three different inlets: the bellmouth, the straight tube, and the reverse conical.

The pressure drop at the entrance to the augmentor tube increased with flow rate and the severity of the inlet loss. Although the low pressure point became more depressed with increasing flow rate, it remained at approximately the same distance from the augmentor lip.

Another interesting result is the crossing point that occurred at approximately 0.1 inch of mercury above atmospheric pressure. The pressure curves on each graph cross at one common point, located between five and five-and-one-half

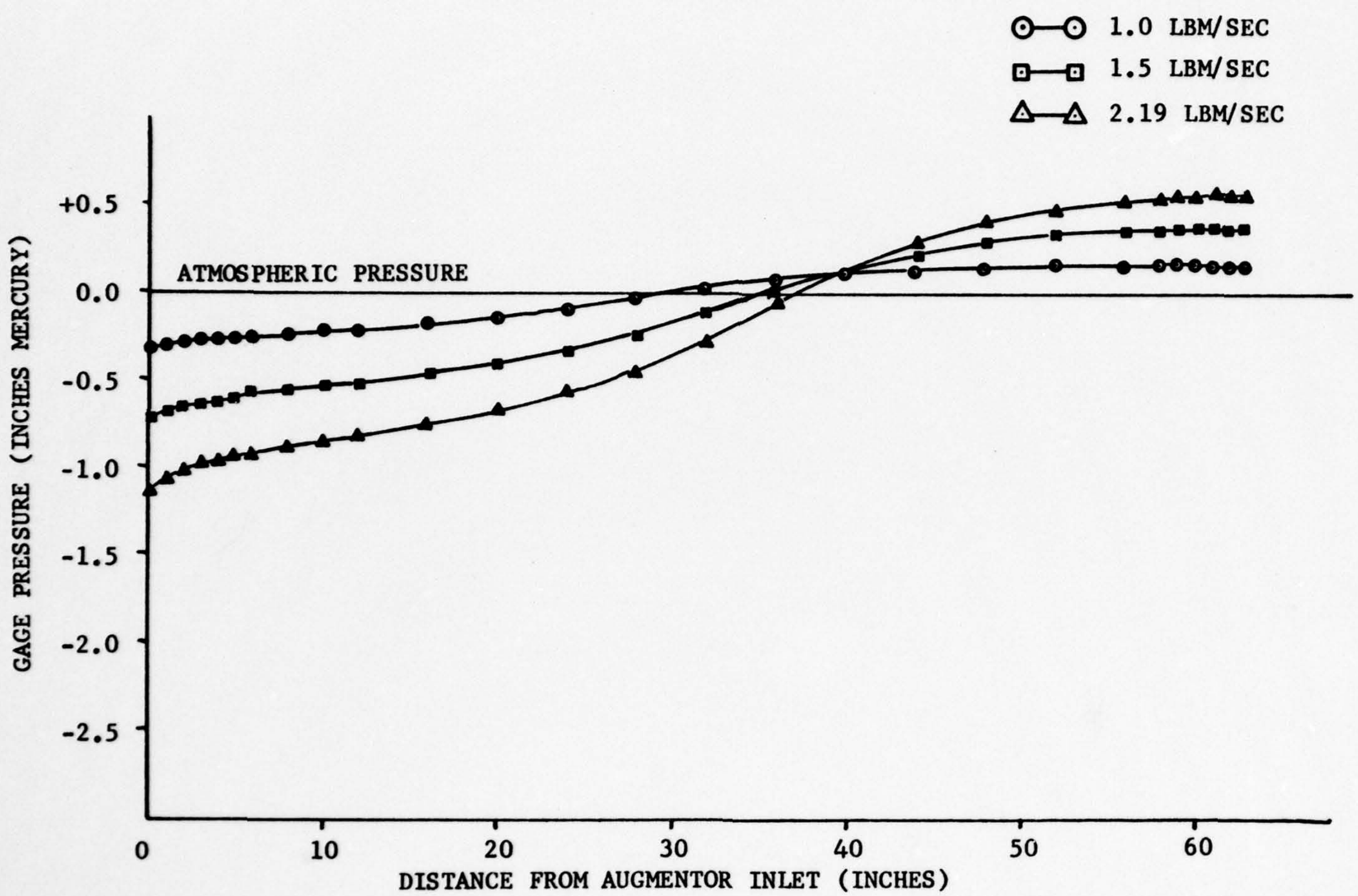


FIGURE 18. PRESSURE VS. AXIAL DISTANCE (FOR VARIOUS FLOW RATES, BELLMOUTH, OD SPACING).

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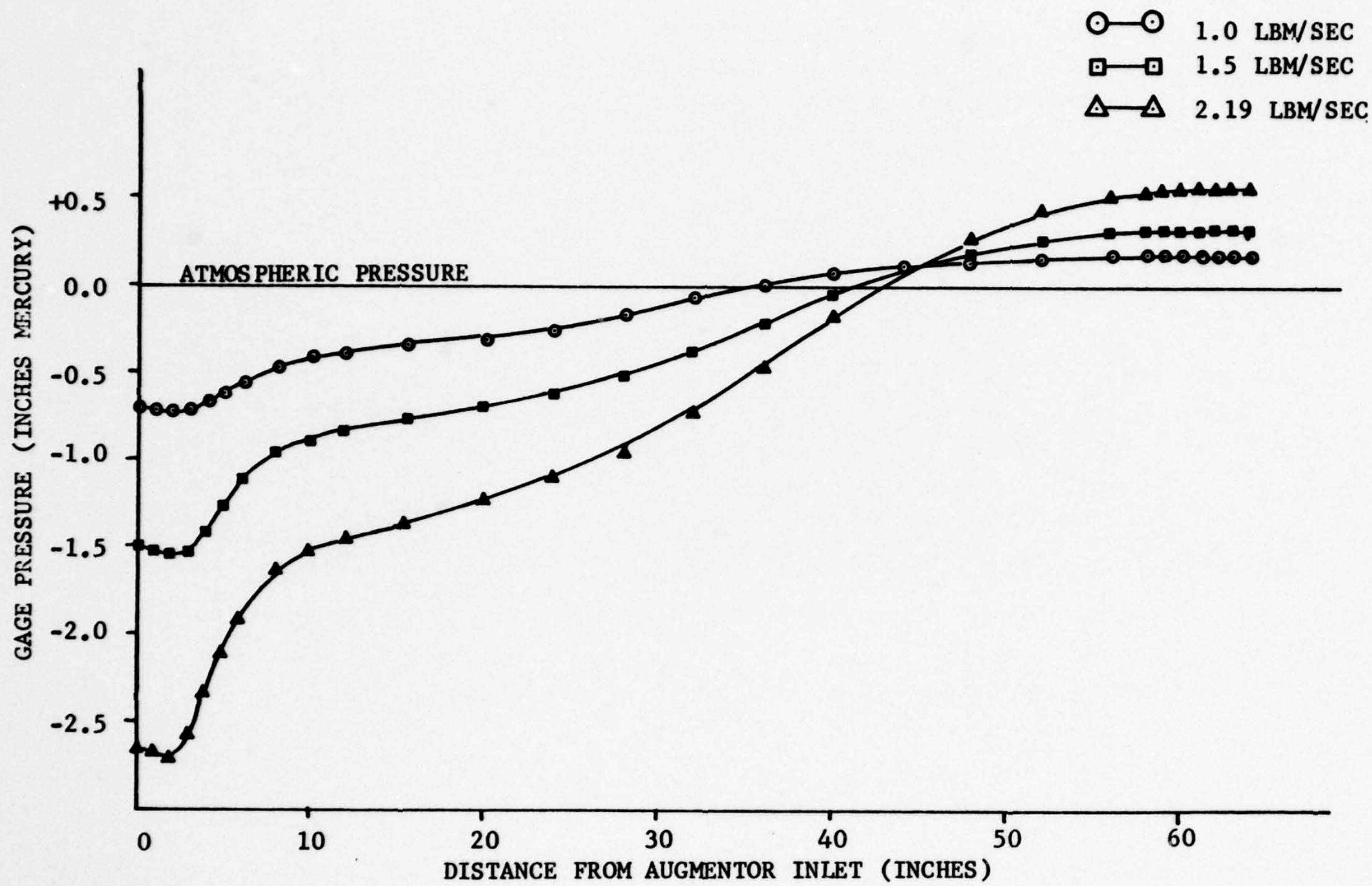

FIGURE 19. PRESSURE VS. AXIAL DISTANCE (FOR VARIOUS FLOW RATES, NO INLET, OD SPACING).

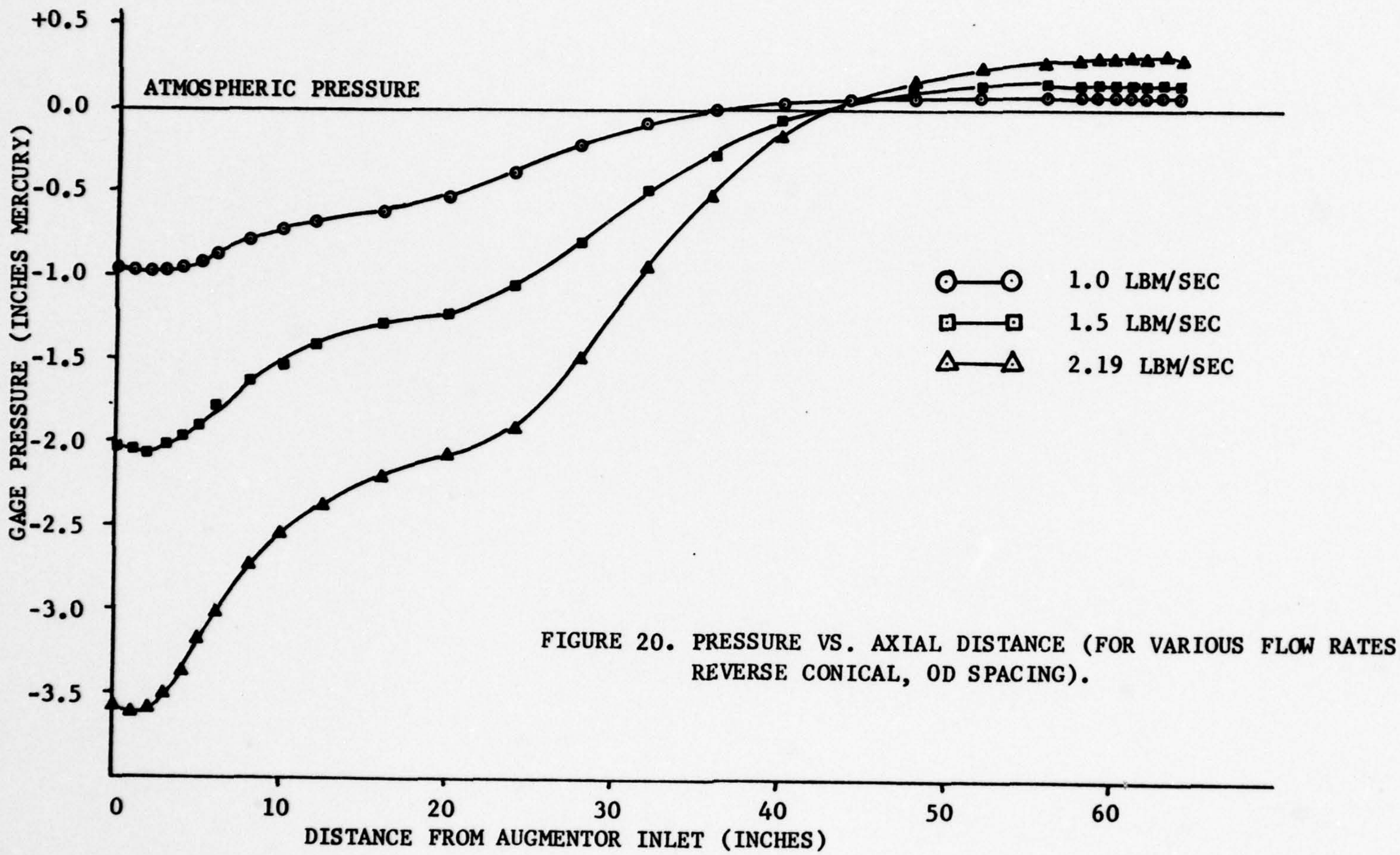

FIGURE 20. PRESSURE VS. AXIAL DISTANCE (FOR VARIOUS FLOW RATES, REVERSE CONICAL, OD SPACING).

diameters down the tube from the entrance. This point coincides closely with the location of the well-mixed point discussed earlier. These results are similar to those presented above in the section on the effects of inlet geometry.

Figure 21 shows the effect that varying the engine flow rate had on the velocity profiles within the augmentor tubes. This example is for the flat plate inlet. As the flow rate increased, the recirculation zone elongated. The same effect was observed when the nozzle-to-augmentor spacing was increased (Fig. 17).

D. TERTIARY AIR AUGMENTOR

The result of the addition of the ten-inch augmentor tube in line with the shortened eight-inch tube was to increase the augmentation ratio and, also, to increase the air pumped through the smaller tube (Fig.'s 5 and 6). The pressure profiles were significantly more shallow and the temperatures remained lower. These responses were not unexpected. The goal of this portion of the investigation was to determine how much the tertiary configuration affected the flow rate through the test cell itself.

As an example, for the 2.19 lbm/sec nozzle flow rate, the flow through the eight-inch pipe with the tertiary system increased by a factor of 1.44 over the flow through the eight-inch pipe alone. The sensitivity of the augmentation ratio to variations in back pressure was once again apparent,

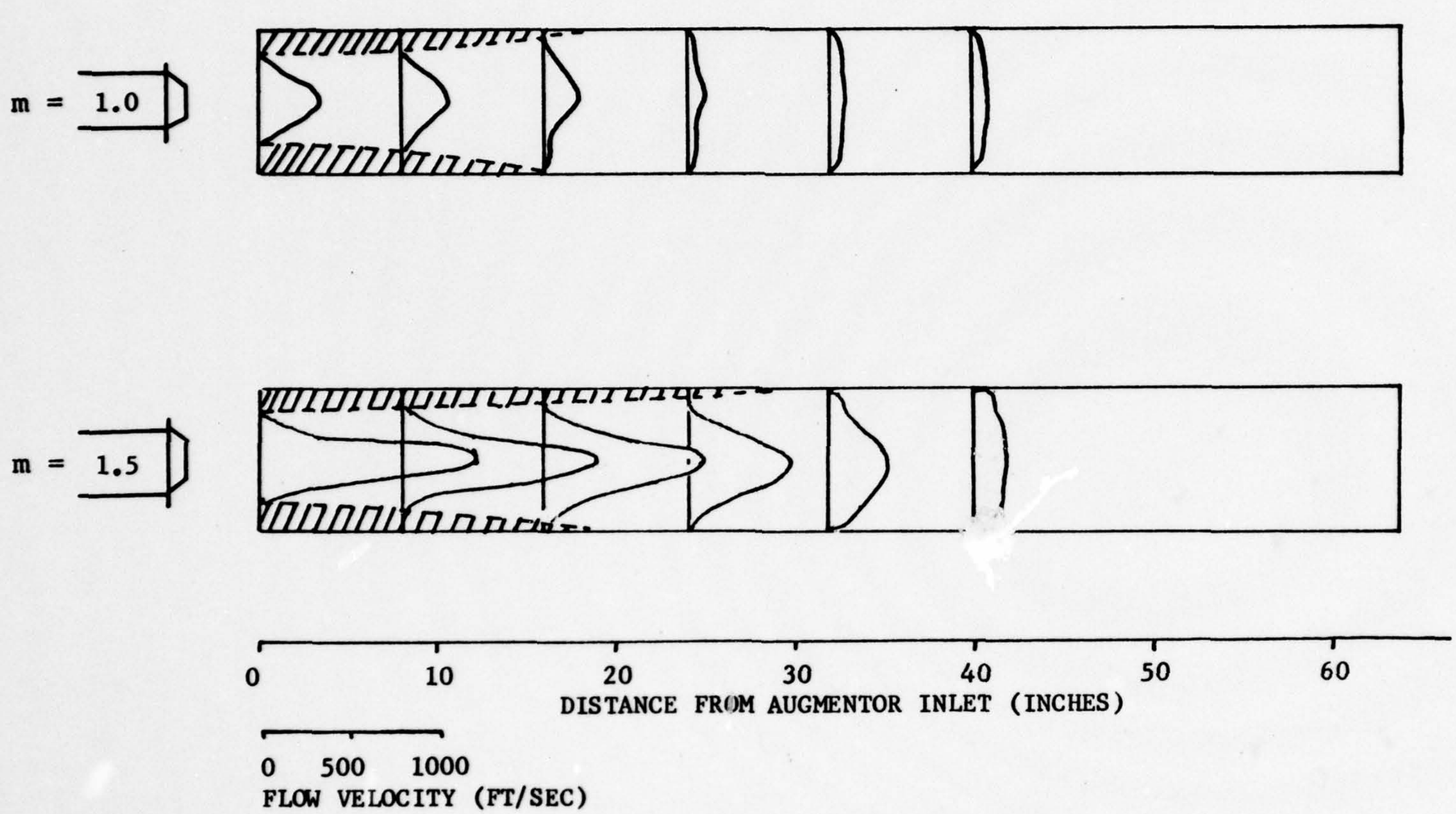

FIGURE 21. VELOCITY PROFILES FOR VARIOUS FLOW RATES (FLAT PLATE, 2D SPACING).

since the replacement of the exhaust stack assembly with the ten-inch tube greatly reduced the back pressure on the eight-inch tube.

During the first runs augmentation ratios actually decreased from what was achieved with a single tube, and air spilled out of the front of the ten-inch tube. After removing two of the angle iron bars from the resistance grid in the stack, the augmentation once again increased, this time to a value much greater than that with the single tube.

More study is needed of the tertiary configuration. The Coanda/Refraction system [Ref. 4] also uses a series of augmentor tubes in short sections which inject air into the exhaust stream at various downstream positions, but more data are needed to understand how this system can be fully utilized. Surely, with some flow-limiting device on the smaller tube, or merely a smaller augmentor-to-nozzle area ratio, the pumping of the first tube could be reduced. With an increased diameter for the outer tube, its pumping could be increased with the possibility, once again, of pumping cooling air from outside the test cell to avoid flow distortions and depression of the cell pressure. The use of large secondary tubes also should allow elimination of large exhaust stacks and adequate space for noise suppression apparatus (Helmholtz resonators, etc.).

E. CONVERGING-DIVERGING NOZZLE

The converging-diverging nozzle (Fig. 1) had little effect on system performance over the range of flow rates investigated. At 1.0 and 1.5 lbm/sec (unchoked flow) the augmentation ratio decreased approximately four percent, compared with that of the converging nozzle, while for the choked flow rates of 2.19 and 1.5 (hot) lbm/sec the augmentation ratio decreased by only one percent. The slightly reduced pumping characteristics of the converging-diverging nozzle probably resulted from the increased secondary flow blockage from the diverging nozzle flow. Higher flow rates and, consequently, higher nozzle pressures might show some greater effect on performance and should be the subject of future studies.

F. AUGMENTOR TUBE DIAMETER

Going to the larger diameter tube reduced the augmentation ratio at all flow rates tested. As the flow rates increased the difference between the eight-inch and ten-inch augmentation ratios decreased, indicating that at some higher flow rate the larger tube might have better pumping characteristics. Variations in stack resistance would change the relative pumping characteristics of the two augmentors.

The inlet pressure drop was somewhat less than for the eight-inch tube at equivalent flow rates, and the temperature/pressure profiles indicated that mixing had taken place by about four diameters into the augmentor tube. The peak temperatures were only about seventy percent of those reached in the eight-inch tube.

G. TOTAL TEMPERATURE

As pointed out earlier, the sudden expansion ramjet with the bypass cooling feature simulated the flow characteristics of a mixed flow turbofan engine. This provided a non-uniform exhaust temperature profile across the jet. The results showed augmentation ratios which varied somewhat less than the square root of the ratio of the nozzle total temperature to the cell total temperature.

The Hasinger 1-D model [Ref. 13] showed that the augmentation ratio should vary approximately as the square root of the temperature ratio, which agrees closely with the results of this study. The FluiDyne experience with the Miramar Hush House [Ref. 1] confirmed this dependency on temperature. Deleo and Wood [Ref. 10] proposed that augmentation ratio was not a function of temperature but rather of nozzle total pressure. One difference which could account for the variation in results was in Deleo and Wood's ability to control cell pressure, whereas this study and the FluiDyne study allowed the cell pressure to change at will with changing flow conditions.

Not enough data were taken in this investigation to reach any definite conclusions, and there is enough variation in experimental results to warrant further research to determine the influence of nozzle total temperature on augmentor performance.

H. TOTAL PRESSURE

As nozzle pressure increases the flow rate through the nozzle increases. When the nozzle is choked, the flow rate becomes a direct function of nozzle pressure ratio. Since it has been shown that augmentation ratio decreases with increasing flow rate, it stands to reason that the same relationship should also exist vis a vis nozzle pressure. The data indicated that, as nozzle total pressure increased, augmentation ratio decreased slightly, and that once choked flow had occurred, it decreased at a greater rate. The Hush House data [Ref. 1] were in agreement; for a fixed nozzle total temperature, augmentation ratio varied inversely as the nozzle pressure, and the pressure effect was not a very strong one.

V. CONCLUSIONS AND RECOMMENDATIONS

1. Considering the ease of manufacturing, along with pumping performance, the conical inlet proved to be the most efficient design.
2. Inlet geometry has a very large effect on augmentor performance for the lower augmentor-to-nozzle area ratios.
3. The reverse conical inlet proved to be the best flow reducing inlet, providing reduced flow with a minimum increase in augmentor wall temperature.
4. Augmentor tube pressure profiles provide an accurate indication of the degree of mixing taking place.
5. Velocity profiles within the augmentor tube are very much influenced by the effects of the cell floor on incoming air flow. The variation in the velocity profile within the augmentor depends primarily upon distance from the nozzle exit, and not on the engine-to-augmentor spacing.
6. Mixing is essentially completed after approximately five diameters of travel into the augmentor tube, independent of inlet design and inlet flow rate.
7. Augmentation ratio was insensitive to nozzle-to-augmentor spacing, except when it was so small that blockage played an important role.

8. Acoustic considerations far outweigh any change in augmentation ratio that might result from increasing nozzle spacing.

9. More work needs to be done to determine the effects of nozzle total temperature on augmentation ratio for flows that realistically simulate actual turbojet exhaust jets.

10. Nozzle total pressure had only a weak effect on augmentation ratio.

11. Velocity profiles indicate that any device introduced into the augmentor tube to mechanically break up the high velocity core has an optimum position: too close to the inlet could generate high noise levels within the test cell, while too far downstream, past approximately three diameters, would have a minimum effect, since significant mixing has already taken place.

12. Testing needs to be done to determine the effects of the design variables considered in this study on noise and chemical pollution levels.

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