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THRUST AUGMENTED INTERMITTENT JET LIFT-PROPULSION SYSTEM

"PULSE REACTOR"

FINAL REPORT

Report No. ARD-256

February 1960

THRUST AUGMENTED INTERMITTENT JET LIFT-PROPULSION SYSTEM

"PULSE REACTOR"

FINAL REPORT

Bureau of Naval Weapons
Contract No. Noa(s)59-6055c

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1. SUMMARY

The Pulse Reactor is the name for the world's simplest lift-propulsion system. It consists of three properly shaped tubes: a valveless combustor, and two short jet thrust augmenters, plus a spark for starting ignition only, a starting air blast tube and a simple low-pressure fuel system. The engine has no moving parts, however, it is competitive in static or hovering performance with turbojet engines, having a thrust specific fuel consumption at this early stage of development of better than 1.0 pound of fuel per hour per pound of thrust.

The effect of the intermittent jet thrust augmenters is to more than double the thrust of the intermittent jets that issue from both ends of the resonant combustor. This thrust augmentation, which is much greater than can be achieved with steady flow ejector type augmenters, is accomplished with devices that are relatively quite small.

The effect of the thrust augmenter is to reduce the jet velocity at a distance of 7 jet outlet diameters downstream of the jet outlet to only about 190 feet per second and the temperature to about 200^{o}F.

The Pulse Reactor is quite insensitive to climatic and other environmental hazards. It has no problem from ingestion of foreign particles. In fact it is practically impossible to induce particles into the combustor through the inlet, if the particles are heavier than air. This peculiar characteristic is due to the difference in flow between the inflow, which is "potential" flow, and the efflux, which comes out of the so-called "inlet", as well as the tailpipe, in the form of a "starting" jet. This

intermittent jet is club-shaped and acts like a jet piston to induce flow through the augmenters.

The basic simplicity of the engine permits low cost development, production, and maintenance. Furthermore, it is practicable to build the engine in a wide variety of shapes to fit the requirements of aircraft design.

TABLE OF CONTENTS

LIST OF FIGURES

2. INTRODUCTION

In the VTOL aircraft field there is an evident trend towards aircraft with higher disc loading and greater installed power. This trend of increasing power loading is shown in Figure 1 which shows the increase from helicopters through tilt-wings to pure jet VTOL aircraft. Figure 2 is a reminder that as the disc loading and installed power increase so do the cost and complexity of the lift-propulsion system. For several years Hiller Aircraft Corporation has been searching for a way to reverse this trend of increased costs and complexity.

A system has been under development at Hiller Aircraft Corporation that sharply reverses the upward trends of cost and complexity. It is a lift-propulsion system that has no moving parts, yet it provides hovering performance that is competitive with turbojets. Furthermore, its downwash characteristics are definitely superior to that of turbojets. It should be noted that the gas turbine engine is only the primary power element in many power systems and when gear trains and other elements such as propellers are added to the power train the complexity and resultant costs are compounded.

2.1 The Pulse Reactor Concept

2.1.1 Description

The Pulse Reactor consists merely of three properly shaped tubes, a fuel system, a simple air start system, and an igniter. A complete model is shown in Figure 3 and a cutaway model in Figure 4. After the engine has started the igniter is no longer used. The starts are practically instantaneous. The combustor is a U-shaped tube that has thrust-producing jets issuing from both ends of the tube. A short tube (thrust augmenter) is attached to each end and more than doubles the thrust of the jet that emanates from that end. The combustion is of the resonant type, and the high degree of thrust augmentation, which is much higher than can be obtained from much larger steady flow jet ejector type thrust augmenters, depends on the intermittency of the jet flow. Reference 3 describes a basic study sponsored by the Air Branch of the Office of Naval Research that is concerned with the basic mechanism of energy transfer from an intermittent jet to ambient fluid in a thrust augmenter.

2.1.2 History

The Pulse Reactor is a combination of two separate and distinct developments: (1) the intermittent jet engine and (2) the intermittent jet thrust augmenter. The modern intermittent jet engine, in the form of a valved pulse jet, was invented by Paul Schmidt in Germany in the 1930s. This was the propulsion unit used to power the V-1 "Buzz-Bomb" that was used to bombard London during WWII. The V-1 was followed by the invention of the front-entry valveless pulsejet by Dunbar, Schubert et al in 1943, at the U. S. Naval Engineering Experiment Station at Annapolis. In an independent development the French SNECMA company made a further improvement of the valveless pulsejet and bent the engine so as to take advantage of the thrust from the so-called inlet as well as from the tailpipe. For more details see App. II of Reference 1.

The development of jet thrust augmenters is traced in detail in Appendix IV of Reference 1. The highlights are shown in Figure 5. The intermittent jet thrust augmenters are shown to be unusual in two ways:

(a) the very great amount of thrust augmentation that has been achieved (140% as compared with less than 50% for steady flow ejectors) and (b) the relatively small size of the intermittent jet thrust augmenters. The combination of the valveless intermittent jet combustor and the high-performance thrust augmenters is called the Pulse Reactor engine.

2.1.3 Pulse Reactor Development under BuAer contract Noa(s) 59-6055c

The Pulse Reactor has been under development during the year 1959 under BuAer auspices and the thrust augmentation has been increased from a maximum of about 80 to 90% to as high as 140%. This improvement has been achieved with the use of conical augmenters with an included angle of divergence of 8°.

2.1.4 Basic Research under ONR contract Nonr 2761(00)

A study of the basic means of energy transfer from an intermittent jet to ambient air was undertaken over a six months period ending on 30 June 1959 (References 2 and 3). The intermittent jet efflux (Fig. 6) was made visible by means of high-speed schlieren photographic equipment (Fig. 7). The typical club shape of the jet is clearly shown. It was proposed in the initial proposal (Ref. 2) for this study that the major transfer of energy occurs across an interface between the club-shaped primary jet and the ambient air as a pressure wave. The next phase of this basic study will be concerned with verifying or modifying this concept.

3. PERFORMANCE OF THE PULSE REACTOR

3.1 Pulse Reactor Cycle of Operation

The operating cycle of the Pulse Reactor is revealed in Figure 8, commencing with the starting phase. Starting is accomplished by simultaneously turning on the ignition, fuel and starting air. The resulting combustion causes a pressure buildup and the burning gases expand out of both ends of the combustor shell, introducing the exhaust phase of the cycle.

In this phase the ignition and starting air are turned off, and the pressure rise in the combustion chamber is greater than the fuel line pressure so that the fuel flow ceases momentarily. During the exhaust phase, air is induced into the exhaust augmenters by the peculiar action of the intermittent jets. The jet efflux emerges as a club-shaped jet, (see Fig. 6) which seems to form an incipient ring vortex. Air that is between the exhaust ports and the thrust augmenter is swept into and through the augmenter by the piston-like action of the jet. As the jet piston sweeps through the augmenter, it causes a pressure drop ahead of and inside of the augmenter. This results in inflow over the lips of the thrust augmenters which, due to the curvature of the inflowing streamlines, causes a pressure drop over the lips of the augmenters and is the main source of the thrust augmentation. It should be noted that this inflow occurs throughout most of the phases of the operating cycle.

When the intermittent jet leaves the engine shell its momentum causes a reversal of airflow back into the combustor at both ends, and the commencement again of fuel flow. This flow reversal introduces the inflow phase of the operating cycle. It is particularly important to note the basic difference between the nature of the efflux and inflow. Whereas the efflux is that of a so-called "starting" jet, the inflow is "potential" flow which comes evenly distributed from all around the openings to the combustor.

The establishment of the flow back into the combustor through both ends results in a collision of both flows in the combustion chamber and a pre-combustion pressure rise of about 0.3 atmosphere which introduces the pre-combustion phase of the operating cycle.

Of even greater importance than the pressure rise is the nature of the ignition of the succeeding cycle. No longer is the spark ignition system needed. Instead ignition is caused by the presence of hot gases from the preceding combustion phase of the cycle which did not quite escape from the shell. These hot gases are swept back into the combustor with the fresh charge of fuel and air, and there occurs a very large-scale mixing and stirring so that the hot gases are widely dispersed in the new combustible charge. These hot gases then act as multiple points of ignition of the new charge. Since combustion starts in so many places practically simultaneously, the combustion time is greatly reduced as compared to single point ignition, and the combustion pressure rise is significantly greater. The predominance of this large scale mixing and stirring resulting in the multiple-point ignition is the reason why the resonant combustor is quite insensitive to the use of fuels with high flame speeds. The effect of fuel laminar flame speeds is quite overshadowed by the effect of the multiple-point ignition as indicated in Reference 5.

A water tank device has been used to help visualize and to study the flow patterns associated with the intermittent jet and thrust augmenter, as shown in Figures 9, 10, 11 and 12. The tank, as indicated in Figure 9, has a piston-in-tube arrangement built into one wall. When a sudden impulse is given to the piston, the resulting intermittent jet is made visible by air bubbles in the water. The intermittent jet causes the formation of a ring vortex as shown in Figures 10 and 11. It is of interest to note that the ring vortex outdistances the jet which created it. When a properly shaped thrust augmenter is placed in front of the intermittent jet it converts energy from the jet into thrust on the augmenter. The thrust on the augmenter is revealed in Figure 12 by the forward motion of the augmenter, which is suspended from above by a rod. The augmenter breaks up the ring vortex and diffuses the particles contained in it as shown in the photograph. The ring vortex when unimpeded travels at relatively high speed and strikes the end of the tank with a sharp impact. However, when the augmenter is in position, the velocity of efflux from the augmenter is greatly reduced.

3.2 Performance Comparison of Steady and Intermittent Jet Thrust Augmentation

Figure 13 reveals the great superiority of the intermittent jet thrust augmenter as compared to the performance of steady flow jet ejectors. It also shows that this superior performance is achieved with augmenters that are much smaller in diameter and shorter in length than are typical steady flow ejectors. Figure 13 shows the improvement in performance that was obtained by changing the shape of the augmenters from simple cylinders with flared inlets to the shape of an 8° divergent cone. The angle of divergence was determined from model tests that were performed on contract Nonr 2761(00), (Reference 3). It is believed that further improvement of the conical augmenters is likely, as an adequate survey of area ratios has not yet been completed.

The fact that the flow pattern of the intermittent jet is so different from that of the steady flow jet is believed to be the source of the higher performance of thrust augmenter that is associated with the former type of jet.

The development of the full-scale thrust augmenters was conducted on a test stand that was specially designed for the purpose. This test stand is shown in Figure 14. It provides for simultaneous but separate measurement of the thrust from both ends of the basic combustor and from both of the augmenters. The combustor is built in a 90° configuration in order to separately measure the thrust from each end of the combustor. The augmenters shown are short cylindrical augmenters of the largest diameters tested. As the augmenter diameters were decreased the performance improved, until an optimum was reached at a diameter of about twice the tailpipe diameter and in the case of the inlet augmenter, at about 3 times the inlet diameter, as shown in Figure 15.

3.3 Performance of Pulse Reactor Engines

Figure 16 shows the performance of the Pulse Reactor engine. This is the combination of the intermittent jet combustor with thrust augmenters on both the inlet and tailpipe. It is of particular interest to note that the thrust specific fuel consumption remains remarkably constant over a

50% range of thrust. The peak performance of better than one pound of fuel per hour per pound of thrust shows the Pulse Reactor to be competitive with pure turbojet engines. Another valuable characteristic of the Pulse Reactor that should be mentioned at this point is that it can be throttled from maximum thrust to near lean-out and back to maximum thrust again in a matter of a fraction of a second. This extremely rapid thrust change is made possible by the fact that the engine has no moving mechanical parts.

An important feature of this type of system is that it can be built in a great variety of configurations, some of which are shown in Figure 17.

3.4 Comparison of Pulse Reactor Hovering Performance with other VTOL Systems

The ratio of lift-propulsion system weight to maximum thrust for several VTOL systems is compared in Figure 18. It is noted that the Pulse Reactor, in its present state of development, is competitive with pure turbojets. Also shown is what seems to be a reasonable near goal for further development of the Pulse Reactor. On the right half of the figure, curves are plotted that show the trend of hover time available for various fuel loads.

It should be noted that the Pulse Reactor performance is achieved with a system that is quite complex and difficult to analyze, but the hardware is the ultimate in simplicity, whereas the turbojet cycle is relatively simple of analysis but the hardware is quite complex and costly. The typical turbojet engine shown in cutaway in Figure 19 consists of approximately 10,000 parts, as compared to seven basic parts for the Pulse Reactor.

4. OPERATIONAL CHARACTERISTICS OF THE PULSE REACTOR

The performance of a VTOL aircraft lift system in terms of thrust and fuel flow rate is not necessarily the factor that determines whether or not the system will be successful. At least as important, as far as field use in concerned, are the characteristics of the downwash, and the vulnerability of the system to the operating environment.

4.1 Down-wash or Jet Wake Characteristics

4.1.1 Wake Velocity

The effect of the augmenter in reducing the jet wake velocity at a distance of 7 diameters downstream of the tailpipe exit is shown in Figure 20. It is shown that the average wake velocity of the Pulse Reactor is less than 190 feet per second as compared to at least 1000 feet per second for a typical turbojet.

4.1.2 Wake Temperature

The intermittent jet augmenter has a similar effect in reducing the wake temperature. Data again is given at a distance of seven tailpipe diameters aft of the tailpipe exit and it shows only about 200°F for the Pulse Reactor as compared to about 750°F for a typical turbojet.

4.1.3 Noise

The noise of the basic intermittent jet combustor is generally comparable in overall noise output to that of a turbojet engine of similar thrust characteristics (Ref. 4), as shown in Figure 20. However, the character of the noise is different in the two cases, the intermittent jet engine having a much greater radiation of energy in the low-frequency band of the spectrum. In contrast, the turbojet noise is essentially random in nature while that of the intermittent jet has a strong fundamental frequency and a series of harmonic frequencies. Pulse Reactor noise reduction will be accomplished by the application of the following three techniques:

(1) A reduction of noise has been achieved by the effect of the augmenter in reducing the wake velocity.

(2) Tests have shown that intermittent jet engines can be operated out of phase, that is, when one engine is exhausting the other is in the intake phase of its operating cycle. This out-of-phase operation of dual engines can cause a reduction of as much as 15 decibels in the noise that is generated in the portion of the spectrum that represents the fundamental frequency of the engines.

(3) The use of aerodynamic shrouding will permit treatment with acoustical materials of the portion of the jet efflux in the region between the combustor ports and the augmenters. Acoustic materials are effective in reducing high frequency noise, as compared to the low frequency of the operating cycle.

4.2 Starting

An important feature of the Pulse Reactor is practically instantaneous starting, which is accomplished by simultaneously turning on the fuel system, ignition and a brief blast of starting air. After the start is accomplished the starting and the ignition systems are then turned off. It has been demonstrated that after one engine has been started, others can then be started without the use of a blast of starting air by use of an inter-connecting tube between engine inlets.

4.3 Thrust Control

The control of the engine thrust is achieved by changing the fuel flow rate. Since there are no moving mechanical parts in the system, the engine thrust can be changed from less than 100 pounds of thrust to 500 pounds of thrust in a fraction of a second. This feature, when combined with multiple units in lift-propulsion systems, can provide all of the required flight control forces.

5. NO SUSCEPTIBILITY TO DAMAGE CAUSED BY OPERATING ENVIRONMENT

5.1 Ingestion of Foreign Particles

A film supplement accompanies this report that portrays a common problem that plagues operators of VTOL aircraft under field conditions. This problem stems from the stirring up of dust, sand and heavier foreign material by the aircraft lift system downwash. Even in the case of helicopters, which have the lowest disc loading, this is a serious problem, and the amount of recirculation of foreign material through rotors, propellers, and into the engine air intakes, is greatly increased as the disc loading of the lift system is increased.

The Hiller Aircraft Corporation is studying the downwash of propellers, ducted propellers and rotors with the test rig shown in Figure 21 under a Department of Army contract. (DA44-177-TC-500)

Due to the simplicity of the Pulse Reactor system, it was believed that it would not suffer from these problems, but tests were conducted to verify this assumption. It was expected that any foreign particles inducted into the combustor would merely be carried out the tailpipe without doing any damage. However, the actual tests demonstrated that it is practically impossible to get particles that are heavier than air into the combustor. The films revealed that even when nuts, bolts and rocks are dumped down a chute towards the inlet that the particles will not enter the engine. This is due to the difference between the inflow and efflux. The cycle time is too brief to allow particles that are heavier than air to enter the engine before the flow reverses and the particles are swept away from the inlet by the jet efflux.* On the other hand, the motion pictures show the very serious damage done to a typical gas turbine engine by the ingestion of foreign particles.

5.2 Inlet Screen Unnecessary for Pulse Reactor

One way of reducing the hazard due to ingestion of foreign particles into engine inlets has been the use of screehs over the inlets. Figure 22 shows a rather unexpected problem that has arisen concerning the use of inlet screens. This figure portrays the English Short SC-1 VTOL aircraft in operation at the British Air Show at Farnborough in September of this year. The SC-1 uses turbojets mounted vertically in the fuselage for vertical and hovering flight. As the SC-1 was flown over a newly mown field, the grass particles were blown into the air and caught in the engine's inflow, where they so clogged the inlet screens as to cause a power failure and a forced landing of the aircraft. So here aircraft designers are faced with a dilemma: if engine inlet screens are used to

* Figure 21a illustrates this point using rocks

lessen damage due to ingestion of foreign particles they pose the danger of causing engine power failure due to clogging of the inlet screens when operated under field conditions. No such problem exists in the case of the pulse reactor system. In order to emphasize this feature the motion pictures show the effect of dumping baled hay in front of the engine inlet. The hay is merely sucked through the inlet augmenter and diffused throughout the surrounding air, without affecting the operation of the engine.

5.3 Effect of Climatic Environments on Engine Durability

Most powerplants require considerable care during storage and operations in extremes of climate such as the damp tropics and in Arctic surroundings. In the case of the Pulse Reactor no special care in storage or operation is required due to the basic simplicity of the system. The use of ordinary corrosion-resistant materials is sufficient treatment to render the Pulse Reactor practically impervious to its operating environment.

6. LOW COST OF PULSE REACTOR LIFT-PROPULSION SYSTEM

The basic simplicity of the Pulse Reactor contributes directly to a low development cost and production cost. This same simplicity also insures low operational, maintenance, and storage costs. It may be expected that such a system will have a high level of availability. Furthermore, the lack of requirements for precision manufacturing and the limited use of critical strategic materials greatly reduces the manufacturing and mobilisation requirements of this system as compared to other power systems. Finally, the ability of the Pulse Reactor to use a wide variety of fuels greatly increases its versatility and reduces the problem of fuel logistics. The many advantages of the system are summarized in Figure 23.

7. APPLICATIONS

From the foregoing section it is obvious that the Pulse Reactor propulsion system will have many very unusual characteristics. It would be expected that aircraft configurations employing them, and the performance of these aircraft would also be quite unusual. The Hiller Aircraft Corporation believe that the unique operating characteristics of these aircraft may provide new solutions to existing mission requirements and may be used in new weapon system concepts.

At the present time, the contractor has, with the support of the Navy, established the feasibility of an extremely simple and rugged propulsion system which is comparable in hovering performance to that of a turbojet engine. These accomplishments allow the Pulse Reactor to be considered now for hovering or lift engine type applications. However its forward flight characteristics have not yet been adequately explored experimentally. Therefore the types of aircraft configurations discussed below feature mixed propulsion schemes or rely on assumptions concerning the inflight characteristics of the Pulse Reactor.

7.1 A possible ASW drone configuration for the DASH mission is shown on Figure 24. It uses eight Pulse Reactors in the fuselage for hover lift and two that are fixed horizontally to provide thrust for forward flight.

7.2. Figure 25 shows a ring wing configuration. In this design the fast thrust response of the engines to a fuel flow change is utilized to accomplish attitude control by differential throttling of diametrically opposite units.

7.3 A tail-sitter configuration is shown in Figure 26. The engines are arranged span-wise and enclosed with fairings to form a wing. The augmenter assembly is deflected for pitch and roll control. Differential throttling provides directional control.

7.4 For the configuration shown in Figure 27 the engines are in an inverted open U form with individual augmenters at each inlet and outlet. Forward flight is obtained by rotating the combustor-augmenter assembly, and control is achieved by both differential throttling and rotation of the propulsion package.

7.5 A similar configuration is shown in Figure 28 except that the engines are fixed with augmenter exit vanes for wake deflection for forward flight. Front and rear flaps are lowered to convert to Ground Effect Machine (GEM) operation.

7.6 A boost or launch application is pictured in Figure 29. This is made feasible due to the low cost of the Pulse Reactor.

7.7 The use of the Pulse Reactor for propulsion of Ground Effect Machines is very attractive. The sketches in Figure 30 show a number of ways in which they could be used.

7.8 The large weight lifter, flying crane or cargo unloader shown in Figure 31 is an attractive application because it permits building very large aircraft at a reasonably low cost.

7.9 Figure 32 shows an assault aircraft featuring a multiple-tube resonant reactor that is currently being studied. Forward flight is obtained by inclining the pulse reactor units. This arrangement can be readily applied to macnines with "ground effect" augmentation features.

7.10 Figure 33 shows a mixed propulsion personnel carrier with Pulse Reactors in the wings, augmenters in outboard pods, and a turboprop unit for forward propulsion.

7.11 A high speed VTOL aircraft is shown in Figure 34 with the Pulse Reactors enclosed in a body so shaped as to provide lift efficiently. A turbojet is used for forward propulsion.

These are possible configurations and applications. In order to be properly prepared for prototype development of many of these applications, considerable additional work is required to establish the inflight characteristics of the Pulse Reactor and to work out problems associated with multiple installations.

8. PULSE REACTOR DEVELOPMENT PROGRAM

The Pulse Reactor program proposed for the next phase of development is directed to obtain the information needed prior to developing a medium speed prototype aircraft, such as the ASW Drone. It consists of 5 principal development efforts which are to be carried out simultaneously in an 18 month program, as indicated in Figure 35:

1. Basic Pulse Reactor development, which includes cycle analysis and experimentation to develop a better understanding of the mechanism of

operation of the combustor-augmenter combination so that it's full potential can be more nearly realized.

2. Sub-systems development where items such as starting, control and accessory power systems would be worked out.

3. Forward flight development would be a major effort. It would start with simulated in-flight test using the Hiller blower facility followed by truck tests with the former Hiller ducted fan platform rig shown in Figure 36, and finally truck tests of multiple engine installations simulating actual applications. A possible test rig for this purpose is pictured in Figure 37. In these latter tests differential and collective engine throttling for attitude control would be worked out and documented.

4. Durability would be another major effort. This work would terminate in PFRT runs.

5. Parametric analysis would be performed to better recognize the merits and implications of the pulse reactor propulsion system.

This program should produce realistic information so that this simple and rugged propulsion system can be seriously considered in prototype aircraft development.

The work contemplated is indicated in greater detail in the following suggested work statement.

9. RECOMMENDED WORK STATEMENT FOR FUTURE DEVELOPMENT

9.1 Basic Pulse Reactor Development

9.1.1 Theoretical Analysis

9.1.1.1 Pulse Reactor Cycle Studies

a) Investigation of shock wave and resonant combustion processes

b) Analysis of instantaneous pressure distribution data of SNECMA, N.Y.U., N.R.L., C.A.L., and correlation with experiments of item 9.1.2.1 in the development of a useful theory.

9.1.1.2 Augmentation Phenomena (ONR supported)

a) Investigation of mechanism of energy transfer from an intermittent jet to ambient fluid in a thrust augmenter.

b) Flow investigations of ring vortex passage through ejector-type augmenter.

9.1.1.3 Studies to understand and optimize mutual interactions between combustor and augmenters.

9.1.2 Experimental Development

9.1.2.1 Pulse Reactor

a) Systematic investigat... effects of reactor geometry and fuel injector type and location.

b) Instantaneous pressure pickup pressure surveys.

c) New engine forms such as: 1) single combustion chamber with multiple inlet and exit tubes,

2) coaxial configuration, 3) resonant coupled tail pipe turn chamber.

9.1.2.2 Augmenter Development

a) Effect of shape and proportion such as: 1) cylindrical; 2) conical; 3) flattened; 4) square; 5) length-to-diameter ratio; 6) axial expansion rate; and 7) augmenter cross-sectional area to engine cross-sectional area.

b) Investigation of common augmenter with 1) plurality of exits; 2) plurality of inlets; 3) inlet and exit ejection.

9.1.3 Integrated Pulse Reactor Development

9.1.3.1 Simultaneous development of combustor and augmenter components. This will proceed by applying theories and experimental results of 9.1.1 and 9.1.2 above in the development of an optimum combustor-augmenter package. Instrumentation would include instantaneous pressure surveys and flow visualization techniques to guide optimization work.

9.1.3.2 Noise reduction research - overall noise and frequency spectrum analyses will be taken to evaluate the following noise reducing means:

a) Effect of augmenter action in reducing wake velocity.

b) Effect of operating multiple engines out of phase.

c) Effect of the use of aerodynamic shrouding treated with acoustical material at the jet efflux region between the combustor ports and the augmenters.

9.2 Sub Systems Development

9.2.1 Starting System

9.2.1.1 Development of air blast starters including (a) low and high pressure jets and jet location, (b) cross-over tubes which allow one engine to start another engine, (c) spark plug and ignition coil.

9.2.1.2 Investigation of explosion starters such as (a) cartridge, (b) squib (blasting cap), (c) hypergolic fuel injection.

9.2.1.3 Development of automatic sequencing mechanism, including (a) regulation of fuel, air blast, ignition and or explosion, (b) safety features preventing flood-out, flame or unburned fuel as in false starts.

9.2.2 Fuel System

9.2.2.1 Investigation of fuel pumping means such as (a) electric pumps, (b) combustion chamber pulse actuated diaphragm pump, (c) combustion chamber pressure or exhaust jet turbine-driven pump.

9.2.2.2 Development of suitable flow divider for engine injection nozzles and for multiple engine installations.

9.2.3 Engine Control System

9.2.3.1 Development of rich-out and lean-out limiters

9.2.3.2 Development of fuel control system for differential and collective fuel flow rate modulation in multiple engine installations and to accomplish altitude compensation.

9.2.4 Accessory Power System

9.2.4.1 Investigation of turbo-generator unit using combustion chamber bleed or immersion in exhaust jet.

9.2.4.2 Investigation of pulse oscillated coil or magnetic generation of A. C. current by diaphragm motion.

9.2.4.3 Investigation of magnetohydrodynamic power generation created by ionized gases in shock waves traversing combustion chamber transition section.

9.2.5 Cooling System

9.2.5.1 Optimization of suction pumping with cooling shroud overhang at tail-pipe outlet.

9.2.5.2 Development of cooling jacket shroud and fins or baffle for improved heat transfer.

9.2.5.3 Investigation of ram air pump at augmenter exists for cooling purposes.

9.3 Forward Flight Development

9.3.1 Theoretical Studies

9.3.1.1 Analyses of fixed and variable augmenter geometry configurations.

9.3.1.2 Investigation of means of improving ram air recovery such as (a) inlet guide vanes, (b) inlets and cowling in engine-augmenter nacelles.

9.3.1.3 Investigation of possibility of obtaining thrust from heating ram air in cooling shroud.

9.3.2 Tests and Development

9.3.2.1 Forward flight testing with Hiller blower facility where a reduced scale Pulse Reactor package is suitably ducted to simulate ram air conditions.

9.3.2.2 Truck tests of full scale Pulse Reactors using the former Hiller ducted fan flying platform truck test rig. Preliminary tests would be made with unit at speeds up to 80 MPH. Thrust, pitching moment, drag, fuel flow rate, ram air pressure recovery, shell temperatures and other pertinent data would be recorded.

9.3.2.3 Truck tests of multiple Pulse Reactor units simulating actual applications. A larger test rig will be constructed. The development work will include: (a) several multiple engine configurations in combination with augmentors of circular, rectangular and variable cross-sectional forms, (b) tests to determine wake velocity, temperature, erosion, recirculation, noise level and effects of frequency coupling in and out of phase, (c) development of attitude control by (1) differential throttling, determination of control response time, etc., (2) differential inclination of exit wakes, (3) differential inclination of augmentor exit vanes.

9.4 Durability Development

9.4.1 Material Studies

9.4.1.1 Identification of suitable non-strategic materials with satisfactory strength-to-weight ratio, fatigue life, and corrosion resistance at operating temperatures, for combustor and augmenters. This would include considerations of protective coatings for combustor assemblies, and fiberglass augmenter designs.

9.4.2 Design Details

9.4.2.1 Investigations of (a) welding and forming techniques, (b) methods to relieve thermal stress, (c) vibration isolating mountings.

9.4.3 Endurance Runs

9.4.3.1 Preliminary endurance runs with suitable instrumented engine assemblies to determine causes of failures which may result.

9.4.3.2 Pre-flight rating tests (PFRT) -- a developed Pulse Reactor lift-propulsion unit would be run in accordance with applicable (PFRT) requirements. The resulting performance would constitute the basis of an engine specification report.

9.5 Parametric Analysis

9.5.1 Application design studies to determine the most promising applications.

9.5.2 Operational analysis studies to determine expected performance.

9.5.3 Correlation and comparison with other current and future lift-propulsion systems.

9.5.4 Assessment of relative merits including environmental situations and wake characteristics, and identification of areas of most effective applications.

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7. Lockwood, R. M.: "Pulsejet Ejectors, a Thesis for the Professional Degree of Mechanical Engineer", Oregon State College, 1953.

8. Cunningham, W. R.: "Development of High Performance Rotary-Wing Tip Mounted Pulsejet Engine Components." American Helicopter Company. Final Report No. 172-D-3, 1 November 1954, Contract A.F. 33(600)-5860.

9. Lutz, O.: "Graphical Method on Problems of Gasdynamic Mixing, in Combustion and Propulsion", Third AGARD Colloquium, Pergamon Press, New York, 1958, pp 598-610, inc. (In English)

10. Bertin, J.: "Quelques Propriétés de la Combustion Pulsatoire: le Pulso-Reacteur, Action des Carburants Dopes", SNECMA Co., France, article in "Selected Combustion Problems", AGARD, publisher Butterworths Scientific Publications, 1954, pp 4[illegible]-505 Incl.
English Summary:

"It is natural to expect that the correct choice of fuels should enable the characteristics of machines with pulsating combustion to be improved. For some time the SNECMA has been studying the effect of promising additives, but no appreciable improvement in the overall performance of pulse-jets has yet been found. In the course of this work a number of measurements of instantaneous temperatures and pressures have been made at different parts of the machine. Simultaneously attempts were made to obtain accurate gas analyses and flame photographs. It was concluded that the pressure actually reached in the chamber is close to the theoretical value corresponding to an infinite rate of reaction. Then the low volumetric efficiency of the combustion chambers is largely responsible for the marked difference between actual and theoretical performances. This conclusion may explain why dopes have hitherto not been effective and raises the question as to whether their effects may in future be neglected. Since, however, these results have been obtained from machines pulsating at low frequency and with low volumetric efficiencies, both of which must be raised in order to make progress, it is to be expected that the reaction rate will eventually become a limiting factor and that the use of dopes and improved fuels will be necessary."

11. Bertin, J. and Salmon, B.: "Combustion Research and Reviews 1957" pp 123-133 incl., Butterworths, London
English Summary:

"The authors first study the back-flow of pulse-jets. The amount of back-flow air is a very important parameter of regular pulse-jet operation. The rear-length of the pulse-jet on which this air may act is determined by means of classical gas analysis.

The instantaneous pressure and temperature measurements give a picture of pulse-jet operation. A slight pre-compression and pre-burning is detected thus in the combustion chamber and the ignition of the carburated air is explained by the mixing of this air with some residual products of the combustion of the preceding cycle.

The pressure measurements also allow the computation of the instantaneous pulse-jet thrust, as well as the analysis of the influence on thrust of the various parts of the engine.

Finally, by means of the one-dimensional equations of fluid flow, the periodical flow pattern is derived from pressure and temperature measurements."

12. Salmon, B.: "Examen de la flamme dans la chambre de combustion du pulso escopette," (suite), (Examination of the flame in the combustion chamber of the (scoop-type or Escopette?) pulse-jet (results or continued?) SNECMA, Note ES XIII-10, January, 1952

13. Salmon, B.: "Pressions instantanees dans la trompe de dilution du pulso 5158 avec capacite arriere," (Instantaneous pressure with rear capacity in the dilution duct of pulse-jet 5158) SNECMA Note ES XIII-14, January 1952.

14. Salmon, B.: "Examen de la flamme dans la chambre de combustion du pulso 509." (Examination of the flame in the combustion chamber of pulse-jet 509) SNECMA Note ES XIII-17, February, 1952.

15. Vigne, H.: "Compte rendu d'essais de post-combustion en aval du pulso 5158," (Explanation of studies on post-combustion downstream of pulsejet 5158) SNECMA Note ES II-68, 26 September 1952.

16. Schmitt, H.: "Examen de la flamme dans un pulso a ecoulement bidimensionnel," (Examination of the flame in a two-dimensional flow pulsejet) SNECMA Note ES XIII-24, September 1952.

17. Pinnes, R. W.: "A New Concept in the Design of Light Weight Turbo-jet Engines", March 1957, ASTIA No. AD 119635.

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20. Rudinger, G.: "Wave Diagrams for Nonsteady Flow in Ducts", D. Van Nostrand Co., Inc., Princeton, 1955.

21. Oppenheim, A., Urtiew, P. A., Stern, R. A.: "Peculiarity of Shock Impingement on Area Convergence". Physics of Fluids, Vol. 2, pp. 427-431 (July-August 1953).

POWER vs. DISC LOADING

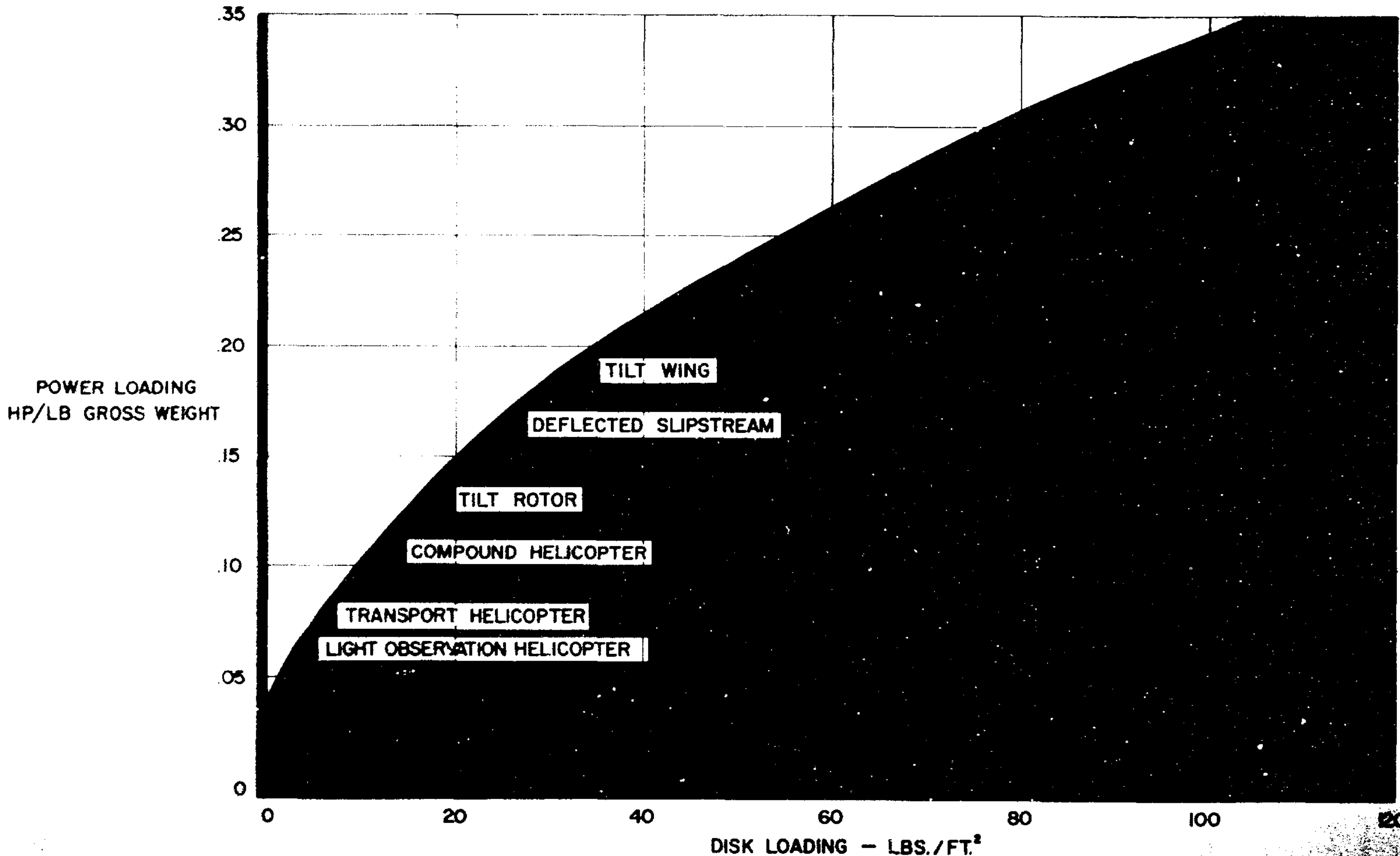


FIGURE 1

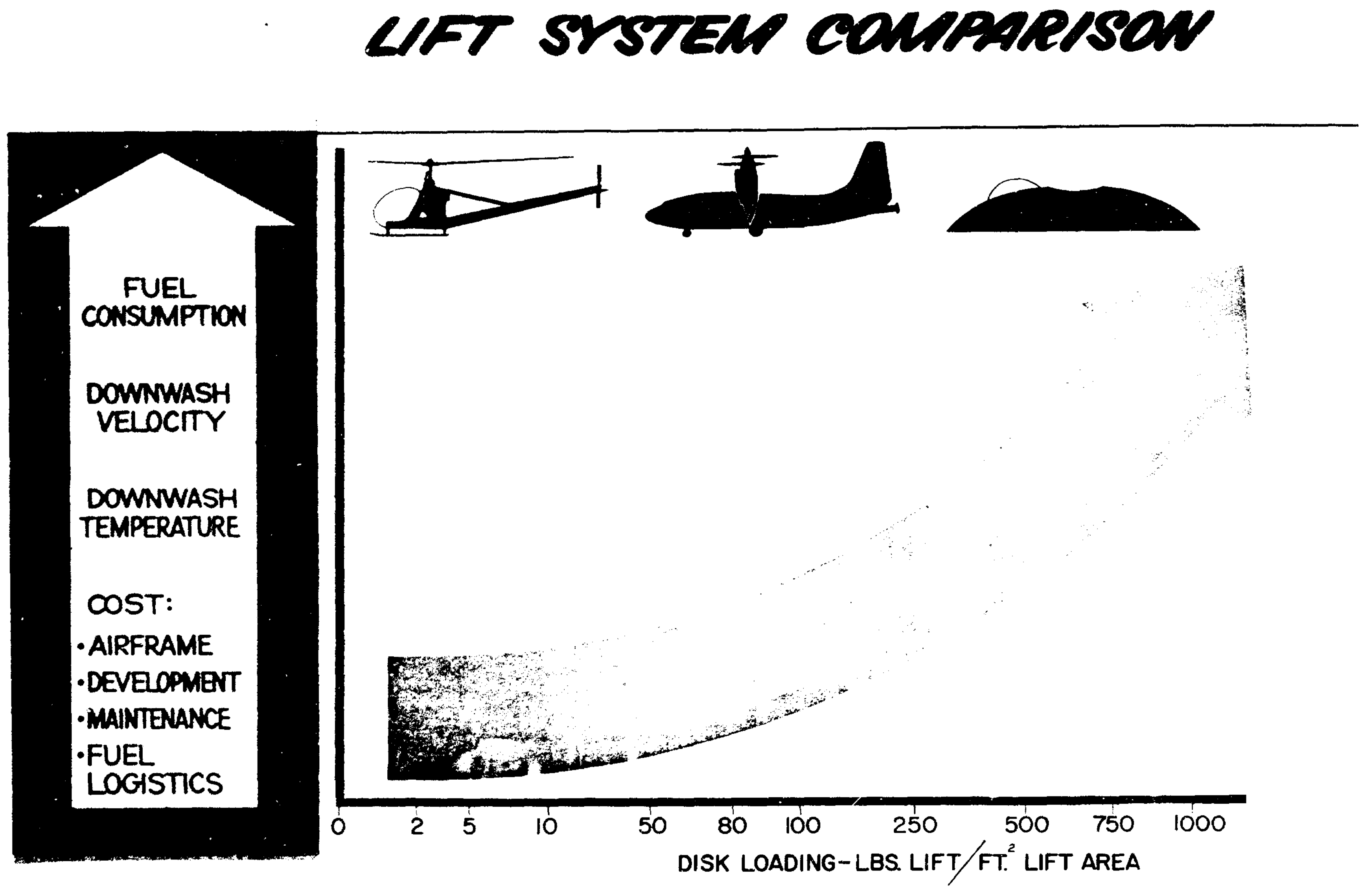

LIFT SYSTEM COMPARISON
FUEL CONSUMPTION
DOWNWASH VELOCITY
DOWNWASH TEMPERATURE
COST:
•AIRFRAME
•DEVELOPMENT
•MAINTENANCE
•FUEL LOGISTICS
0
2
5
10
50
80
100
250
500
750
1000
DISK LOADING-LBS. LIFT/FT.² LIFT AREA

FIGURE 2

FIGURE 3. PULSE REACTOR SCALE MODEL

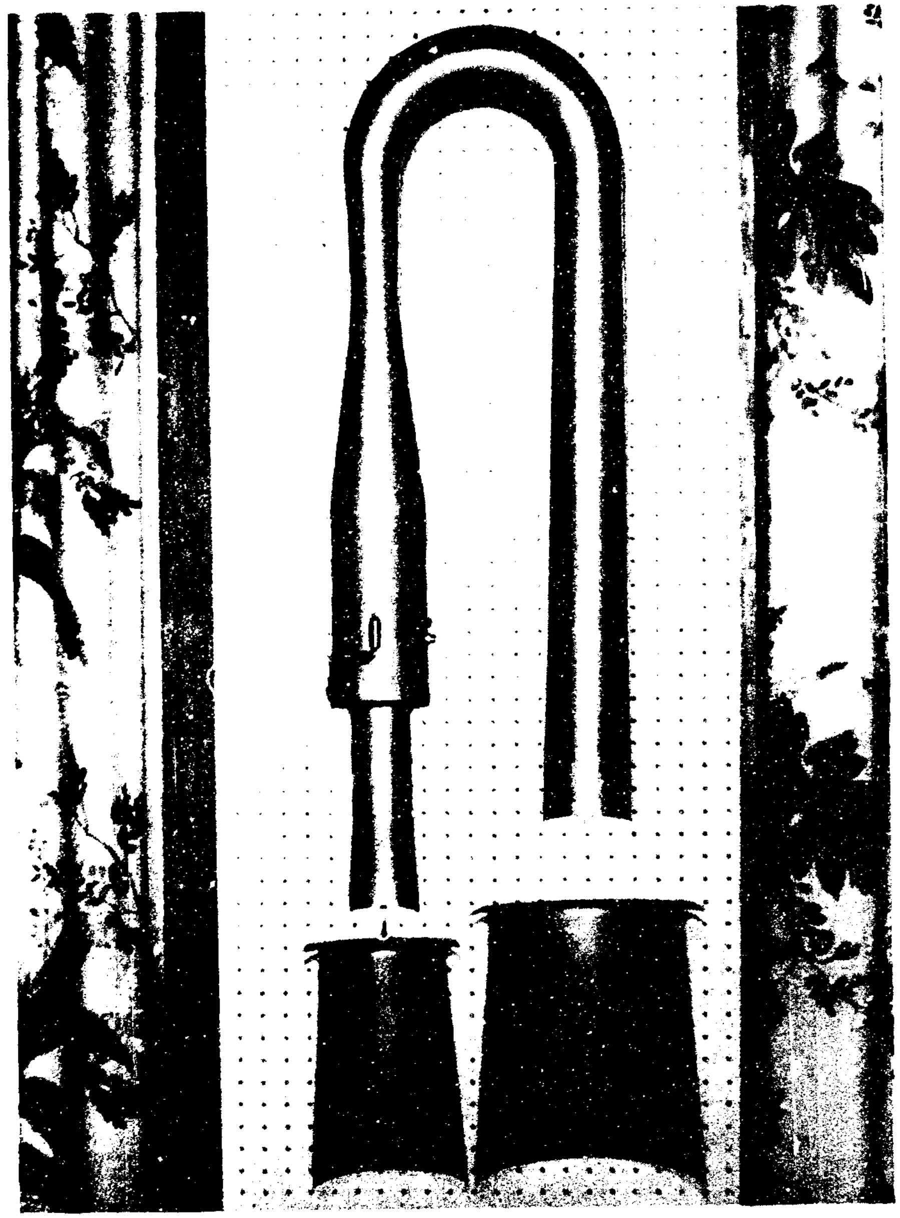


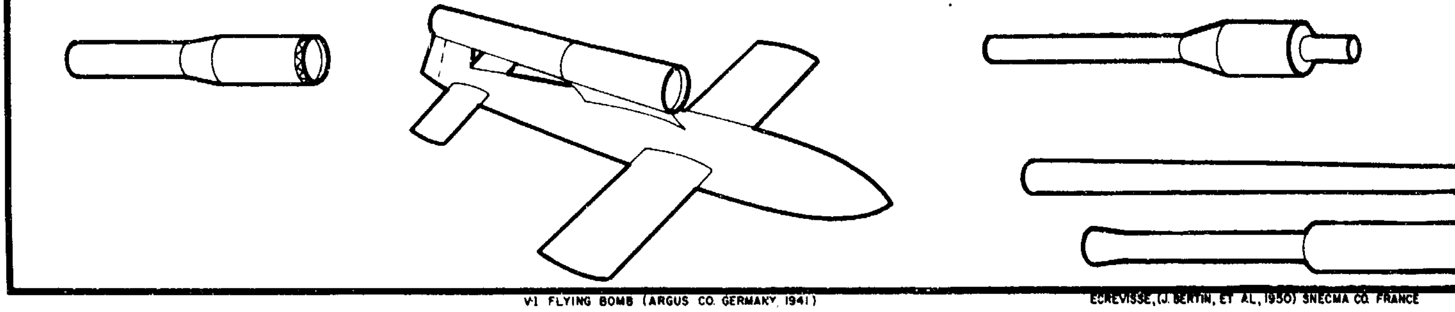
FIGURE 4. PULSE REACTOR CUTAWAY MODEL

EVOLUTION OF PULSE R

INTERMITTENT JET ENGINES

VALVED PULSEJET (PAUL SCHMIDT, 1930's) GERMANY

VALVELESS FRONT-ENTRY ENGINE (SCHUBERT ET AL, 1943) U.S. NAVAL ENGR. EXP. S



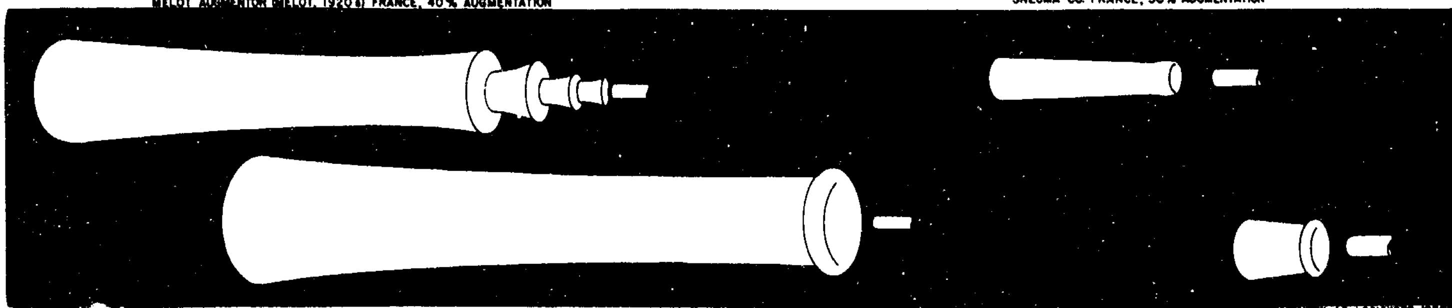
V-1 FLYING BOMB (ARGUS CO. GERMANY 1941)

ECREVISSE, (J. BERTIN, ET AL, 1950) SNECMA CO. FRANCE

THRUST AUGMENTERS

MELOT AUGMENTOR (MELOT, 1920's) FRANCE, 40% AUGMENTATION

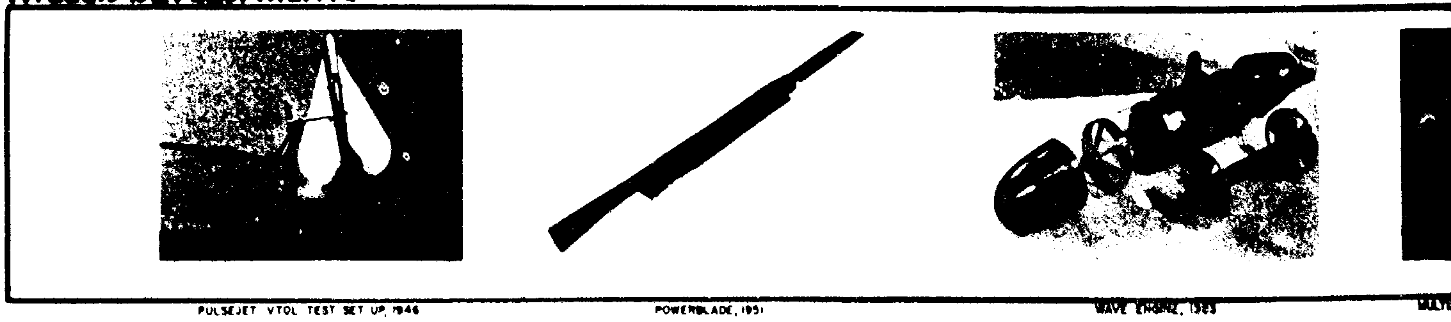
"DILUTION DUCT" (J. BERTIN, ET AL. 1950's) SNECMA CO. FRANCE, 50% AUGMENTATION



JET EJECTOR (193[illegible] 1959) 40% AUGMENTATION (MANY INVESTIGATORS)

HIGH-PERFORMANCE AUGMENTER (R. LOCKWOOD, 1
HILLER AIRCRAFT CORPORATION, 120% THRUST AUGMENT

HILLER DEVELOPMENTS



PULSEJET VTOL TEST SET UP, 1946

POWERBLADE, 1951

WAVE ENGINE, 1953

MULTI

FIGU

A

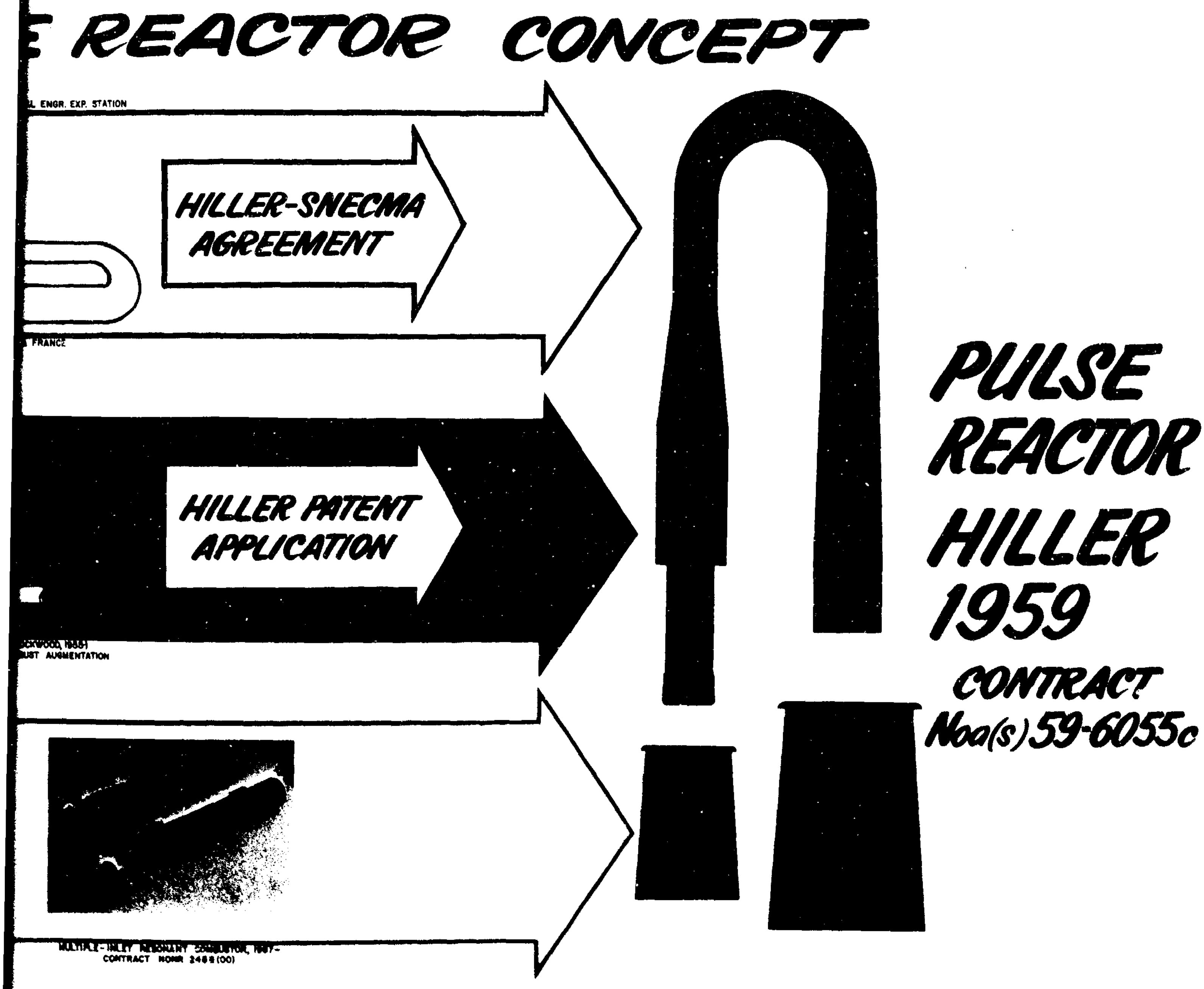

E REACTOR CONCEPT
ENGR. EXP. STATION
HILLER-SNECMA AGREEMENT
FRANCE
HILLER PATENT APPLICATION
AUGMENTATION
CONTRACT NONR 2485(00)
PULSE REACTOR
HILLER
1959
CONTRACT
Noa(s)59-6055c

FIGURE 5

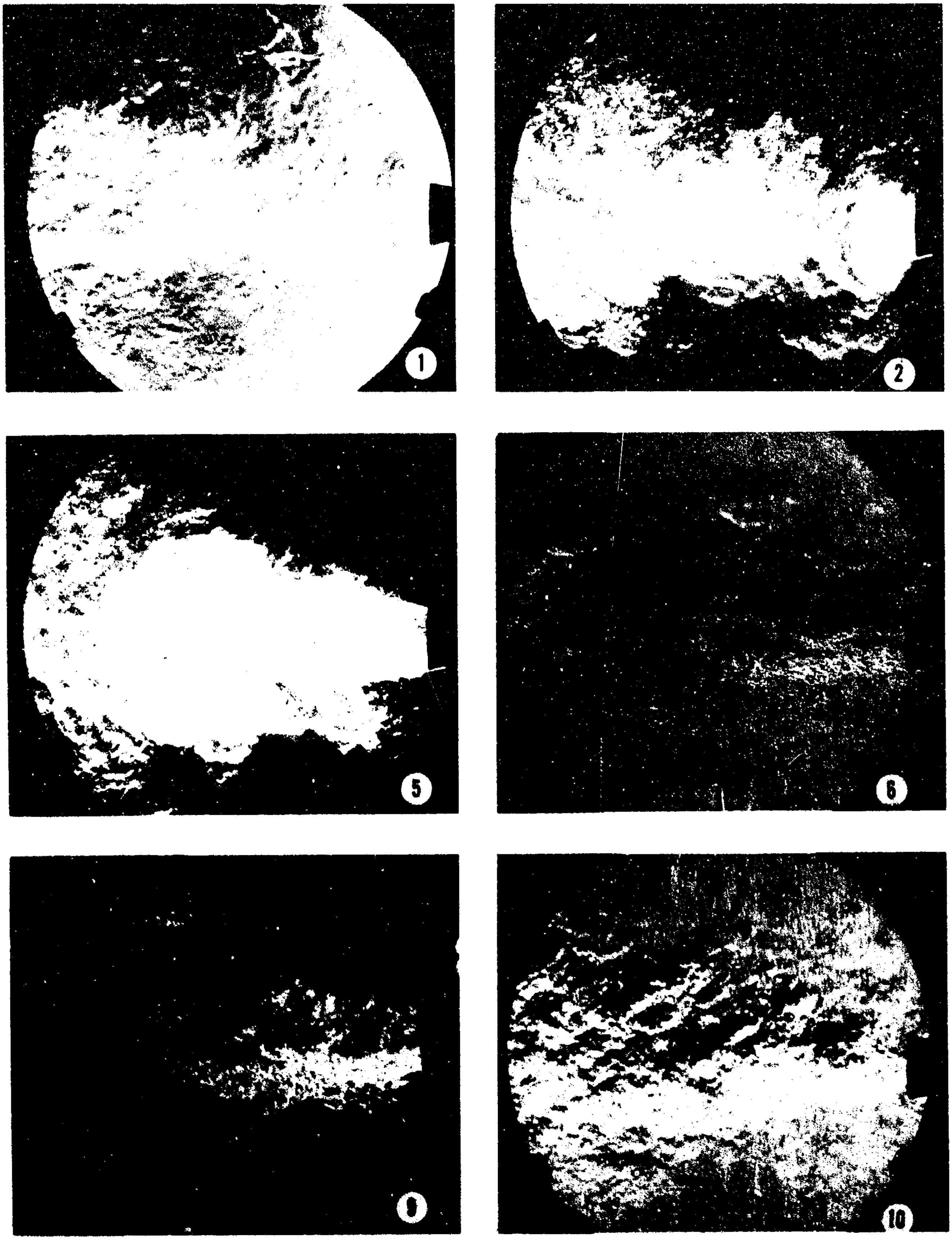


FIGURE 6: SCHLIEREN FLASH PHOTO SEQUENCES OF BASIC PULSEJET CYCLE (FROM RANDOM SHOTS OF DYNAJET EXHAUST)

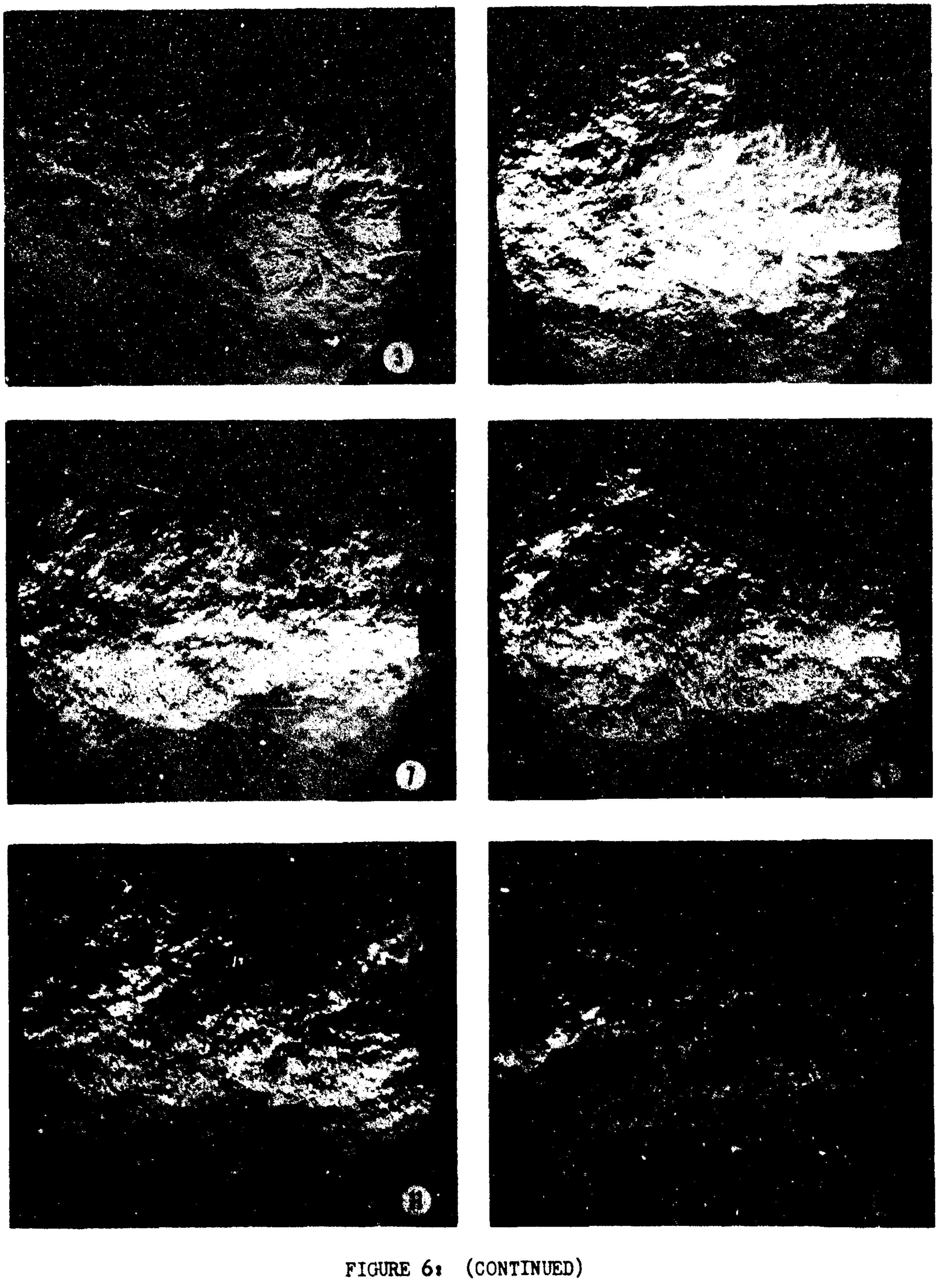
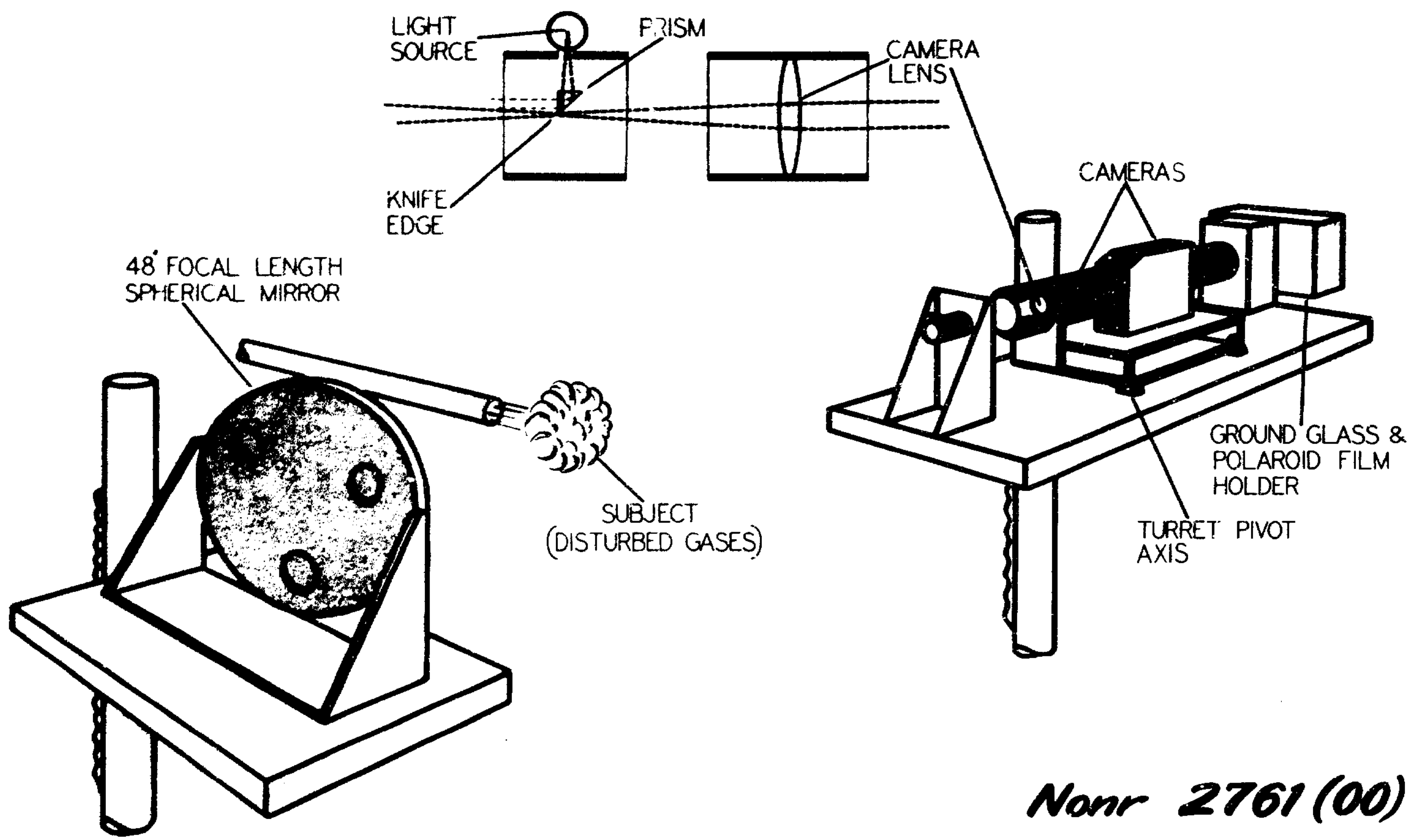


FIGURE 6: (CONTINUED)

SCHLIEREN HIGH-SPEED PHOTOGRAPHIC INSTALLATION



Nonr 2761(00)

FIGURE 7

PULSE REACTOR CYCLE DI

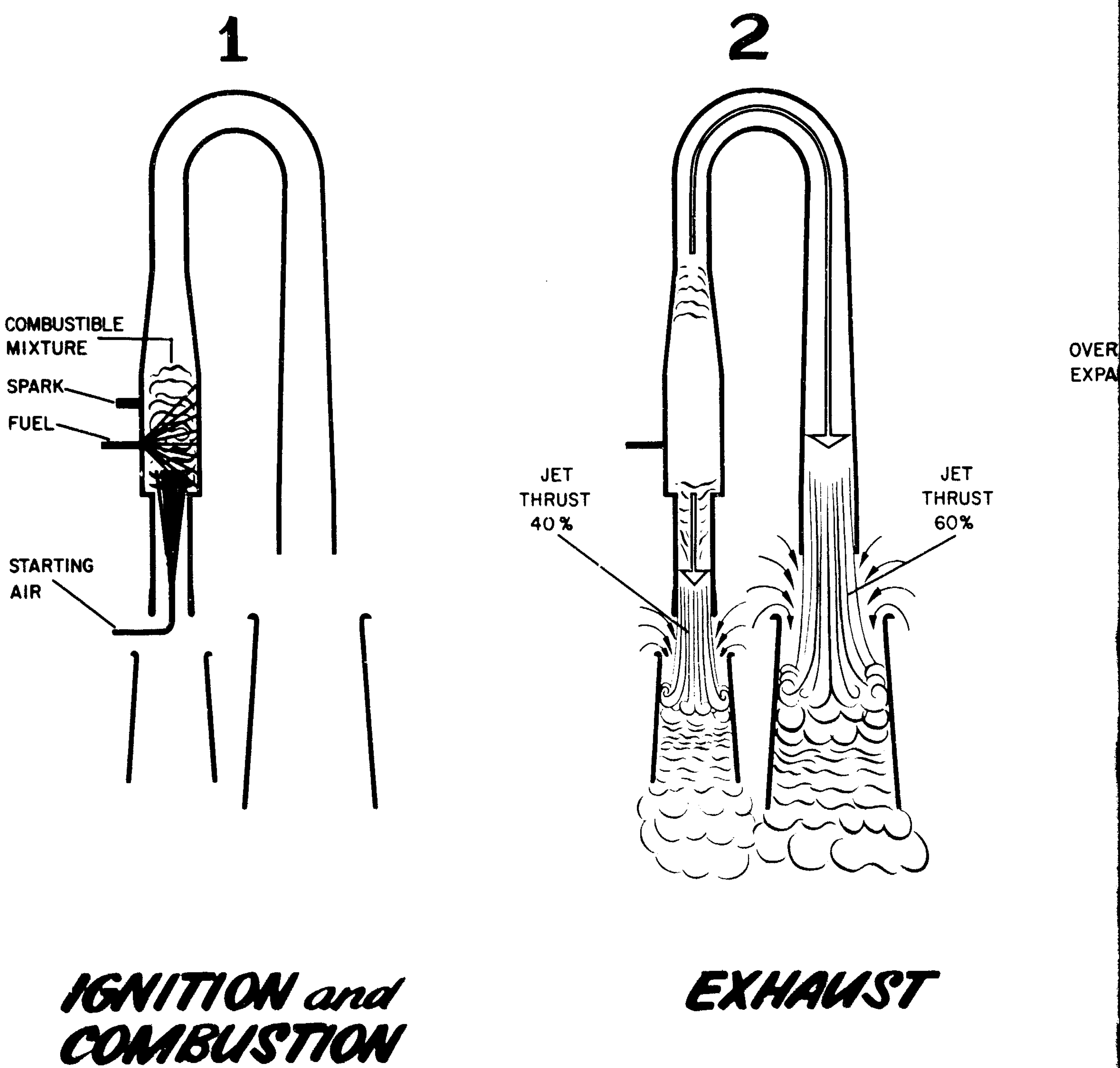


FIGURE 8

E DIAGRAM

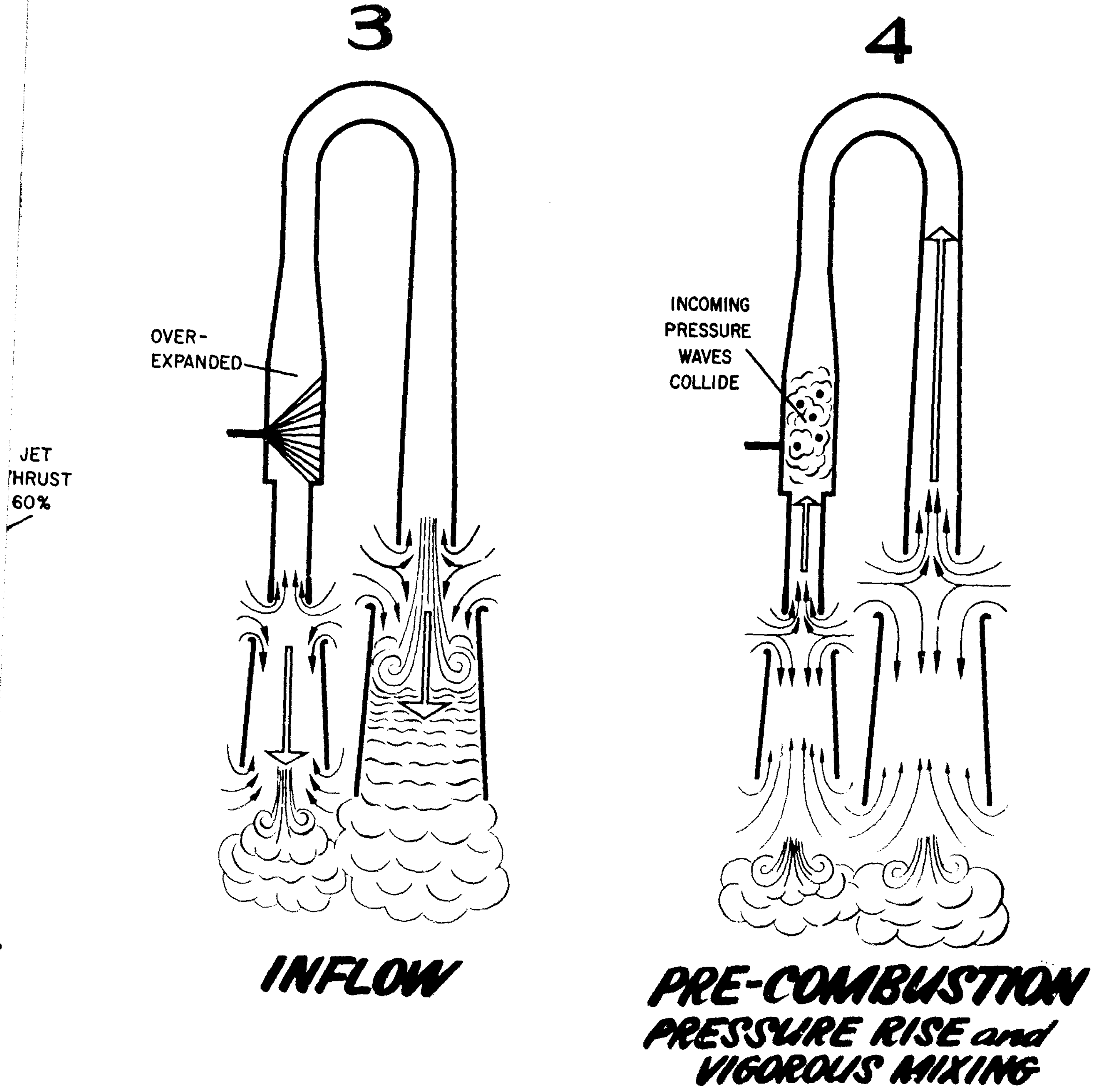


FIGURE 8

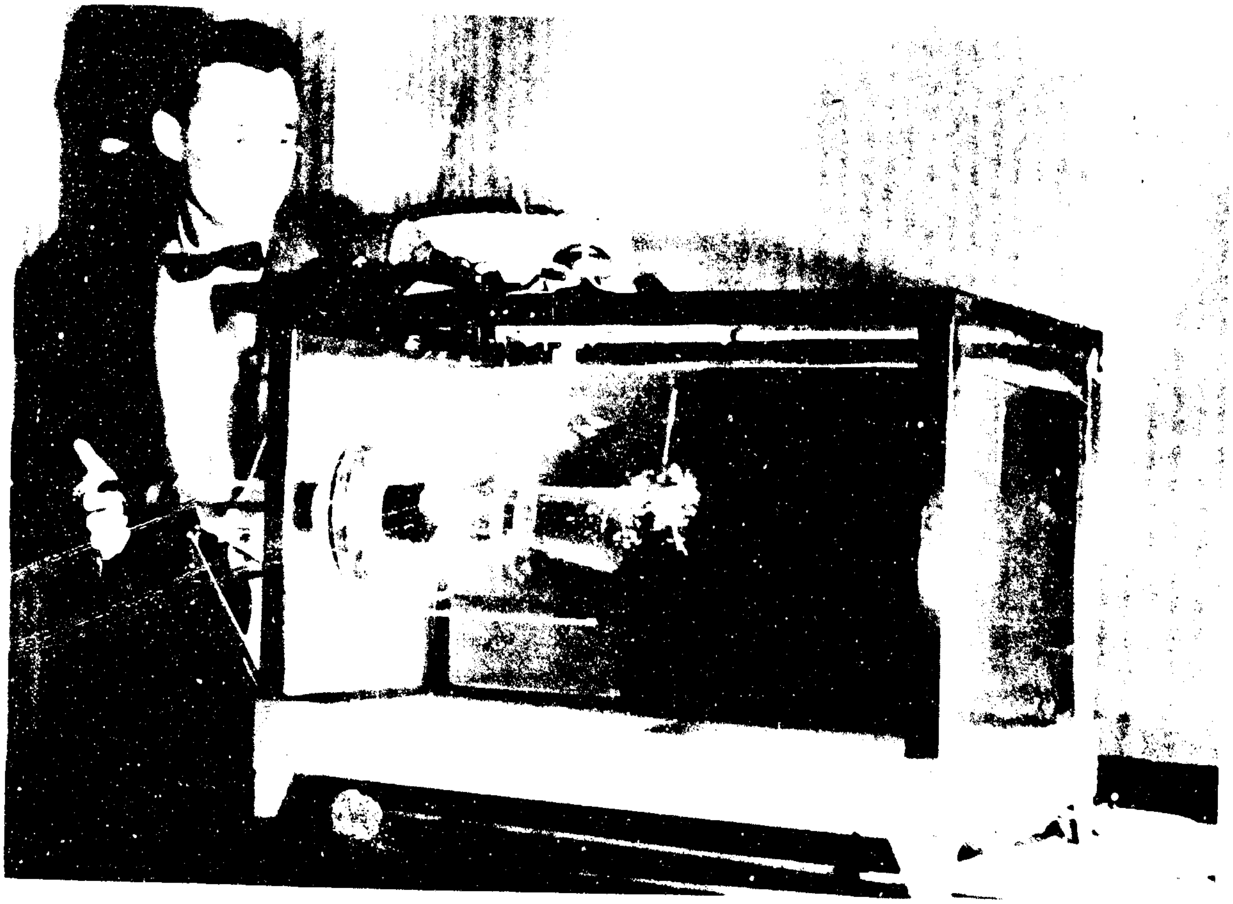


FIGURE 9. WATER TANK DEMONSTRATION OF INTERMITTENT JET FORMATION AND THRUST AUGMENTATION

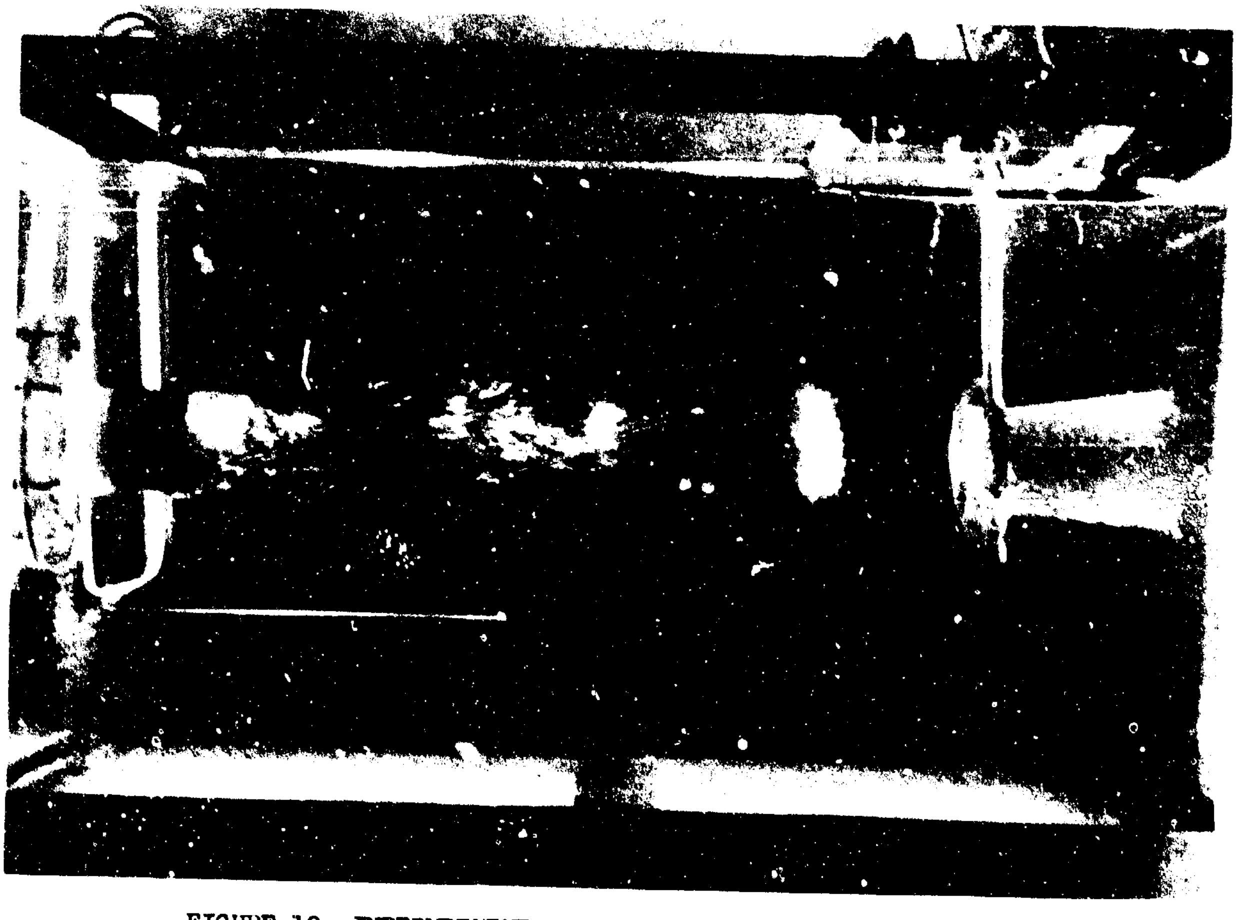


FIGURE 10. INTERMITTENT JET CAUSES RING VORTEX FORMATION

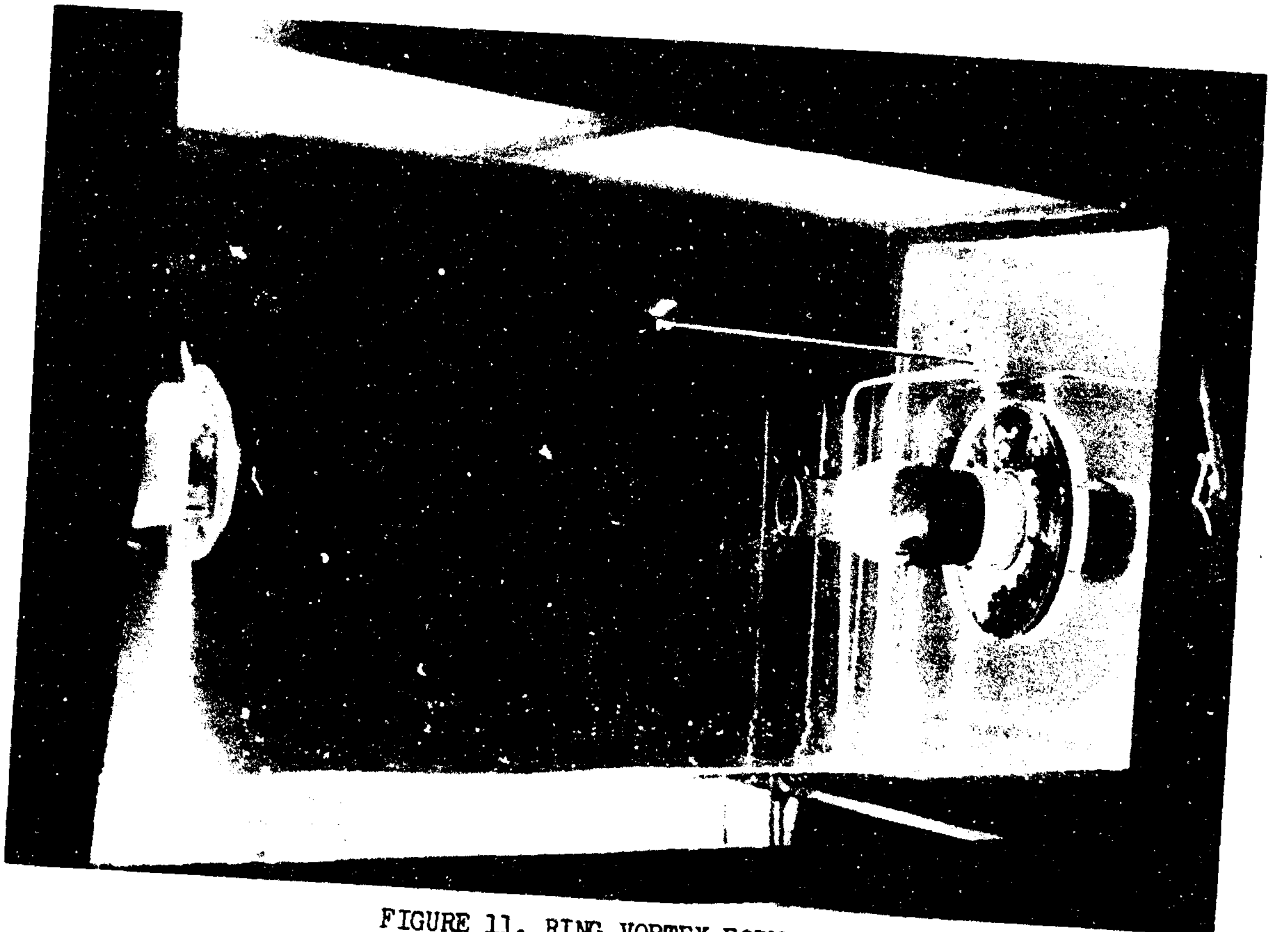


FIGURE 11. RING VORTEX FORMATION

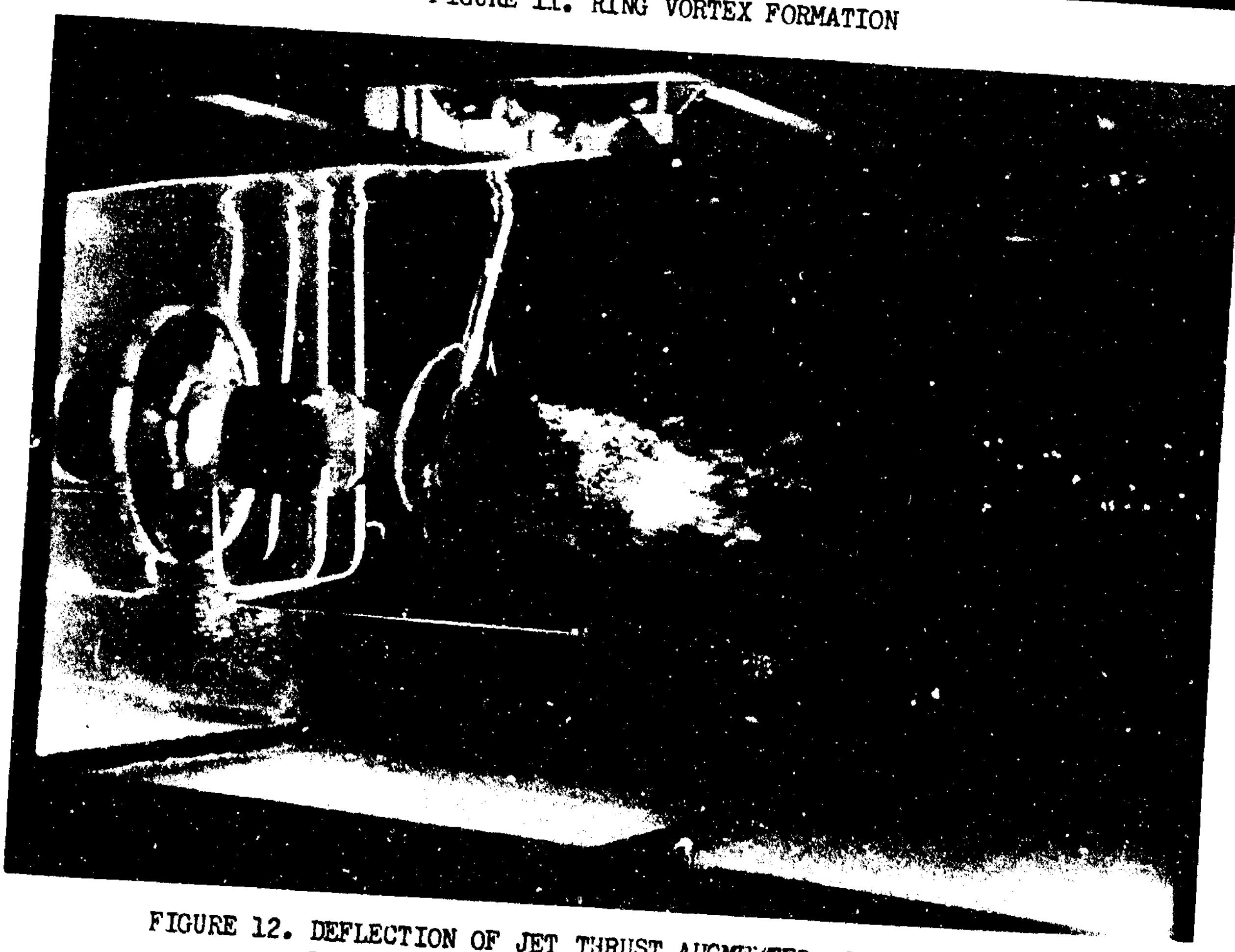


FIGURE 12. DEFLECTION OF JET THRUST AUGMENTER AS A RESULT OF ENERGY TRANSFER FROM INTERMITTENT JET TO AUGMENTER

AUGMENTER PERFORMANCE

COMPARISON OF STEADY and INTERMITTENT JET FLOW

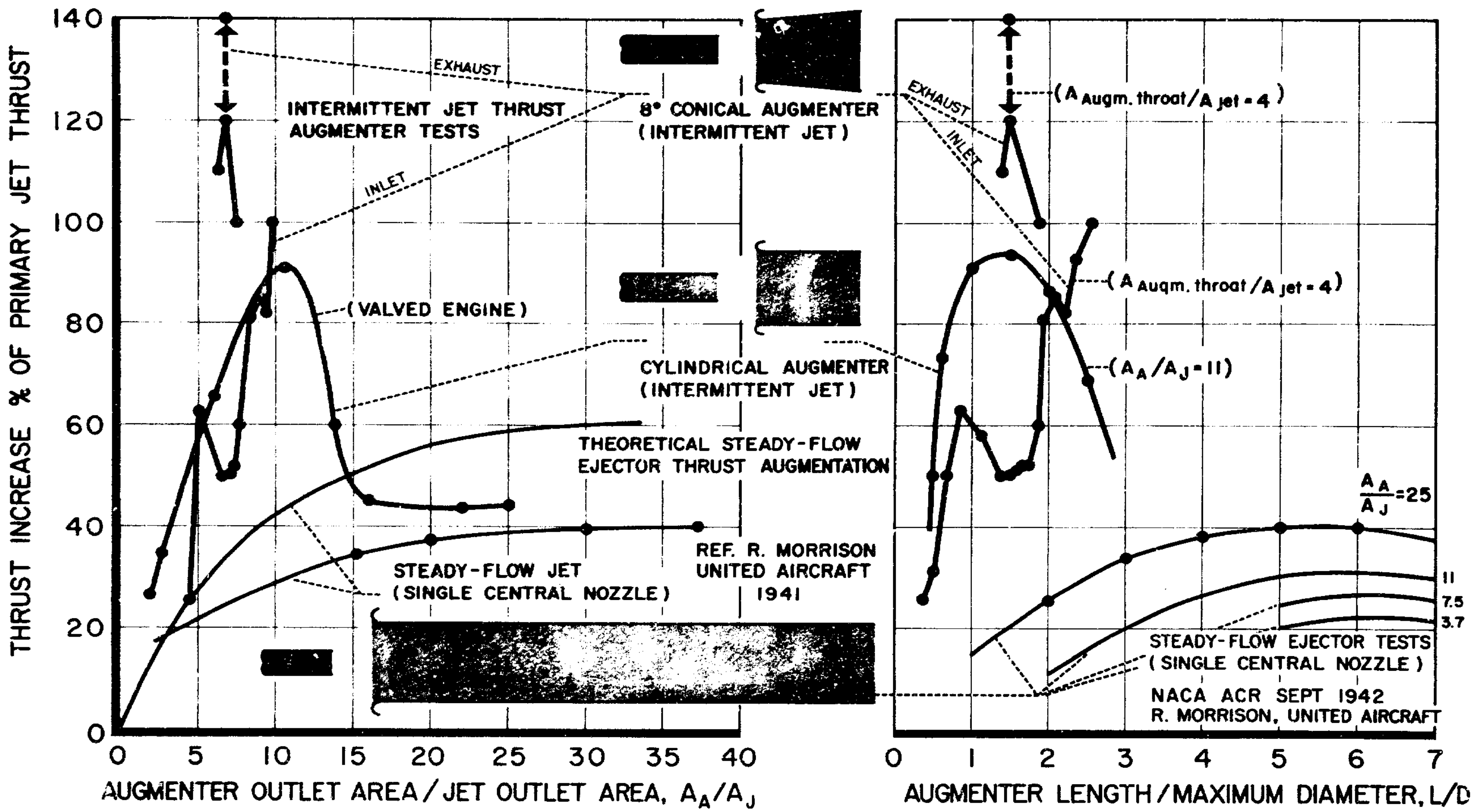


FIGURE 13

FIGURE 14. PULSE REACTOR TEST STAND

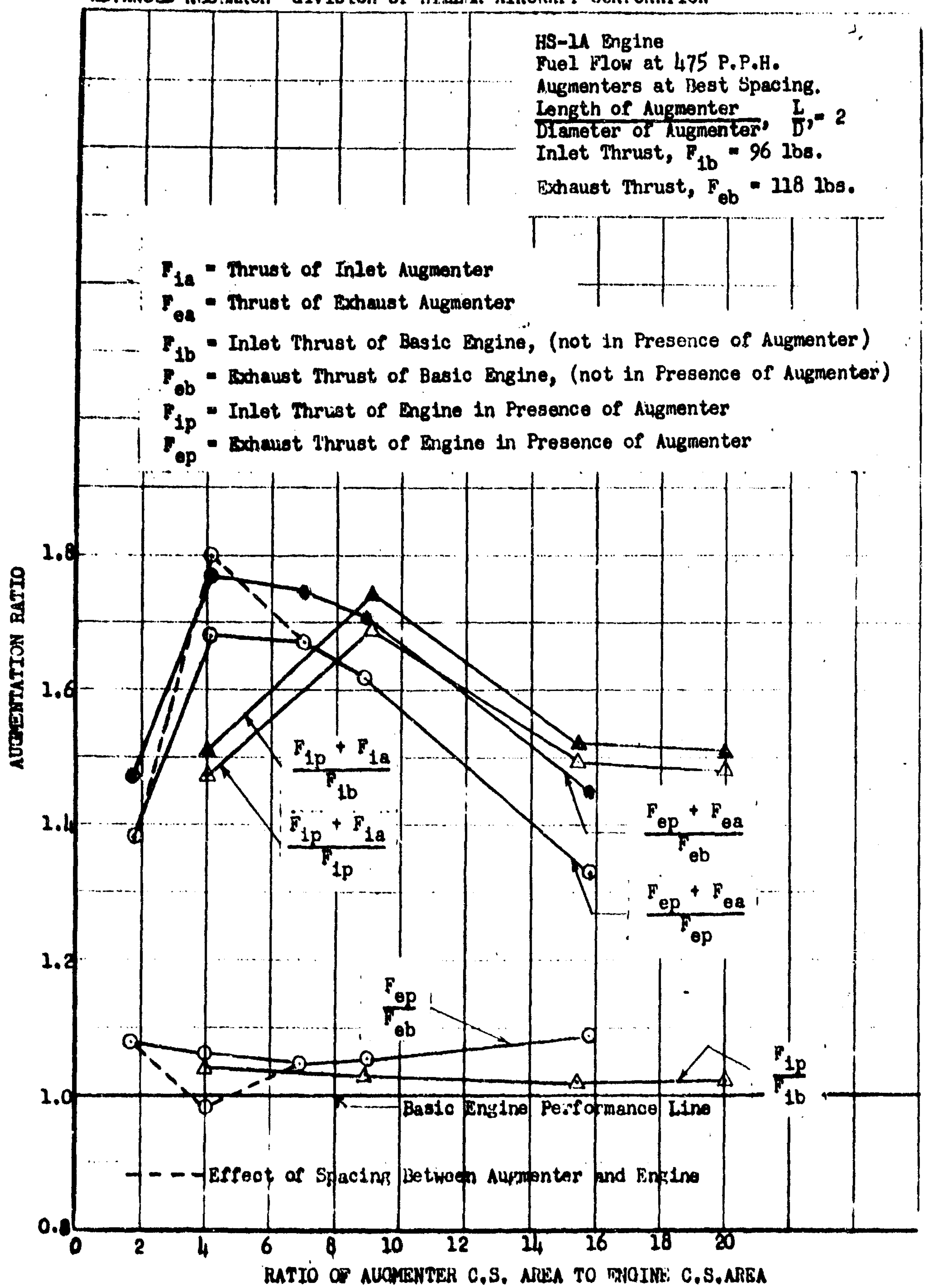


FIGURE 15: PERFORMANCE OF CYLINDRICAL AUGMENTERS

PULSE REACTOR PERFORMANCE

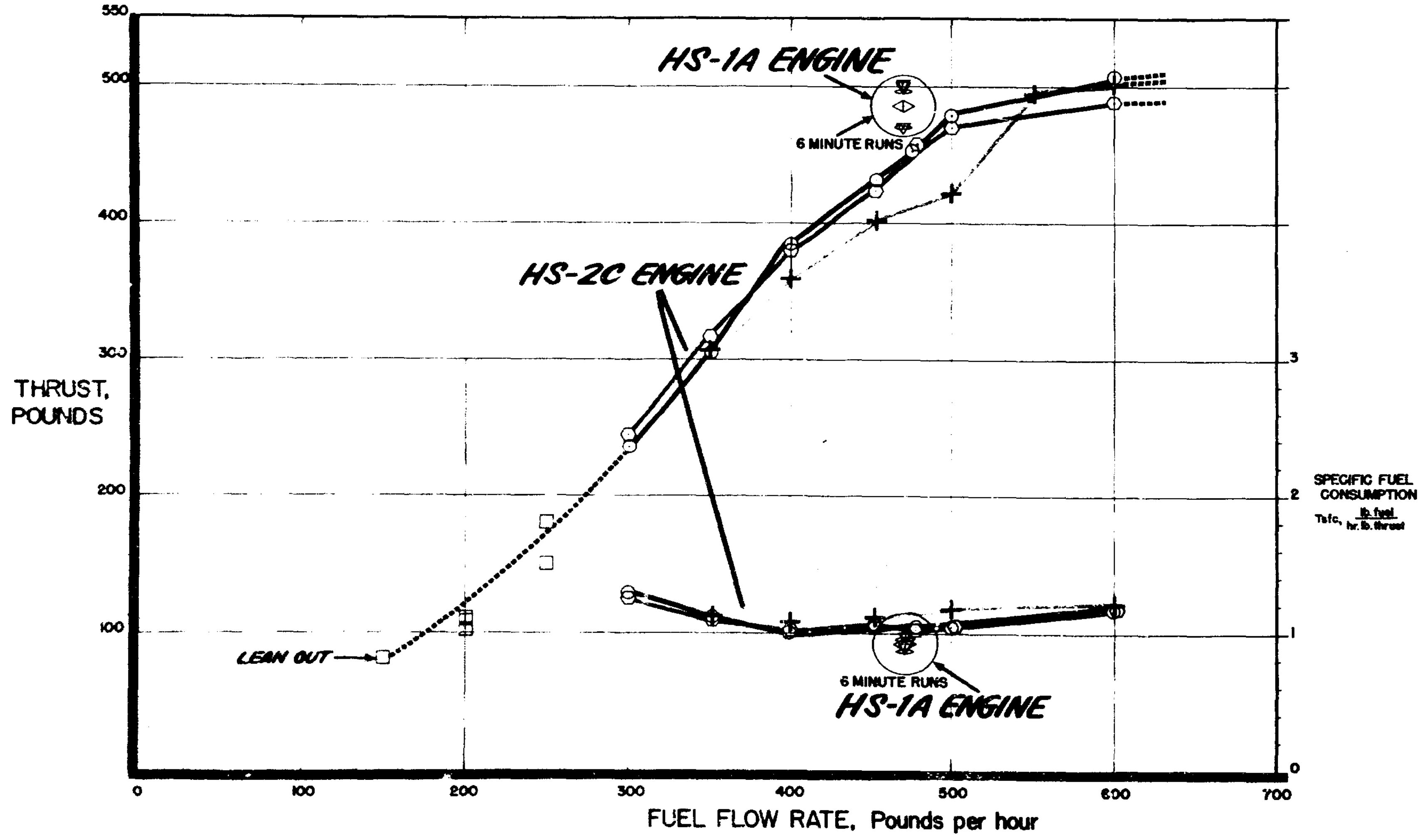


FIGURE 16

TYPICAL PULSE REACTOR CONFIGURATIONS

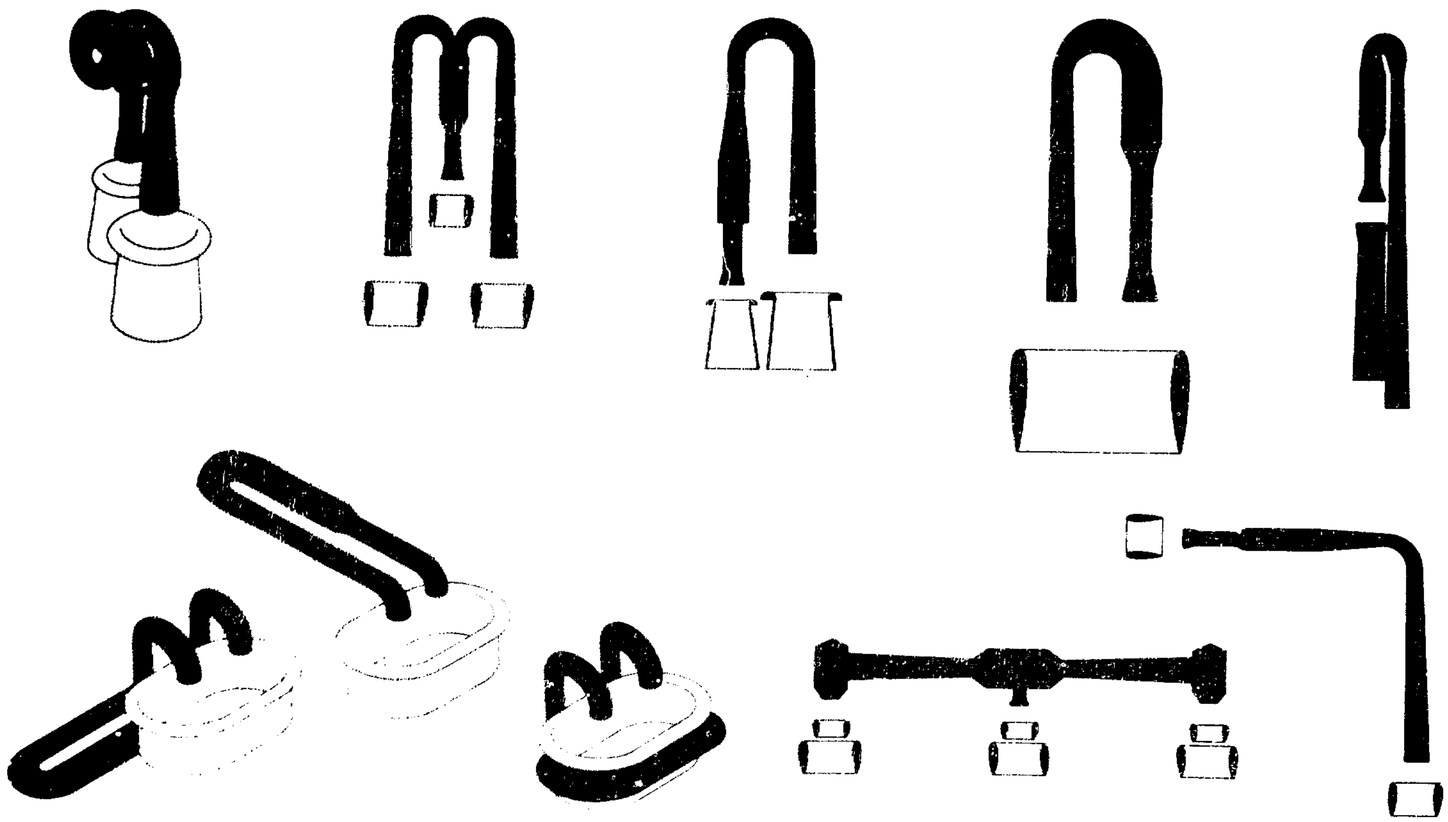


FIGURE 17

PROPULSION SYSTEMS COMPARISON

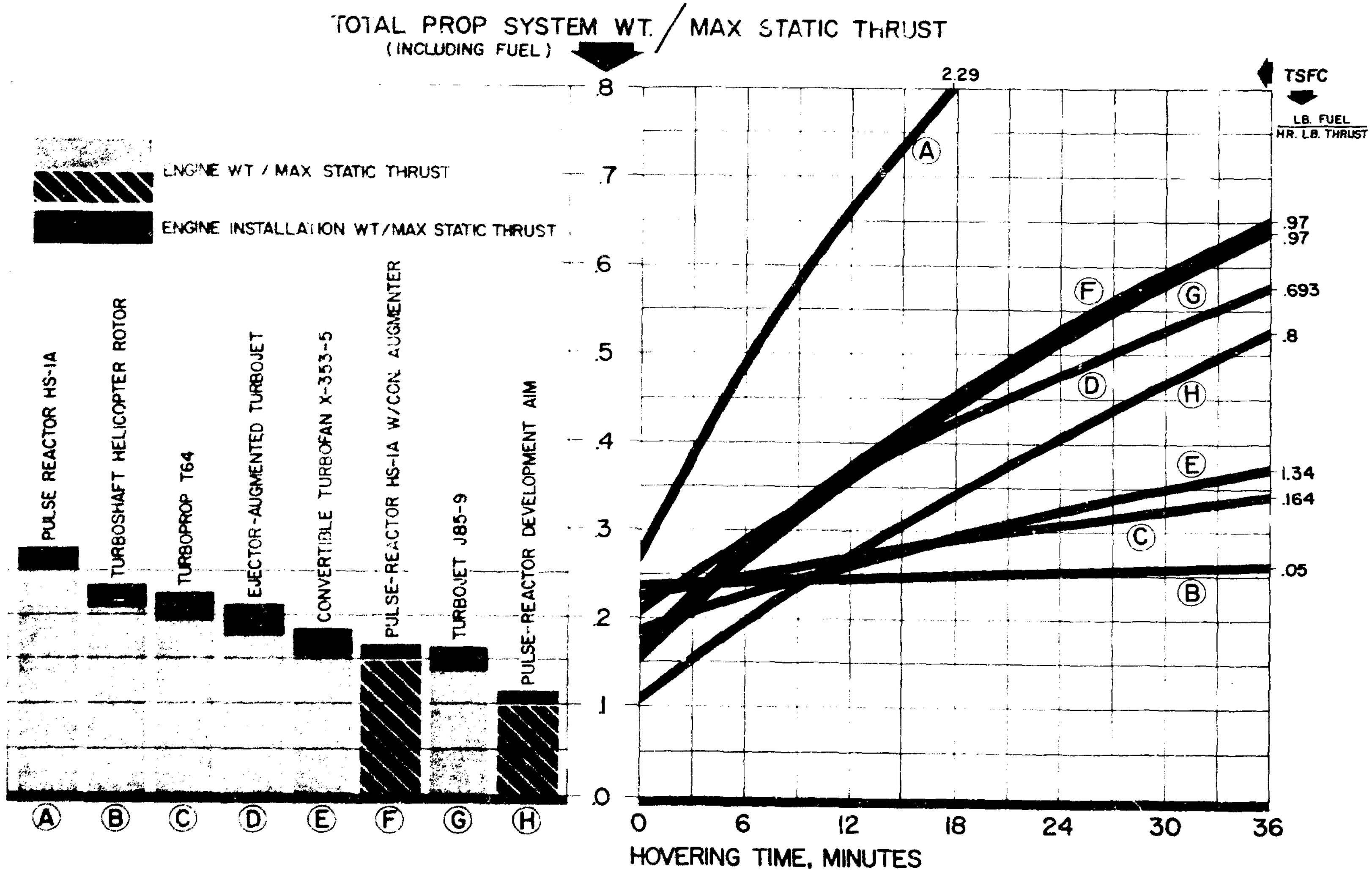


FIGURE 18

TYPICAL TURBOJET ENGINE

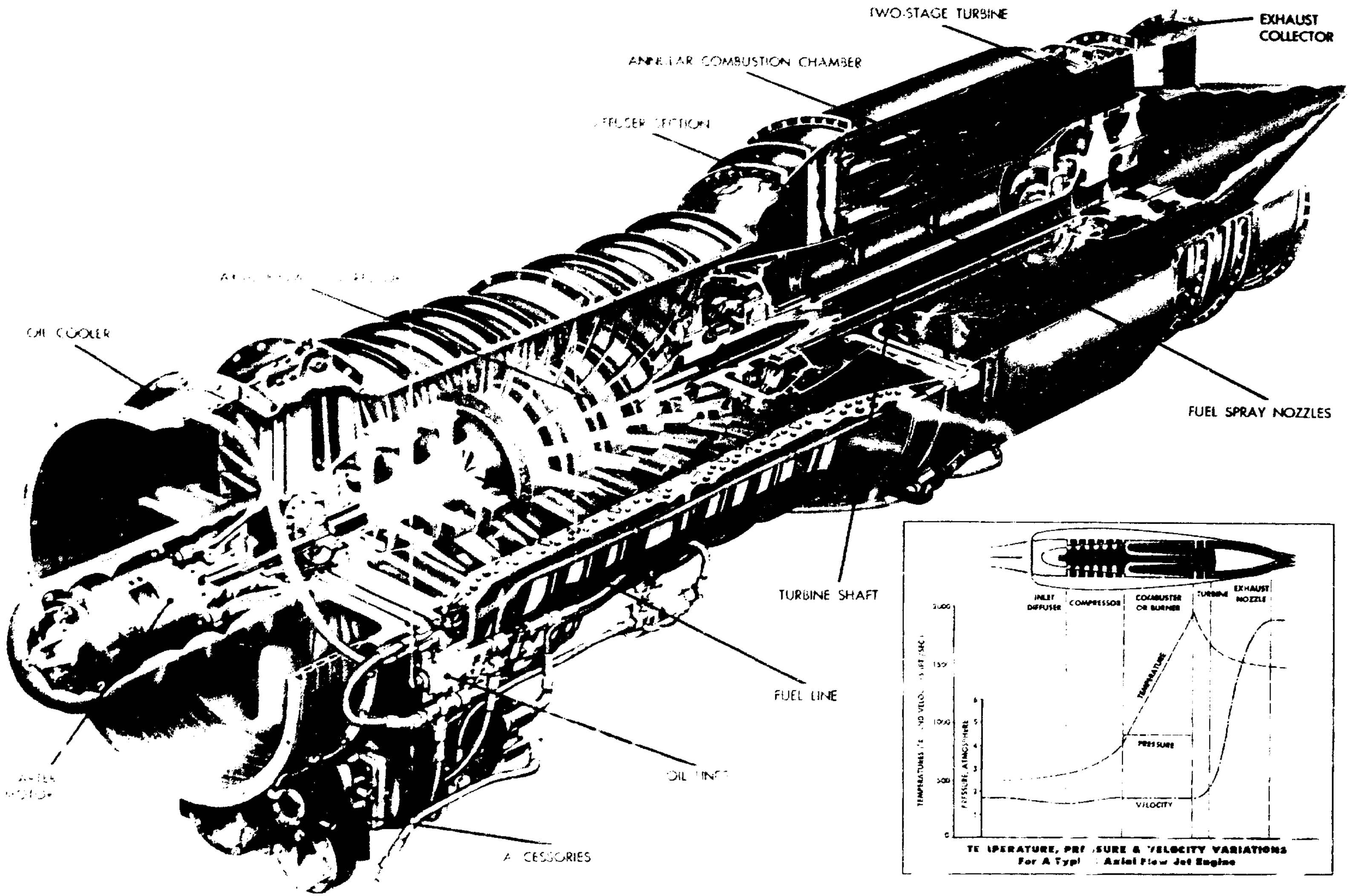


FIGURE 19

PULSE REACTOR WAKE CHARACTERISTICS

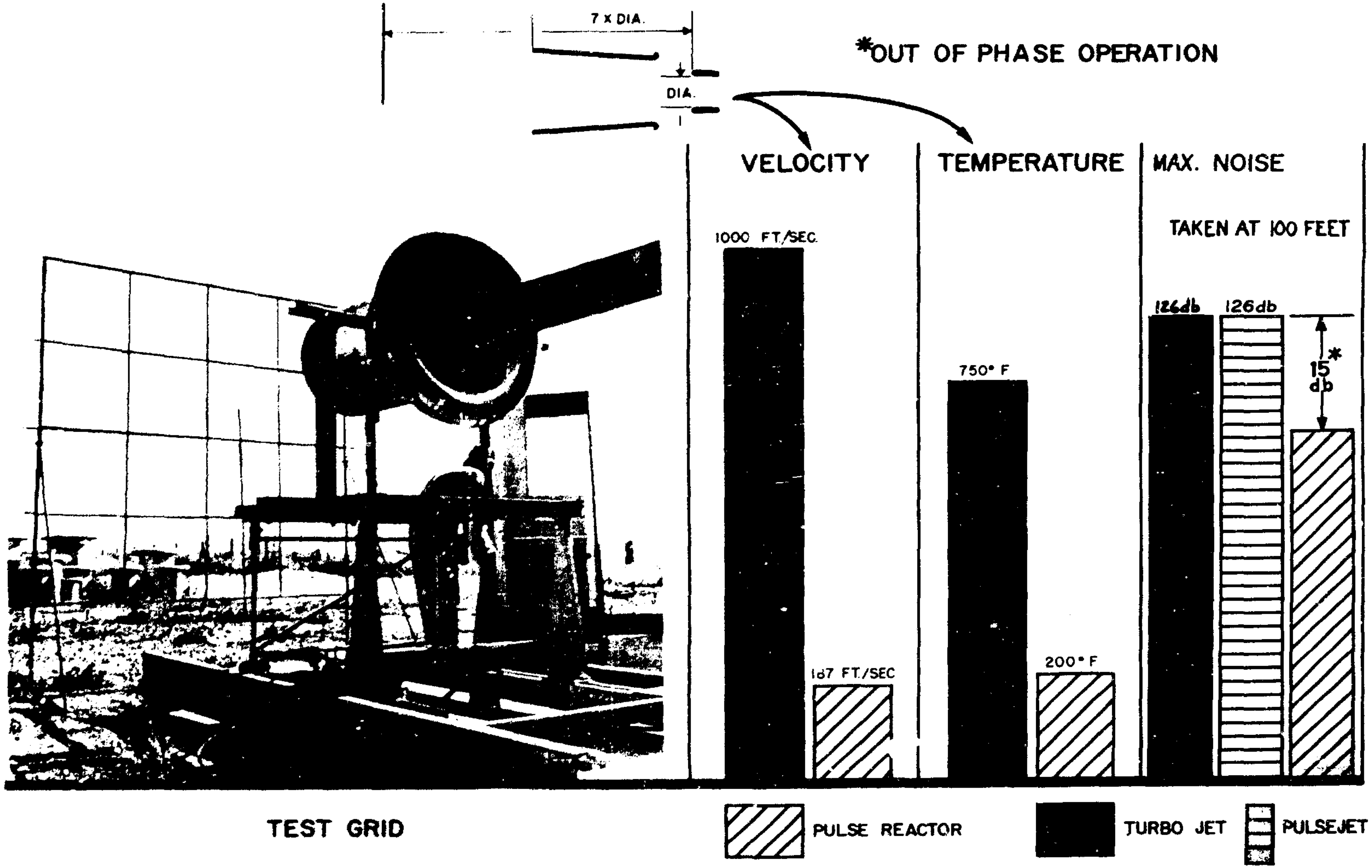


FIGURE 20

RECIRCULATION

DA44-177-TC-500

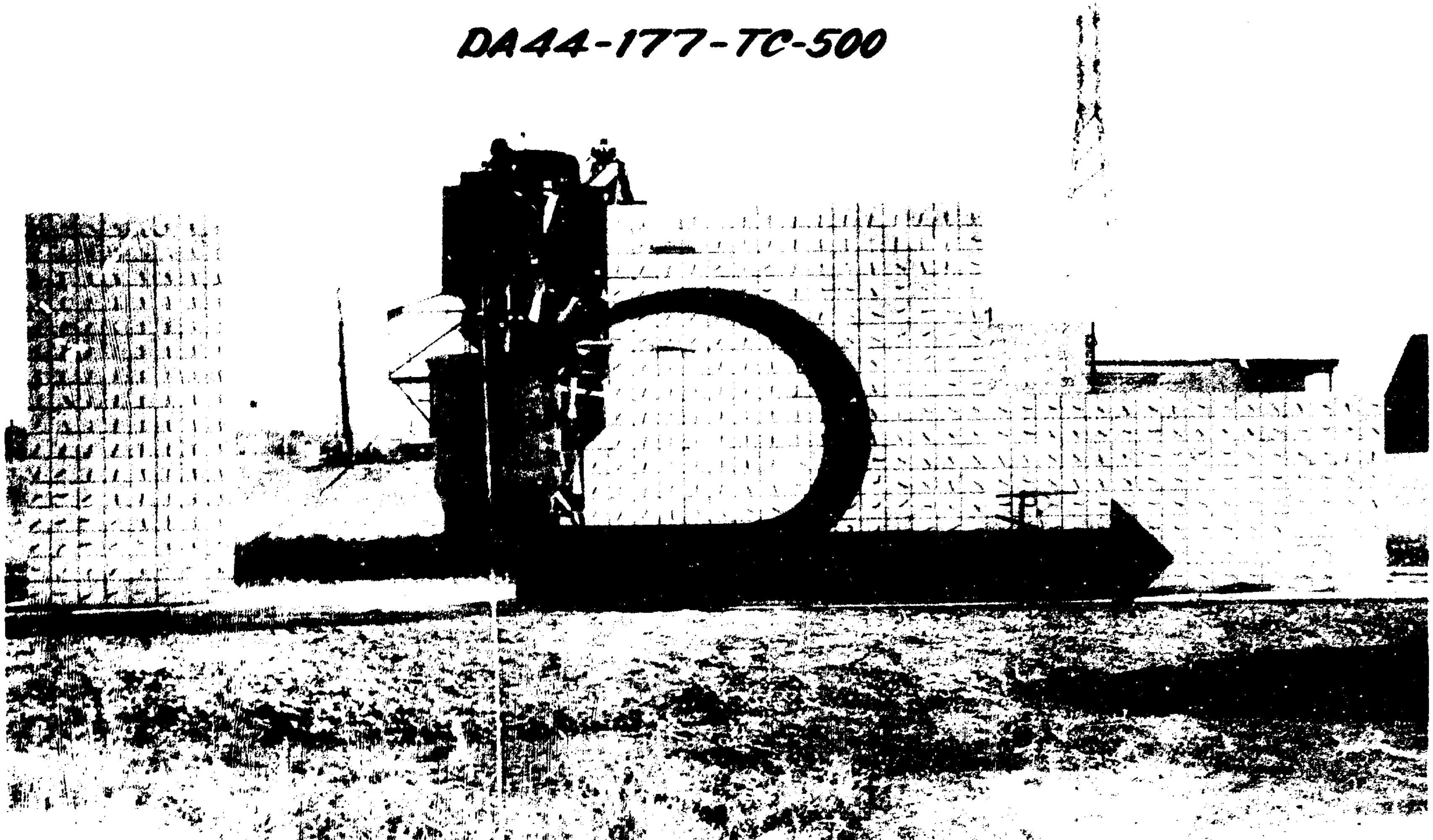


FIGURE 21

FIGURE 21a: PULSE REACTOR FLOW PATTERN REJECTING ROCKS DUMPED DOWN CHUTE TOWARDS AIR INLET

SC.1 INTAKE BLANKETING

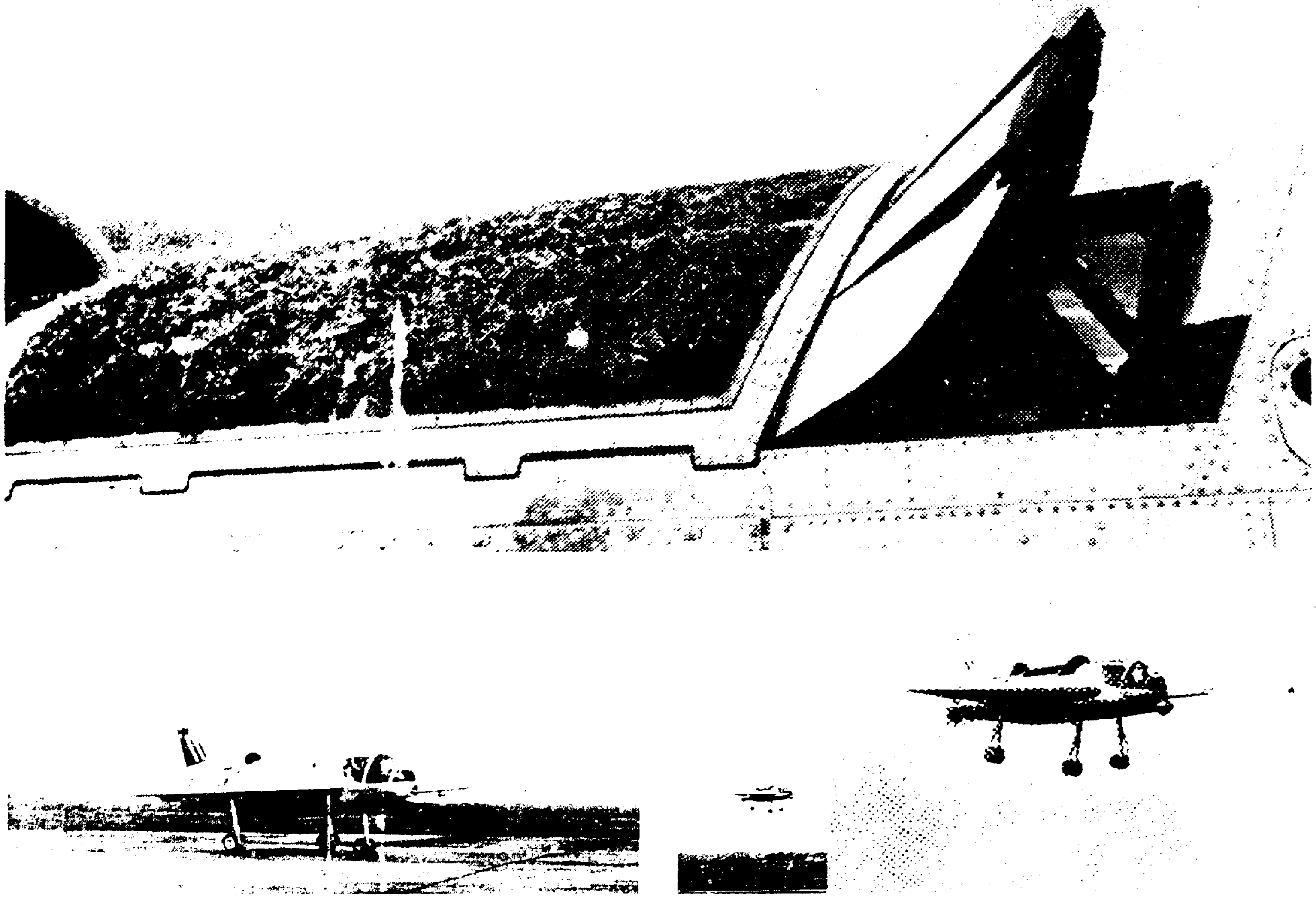


FIGURE 22

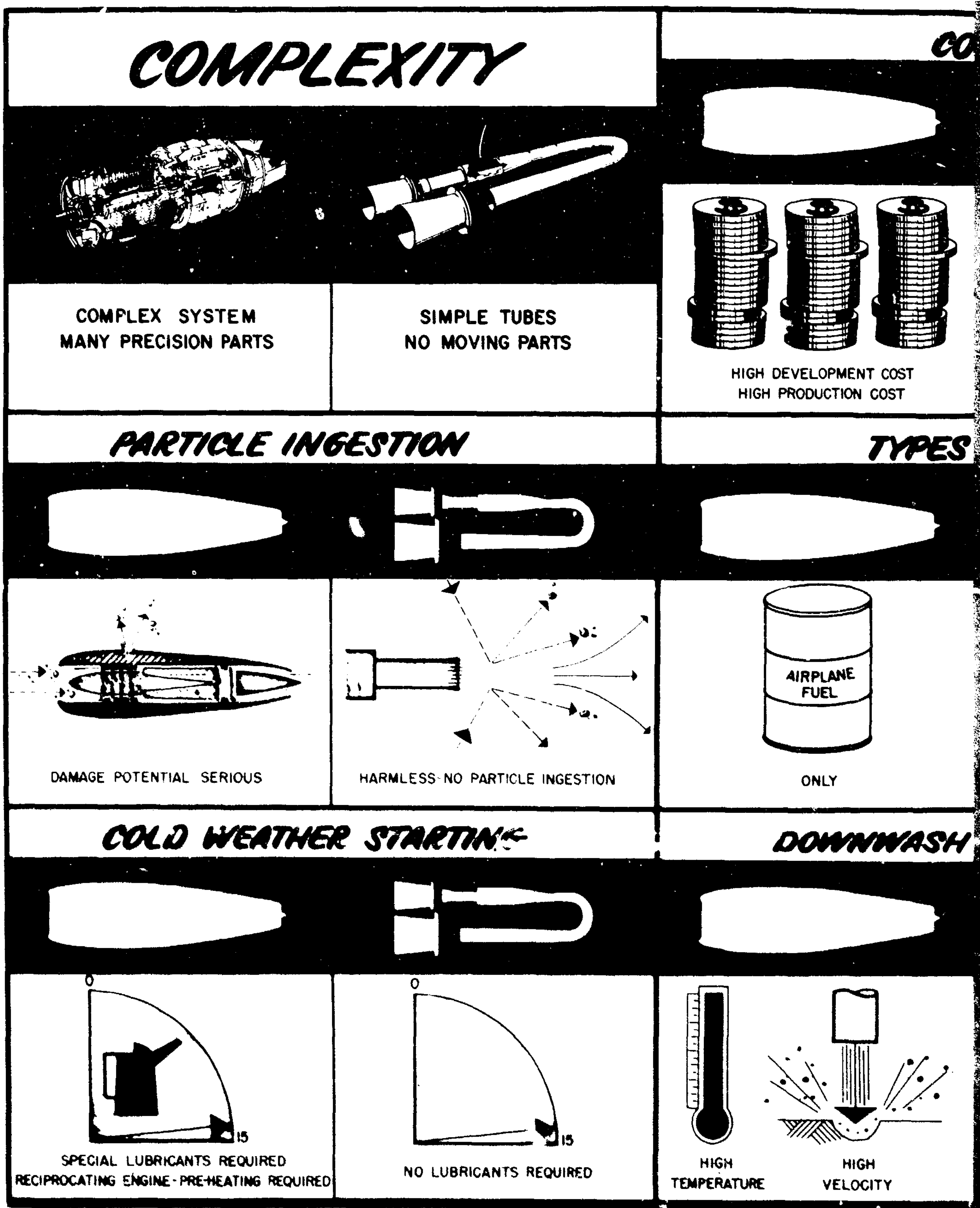
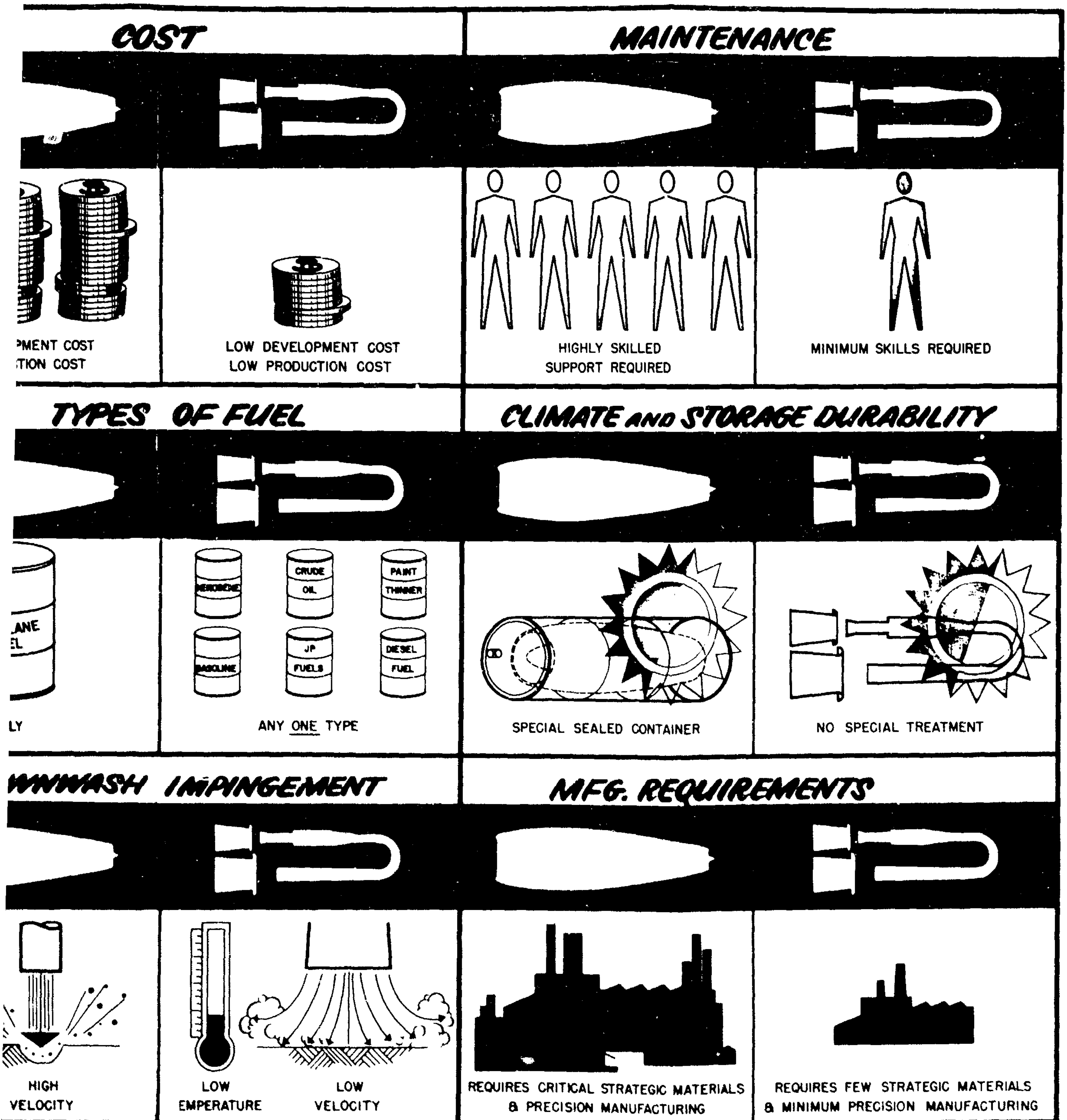
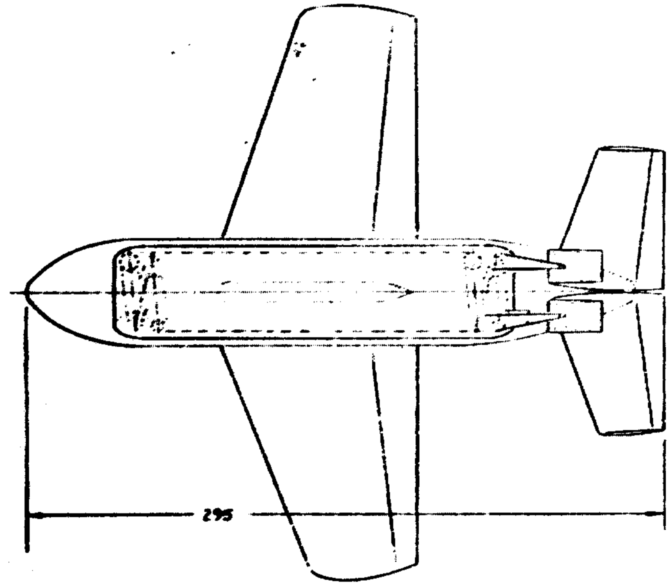


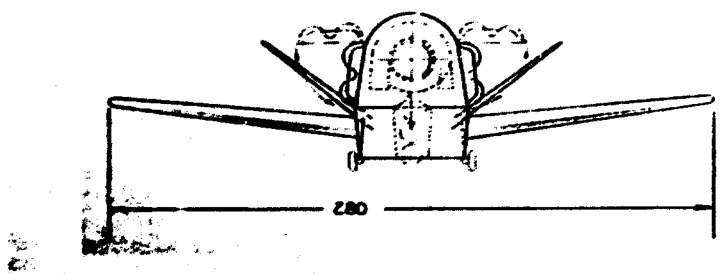
FIGURE 23: SUMMARY OF P

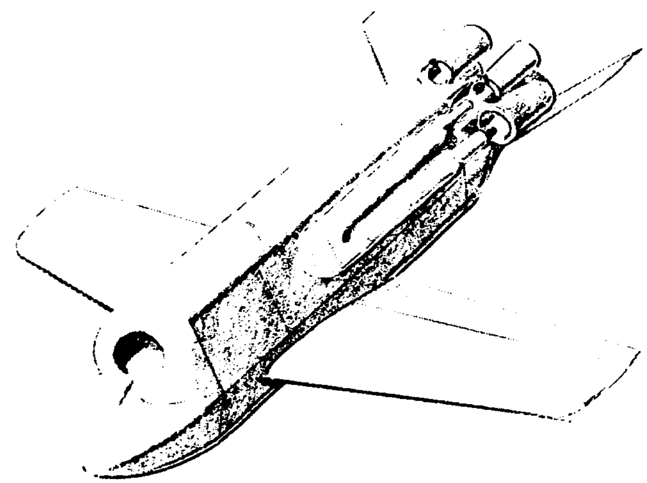


SUMMARY OF PULSE REACTOR CHARACTERISTICS

ASW DRONE-WINGED AIRCRAFT







PERFORMANCE

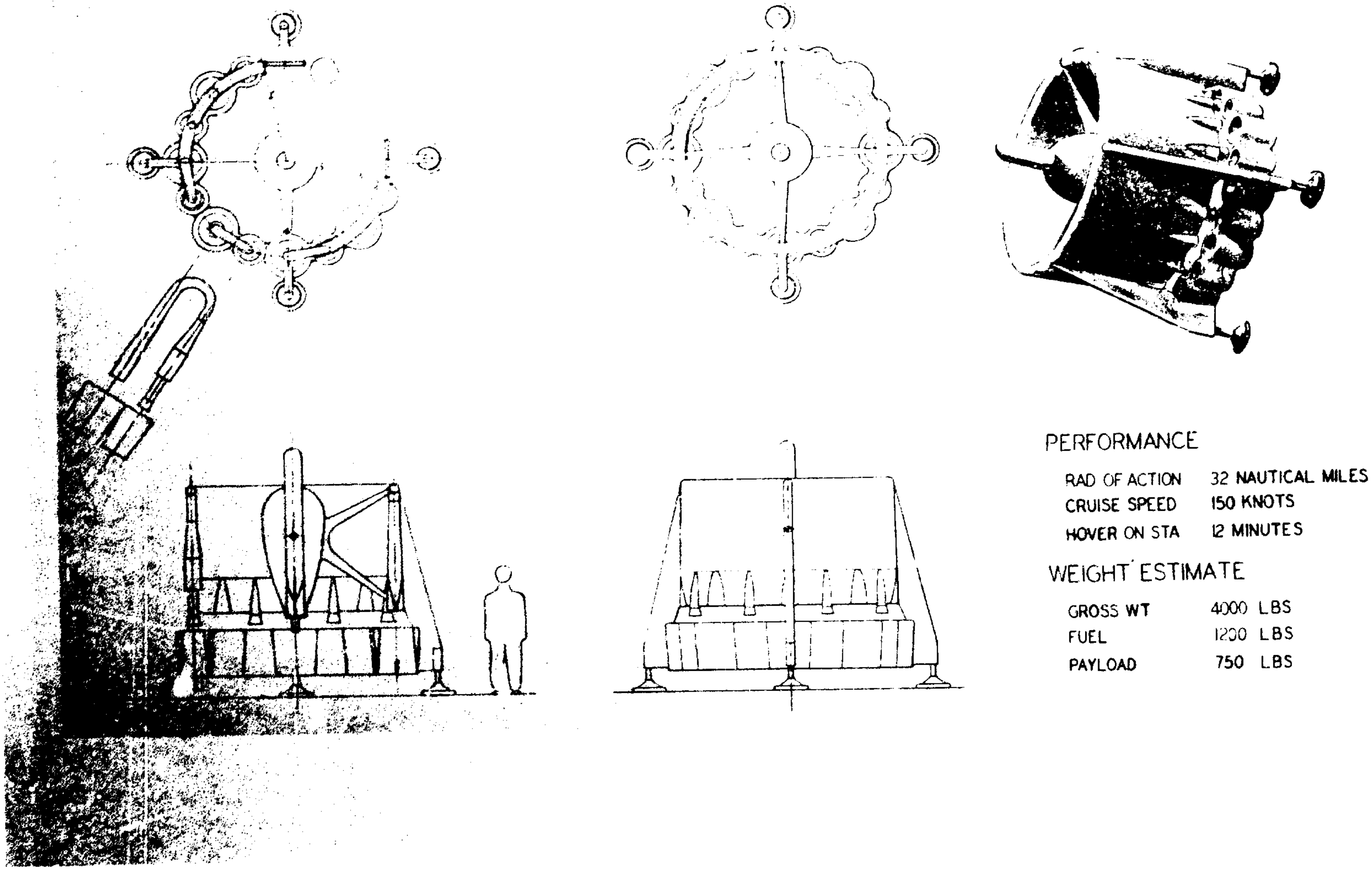
RAD OF ACTION	32 NAUTICAL MILES
CRUISE SPEED	150 KNOTS
HOVER ON STA	12 MINUTES

WEIGHT ESTIMATE

GROSS WT	[illegible] LBS
FUEL	1020 LBS
PAYLOAD	750 LBS

FIGURE 24

ASW DRONE - RING WING



PERFORMANCE

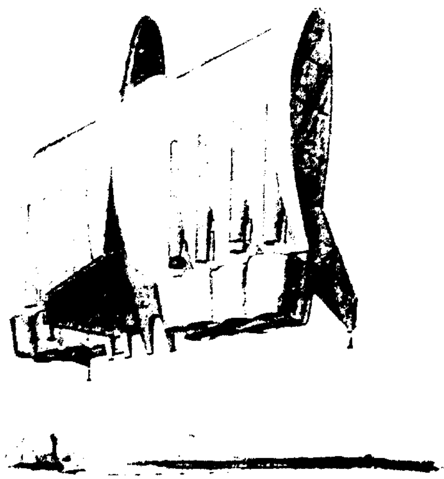
RAD OF ACTION	32 NAUTICAL MILES
CRUISE SPEED	150 KNOTS
HOVER ON STA	12 MINUTES

WEIGHT ESTIMATE

GROSS WT	4000 LBS
FUEL	1200 LBS
PAYLOAD	750 LBS

FIGURE 25

ASW DRONE TAIL SITTER



PERFORMANCE

RAD OF ACTION	32 NAUTICAL MILES
CRUISE SPEED	150 KNOTS
HOVER ON STA	12 MINUTES

WEIGHT ESTIMATE

GROSS WT	3700 LBS
FUEL	1150 LBS
PAYLOAD	750 LBS

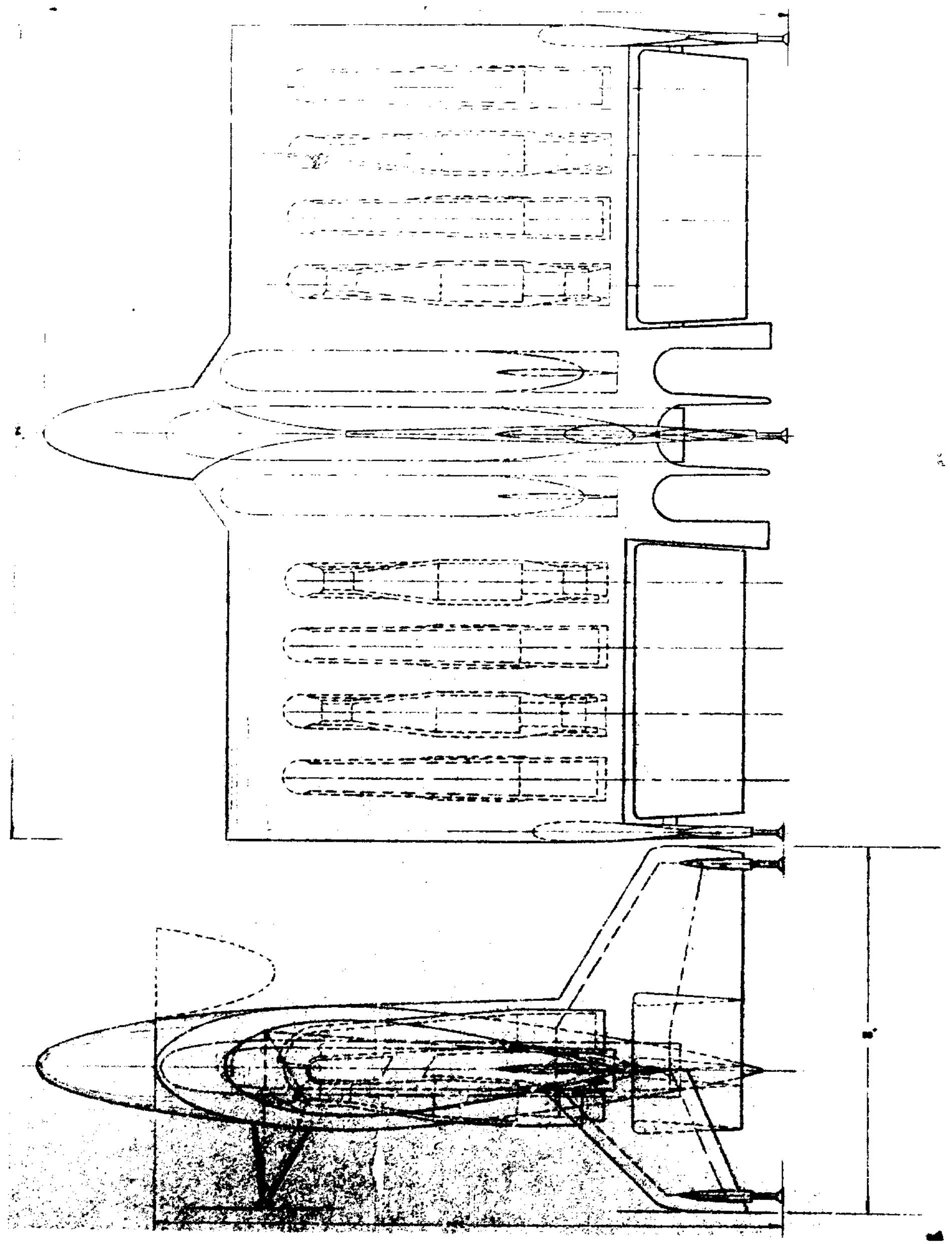
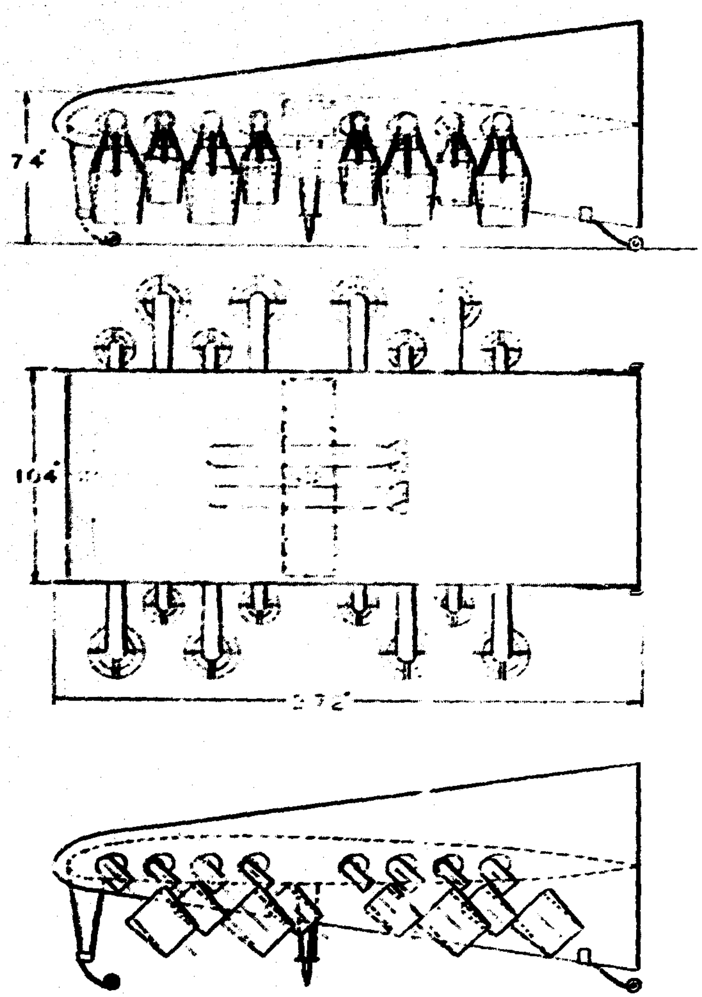


FIGURE 26

BODY LIFT-ROTATABLE PULSE REACTORS



PERFORMANCE

RAD OF ACTION	32 NAUTICAL MILES
CRUISE SPEED	150 KNOTS
HOVER ON STA	12 MINUTES

WEIGHT ESTIMATE

GROSS WT	3700 LBS
FUEL	1150 LBS
PAYLOAD	750 LBS

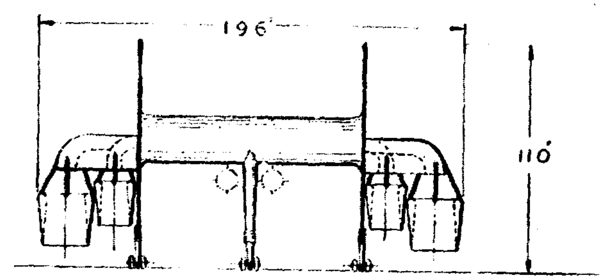
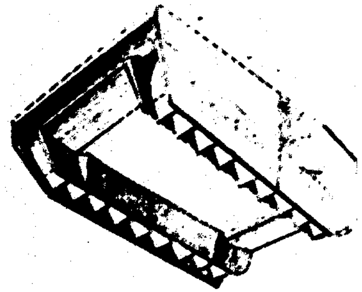


FIGURE 27

BODY LIFT-VARIABLE EXIT VANES

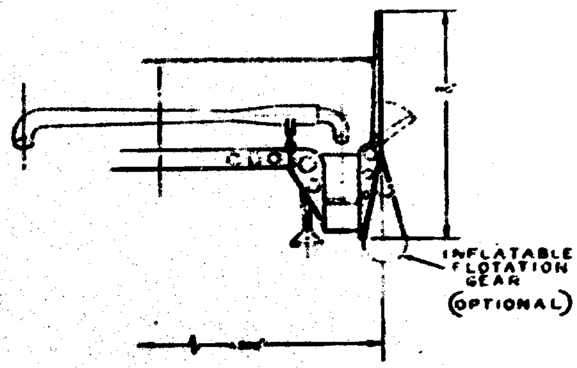


PERFORMANCE

RAD OF ACTION	32 NAUTICAL MILES
CRUISE SPEED	150 KNOTS
HOVER ON STA	12 MINUTES

WEIGHT ESTIMATE

GROSS WT	3800LBS
FUEL	1150 LBS
PAYLOAD	750 LBS



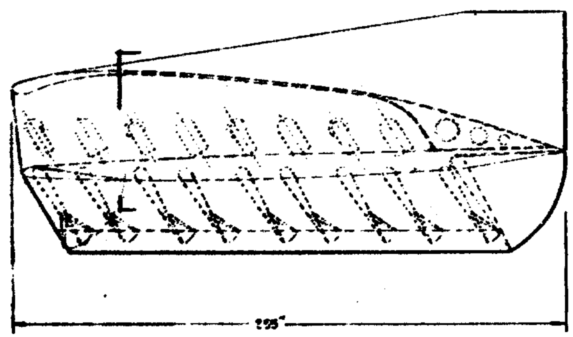


FIGURE 28

PULSE REACTOR BOOSTER

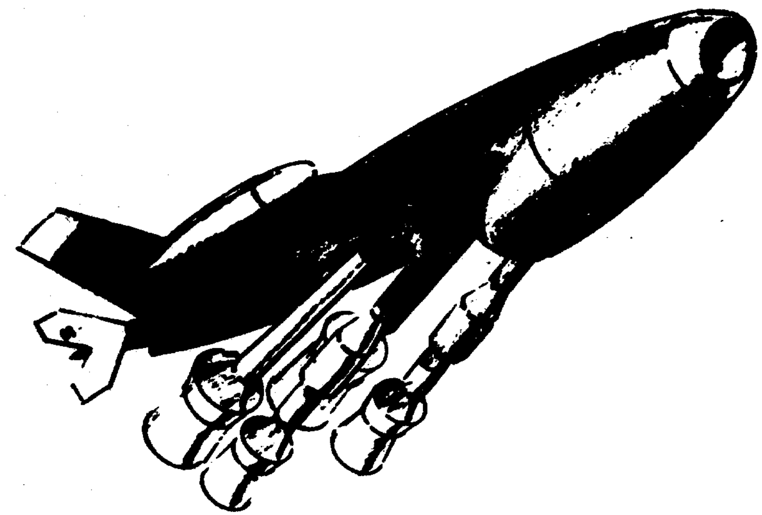


FIGURE 29

GROUND EFFECT MACHINES with PULSE REACTOR PROPULSION

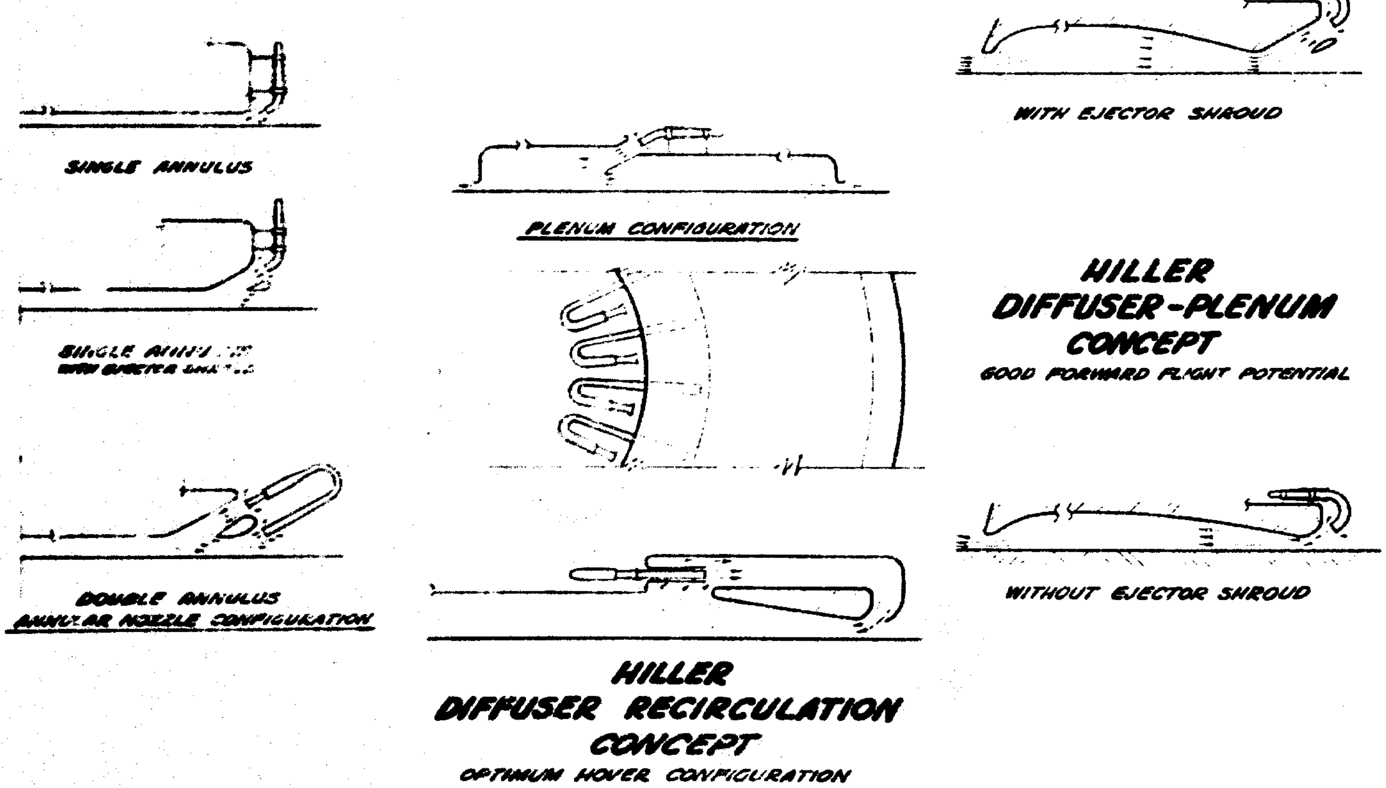
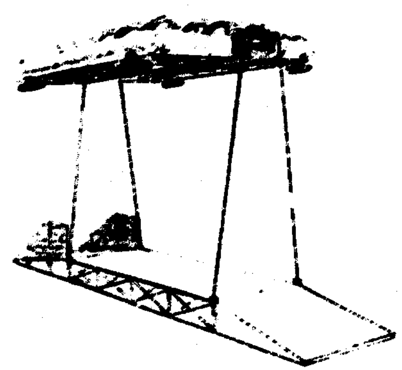


FIGURE 30

FLYING CRANE



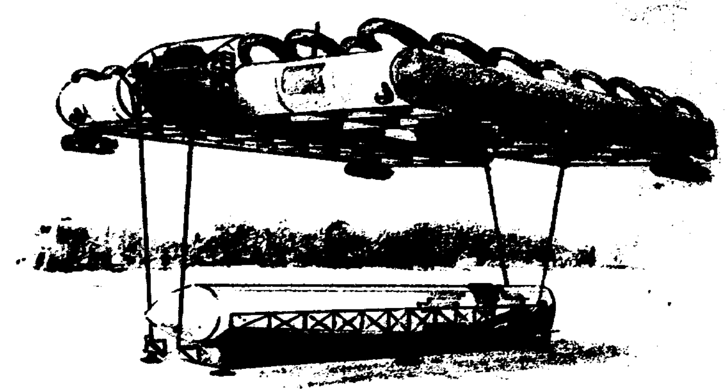


FIGURE 31

ASSAULT AIRCRAFT

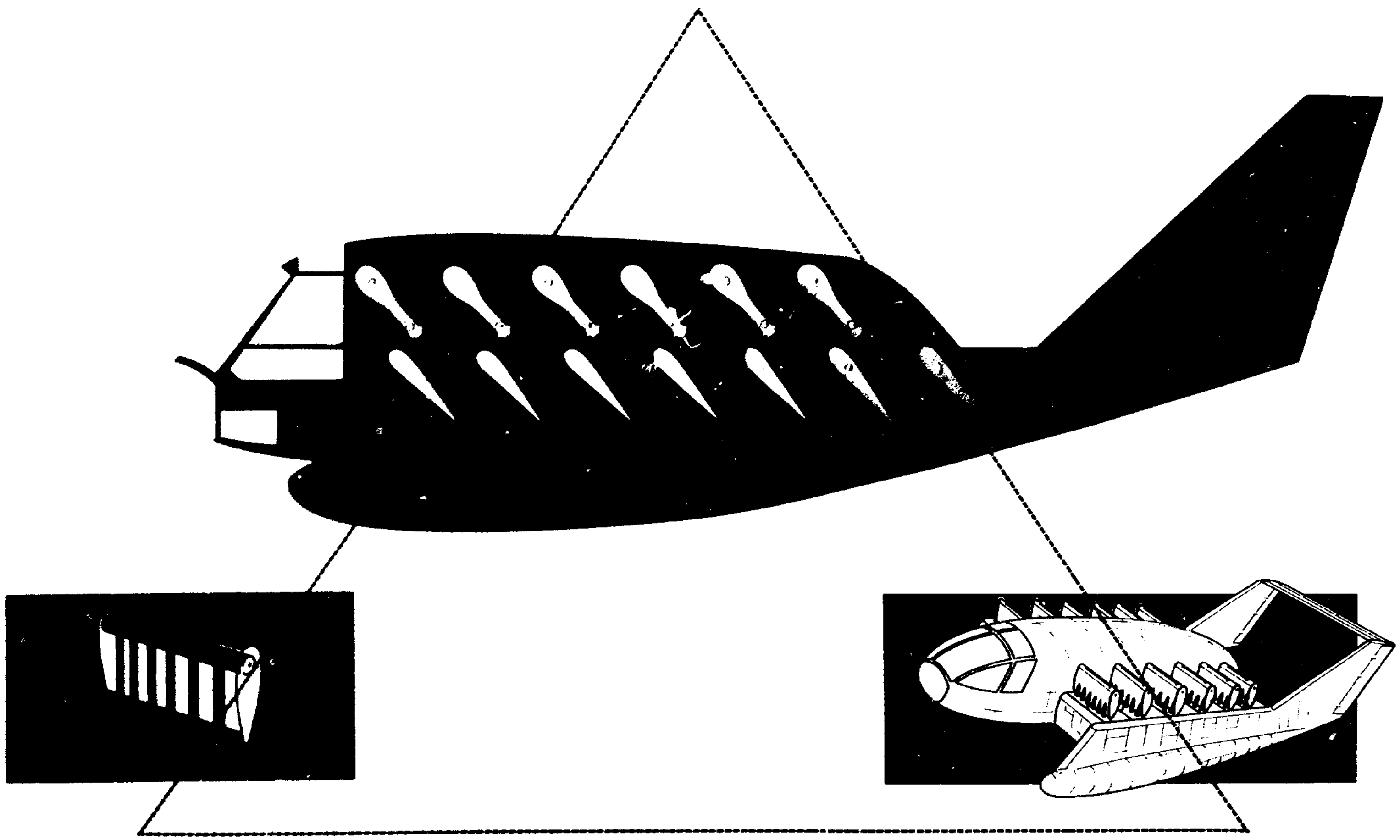


FIGURE 32

MIXED PROPULSION AIRCRAFT

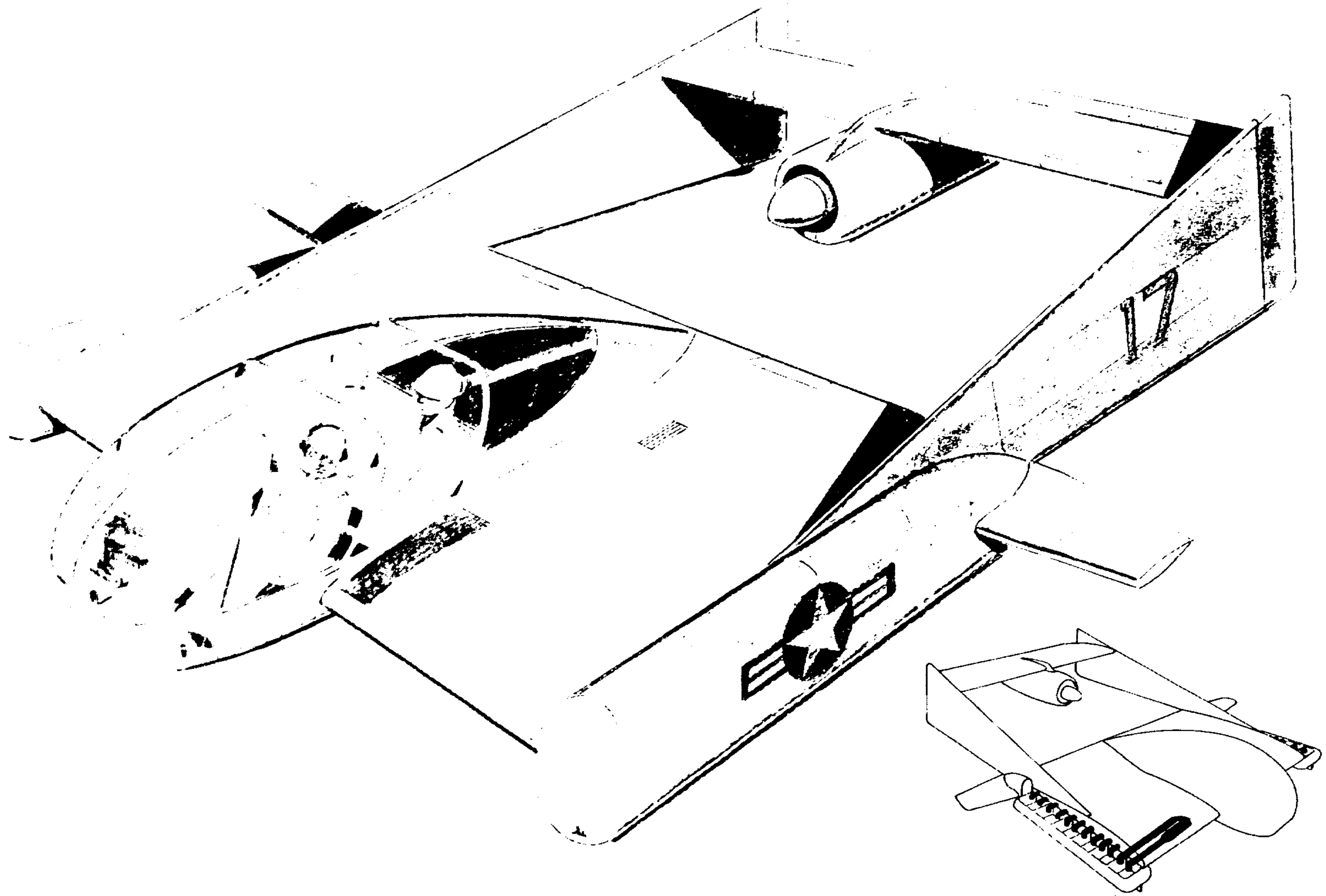


FIGURE 33

HI-SPEED - BODY LIFT - JET VTOL

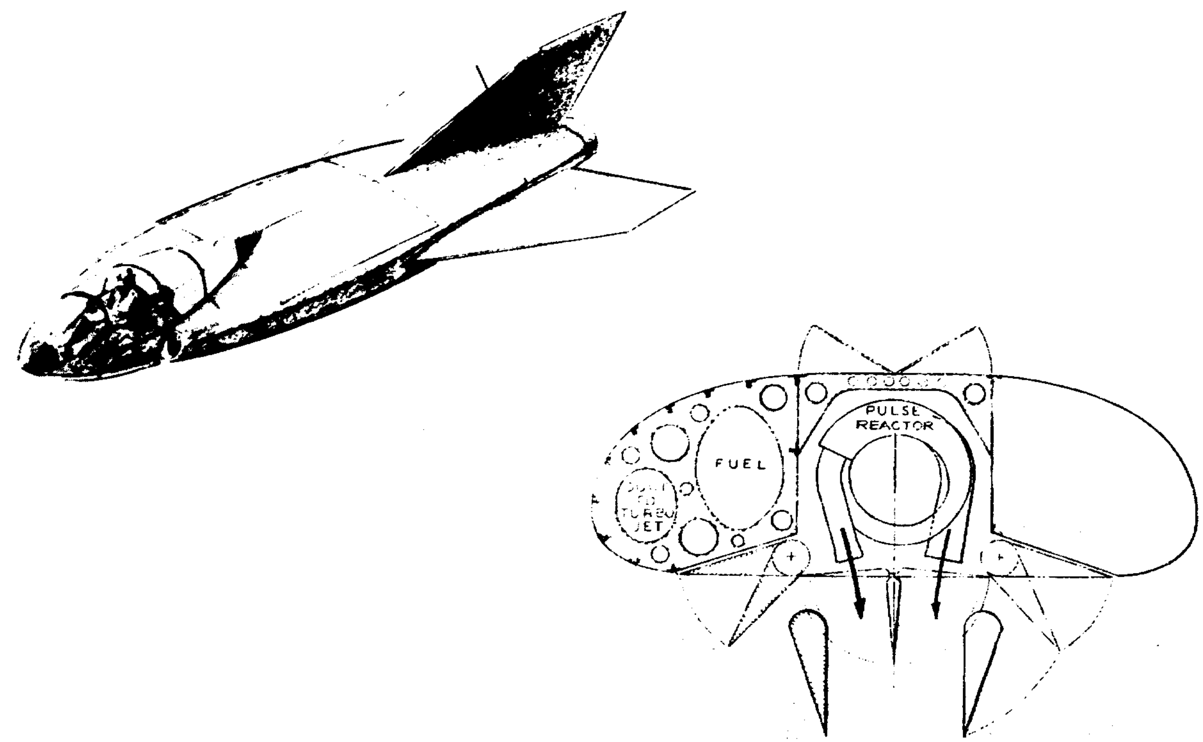


FIGURE 34

RECOMMENDED PROGRAM FOR FUTURE

PULSE REACTOR DEVELOPMENT

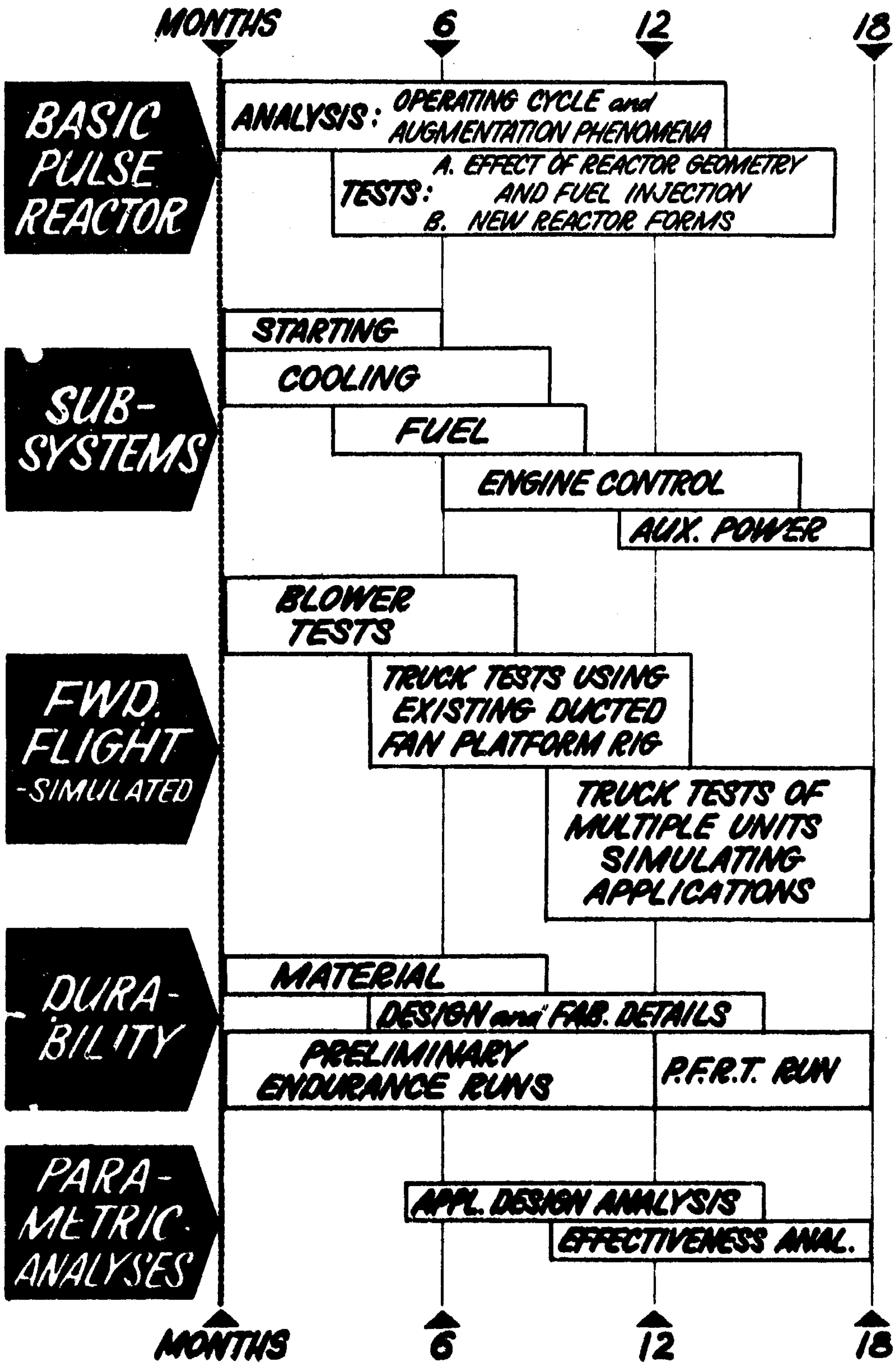


FIGURE 35

FIGURE 36

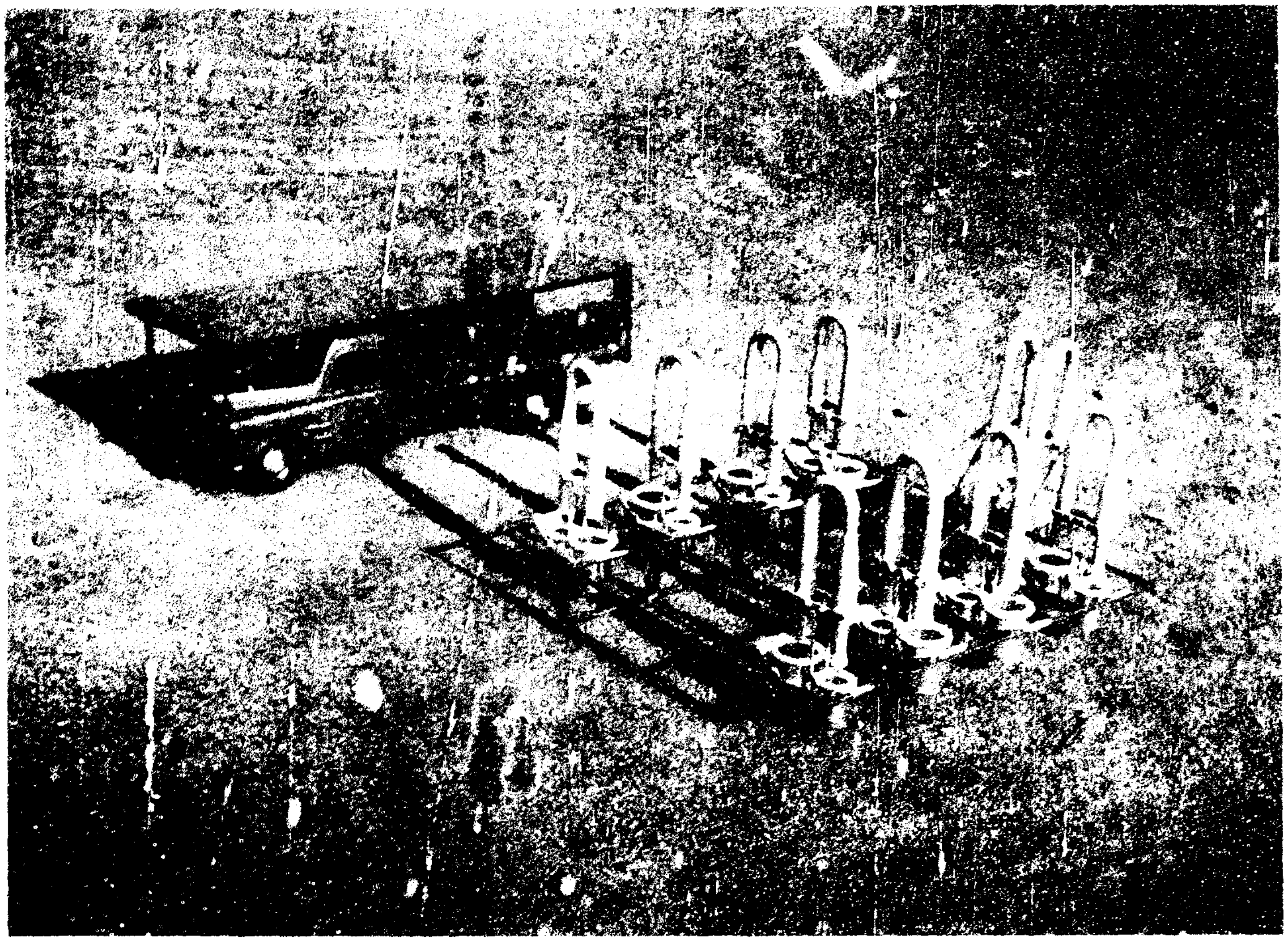


FIGURE 37 MODELS OF PULSE REACTORS AND TRUCK MOUNTED TEST RIG

ACKNOWLEDGMENTS

The authors are pleased to acknowledge valuable assistance from the following individuals:

M. F. Gates for contributions to the design of the thrust stand.

Carl Spiegelberg, Al Laich, Harold Sigler and Z. Ciolkosz for preliminary designs of aircraft applications.

Carl Spiegelberg for contribution to design of fiberglas honeycomb augmenter construction.

APPENDIX A - DETAILS OF PULSE REACTOR DEVELOPMENT

A-1. Pulsejet Engine HS-1

Preliminary results were obtained from tests with the U-shaped HS-1 engine on a test stand which permits measurement of only one thrust force (Fig. A1). This pulsejet was modified to a 90° configuration (HS-1A) so as to be able to separately measure the thrust from the two jet outlets of the engine (Fig. A2). The basic engine provided 117 pounds maximum thrust from the so-called inlet end, and 125 pounds maximum thrust from the tailpipe end. Consistent starts have been achieved with the HS-1 engine as long as starting air line pressure is above 100 psig. A starting air blast of no greater than one second duration is normally sufficient to start the engine. A fuel line pressure of approximately 40 spig is maintained. Some of the test results obtained with this test rig are shown in Figure A3.

Early testing with the HS1-A engine centered around cylindrical type augmenter ducts with length-to-diameter (L/D) ratios of 1.5. The inside diameters of those tested were 34.2", 25.7", 22.7", 17.2", and 11.5". The tests also included the SNECMA dilution duct and a copy of the same which was intended to be shortened in small increments to determine the effect of augmenter length on augmentation performance. Some combined thrust data with cylindrical augmenters in early tests was obtained with the 22.7 inch inside diameter augmenter at the exhaust and the 17.2 inch diameter augmenter at the inlet. It is particularly interesting to note how this specific combination of engine and augmenters operated at practically constant thrust specific fuel consumption (Tsfc) over most of the fuel flow range (Fig. A4).

These preliminary tests showed that there was no basic characteristic of the valveless type of intermittent jet engine to prevent appreciable thrust augmentation with the use of ejector type thrust augmenters. Further development testing was delayed until it could be performed on the new two-directional thrust stand which was nearing completion at that time.

It should be noted that a little more thrust was obtained with the 90° engine configuration than with the original HS-1 engine with the very sharp 180° bend. Furthermore, greater thrust was obtained from the tailpipe end when the dilution duct was in position in front of the inlet. The tabulated values below were based on such considerations.

	Basic engine	Basic engine + dilution duct	Basic engine + "dilution duct" + 25.75" dia aug. at inlet and exit ends
Fuel flow, lbs/hr	500	500	500
Thrust, lbs	244	301	429
Augmentation ratio	1.0	1.23	1.71
Tsfc, lbs fuel/hr lb thrust	2.05	1.66	1.16

A-2. Pulsejet Engine HS-2

The first intermittent jet engine purchased on the contract is shown in Figure A-6. This model is designated the HS-2 engine. It was designed and built by the French SNECMA company to be generally similar in geometry and performance to the HS-1 engine but with the following three modifications:

(a) Engine bent in a right-angle or 90° configuration so that the thrusts from each end of the engine can be measured separately.

(b) Turn radius sufficiently large to guarantee no significant loss in turn.

(c) Center of curvature of engine tube so located as to permit testing a pair of engines side-by-side for interference effects in combinations of (1) inlet-beside-inlet, (2) tail-pipe-beside-tailpipe, (3) inlet-beside-tailpipe.

In addition, SNECMA incorporated in the design several dimensional changes which, in the past, each by itself had produced an improvement in performance. These changes, as compared to the HS-1A engine, were:

(a) The combustion chamber was 6-1/2 inches longer than HS-1A.

(b) The exhaust tailpipe length from end of combustion chamber transition section was 27 inches shorter.

(c) The transition section converged less rapidly.

(d) The tailpipe diverged more rapidly aft of the station of minimum diameter(nozzle throat).

(e) The tailpipe ended in a 27-5/8 inches long cylindrical section of 9.1 inches inside diameter as contrasted to a conical tailpipe on HS-1A that diverged to 8.6 inches, i.d.

Unfortunately, SNECMA's efforts to improve the engine backfired badly. It had not been check tested in France and when tested at Hiller, it would barely operate. In order to prevent delays in the program, a parallel program was launched to:

(a) Incorporate any modifications suggested by SNECMA (which finally resulted in SNECMA sending their engineer, Mr. Servanty to Hiller in July, 1959), and,

(b) Fabricate components to essentially convert the HS-2 engine dimensionally to the HS-1A engine.

After unsuccessful attempts to produce performance comparable to the HS-1 engine, with minor modification, it was finally converted to the HS-1A (Fig. A-7) proportions except for the use of two 45° bends in the tail pipe as shown in Figure A-8 rather than the continuous 90° bend. The performance of this engine was essentially the same as HS-1A, as shown in Figure A-4.

While these particular attempts of SNECMA to improve the engine were unsuccessful, it illustrates again the complicated processes on which an optimum pulse reactor depends. When our understanding has advanced to the point where we can correctly predict effects of configuration changes, major improvements in performance should be possible.

A-3. Pulse Reactor Test Stand

Details of the construction of the engine thrust rig are shown in the pictorial drawing (Fig. A9). This thrust stand represents the solution to a unique problem: that of simultaneous measurement of engine thrust in two directions. The mechanisms which transmit the two separate thrusts into the Hagan Thrustorq load cells are shown in Figure A10. Note that three load cells are installed. The engine test stand is shown fastened in position on the concrete pad in Figure A11.

The basic test stand is also shown partially assembled in Figure A12 with the cable-supported engine thrust support bed suspended in proper position and the pneumatic null-balance Hagan Thrustorq thrust cells placed approximately in position. The cable supports permit two degrees of freedom. Motion is expected to be limited to approximately 0.01 inch at the null-balance thrust cells.

The HS-2 engine is shown (Figure A12) in its approximate mounting position on the partially assembled thrust stand. Provisions are made for varying the distance between engines when pairs of engines are tested.

The augmenter thrust stands consist of two separate stands, each of which measures thrust in only one direction (Figs. A13 and A14). They provide for remotely controlled variation of the spacing between augmenters and engine outlets during engine operation. A somewhat primitive spacing setup is shown connecting the large second-stage augmenter in Figure A2. The spacing device shown is a surplus battery-powered aircraft landing gear actuator, which is limited to six inches travel. Tests with the preliminary test rig shown in Figure A2 verified the idea that this feature is needed, but indicated that both greater speed and greater maximum travel were needed in the new augmenter thrust stands. A hydraulic power unit was chosen to power the actuators for the latter case.

The required instruments are shown installed on the instrument and control console in Figure A15.

A-4. Engine Shell Temperature and Durability

The typical shell temperature distribution for the uncooled HS-1A engine is shown in Figure A16. Looking forward to possible future applications of the pulse-reactor lift-propulsion system, some preliminary consideration has been given to the cooling of the hottest regions of the shell. Tests were conducted with small-scale models as indicated in Figure A17. A valuable characteristic of intermittent jets is that a large cooling effect can be obtained by the use of a cooling shroud with a short overhang, as shown in Figure A17B. The cooling flow is induced through the cooling jacket or shroud by the ejector or jet pumping action of the intermittent jet. Just as intermittent jet thrust augmenters can give high performance with short lengths, so does the intermittent jet pump operate at peak efficiency with a very short "induction" chamber. The word "mixing" chamber is avoided here because the entrainment of cooling or secondary flow does not depend on mixing or diffusion as in the steady flow case. The apparent mechanism of entrainment is described in reference 7. The pressure drop induced in the cooling jacket or shroud at four stations by the ejector action of the intermittent jet exhaust is shown in Figure A18 for (a) the condition of zero flow through the shroud and (b) for a condition in which there is no flow restriction.

In an attempt to increase the cooling effect in the hottest region, the portion of the cooling jacket that covered the combustion chamber was removed so as to introduce the cooling air near the hottest region (Fig. A17C). A further temperature reduction, from approximately 1400°F to approximately 1300°F was achieved. Cooling fins were added next, and a temperature reduction to about 1150°F resulted.

The significance of these temperature reductions lies in the great increase of shell material strength as the temperature is reduced. For example, according to Figure 10 of Reference 8, the ratio of material strength to weight of type 321 stainless steel, of which the test engines are constructed, is about 200 at 1800°F but increases about 24-fold to 4800 at 1300°F and increases to about 6400 at 1150°F, which is 32 times the ratio at 1800°F. It may well be that the weight of the cooling jacket can be more than balanced by a reduction in thickness of the engine shell.

The use of fin-like rings, which perform the dual function of (a) cooling fins and (b) stiffeners, may also contribute to increased shell life and possibly a reduction of shell weight by permitting a further decrease in shell thickness. Current shell failures usually seem to stem from an out-of-round shell condition. When the shell cross-sections are not kept circular, the periodic engine pressure loads cause excessive shell bending which results in fatigue failures in the form of longitudinal cracks.

Another way of reducing engine weight, and/or increasing shell life, is through the use of high-temperature alloys. At a shell temperature of 1400°F the ratio of ultimate tensile strength to material weight (specific gravity) can be approximately doubled by using high-temperature alloys such as Hasteloy B and Inconel "X" in place of stainless steel type 321. With these lines of action open, it appears that a significant reduction of engine weight and increase in engine life can be accomplished.

A-5. Engine Cooling Shroud for HS-2C Engine

Considerable progress has been made in the fabrication and installation of a cooling shroud for the HS-2C, serial 1 engine (Fig. A19). This cooling shroud extends past the engine exhaust 1/8 of an engine exit diameter, so as to induce airflow through the shroud by pumping action of the exhaust gases. Experiments on the smaller scale pulse reactor (Figs. A17 and A18) indicated that the thrust loss due to the pumping action is negligible, and that a shell temperature reduction of approximately 600°F can be achieved.

Preliminary checks with the HS-2C size of engine give some tentative evidence that less cooling may be achieved by intermittent jet ejector cooling as the engine size increases. The reason may be that the amount of heat within the engine shell increases proportional to the engine volume, whereas both the engine shell surface available through which heat may be transferred, and the cooling flow rate seem to be proportional to the diameter of the tailpipe. A reduction of approximately 200°F has been measured with Templaq (temperature sensitive paint), within the cooling shroud of Figure A19. Typical uncooled full-scale engine shell temperatures are shown in Figure A16 for the HS-1A engine for comparison.

A-6. Engine Proximity Effects

The pair of HS-2C engines has been operated in close proximity, i.e., 22 inches between tube centerlines (which is the minimum allowable because of the augmenters) with no significant change in engine performance (Fig. A19).

Auditory checks of sound output indicate that there is a reduction in fundamental frequency, as expected, when two engines are operated 180° out of phase. A complete spectrum analysis will soon be taken in order to compare the operating noise of a single engine with that of a pair of engines operating in close proximity.

A-7. Spacing Between Augmenter and Combustor Exits

Augmenter tests to determine the best area ratio, with simple cylindrical augmenters of a constant L/D of 1.5, were conducted with the HS-1A engine. But the determination of spacing effect for each combination was found to be quite time-consuming, so electrically actuated mechanisms, which consisted of surplus aircraft landing gear actuators, were replaced by hydraulic units with a 48 inch travel.

A schematic layout of the hydraulic augmenter positioners and controls is shown in Figure A22. The electrical units permitted a travel of only 8 inches, so it was necessary to reset several times for each augmenter to determine the spacing effect. Typical curves that show the spacing effect on engine and augmenter thrusts are shown in Figure A23. It is interesting to note that best spacing does not occur at the same distance for both augmenters.

Along with the hydraulic augmenter positioners, which permit rapid determination of best augmenter positions, simple flexible push-pull rods are connected from the augmenter stands into the control room so as to continously show the positions of the augmenters.

A-8. Performance of Cylindrical Augmenters (Figures A-20 and A-21)

Results from tests of the series of cylindrical augmenters are summarized in Figure 15 of this report. The results are presented at a single fuel flow rate of 475 pounds per hour (pph), which represents a condition which is close to maximum thrust and minimum specific fuel consumption (Tsfc). All tests were conducted at a single ratio of augmenter length to diameter (L/D) of 2.0. These tests are believed to be representative of the relative performance of cylindrical type augmenters as used on the HS-1 and HS-2C type of valveless engines. Small-scale tests of cylindrical augmenters in combination with valved intermittent jet engines, in which both the area ratio (A_{aug}/A_{jet}) and the length effect (L/D ratio) were varied over a wide range, are reported in Reference 3.

The large-scale tests with valveless engines (Fig. 15) show that maximum thrust augmentation ratios occur at quite different area ratios for the inlet jet and the exhaust jet. This infers a difference in the nature of the jet efflux from the two ends of the engine. In this connection a significant difference in jet efflux, based on instantaneous flame and pressure measurement, is reported in Reference 6 of preceding Section 10. Conclusions drawn from these reports of tests with an engine generally similar to the HS-1 type, indicate that the average ejection velocity out the "inlet" end is about 2.6 times as great as the average ejection velocity out the tailpipe end. The duration of hot gas ejection from the tailpipe end was about 2.5 times as long as the ejection from the so-called "inlet" end, but the ejection velocity from the tailpipe was given as a maximum of 400 meters per second and an average of 250 m/s, as compared to a maximum of 800 m/s and an average of 650 m/s for the intermittent jet from the inlet end of the engine. These French studies also indicate that "three cycles are necessary to fully eject successively the burnt gases of a single combustion phase" (or combustion event).

Two sets of curves are shown for the augmenters in Figure 15 of preceding Section 11. One set (with open symbols) shows the augmentation ratio as referred to the primary jet thrust from each end of the engine while operating with the augmenters in position. This may give a distorted picture of the effectiveness of the thrust augmentation unless simultaneous consideration is given to the fact that the engine jet thrust (see bottom curve of Figure 15) may be changed from normal due to the presence of the augmenters.

The second set of augmenter curves (solid black symbols) includes the effect of both of the other curves. The augmenter thrust plus the simultaneous thrust from engine jets (i.e., the presence of the augmenters) is divided by the thrust of the jets as measured when the engine is operating alone (not in the presence of the augmenters). In this way of presenting the data the augmenter is either credited or debited, as the case may be, with any change in engine primary jet thrust caused by the presence of the augmenter.

It is important to note that a very large number of combinations of jet-plus-augmenter thrust are possible merely by varying the spacing between the augmenters and the ends of the jet pipes (e.g., see Figure A23 and preceding section A-7). The best combinations, as chosen during engine operation according to the judgment of the test engineer, as he searches for the best spacing by moving the augmenters during the test runs, are presented in Figure 15 of preceding Section 11. The dashed lines at an area ratio of 4.1 show the effect of a change of spacing. In this case augmenter thrust is increased at the expense of engine thrust. Normally, the best combinations are found at augmenter spacings which cause an increase of the thrust of the engine jets as compared to the thrust from the engine jets operating alone.

A-9. Conically Divergent Augmenters

In order to guide the design of improved augmenters for the HS-1A and HS-2C full-size engines, the small test rig used in contract Nonr 2761(00), (Ref. 3) was utilized with small glass augmenters to confirm trends showing the superior augmentation of divergent conical, as compared to cylindrical augmenters. Based on these small-scale tests an 8° conically divergent augmenter was specified for both inlet and exhaust jets. The throat diameter of the exhaust augmenter was 17 1/4 inches, providing an area ratio of augmenter throat csa (cross-sectional area) to jet exhaust exit csa of 3.66, and the length-to-diameter ratio (L/D) was 2.0. The throat diameter of the inlet thrust augmenter was 11 1/2 inches, providing an area ratio of 4.00 and the L/D was 4.0.

It was very gratifying to report the achievement of a thrust augmentation of the HS-1A engine of significantly better than 100% and a thrust specific fuel consumption (Tsfc) of less than 1.0 lb fuel per hour per lb thrust at 97% of maximum thrust.

The following tabulated augmentation data was obtained from two test runs in which the engine was started and brought immediately to 475 pph where fuel flow was held constant as the engine warmed up, followed by an extended run. The data was recorded after the uncooled engine was running hot. We have noted a consistent drop-off in thrust of a few percent as the engine warms up. All past and present reported data have been given for the hot engine case unless otherwise noted.

Source of Thrust	Thrusts, lbs: Without Augments	Tests: No.8-13-5	Tests: No.8-14-4	Fuel Flow Rate, pph
Exhaust Jet	119	142	135	475
Exhaust Augmenter	---	162	168	
Inlet Jet	97	92	88	
Inlet Augmenter	---	96	96	
	Totals:	492	487	475

Thrust is at 97% maximum

Further information concerning performance of 8° conical thrust augmenters is given in Figures 13 and A25, and an HS-2C test setup shown in Figure A24.

Tests of SNECMA's inlet "dilution duct" (Figs A1 and A2), which was delivered with the HS-1 U-shaped engine, revealed a thrust augmentation of 1.41 with an area ratio of only 2.15 (referred to the inlet end) but with a tube length of 6.23 times the minimum diameter. This is a conical tube with flared inlet that tapers from a minimum diameter of 8.35" i.d. to a diameter of ten inches at the outlet. Since our tests have revealed that augmentation begins to drop off rapidly at lengths greater than about two diameters, it is believed that this long "dilution duct" is of such a length that it has the same natural frequency as the basic engine, and that our short augmenters have a natural frequency that is a harmonic of the long duct. Poor performance of intermediate duct lengths is attributed to a mismatching between the gas natural frequency of the ejector tubes and the basic engine operating frequency.

A-10. Effect of Augmenter Length

The effect of augmenter length on thrust augmentation performance has been investigated for inlet augmenters of two different sizes. The body of the 8° conically divergent augmenter with a 11.5 inch throat diameter was shortened in small increments from a length of 46 inches to a length of only one inch. The effect is shown in Figure A25. Also shown in this figure is the effect of the presence of the augmenter on the thrust from the engine inlet itself. This effect is not nearly as great as it is for the tailpipe augmenter and tailpipe performance under similar conditions.

The effect of length on the performance of the SNECMA "dilution duct" is shown in Figure A26. It is interesting to note that for all L/D ratios the presence of this augmenter (8.4 inch throat diameter) causes a reduction of inlet thrust, whereas this is true for the larger throat diameter (11.5 inch) augmenter primarily for lengths between 2.0 and 3.5 diameters. For the smaller augmenter the reduction of inlet thrust is probably due to the crowding of streamlines of inflow air and wave interference, whereas in the latter case it is probably due primarily to wave interference caused by differing natural frequencies of basic combustor and inlet augmenter.

A-11. Augmenter Shell Temperature

Figure A27 is a sketch showing measured augmenter shell temperatures for the 8° divergent, conical augmenters (steel construction) at a fuel flow rate of 475 pph. The moderate temperatures (less than 300°F) indicate the possibility of using a wide range of materials in the construction of augmenters.

A-12. Fiberglass Augmenters

The weight and durability problems not only are attacked by reducing package size but by considering sandwich reinforced plastics construction of augmenters (fiberglass inner and outer skins with fiberglass honeycomb filler). This type of construction and material is attractive because it provides a thick section with high internal vibration damping and reduction of noise transmission.

An inlet thrust augmenter with a throat diameter of 14 inches was constructed of fiberglass laminate and a 1/2" thickness of fiberglass honeycomb. The design resulted in a very light weight augmenter and preliminary results indicate an excellent ability to accept the loading involved. The first augmenter constructed is shown in Figure A28. It has a 14 inch throat diameter with a 16° included angle of divergence, and a length of 40 inches. At the very end of this program another fiberglass augmenter was constructed with the same throat diameter and length but with an 8° included angle of divergence. The latter augmenter gave thrust augmentation as high as any single inlet thrust augmenter tested during the program.

A-13. Angled Augmenter

It has been felt that the augmenter might provide a method of aircraft control by angling the augmenter centerline with respect to the engine centerline. By this method, the basic engine thrust would remain unchanged but the augmenter thrust direction could be changed as desired to impart control moments to the aircraft. Tests have been conducted at angles from zero to greater than 45°, with the exhaust augmenter angled as shown in Figure A29. The effect of angling the augmenter is shown in Figure A30. Evidently the component of the augmenter thrust in the direction of engine thrust can be reduced to nearly zero with 45° or 50° of angle. Crude measurements with the augmenter angled as far as 45° indicate that the total augmenter thrust is reduced in magnitude.

A-14. Rectangular Augmenter

An 8° divergent rectangular dual-engine augmenter has been built, and preliminary tests have been conducted with it. Performance data indicate that thrust augmentation is only about 80% of the augmentation achieved with 8° augmenters of circular cross-section. Figure A31 shows a view of the rectangular augmenter mounted on the test stand.

A-15. Pulse Reactor Wake Temperature and Pressure

Figure A35 shows the temperature distribution in the wake that issues from a conically divergent (8° included angle) thrust augmenter in position behind the HS-2C engine tailpipe. This data is presented to show that the wake temperatures are quite acceptable for vertical-takeoff and landing (VTOL) aircraft applications.

In order to measure the average pressure and temperature of the jet wake a gridwork of steel tubing was constructed as sketched in Figure A32. The grid was designed to cause a minimum of interference with the jet wake while permitting determination of the effect of the augmenters on the velocity and temperature of the jet wake.

The completed jet wake survey grid is shown in Figures 20 and A20 in position aft of the tailpipe of the HS-1A engine. Data is recorded by photographing the multiple bank manometer board with a Polaroid Land Camera.

A-16. Pulse Reactor Noise

Before sound measurements could be taken, efforts were made to isolate the engine intake sound from the exhaust sound. This was accomplished by the construction of a pair of 8 by 10 feet acoustic panels. Figure A33 shows the construction details and materials used in fabricating the panels, which are shown installed in Figure A34.

Two series of acoustic data were taken. In both cases, the characteristics of the exhaust sound were studied at a distance of 100 feet from the engine exhaust and through an arc of 37° on each side of the exhaust centerline. At this 100 foot distance and along the 74° arc, a sound level of 115 to 117 decibels was measured at a "part throttle" fuel flow rate of 250 pph. In the second series of readings, a sound level of 122 to 128 decibels was determined, at maximum thrust fuel flow rate (see Fig. 16). It should be noted that this represents the noise from the bare combustor untreated by (1) addition of augmenters or (2) by operating twin combustors 180° out-of-phase (see preceding Section 4.1.3 for further discussion).

A-17. Scale Effects on Propulsion System Performance

There is, in general, an optimum size for any propulsion system. In the case of jet propulsion, if the supply pressure and temperature of the gas, which produces the thrust producing jet, is held constant, then the thrust will vary directly with the outlet area of the jet. Thus for dimensionally proportional engines, the thrust will vary with the square of a linear dimension, but the volume (and also weight) of the engine will vary with the cube of the linear dimension. This results in the so-called 2/3 law (Ref. 17 and 18) which has been often used to relate the thrust per unit weight, or thrust per unit volume of turbojet engines. In the case of the turbojet engine, this general trend has been found accurate until the dimensions of the blading and other parts become so small that low Reynolds number effects result in a loss in efficiency. The Pulse Reactor, however, operates on a resonating cycle with wave compression and expansion. It has been found in shock tube and wave engine development programs, that Reynold's number effects are much less detrimental to such processes. There is reason, then, to expect good specific thrust and thrust-to-weight ratio from even miniature Pulse Reactors. Some preliminary experiments of the contractor tend to support this fact. A photograph of several research engines is shown in Figure A36. The engine sizes vary from the 8.6 inch diameter tailpipe of the HS-1 engine down to the 0.7 inch diameter of the smallest engine shown in the photograph. Tabulated performances on three of these engines are given in Table 1.* It should be noted that the data includes the assumption of a constant effect of thrust augmenters (i.e., increasing the thrust of the basic combustor by 120% and thereby greatly reducing the jet wake velocity).

In Figure A37 this data is plotted as thrust per unit volume vs. engine thrust. It may be seen that whereas the 2/3 law is not strictly adhered to, substantial improvements are shown by reduction in engine size. Figure A38 shows the trend of specific thrust (i.e., thrust per unit jet exit area) with engine thrust. The 2/3 law would predict this value to be constant, however, the experimental data shows an increase with engine size. In both Figure A37 and A38 it should be pointed out that the large 500 lb Pulse Reactor has been under development for the past year with BuAer (now BuWeps), whereas the smaller engines have essentially only been constructed and given

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*See next page for Table 1

brief tests. These tests were, in some cases, made with gaseous fuel such as propane (and in the case of the smallest engine, acetylene). This was done in order to alleviate fuel atomization difficulties and to reduce the fuel and air mixing time, which may be critical for very small engines.

ENGINE DESCRIPTION	HS - 1A Pulse Reactor Engine	1/3 Size Pulse Reactor Engine	1/4 Size Pulse Reactor Engine	1/20 Size Pulse Reactor Engine
Thrust, lbs *Augmented	500	85	29	.97
Thrust Per Unit Volume, lbs per ft^3	34	63	99	237
Specific Thrust (Per Unit Exit Area) lbs per ft^2	127	112	100	59
Thrust Specific Fuel Consumption, lbs fuel per hour lb thrust	1.0	---	1.3	---

Note* 1/3, 1/4, and 1/20 Scaled Engines Assume the same Augmentation Ratio (120%) as the HS-1A Engine

TABLE 1: PRELIMINARY PERFORMANCE OF SEVERAL PULSE REACTOR SIZES

Since some of these engines have been given only limited development, they still have limitations such as norrow throttling range, apparently rather poor Tsfc, etc, although fuel consumption rates were not carefully measured in the case of some of the smaller engines. Nevertheless, the data strongly supports the belief that small Pulse Reactor clusters can be developed with less bulk than groups of larger units. It appears to be relatively simple to interconnect multiple engines in such a way that one operating engine will start a non-operating engine. Preliminary tests with the large 500 lbs thrust engine showed that an adjacent dead engine would be started by simply interconnecting the engines with a relatively small tube (1.0 inch diameter) whose ends were aligned axially with the inlets of the engines.

Concerning Tsfc, the trend of scaling is not as well documented, as in the case of specific thrust and thrust-to-volume ratio. Statistically, it has seemed that engines above a size represented by a combustion chamber (or tail-pipe exit) diameter of about four inches could be expected to have about the same maximum Tsfc. The limited evidence thus far for the range of diameters less than four inches indicates that the Tsfc may suffer as the size is reduced; in contrast to the trend of volume to weight ratio. This should not be considered as a firm trend at this time because resourceful design and inventiveness may well overcome these early indications.

A-18. LITERATURE SEARCH AND DEVELOPMENT OF ANALYSIS

Contractor personnel have been interested in and working in the fields of resonant combustion and intermittent flow for many years, as exemplified by the projects illustrated in Figure 5 of the summarizing section of this report. Based on this background of experience, and on awareness of the state of the art*, Contractor planned the experimental program. Trends revealed during the program were analyzed and followed in order to meet the program targets. These trends concerning the relationships between the intermittent jet from a double-ended valveless pulsejet combustor and ejector type jet thrust augmenter have been reported herein and are valuable to the extent that they will furnish an important guide for any similar program. However, the analysis and theory of unsteady combustion and gas dynamics and its application to design and performance prediction is not yet sufficiently advanced to permit its use as a practical working tool. The problem is complicated by the difficulty of taking "instantaneous" measurements of the rapidly changing gas pressures, temperatures and velocities, which are typical of the pulse reactors, since they have operating cycles in the range of 40 cps to 400 cycles per second. It is very important that continued effort be applied to this situation, e.g., like that described in Reference 3, which is devoted to understanding of the method of energy exchange between intermittent jets and the secondary air which is induced to flow through the thrust augmenters. With this augmentation research in progress, it is now most important to develop a companion program concerned with the generator of the intermittent jets, i.e., the basic combustor. This work should be motivated not so much from the standpoint of the basic combustion involved, which is a field which has been very intensively researched, but rather concerned strongly with the unsteady gas dynamics and wave motions involved in the cycles. The fact that pulsejets do not typically respond very much performance-wise to large changes in fuel flame speeds (e.g. Ref. 10) is a strong indication that the unsteady gas dynamics is the predominant factor, rather than chemistry of combustion (Ref. 5).

The reference list (Sec. 10) includes important documents that are very pertinent to Pulse Reactor development. Reference 9 is a recent paper by Otto Luts of Brunswick, Germany, the investigator discussed in section 4 of Appendix IV of Hiller Aircraft Corporation report ARD 196 (the proposal for this subject contract). Stemming from his early awareness that

(a) there is a decided superiority in jet thrust augmentation when the primary jet is unsteady or intermittent rather than steady, and

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*There has not yet been published any comprehensive and reasonably detailed textbook or even a clearcut and accurate summary of the state of this art, although the literature is voluminous. A rather comprehensive and convenient bibliography of this field is included in Reference 19.

(b) there is a -- "mixing range in which (steady) mixing of two gas jets in a cylindrical mixing tube results in an incompatibility of the theorem of momentum with the energy equation," --

Lutz described a graphical method of treating problems of steady flow gasdynamic mixing that treats this "gap" where momentum and energy theorems are incompatible. We plan to study this article particularly from the standpoint of its possible applicability to the valveless intermittent jet (or "pulse-reactor") thrust augmentation.

Prior to our agreement with the French SNECMA company the major detailed technical publication about their research available to us was Reference 10, but it had not been translated, and furthermore, Figure 14 of this reference had been cropped so as to conceal information about the nature of the inflow and efflux at the inlet end and tailpipe end. Reference 11 is much more informative concerning the flow in the inlet and outlet ends of the pulsejet, as indicated in the summary following Reference 11. We have had References 6, and 12 to 16 inclusive, translated during this contract period, and have utilized the information in the planning of the subject program.

Included in this important research were instantaneous pressure measurements downstream of the pulsejet outlets and inside the SNECMA "dilution duct" type thrust augmenter. It is understood that these reports represent a research program of high-speed flame photography, and high-speed pressure instrumentation, which cost more than $100,000.

As part of the investigation concerned with the augmentation phenomenon (Ref. 3) consideration is now being given to the wave diagram technique of analysis (References 20 and 21). If sufficient effort of this nature was directed towards the analysis of the gas dynamics within the simple tube (combustor) which generates the intermittent jet, important gains should be made.

A-19. Figures

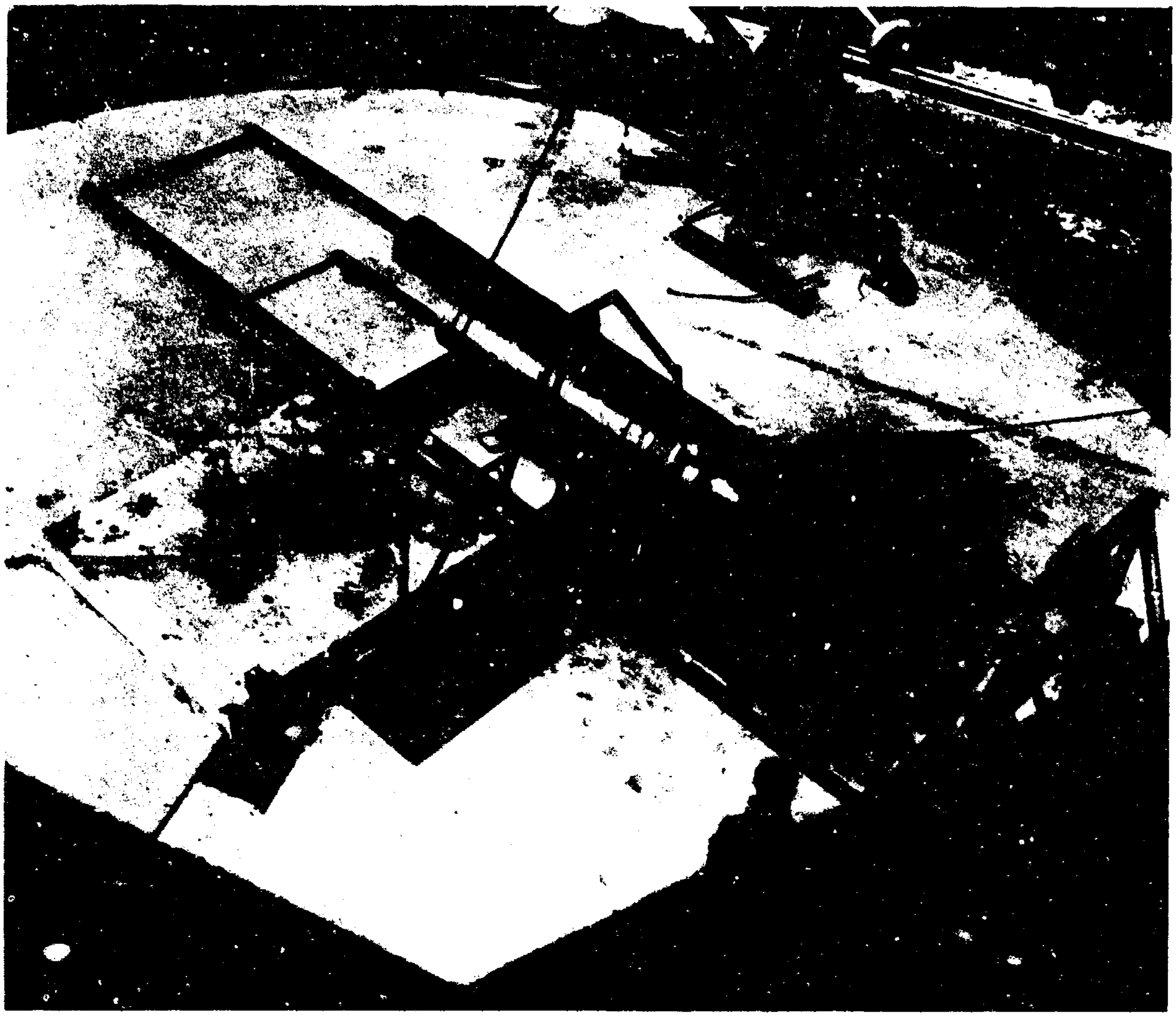


FIGURE A-1: HS-1 VALVELESS PULSEJET ENGINE WITH INLET JET "DILUTION DUCT" THRUST AUGMENTER MOUNTED ON SIMPLE THRUST STAND

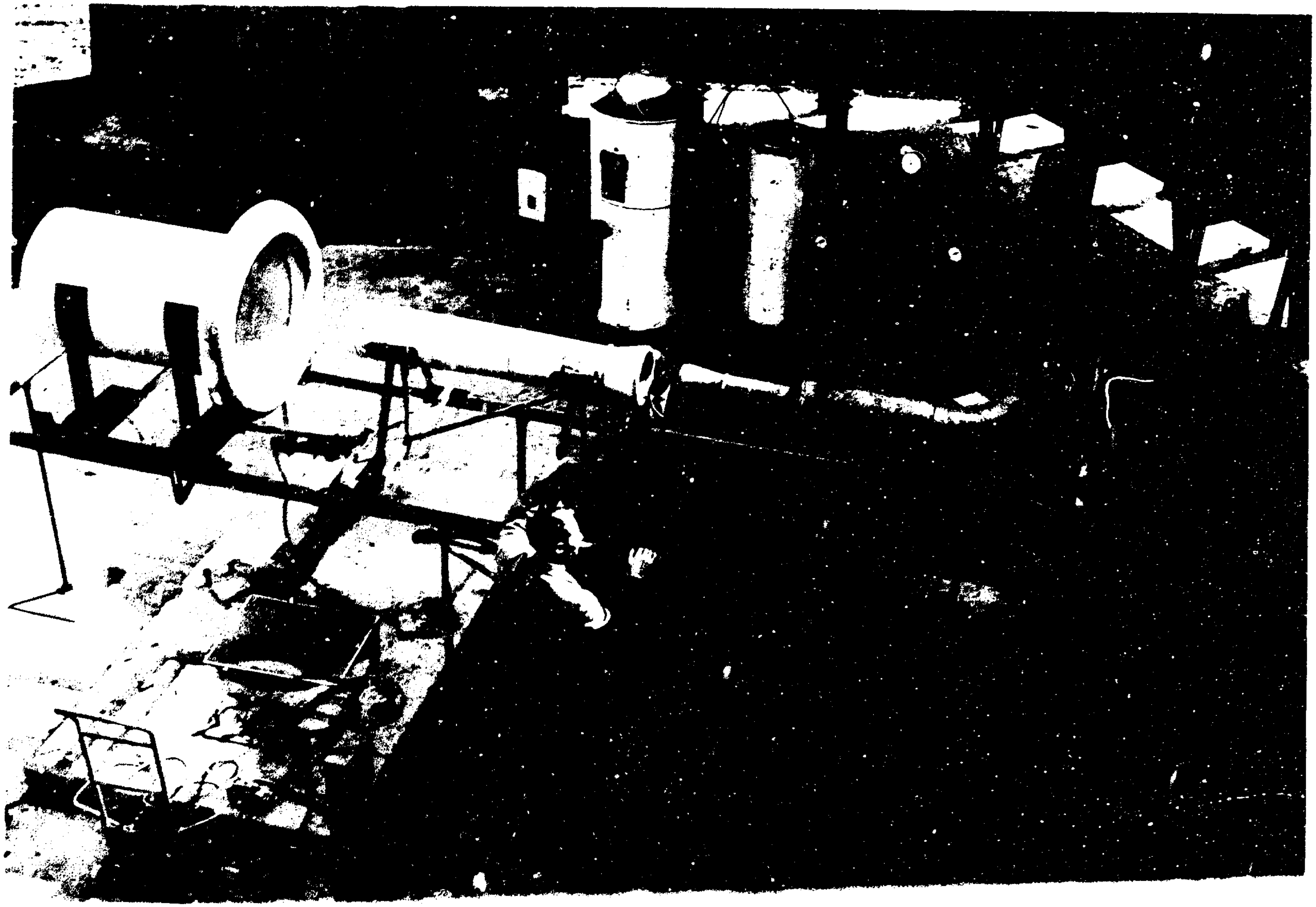
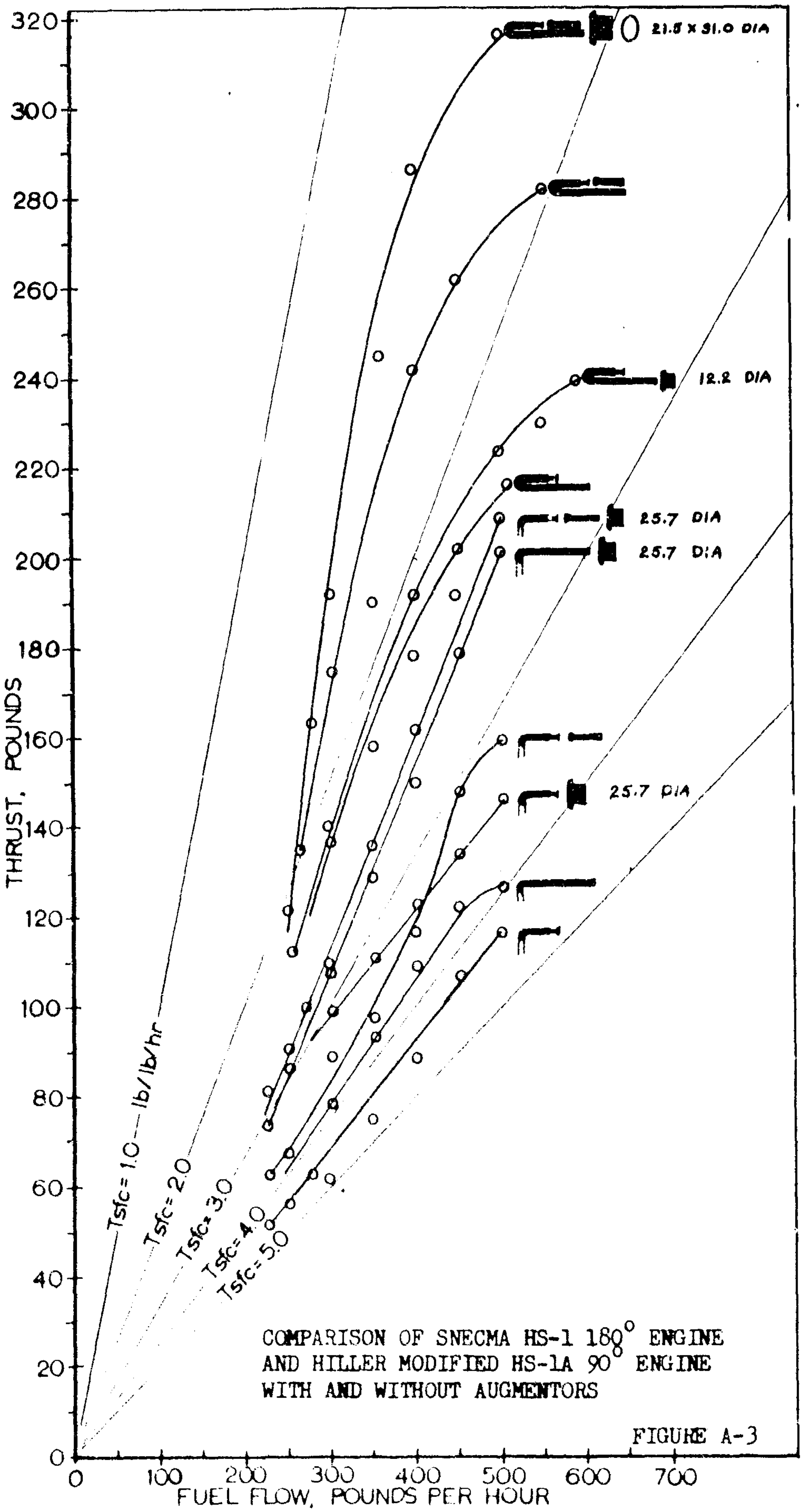


FIGURE A-2 HS-1A INTERMITTENT JET ENGINE AND TWO-STAGE AUGMENTERS IN CENTER AND FOREGROUND. THIS IS THE SNECMA HS-1 U-TUBE SHAPE ENGINE MODIFIED TO 90° SHAPE WITH SNECMA "DILUTION DUCT" FIRST STAGE AND 25.7 INCH DIAMETER SECOND STAGE AUGMENTER.



COMPARISON OF SNECMA HS-1 180° ENGINE
AND HILLER MODIFIED HS-1A 90° ENGINE
WITH AND WITHOUT AUGMENTORS

FIGURE A-3

HILLER AIRCRAFT CORPORATION
(Research Division)

HS -1A PULSE JET ENGINE STATIC PERFORMANCE

Test No. 2 EWA 3588-6-4
Barometric Pressure 30.1 "Hg
Dry Temperature 70 °F
Wet Temperature - °F

EXHAUST END

Augmentor Shape Cylindrical
Augmentor Diameter 22.7"
Exhaust End Diameter 8.6"
Area Ratio 6.4: 1.0
Augmentor Length 34"
Augmentor Position + 7"
Length/Dia. Ratio 1: 1.5

INLET END

Augmentor Shape Cylindrical
Augmentor Diameter 17.5"
Inlet End Diameter 5.7"
Area Ratio 9.0: 1.0
Augmentor Length 25.8"
Augmentor Position + 14"
Length/Dia. Ratio 1: 1.5

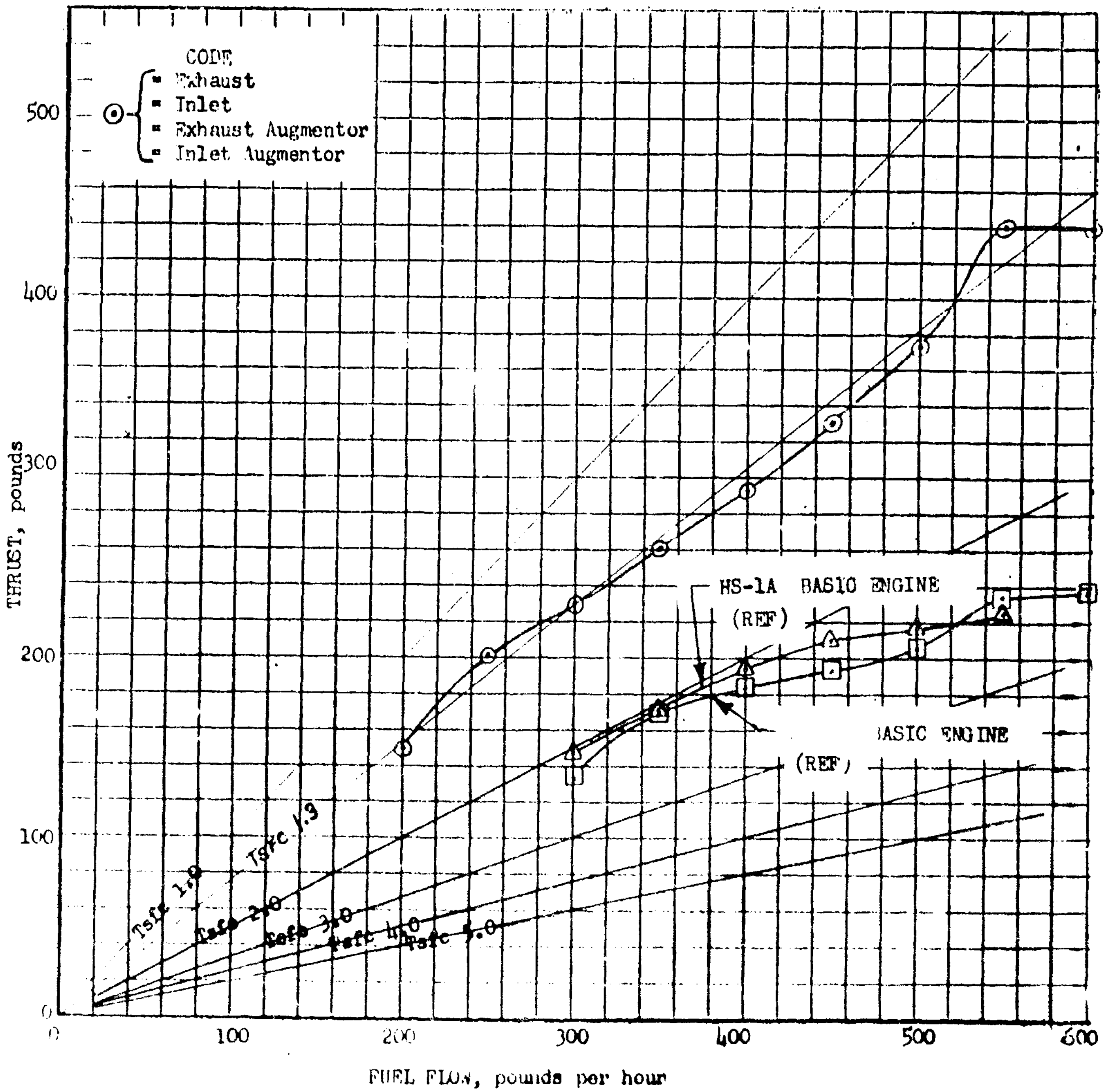
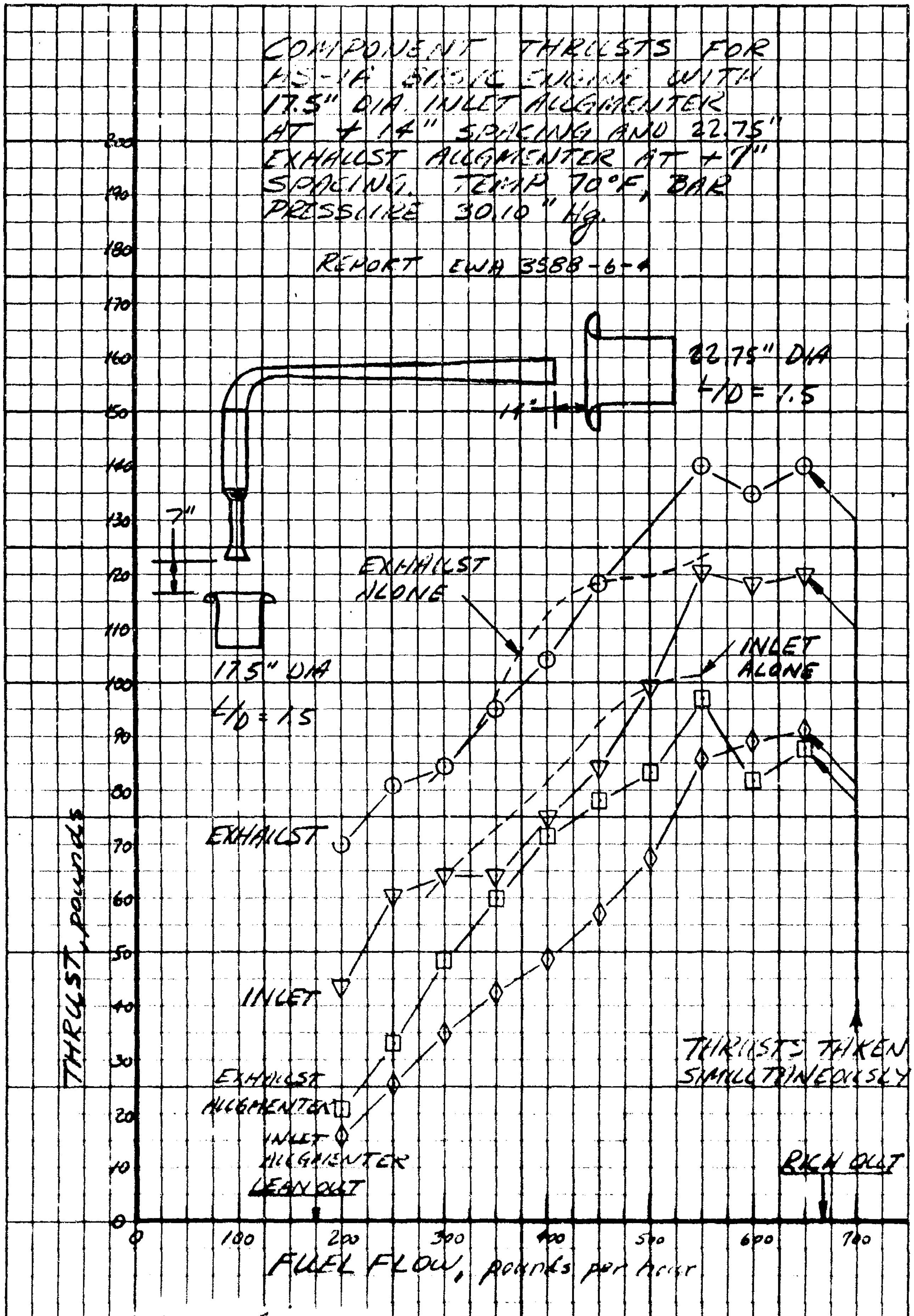


FIGURE A-4: HS-1A ENGINE WITH AUGMENTORS
(Basic engines HS-1A and HS-2C Ref)



COMPONENT THRUSTS FOR
XS-1A BASIC ENGINE WITH
17.5" DIA. INLET AUGMENTER
AT + 14" SPACING AND 22.75"
EXHAUST AUGMENTER AT + 7"
SPACING. TEMP 70°F, BAR
PRESSURE 30.10" Hg.
REPORT EWA 3588-6-4
22.75" DIA
L/D = 1.5
14"
7"
17.5" DIA
L/D = 1.5
EXHAUST ALONE
INLET ALONE
EXHAUST
INLET
EXHAUST AUGMENTER
INLET AUGMENTER
LEAN OUT
RICH OUT
THRUSTS TAKEN SIMULTANEOUSLY
THRUST, pounds
FUEL FLOW, pounds per hour
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
0
100
200
300
400
500
600
700

FIGURE A-5

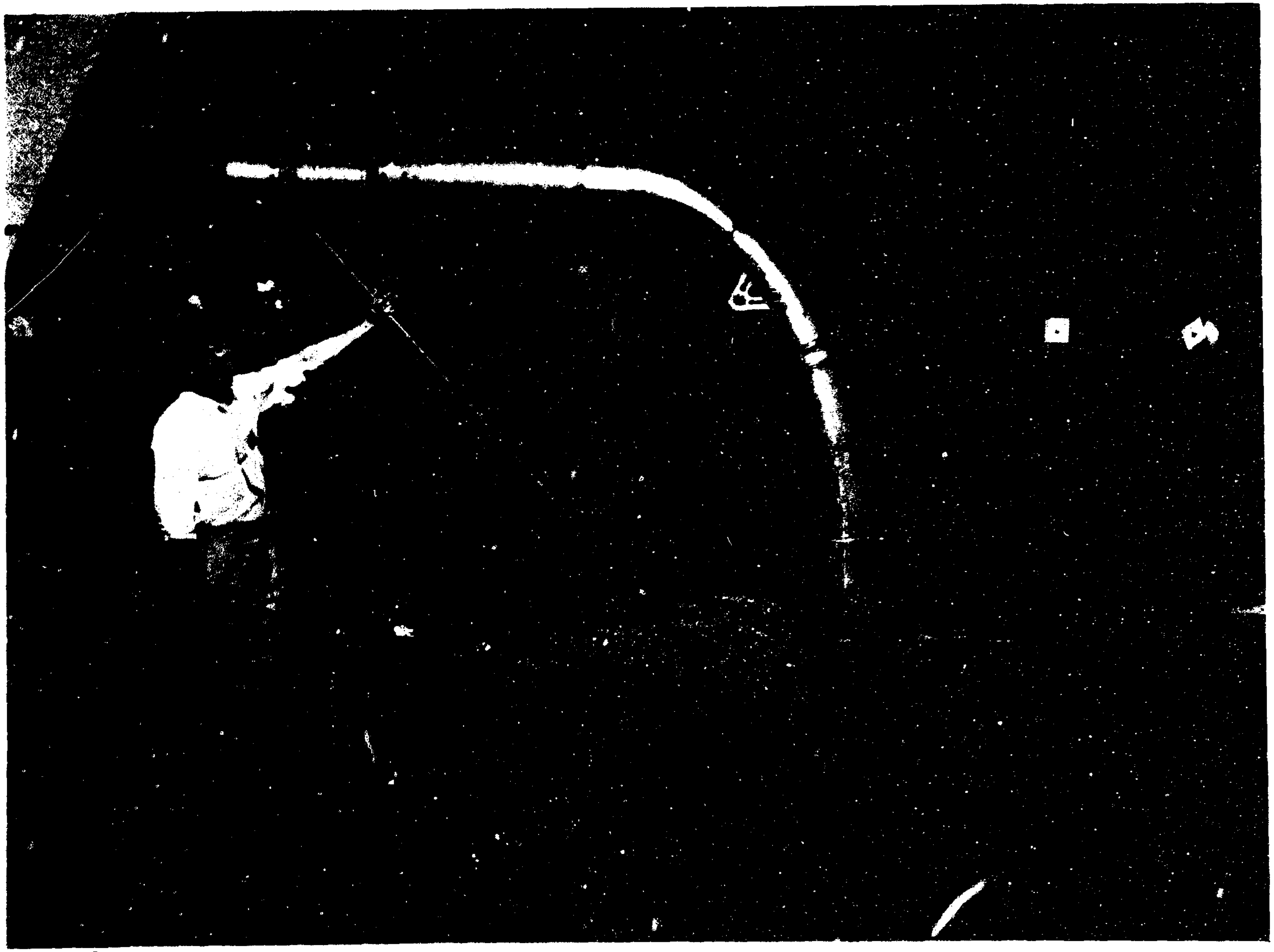


FIGURE A-6 HS-2 VALVELESS INTERMITTENT JET ENGINE.

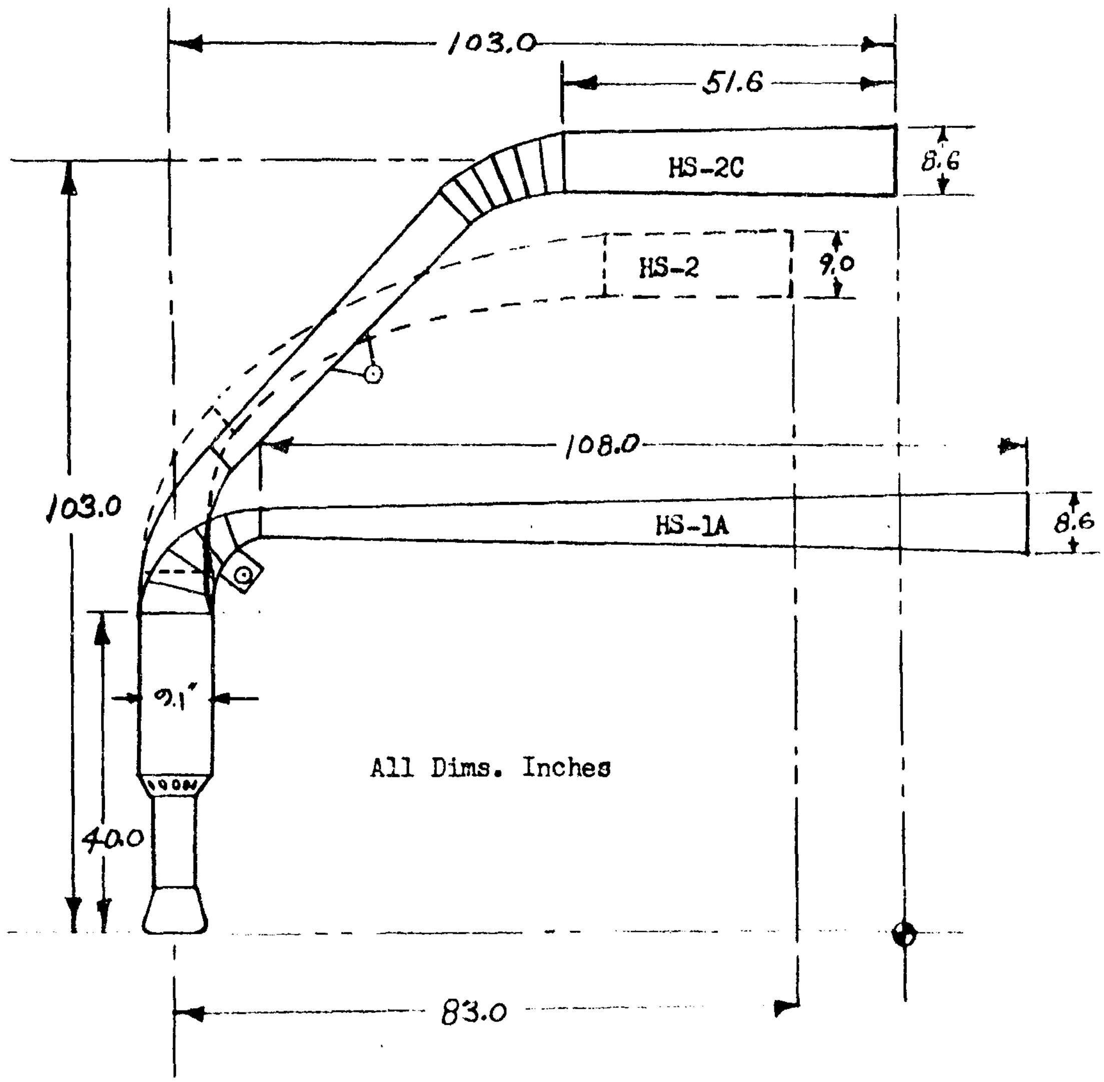


FIGURE A-7: GEOMETRICAL COMPARISON OF ENGINE CONFIGURATIONS HS-1A, HS-2, and HS-2C.

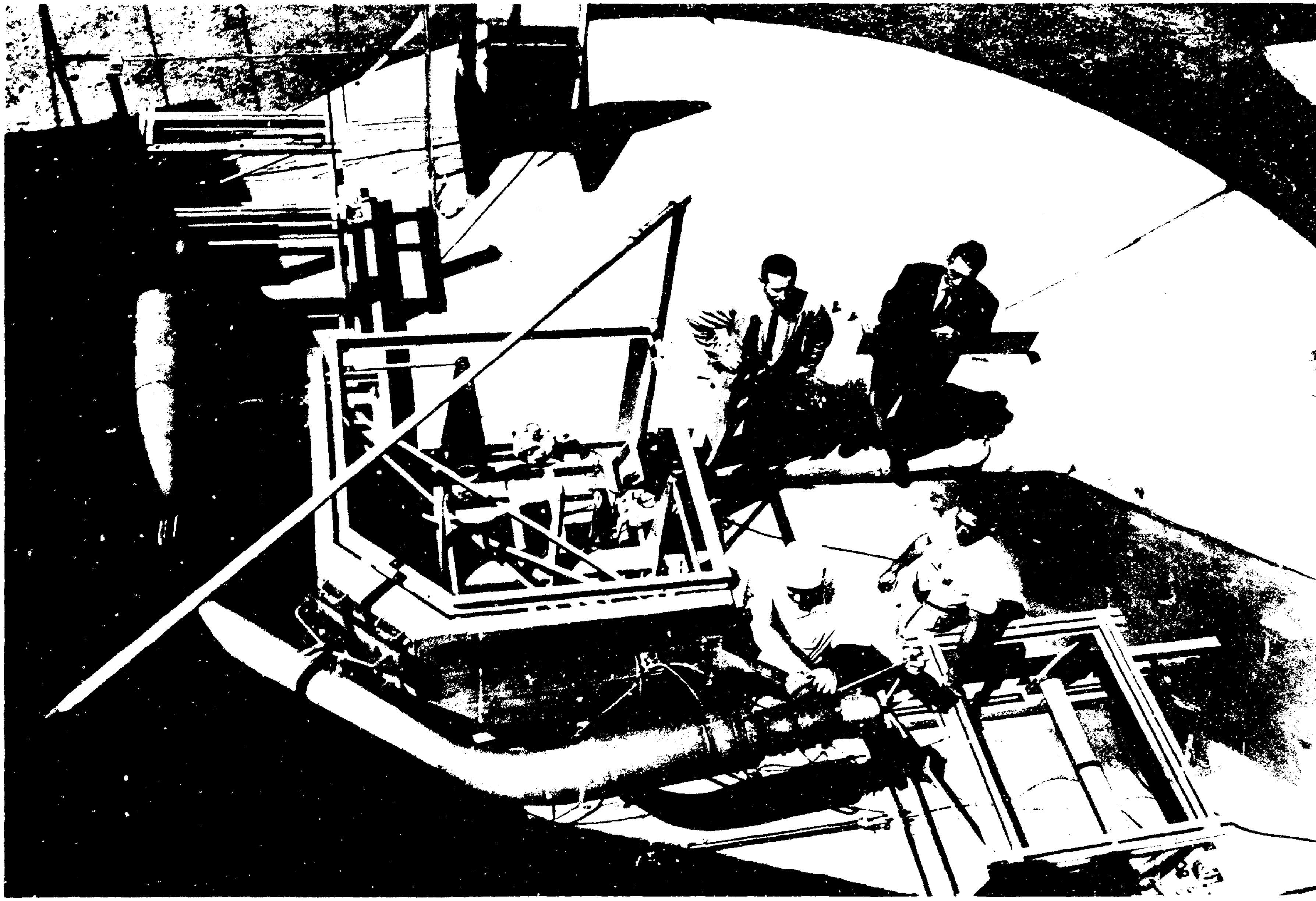


FIGURE A-8 THE HS-2C PULSEJET ON THE 2-DIRECTIONAL THRUST TEST STAND. IN THE HILLER TEST CELL ARE (rear, l. to r.) R. M. LOCKWOOD, PROJECT ENGINEER, P. SERVANTY, SNECMA ENGINEER, (front, r. to l.) J. E. BECKETT, TEST ENGINEER, AND A. L. PETERSON, ENGINEERING MECHANIC.

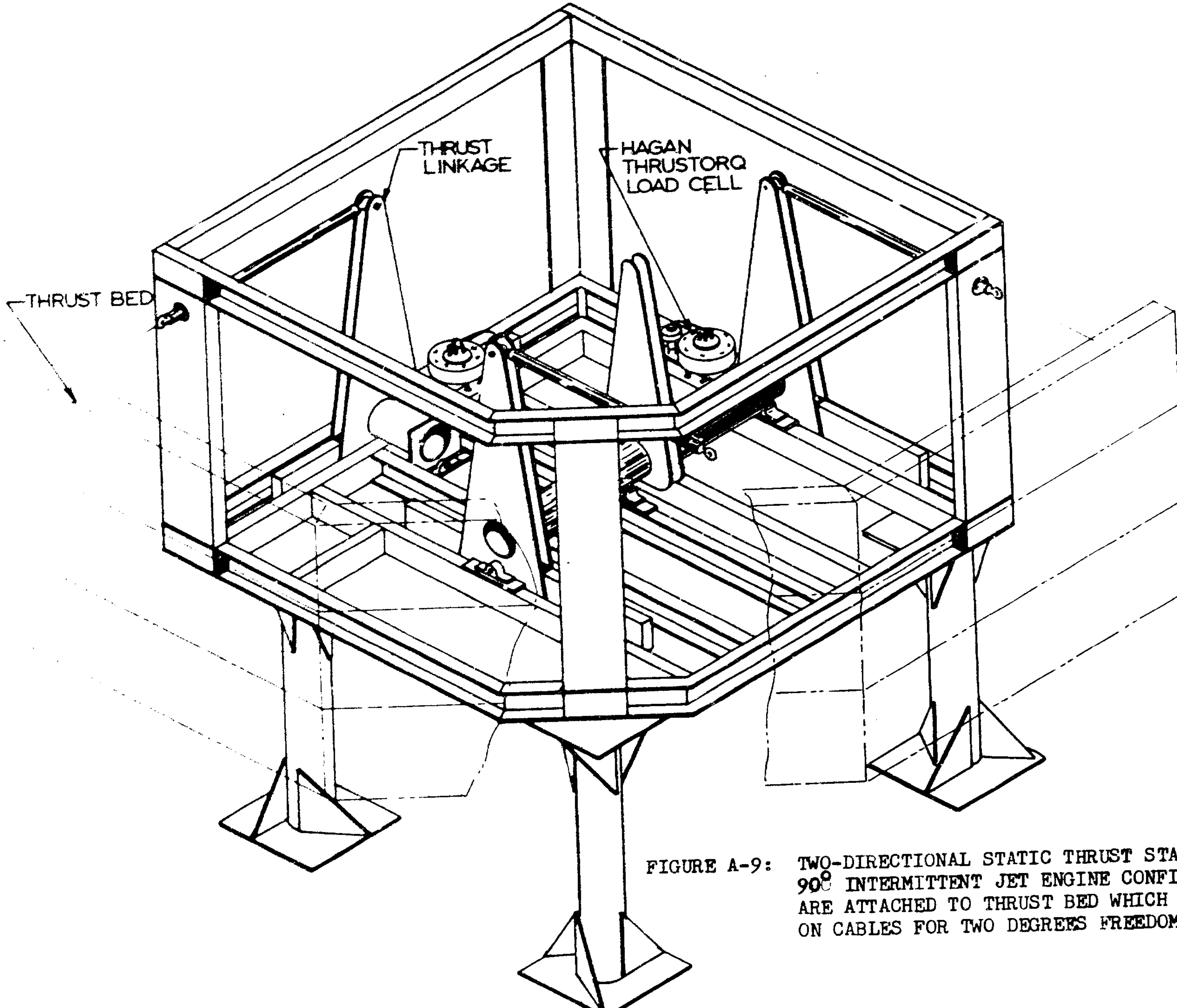


FIGURE A-9: TWO-DIRECTIONAL STATIC THRUST STAND. 90° INTERMITTENT JET ENGINE CONFIGURATIONS ARE ATTACHED TO THRUST BED WHICH IS SUPPORTED ON CABLES FOR TWO DEGREES FREEDOM.

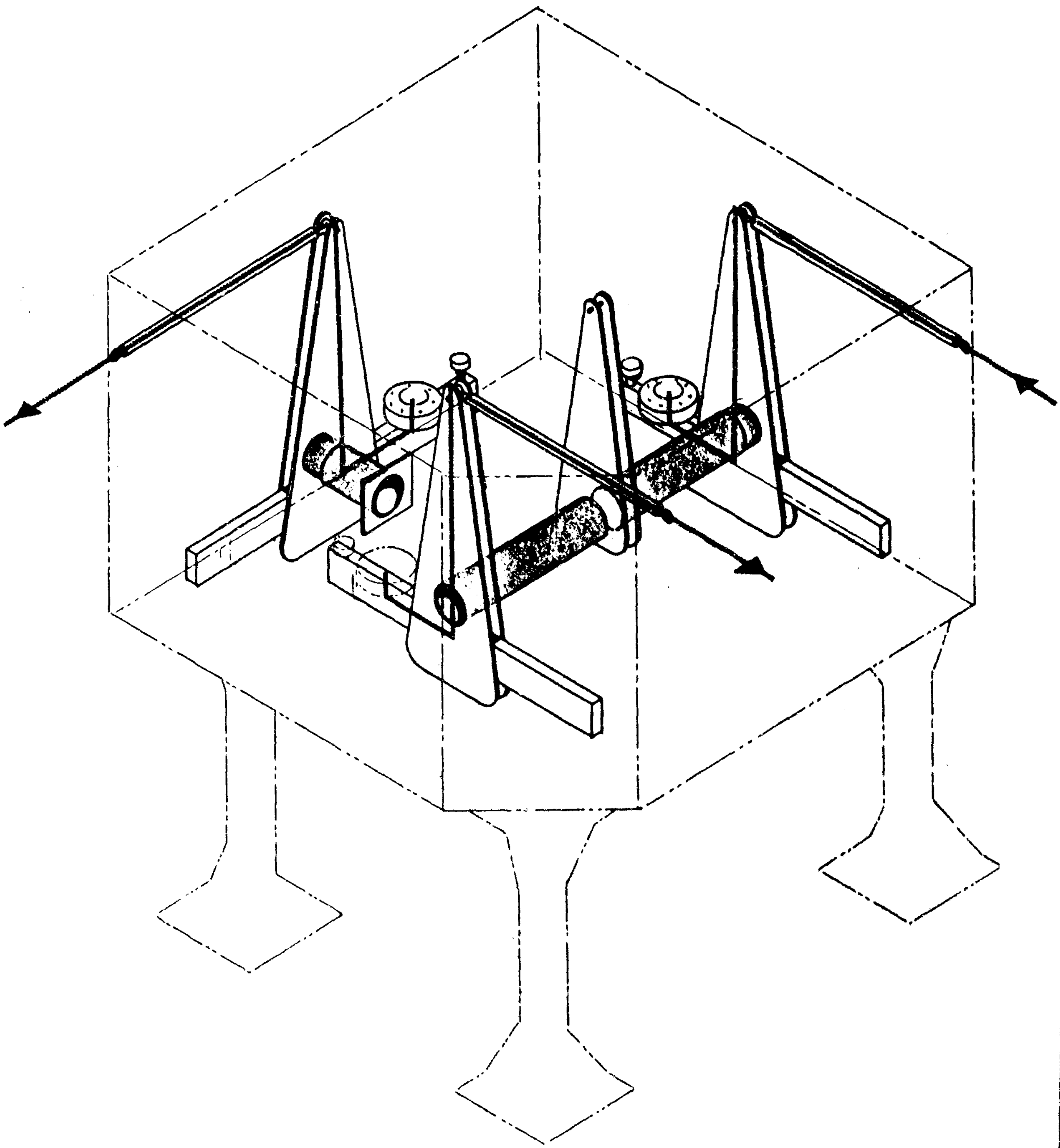


FIGURE A-10: SKETCH SHOWING MECHANISMS FOR TRANSMITTING ORTHOGONAL THRUST VECTORS INTO NULL-BALANCE LOAD CELLS

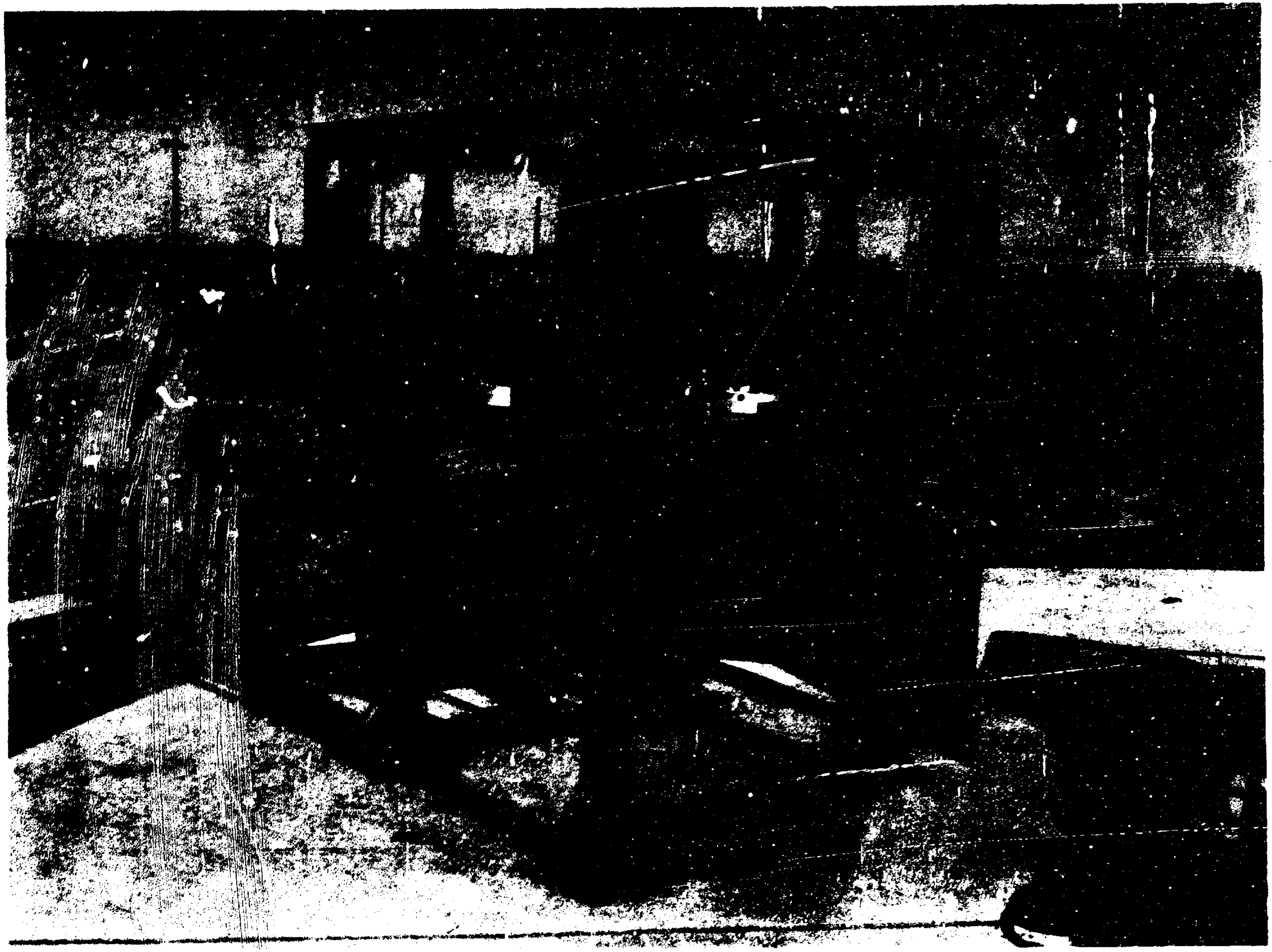


FIGURE A-11 TEST STAND PARTIALLY ASSEMBLED.

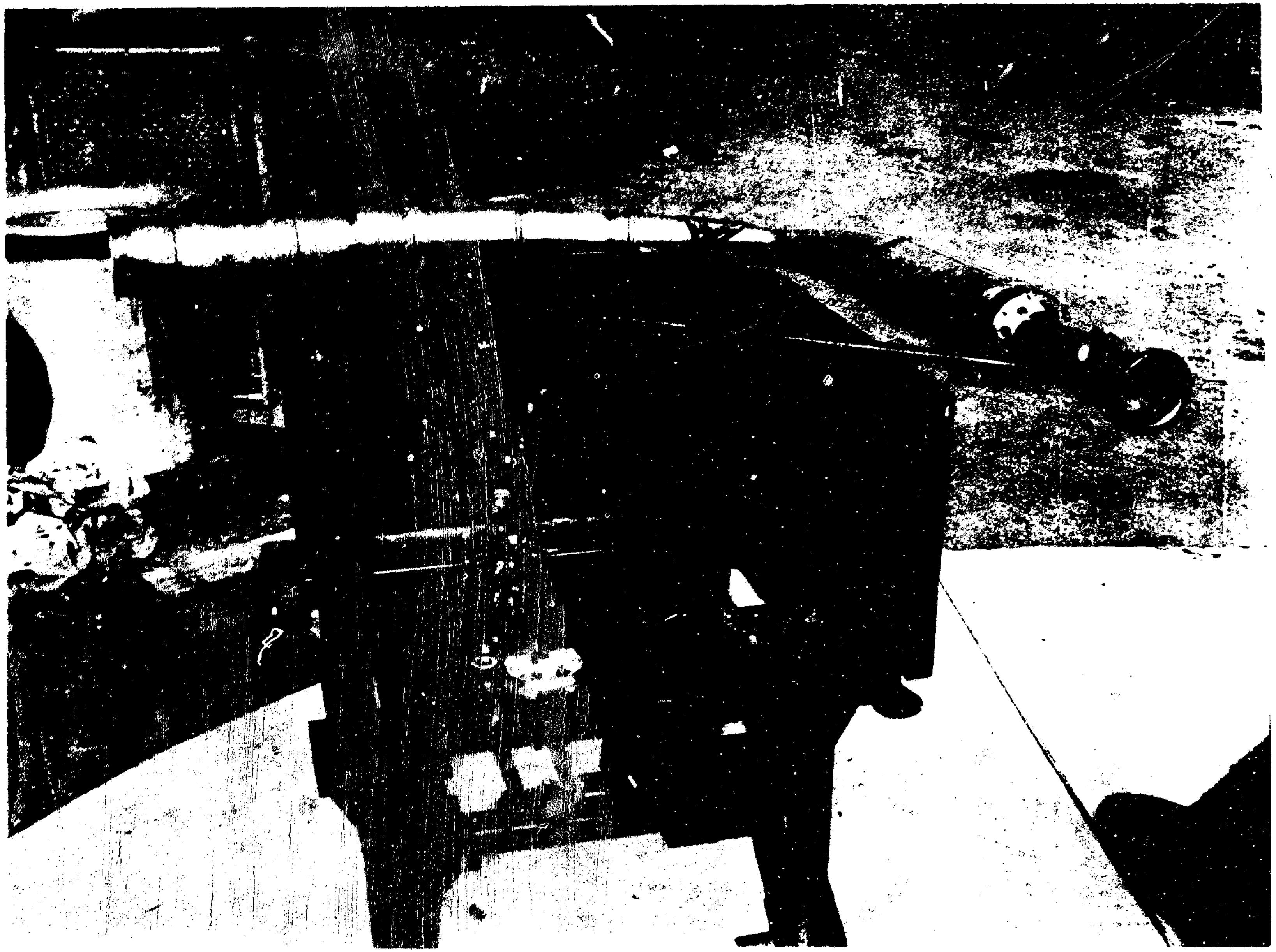


FIGURE A-12 PARTIALLY ASSEMBLED TEST STAND SHOWING HS-2 ENGINE IN APPROXIMATE MOUNTING POSITION.

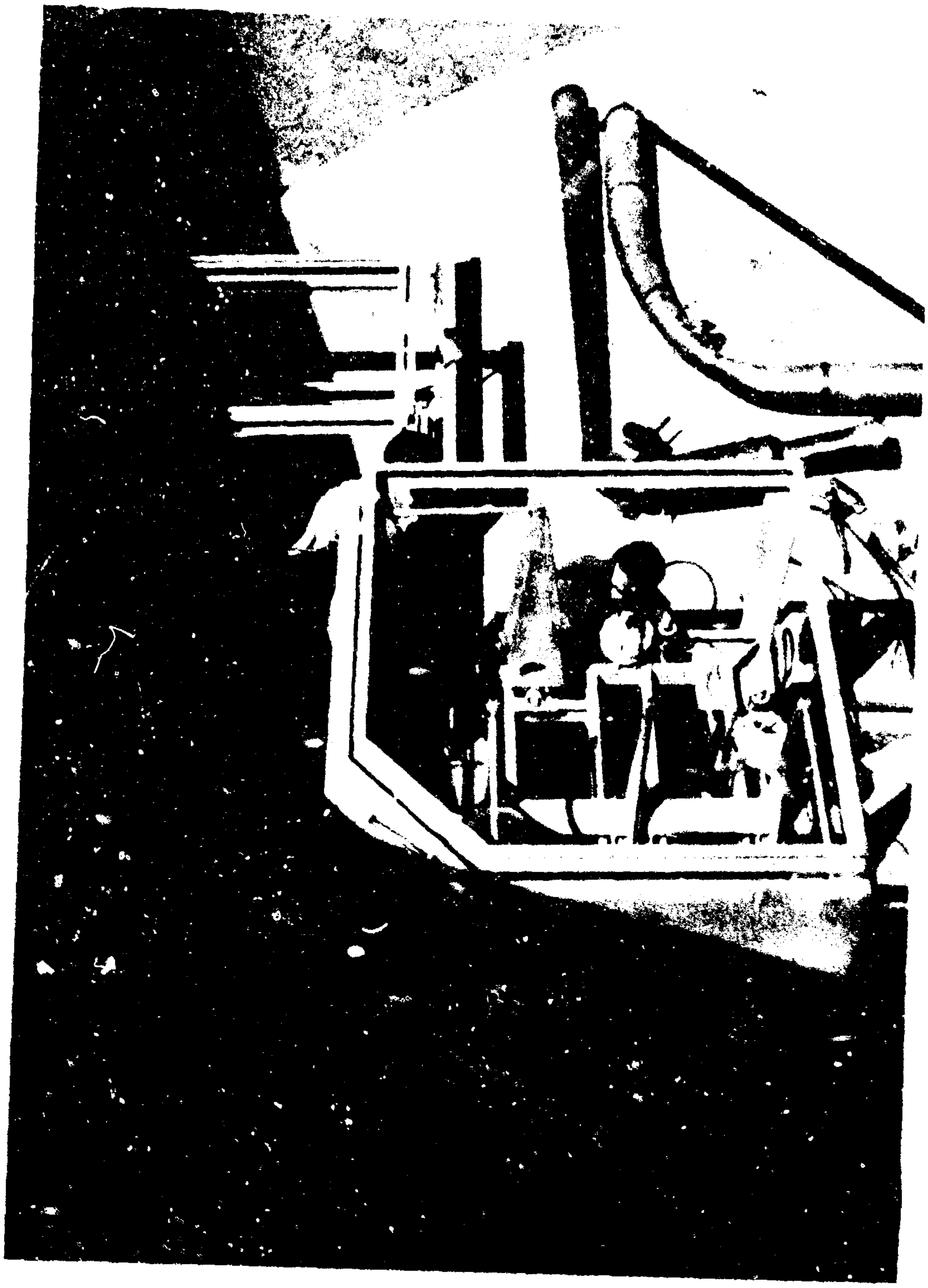


FIGURE A-13 ENGINE AND AUGMENTOR TEST STANDS

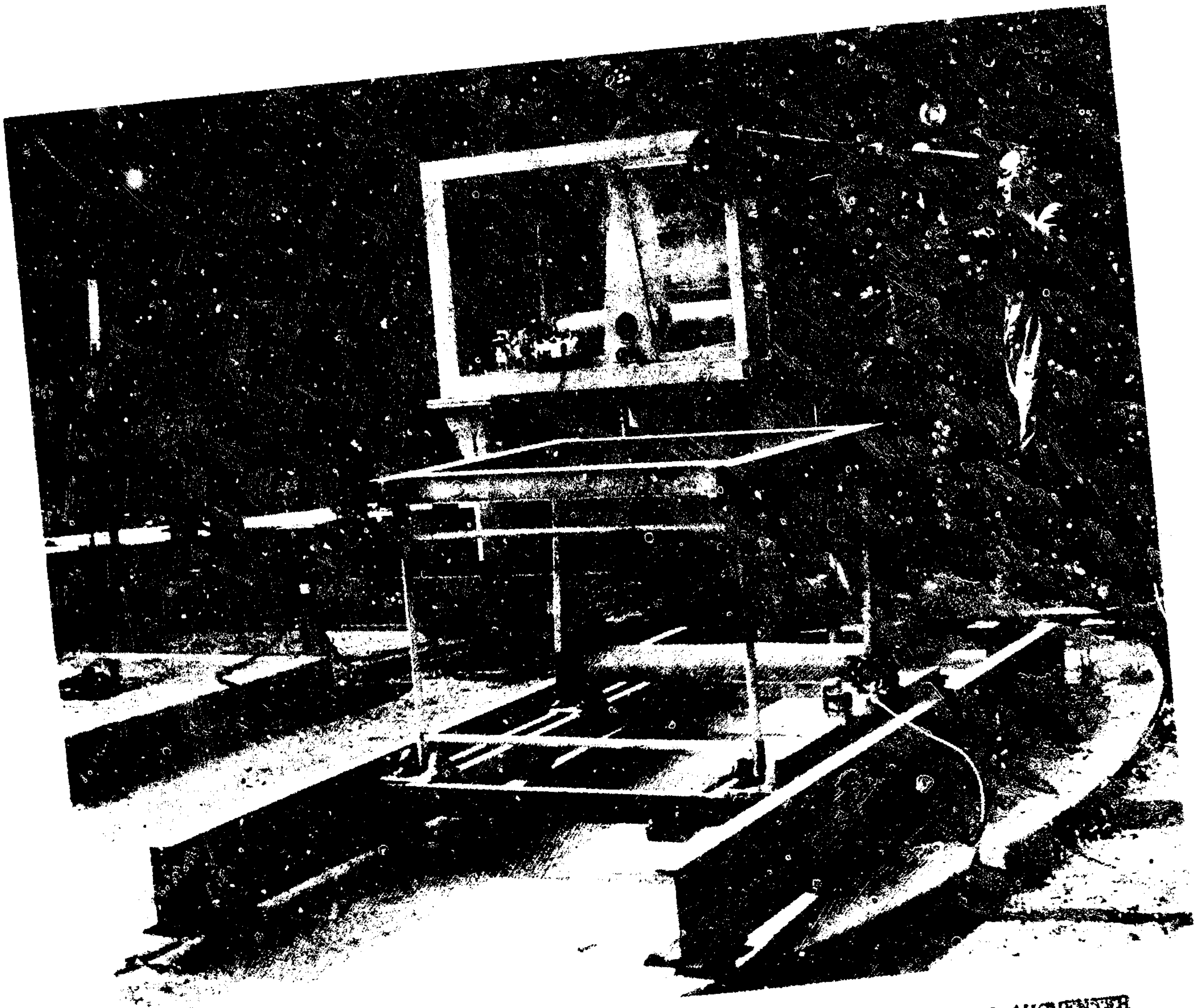


FIGURE A-14 INTERMITTENT JET ENGINE THRUST STAND AND DUAL THRUST AUGMENTER STANDS. HS-1A (90°) ENGINE INSTALLED.

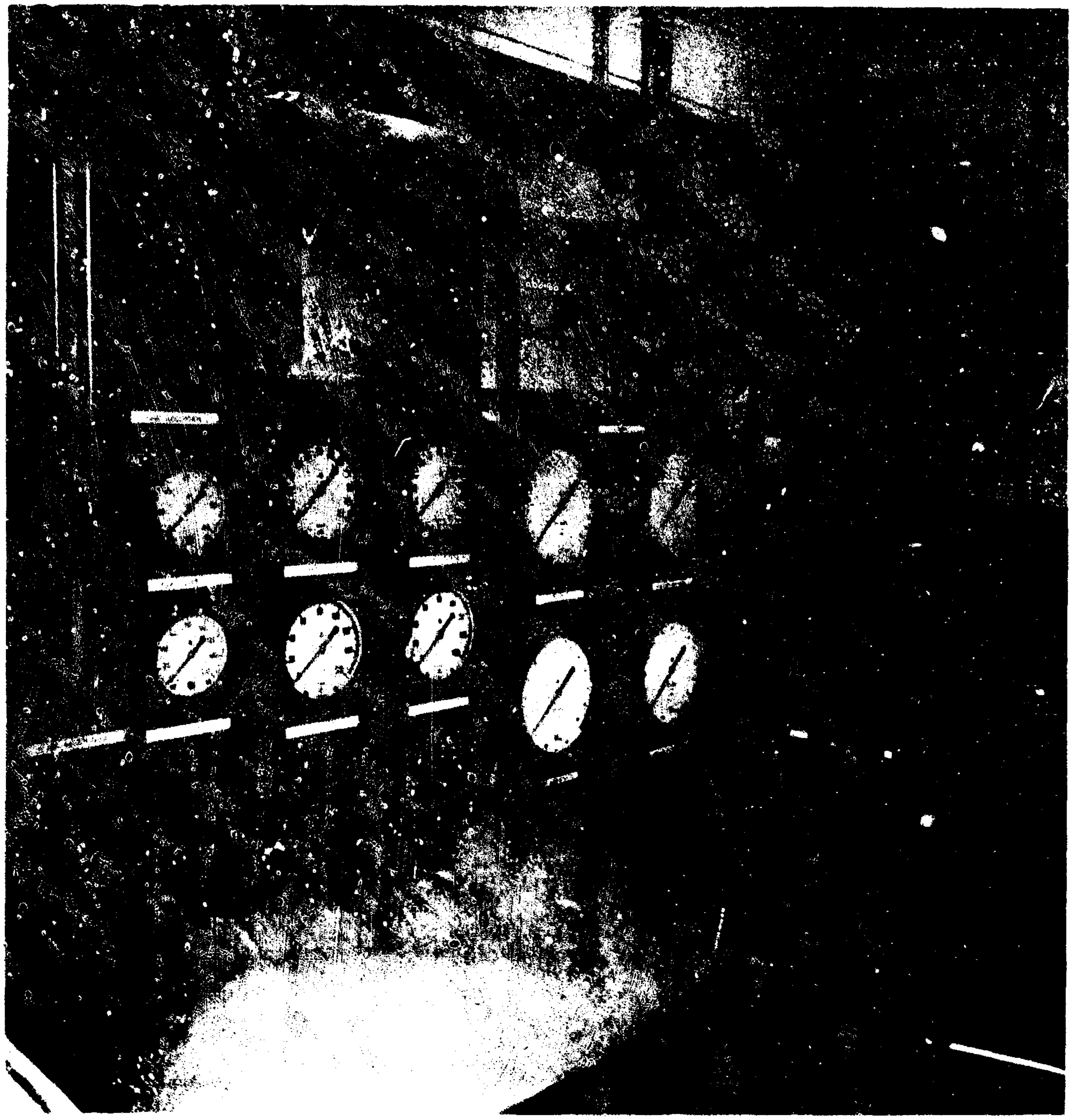
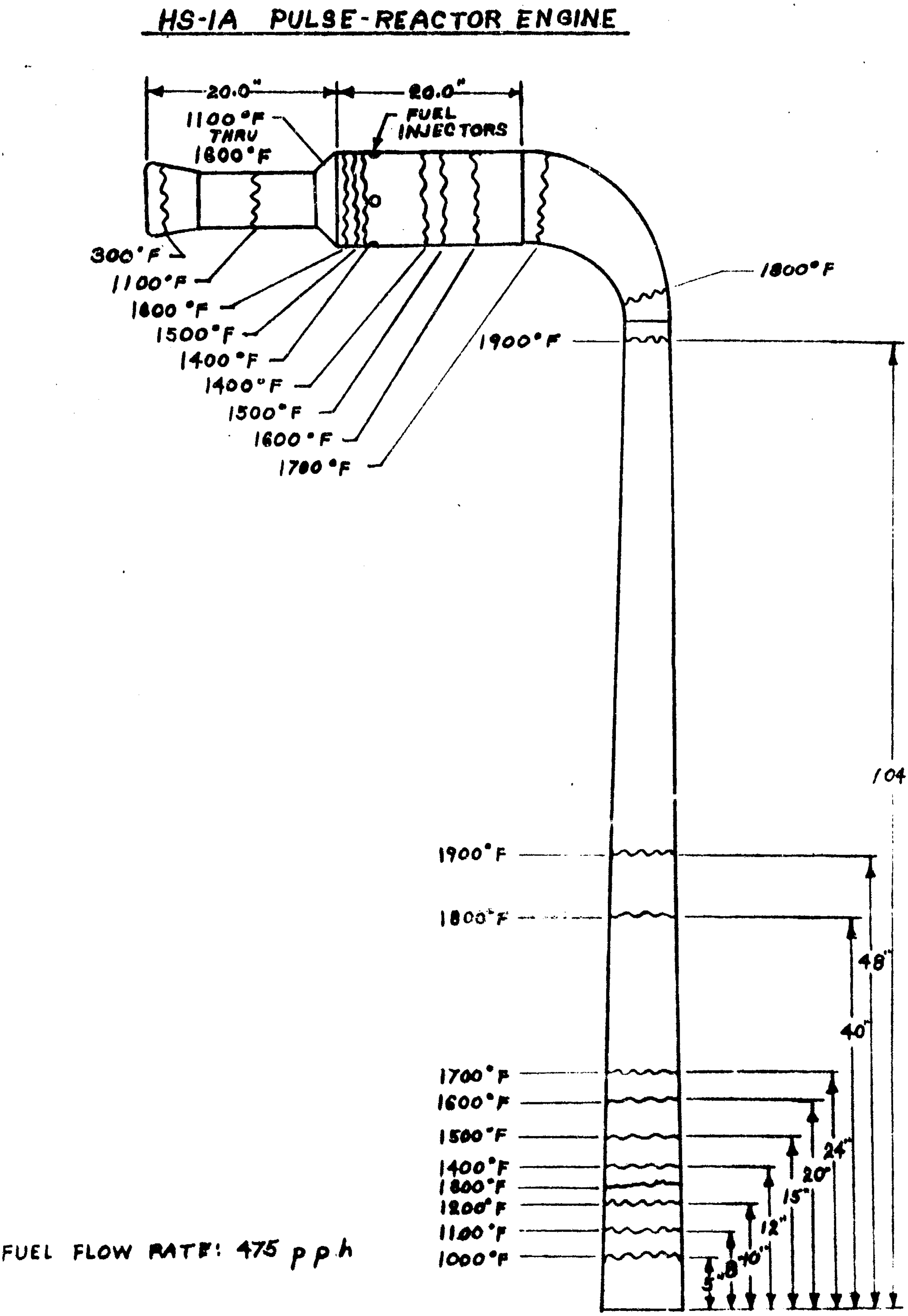


FIGURE A-15 INSTRUMENT AND CONTROL CONSOLE FOR INTERMITTENT JET ENGINE AND AND THRUST AUGMENTER TEST STANDS.



SHELL TEMPERATURE DISTRIBUTION FOR HS-1A ENGINE (UNCOOLED)

FIGURE A-16

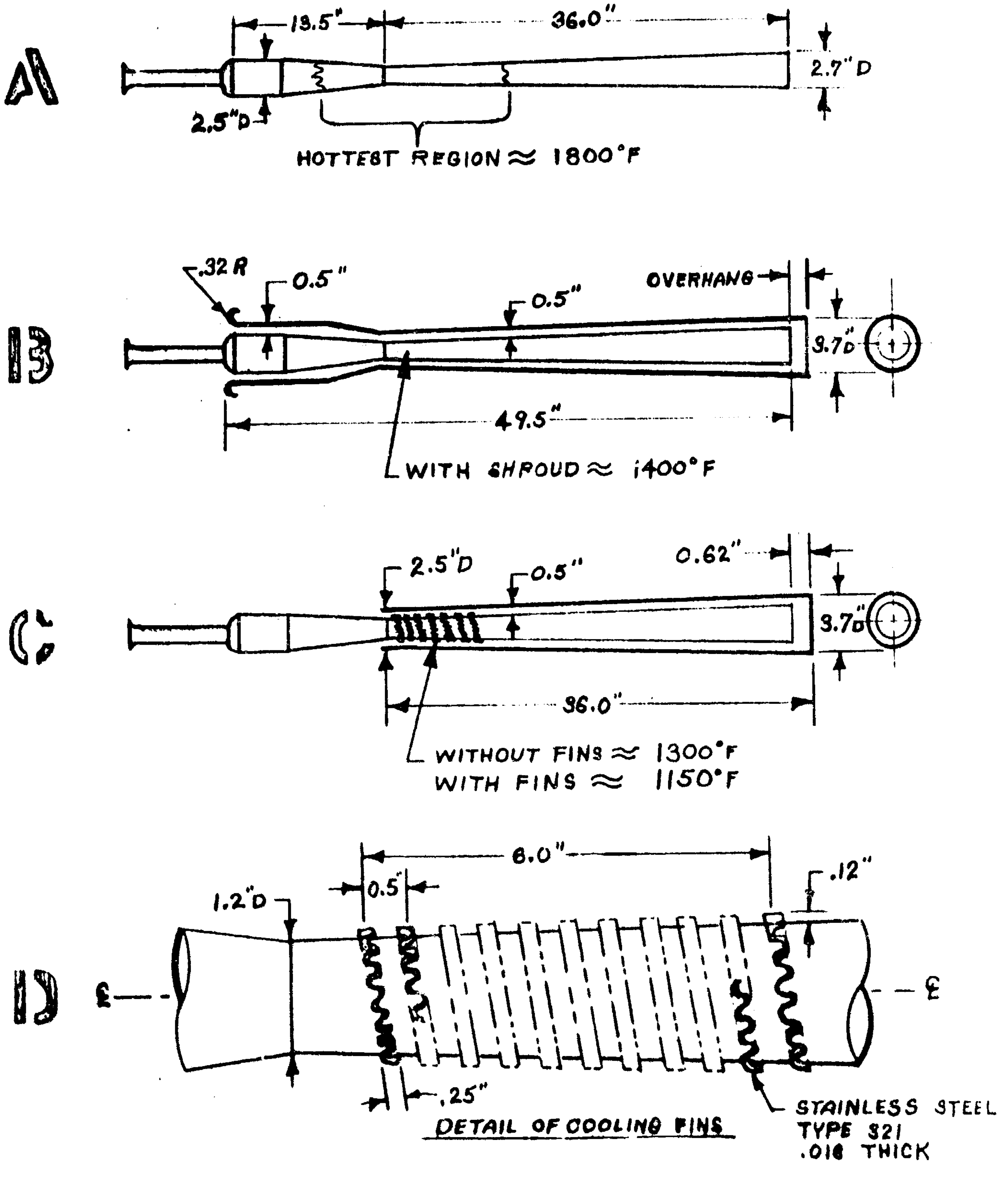


FIGURE A-17: ENGINE COOLING BY JET PUMPING

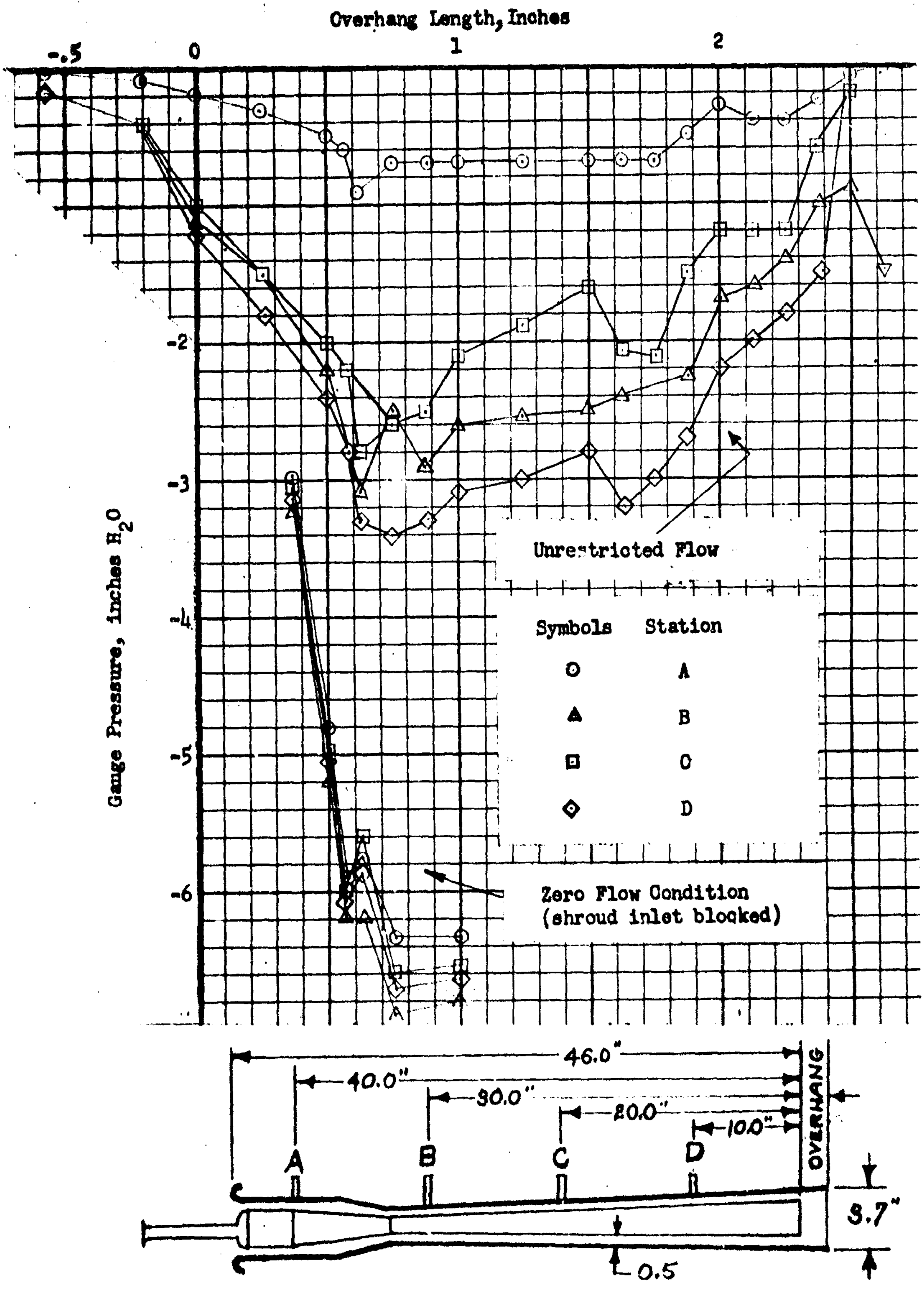


FIGURE A-18: COOLING SHROUD VACUUM INDUCED BY JET PUMPING

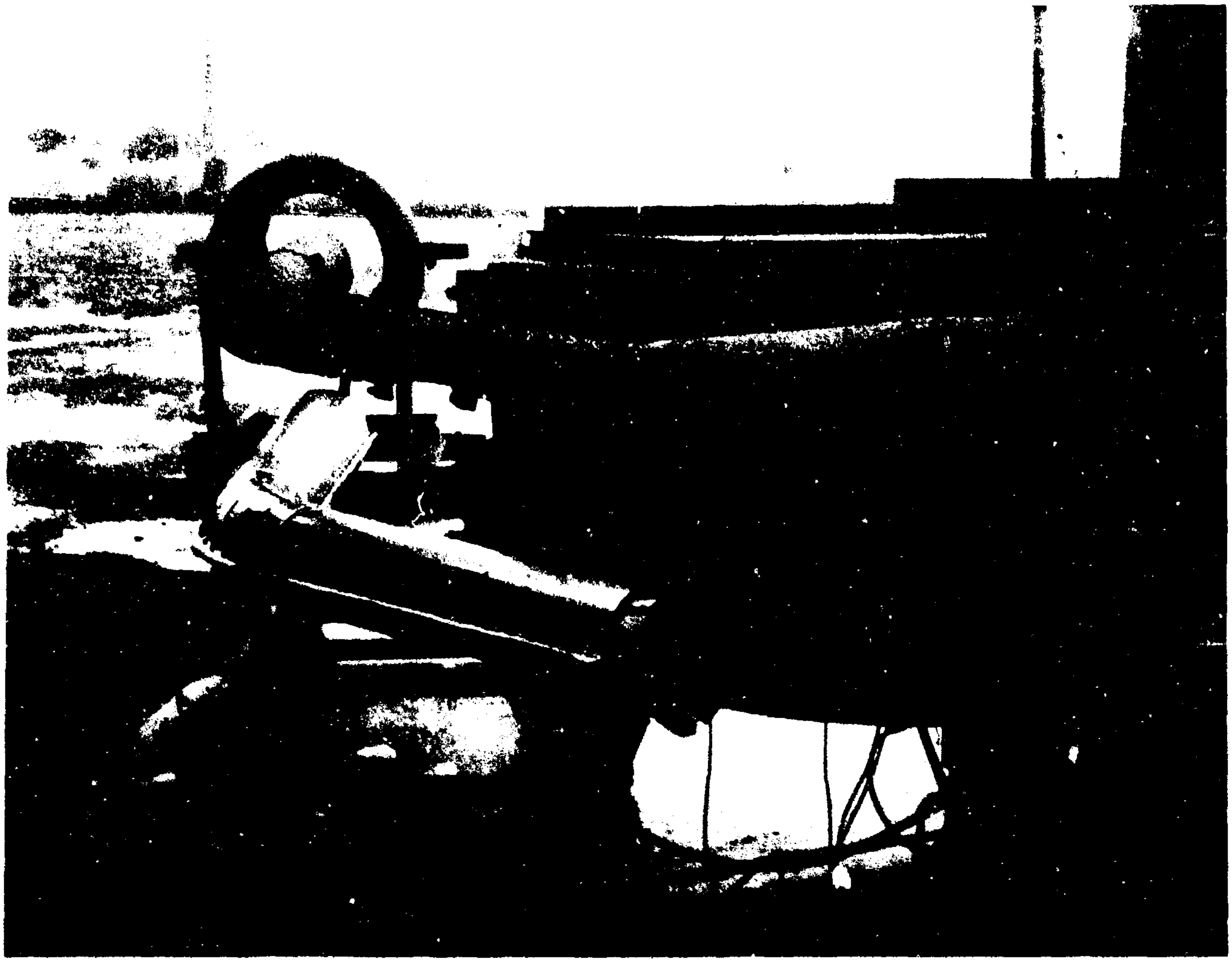


FIGURE A-19 COOLING SHROUD ON HS-2C, SERIAL 1 ENGINE

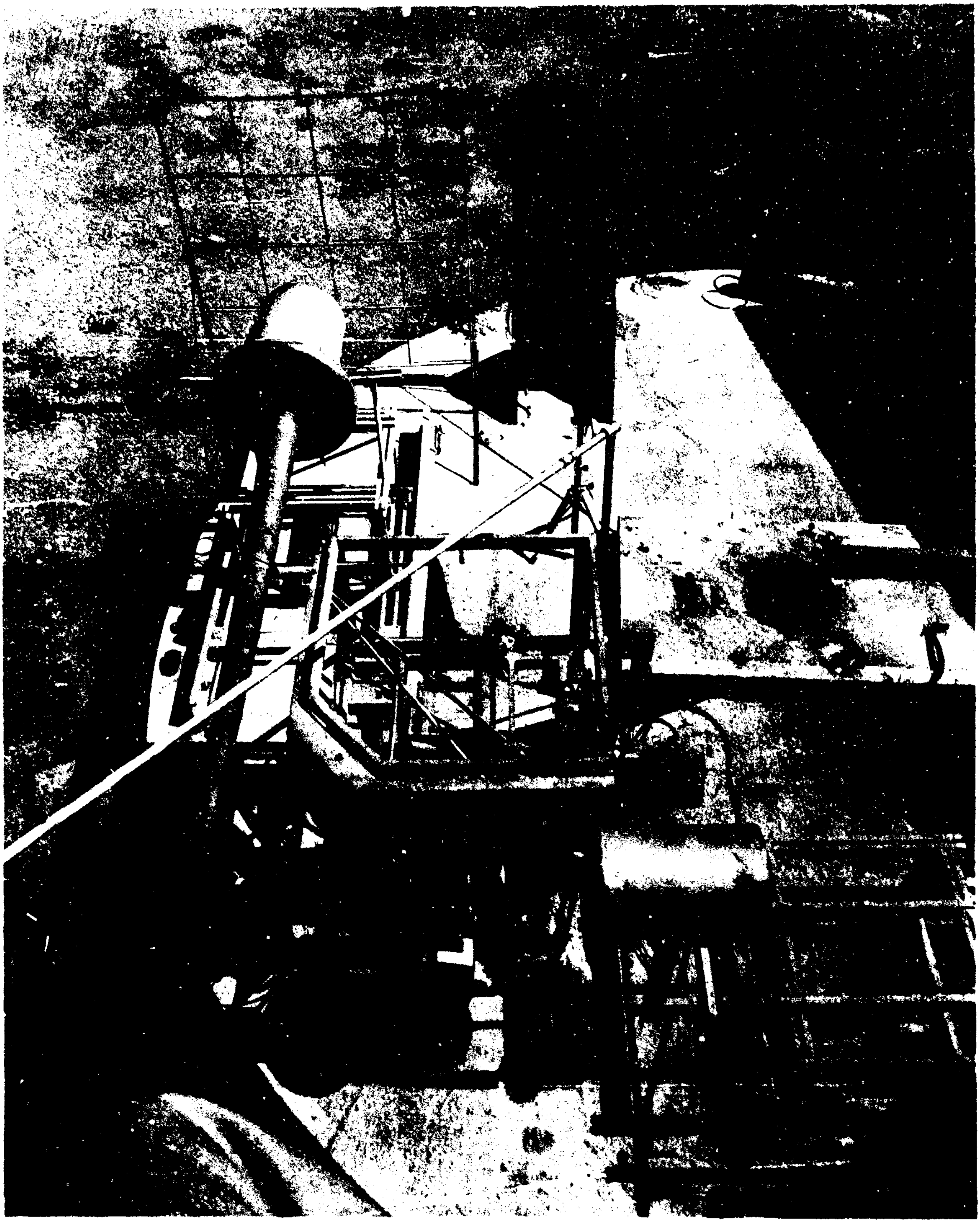


FIGURE A-20 CYLINDRICAL AUGMENTERS ON TEST STAND

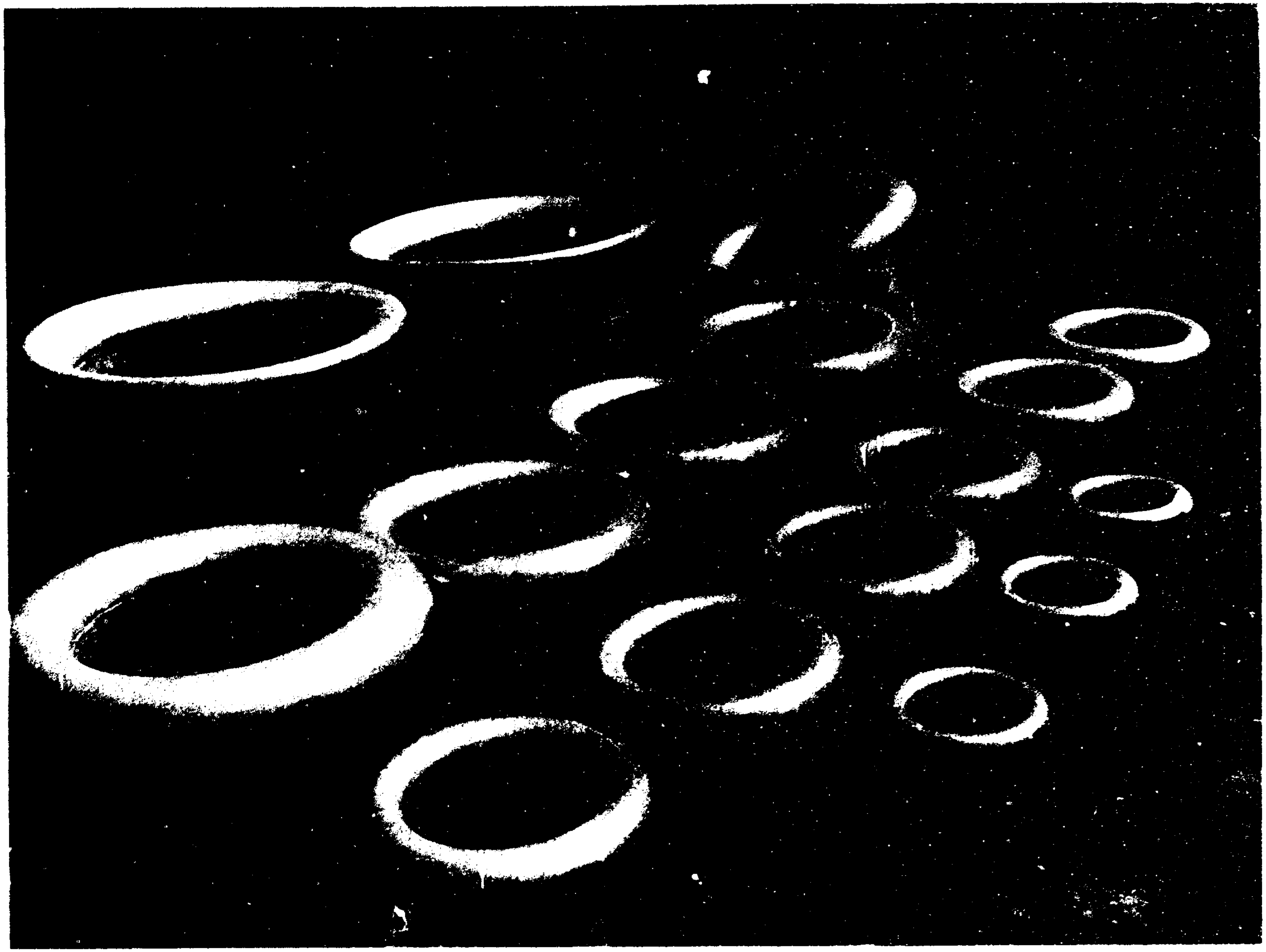


FIGURE A-21 COMPLETED THRUST AUGMENTOR DUCTS

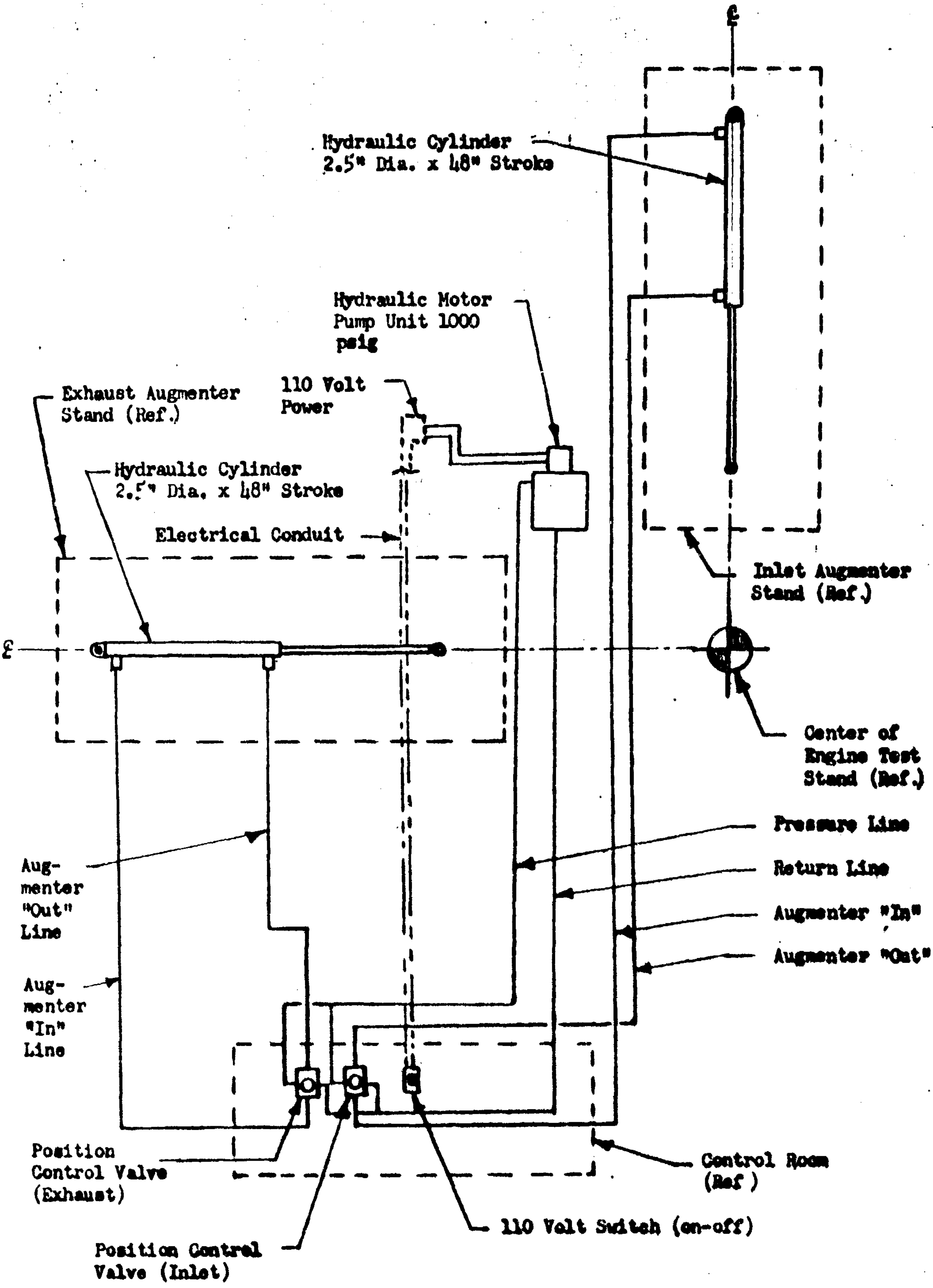


FIGURE A-22: HYDRAULIC-ACTUATED AUGMENTER POSITIONER

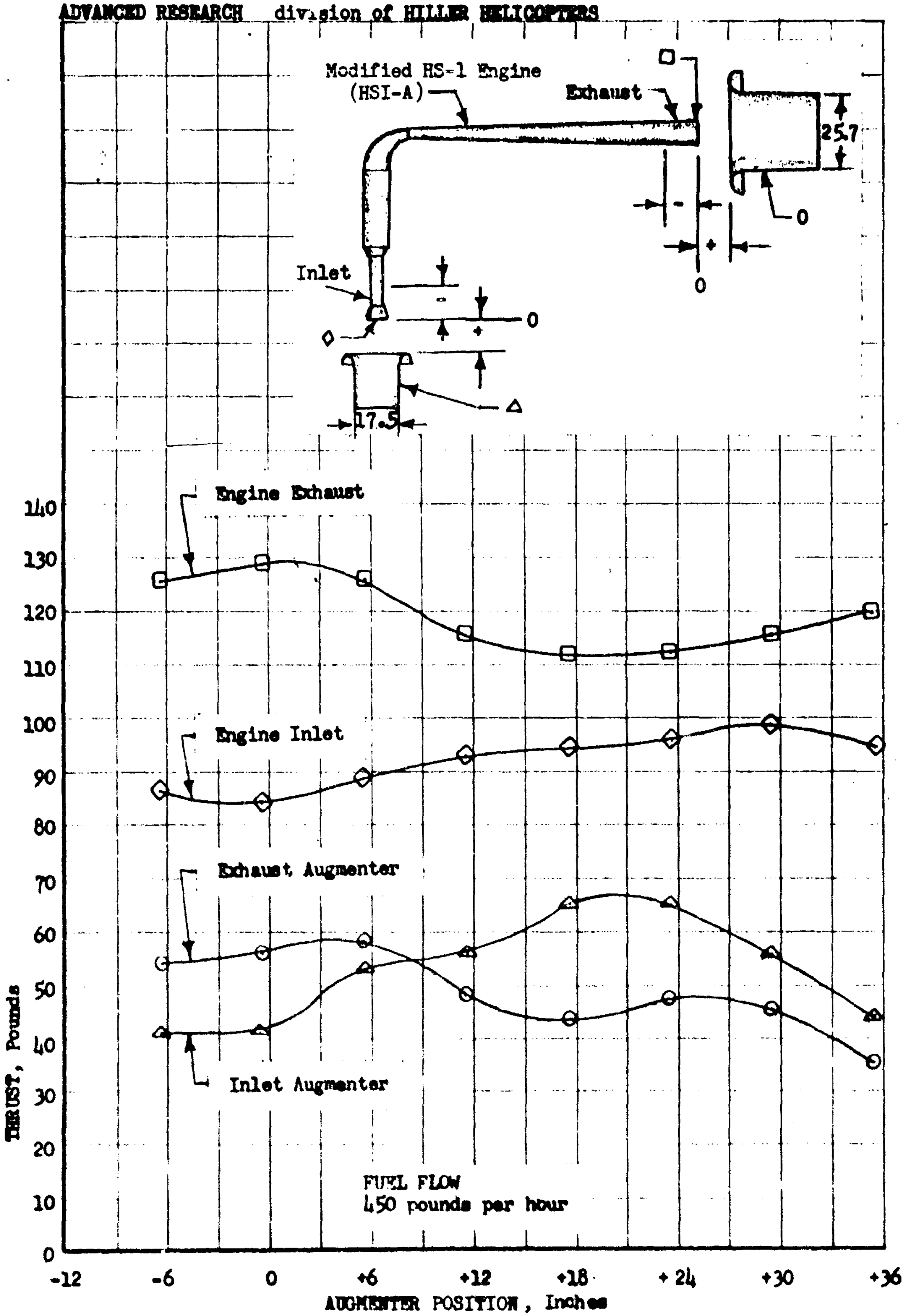


FIGURE A-23: EFFECT OF POSITION OF AUGMENTERS ON ENGINE AND AUGMENTER THRUST

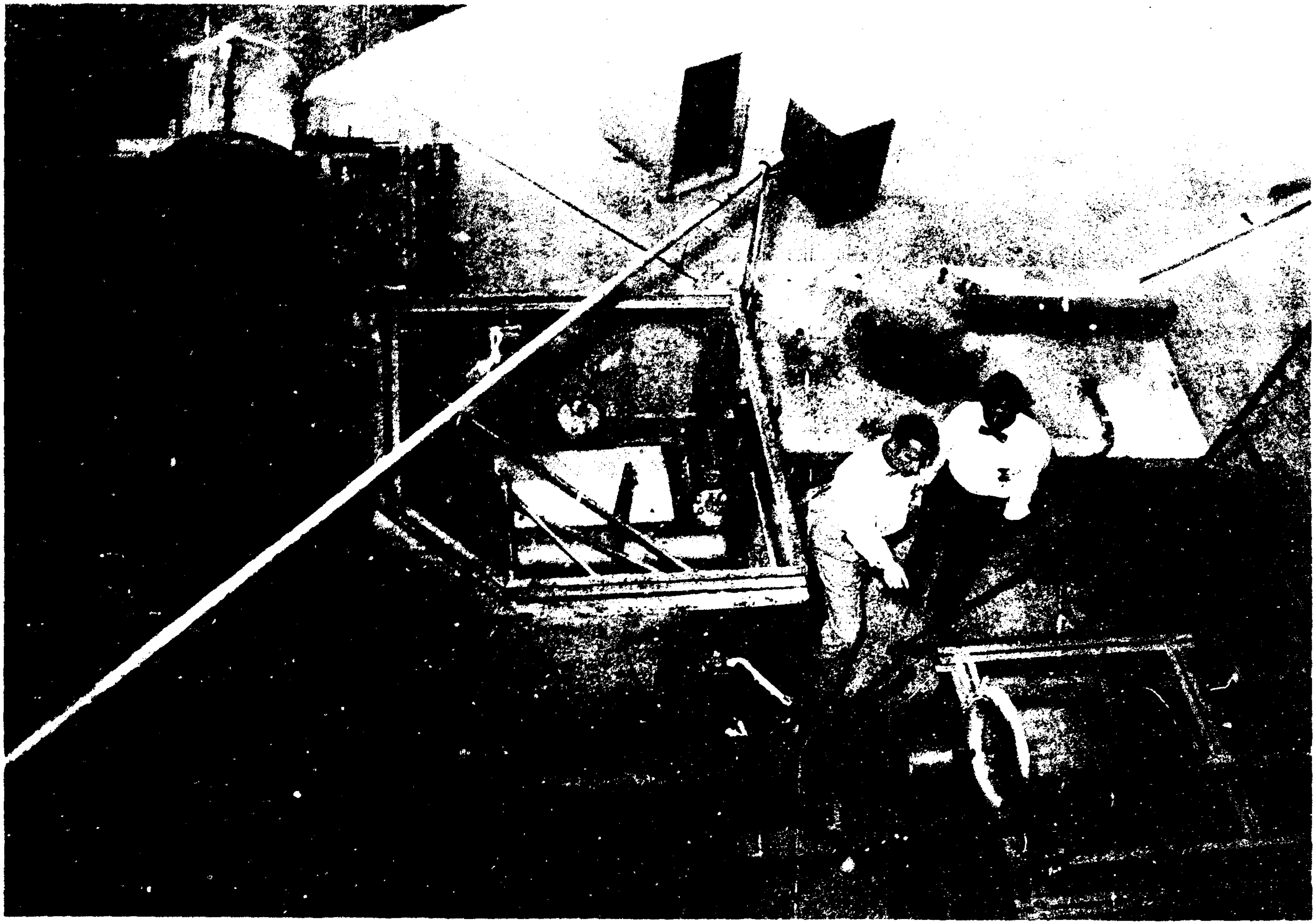


FIGURE A-24 8° DIVERGENT CONICAL AUGMENTERS ON TEST STAND

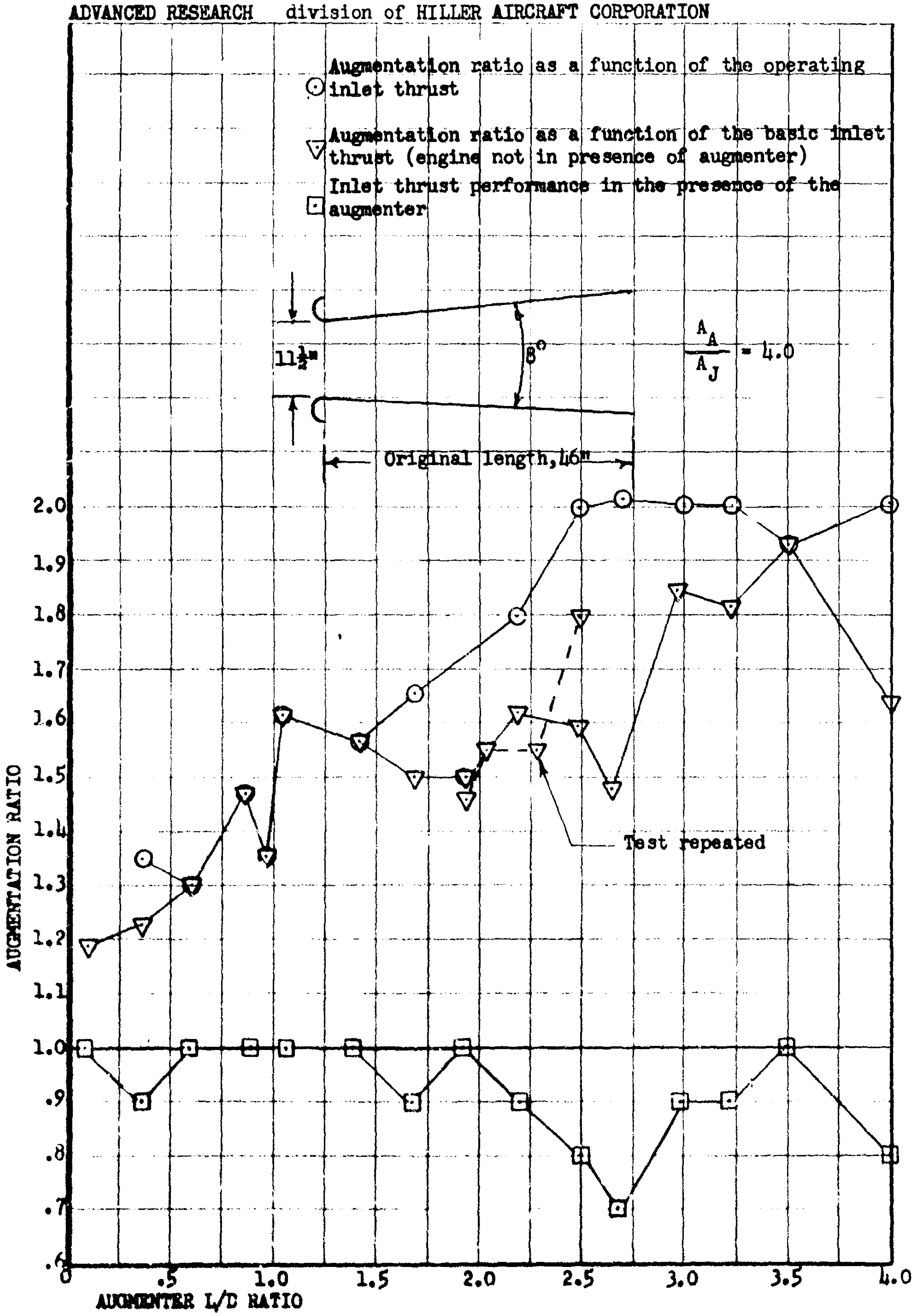


FIGURE A-25: EFFECT OF L/D RATIO ON INLET JET AUGMENTATION PERFORMANCE FOR AN 8° CONICALLY DIVERGENT AUGMENTER

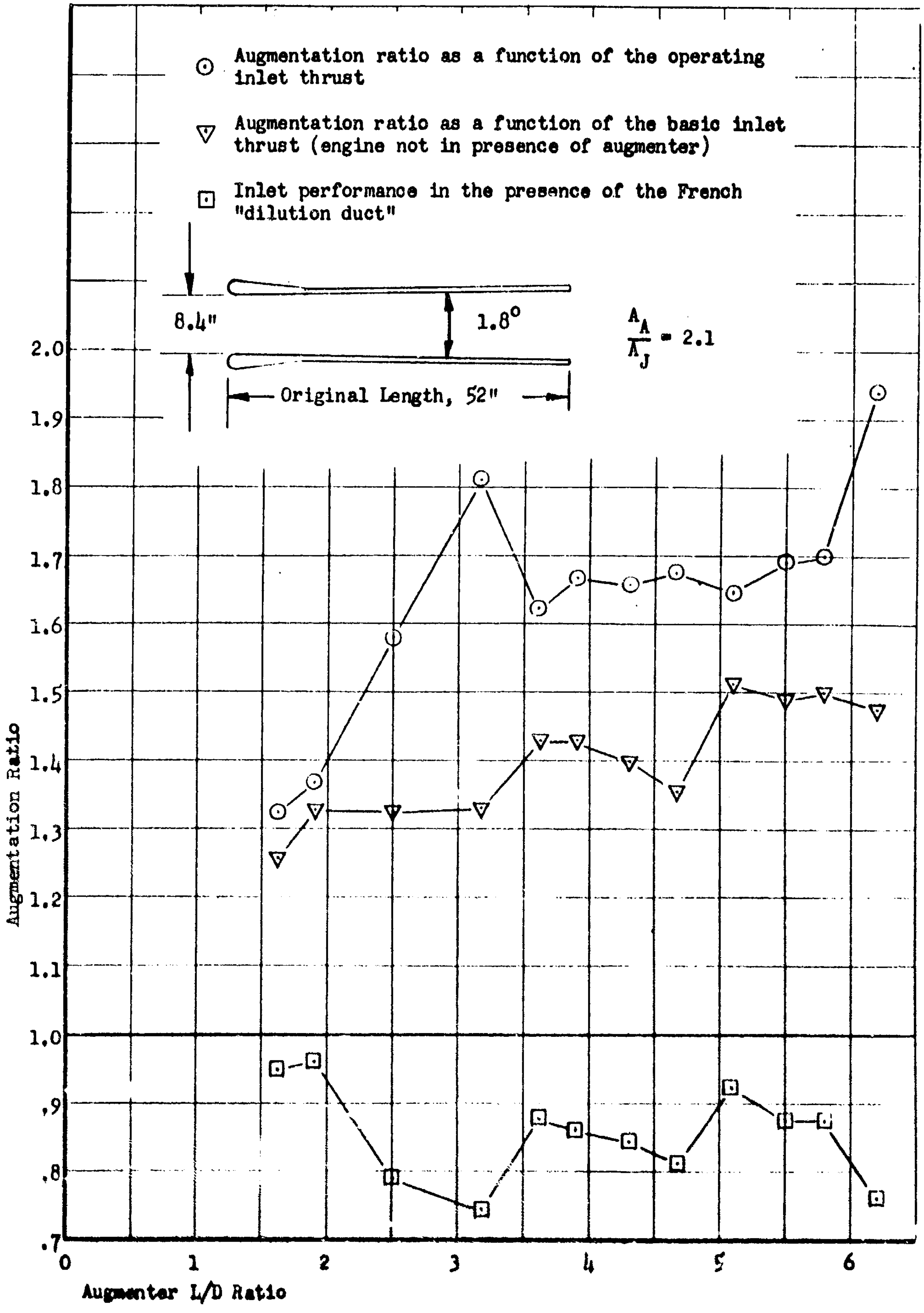
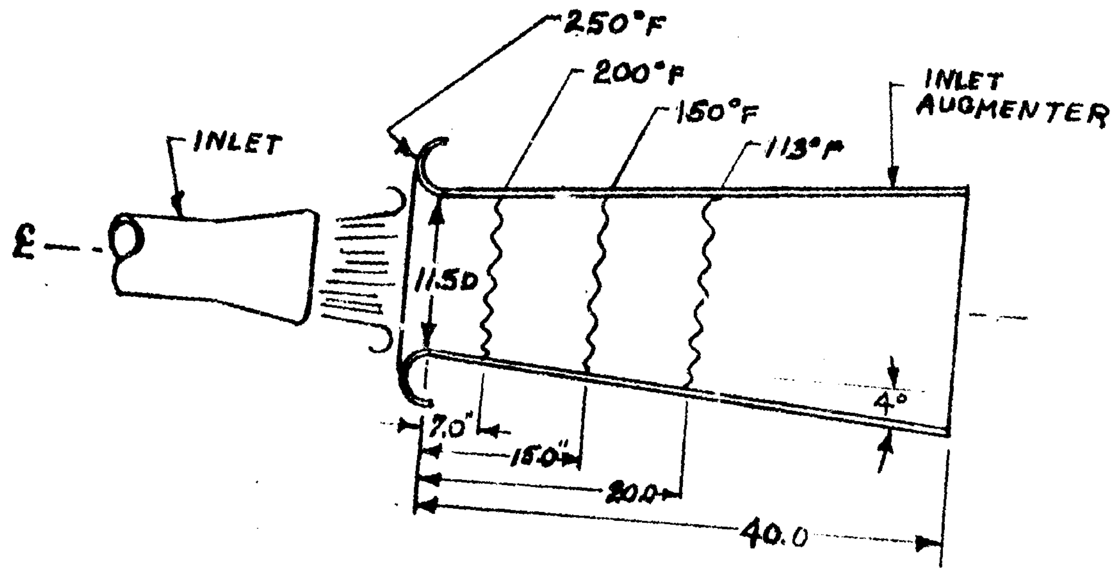


FIGURE A-26: EFFECT OF L/D RATIO ON AUGMENTATION PERFORMANCE FOR THE SNECMA "DILUTION DUCT"

ENGINE FUEL FLOW : 475 p.p.h.



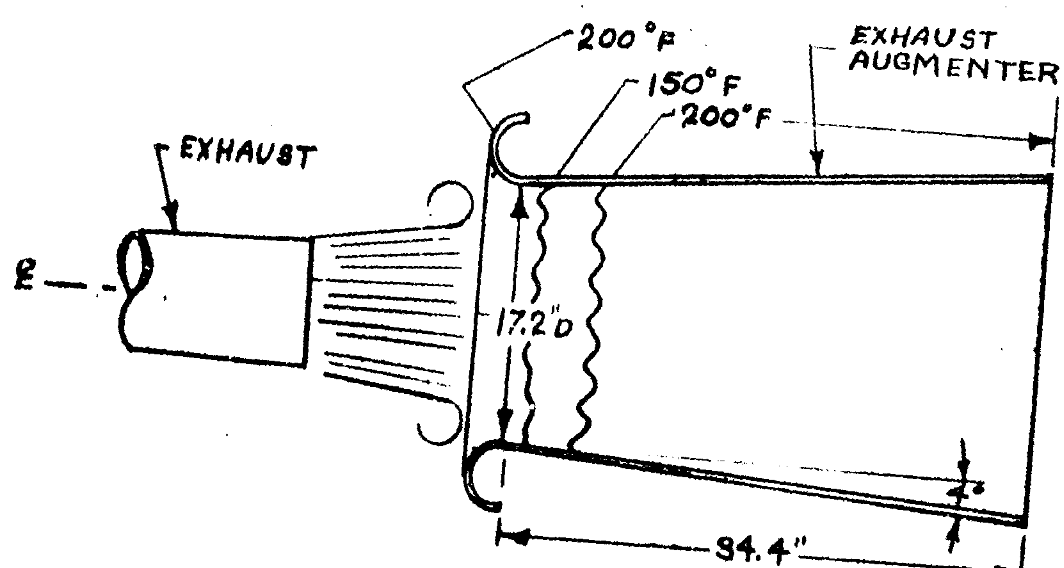
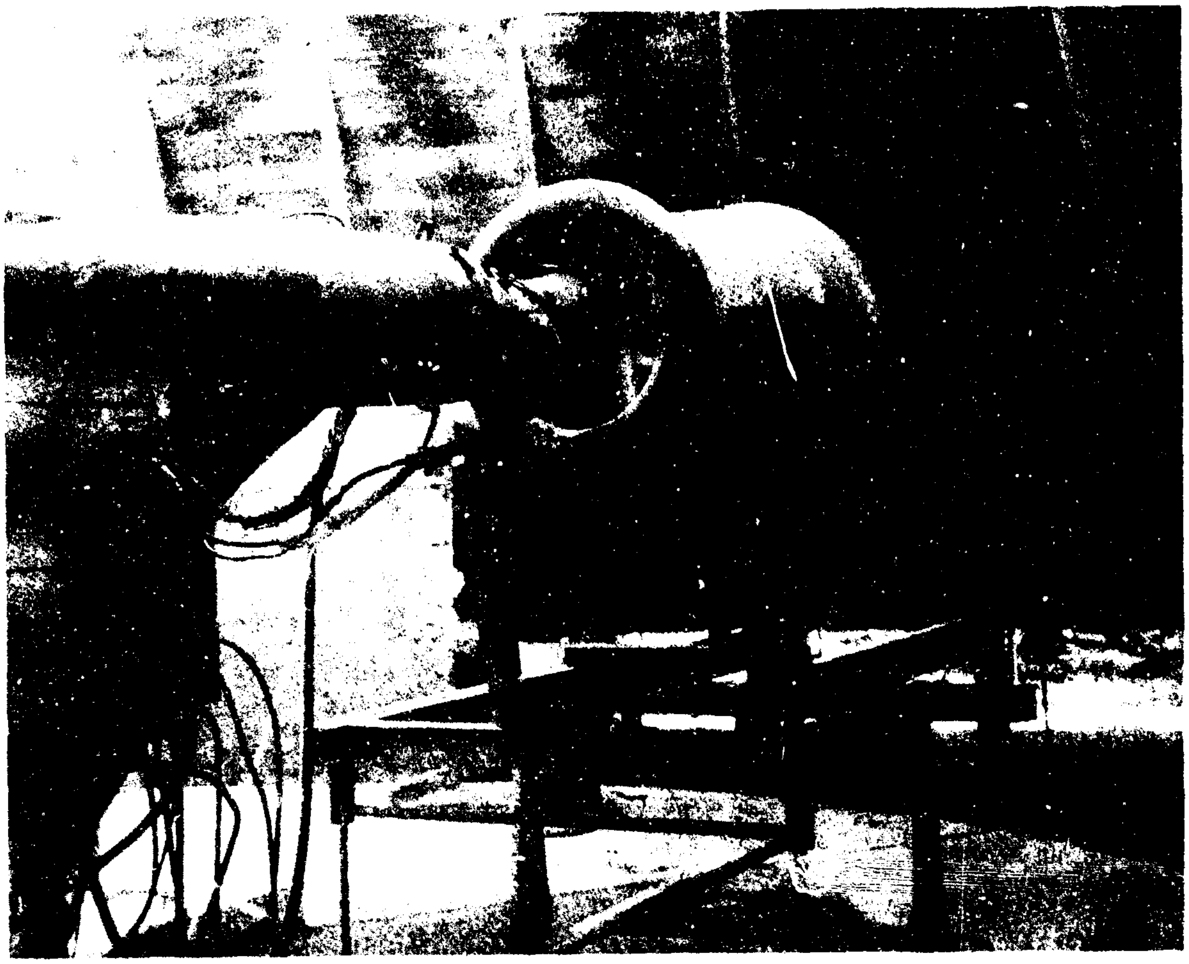


FIGURE A-27: AUGMENTER SHELL TEMPERATURES AT FUEL FLOW OF 475 pph



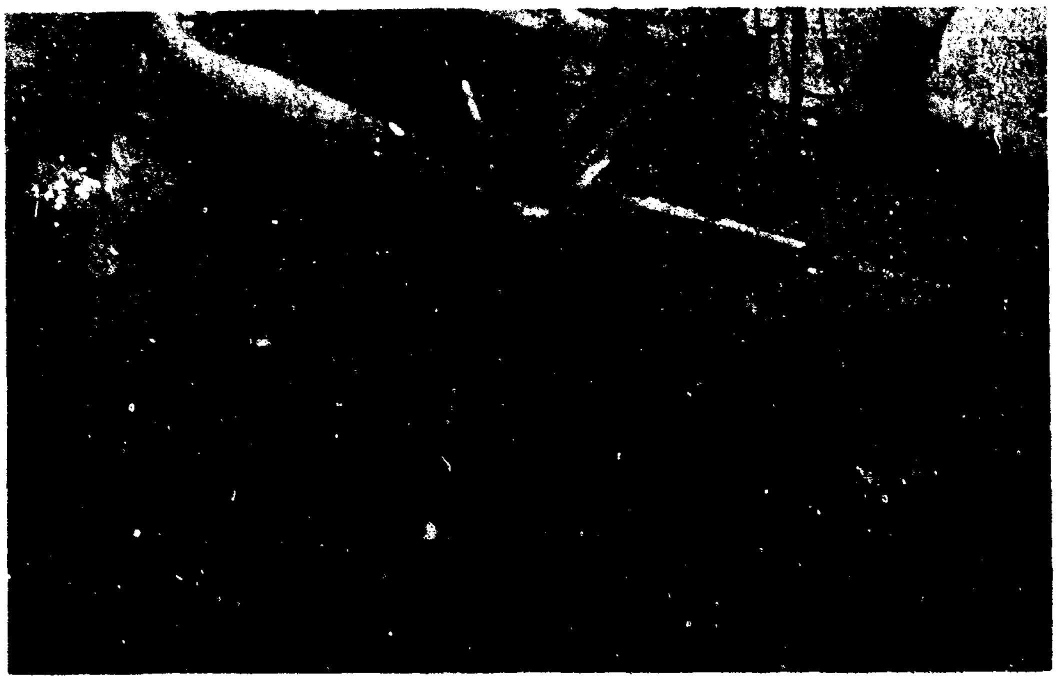


FIGURE A-28 16° DIVERGENT FIBERGLAS CONICAL AUGMENTER ON TEST STAND

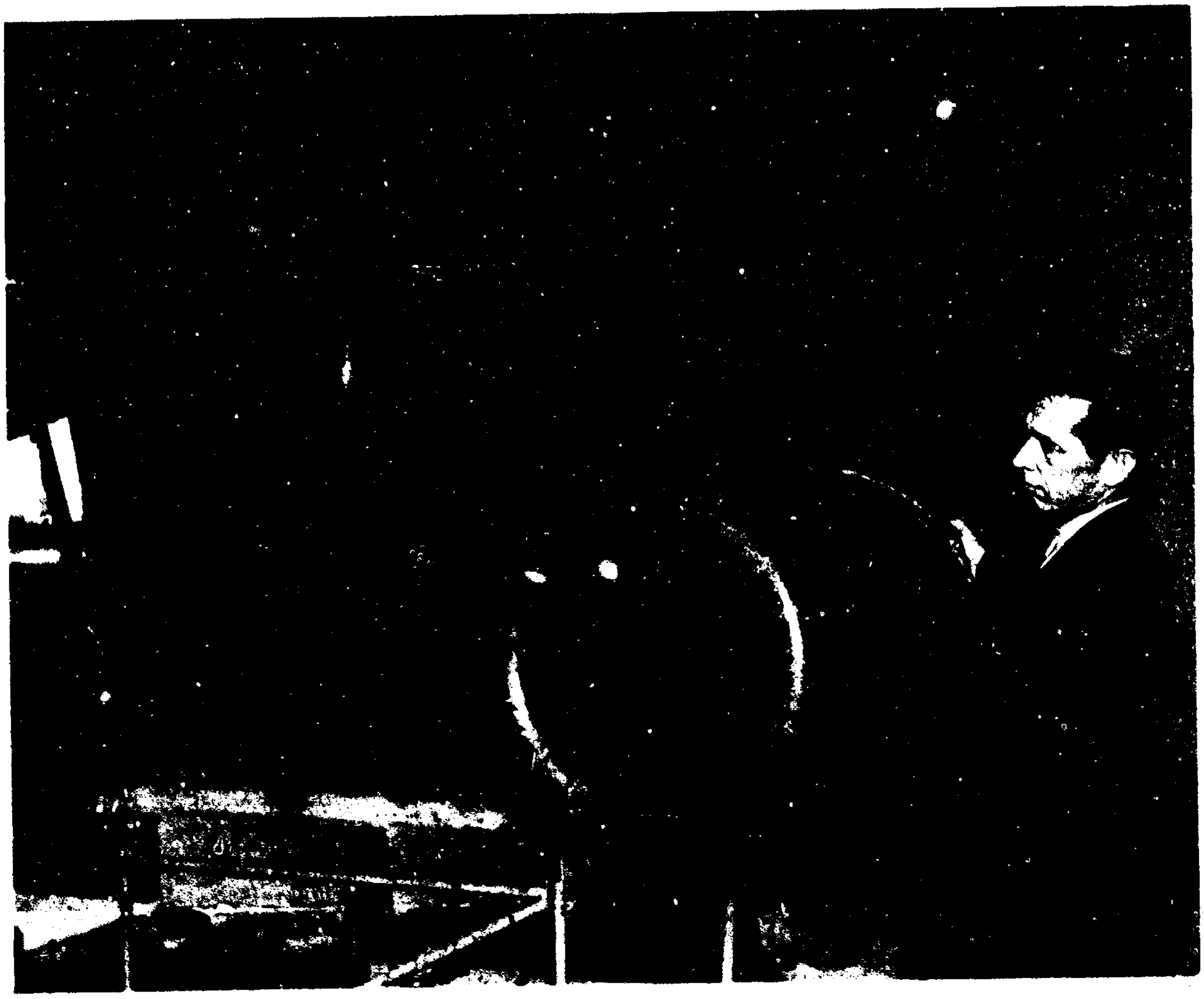


FIGURE A-28a: COMPARISON OF 14-INCH THROAT DIAMETER, CONICALLY DIVERGENT, FIBERGLASS HONEYCOMB. INLET JET THRUST AUGMENTERS. THE INSTALLED AUGMENTER IS AN 8° CONE AS COMPARED WITH 16° INCLUDED ANGLE FOR AUGMENTER BEING HELD IN THE FOREGROUND.

FIGURE A-29 AUGMENTER ANGLED ON TEST STAND

ADVANCED RESEARCH division of HILLER AIRCRAFT CORPORATION

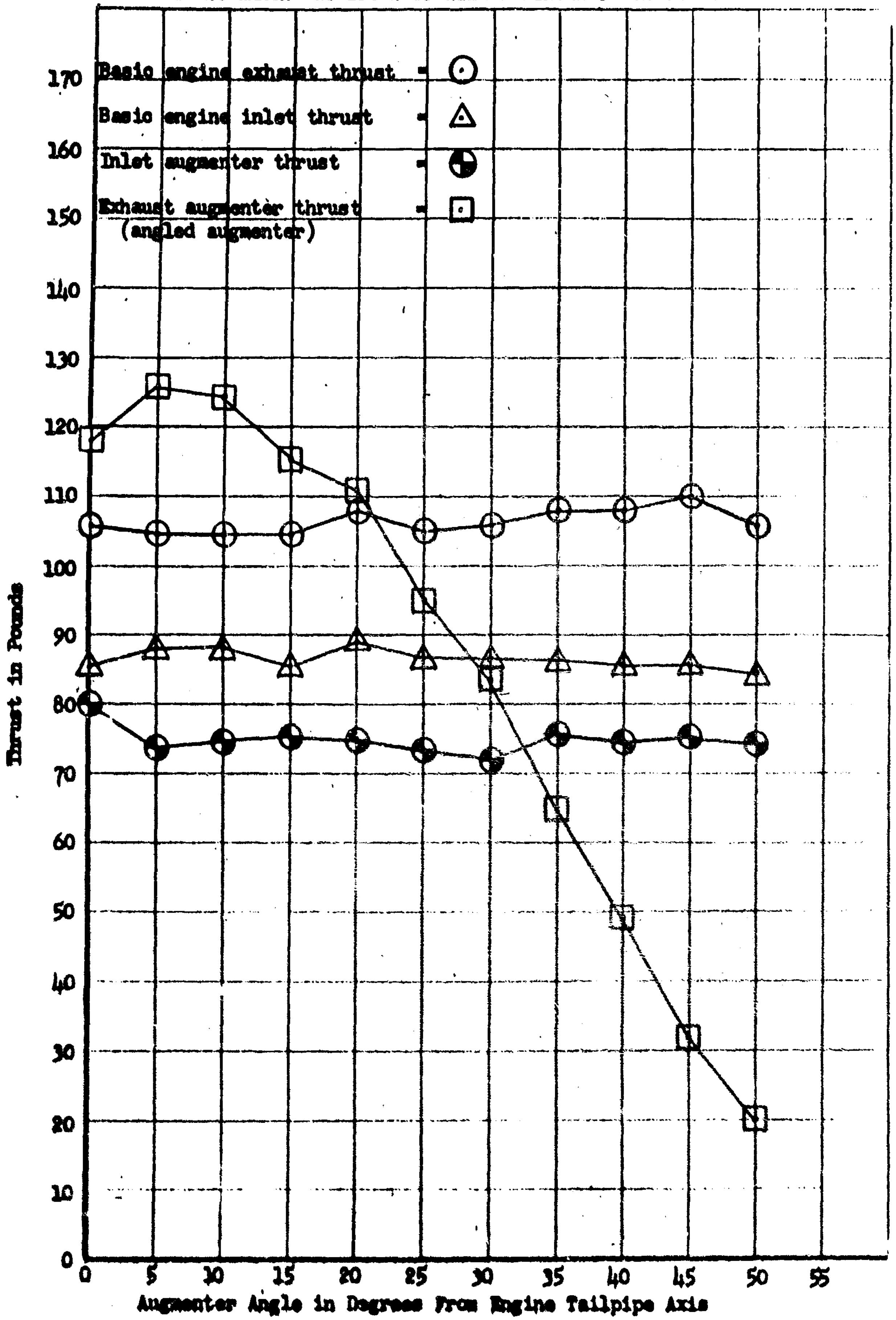


FIGURE A-30: ANGLED AUGMENTER DATA

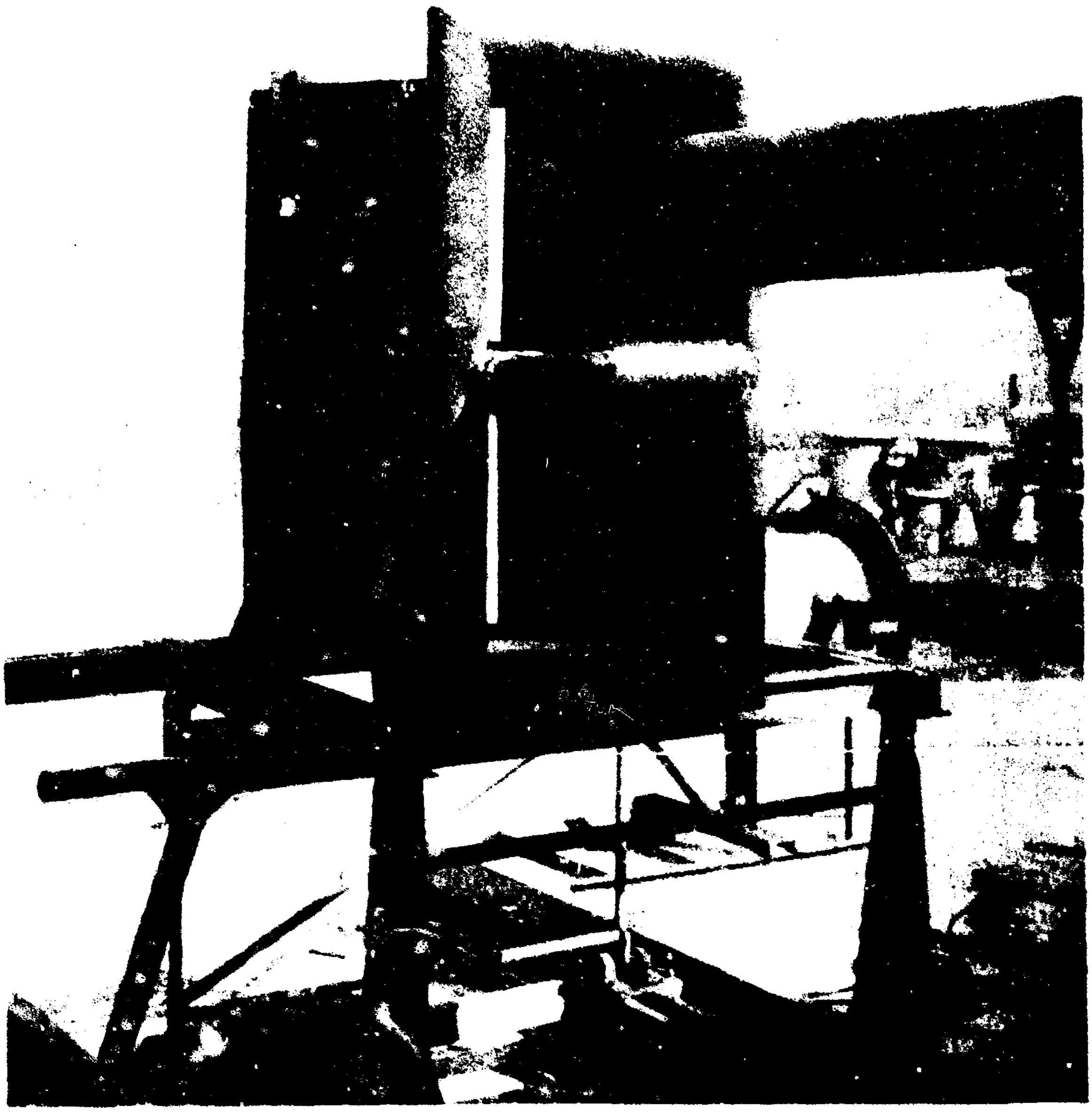


FIGURE A-31 8° DIVERGENT RECTANGULAR AUGMENTER ON TEST STAND

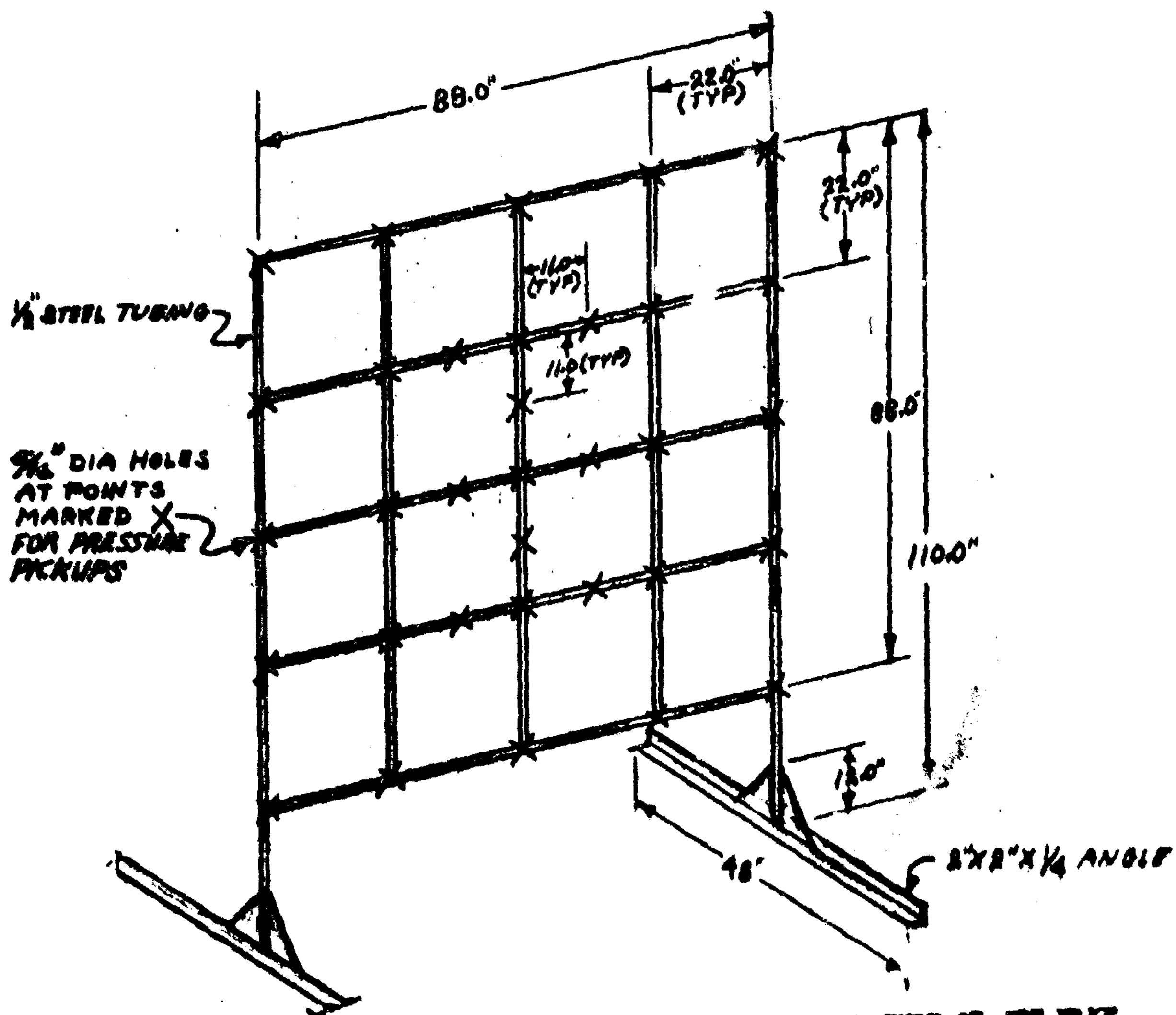


FIGURE A-32: TEST GRID FOR MEASURING PRESSURE AND TEMPERATURE OF JET WAKE.

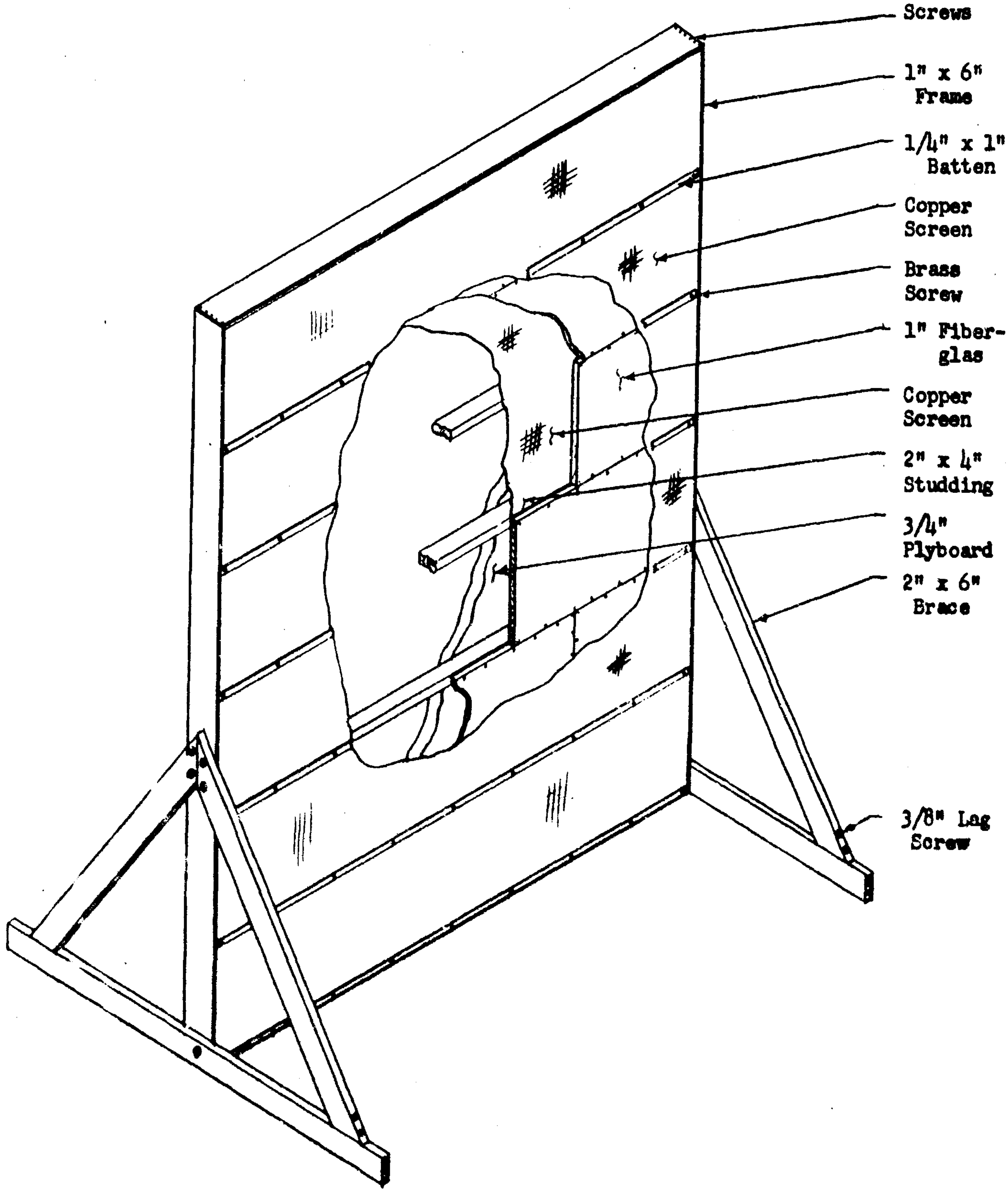


FIGURE A-33: ACOUSTICAL PANELS SHOWING CONSTRUCTION DETAILS AND MATERIAL

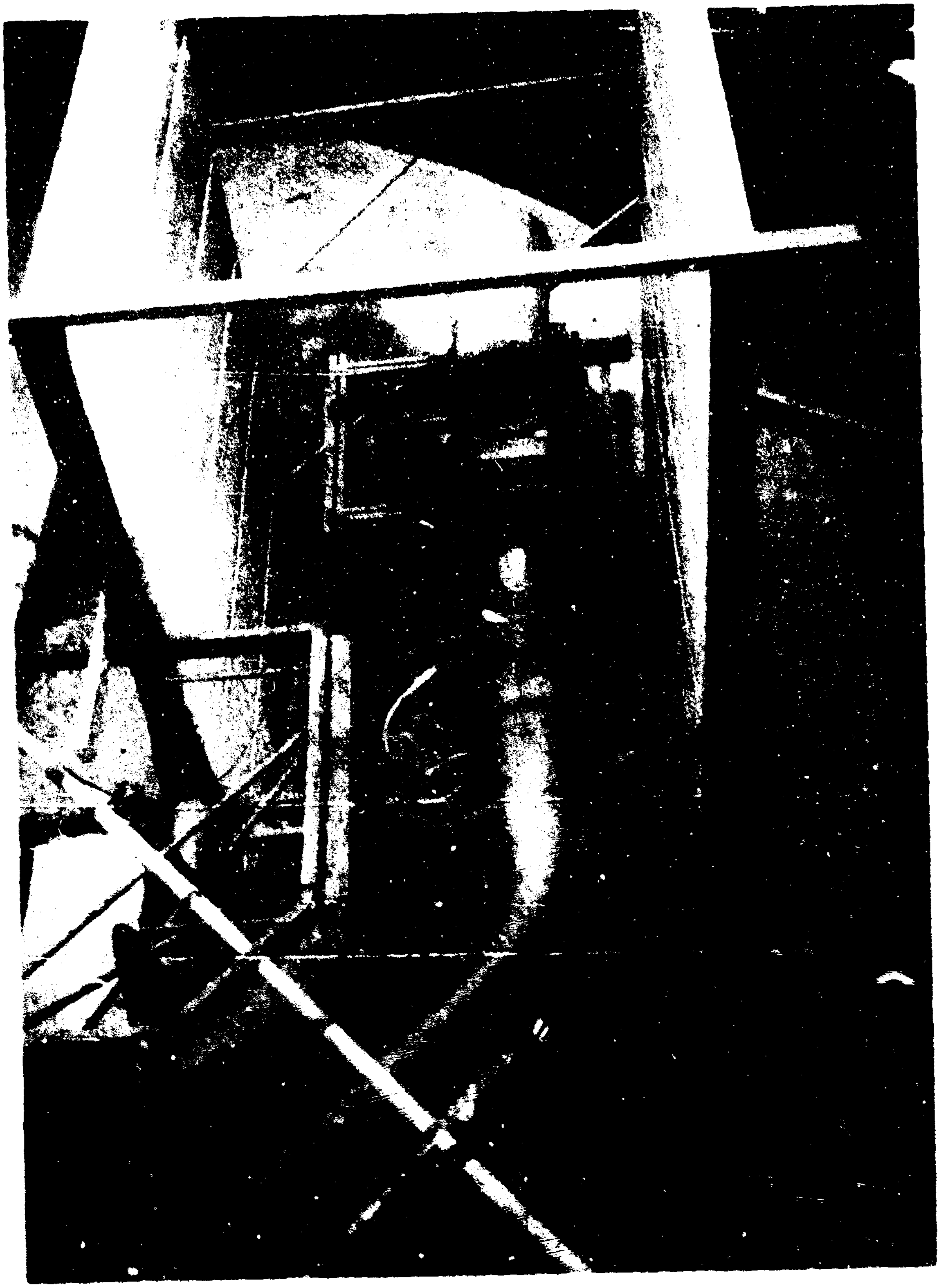


FIGURE A-34 TEST STAND VIEW SHOWING ACOUSTICAL PANELS

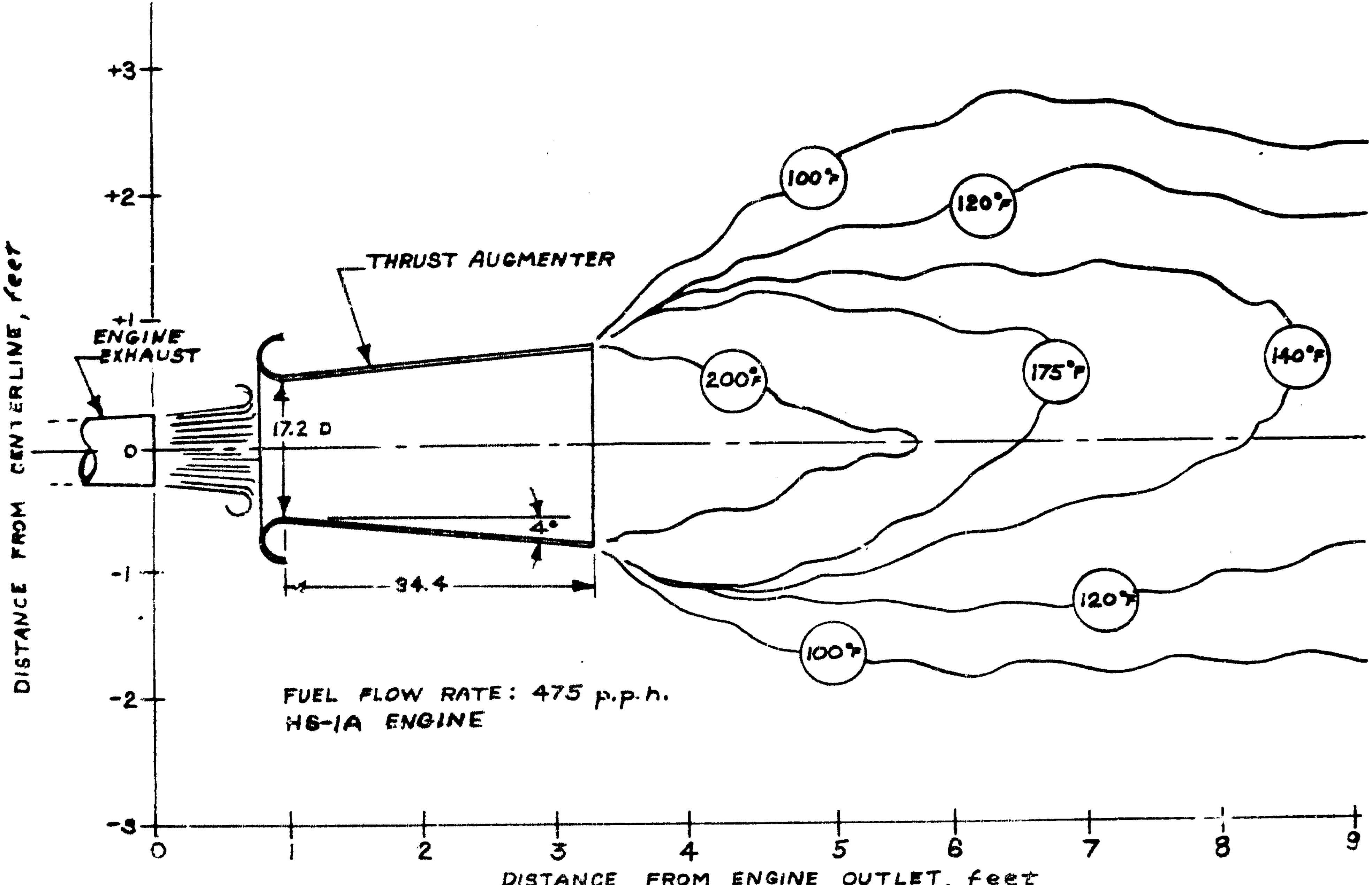


FIGURE A-35 PULSE-REACTOR WAKE TEMPERATURE DISTRIBUTION

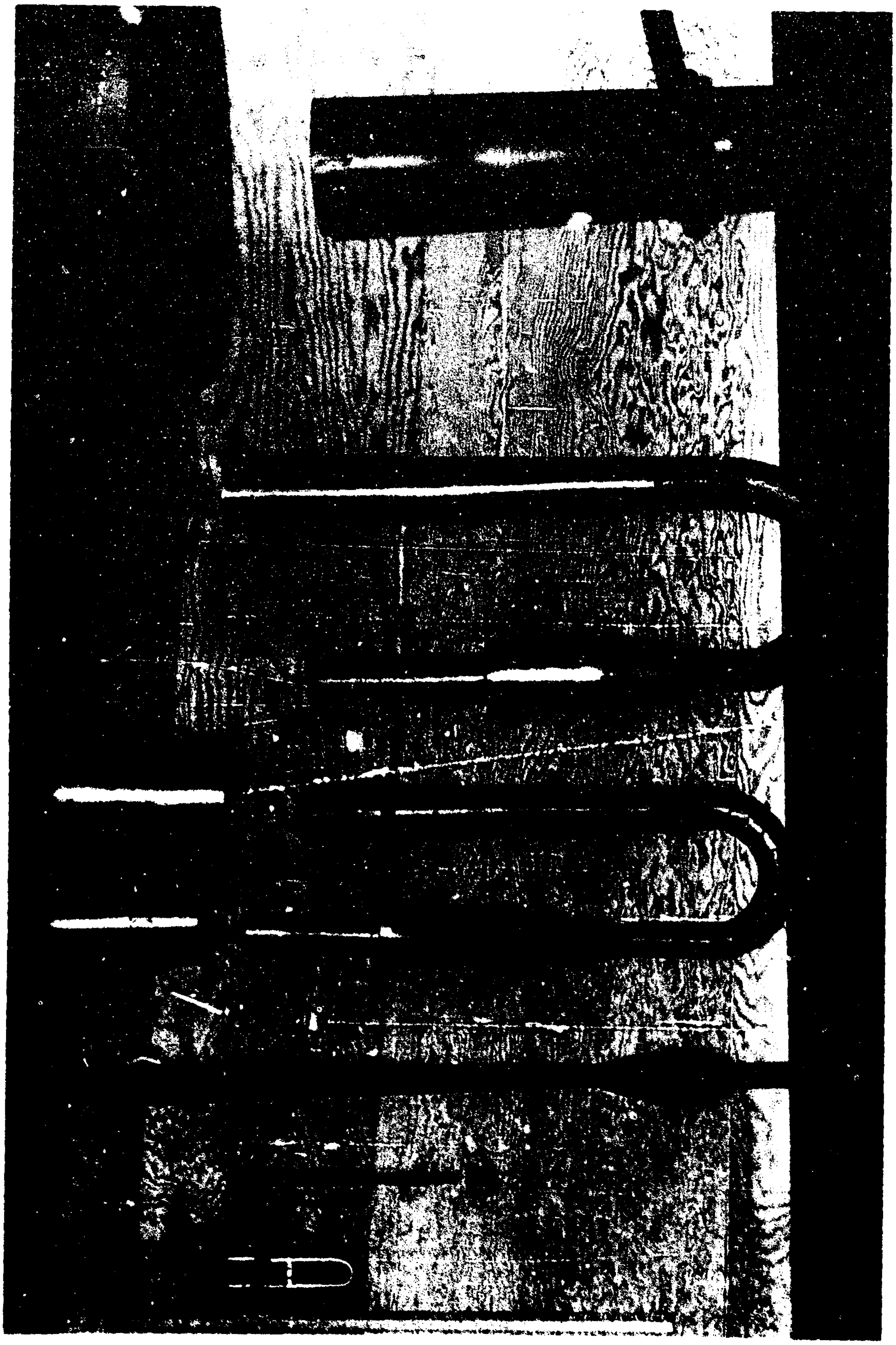


FIGURE A36: EXPERIMENTAL PULSE REACTORS SHOWING A RANGE OF SIZES FROM 0.7 INCH TO 8.6 INCH TAILPIPE DIAMETER

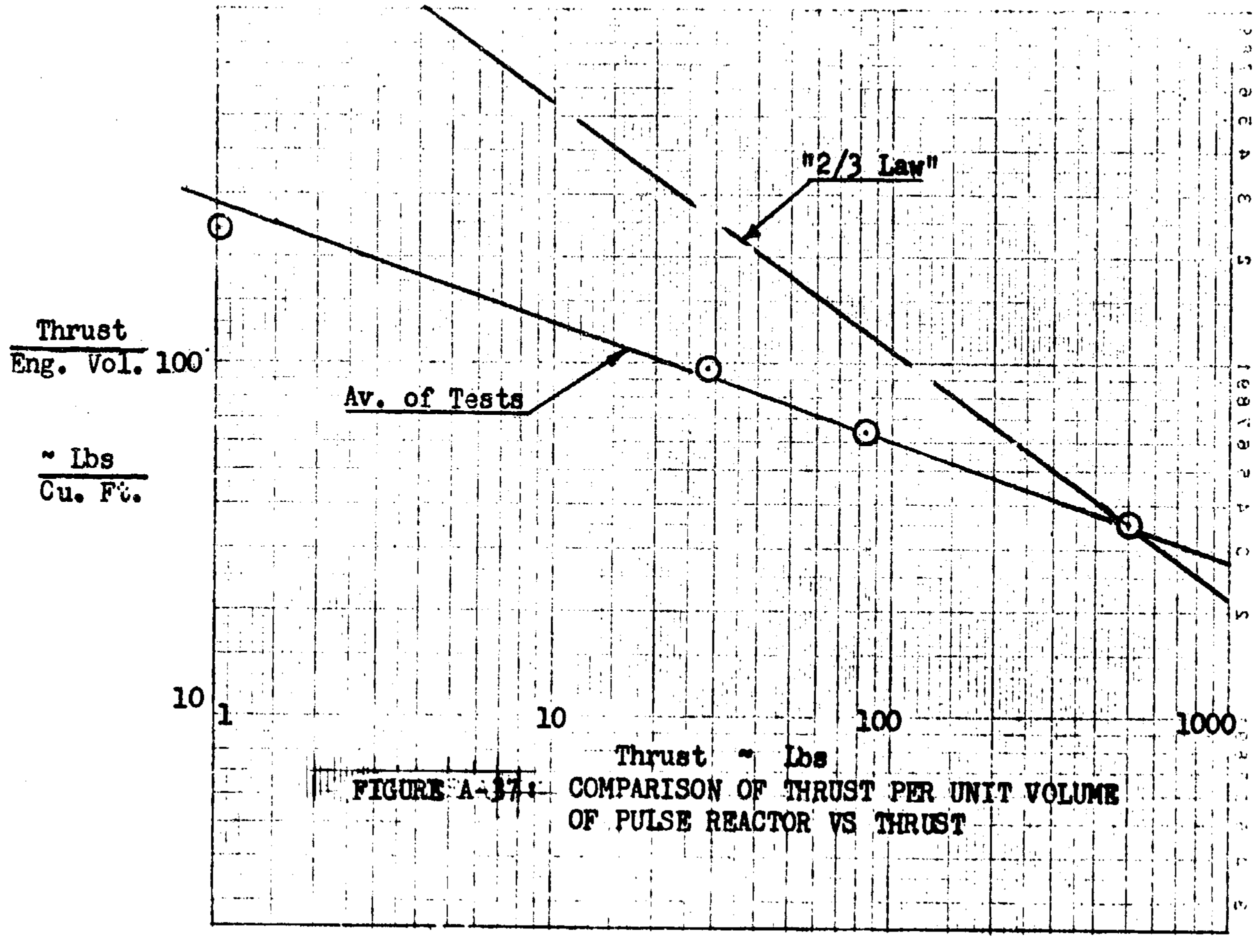


FIGURE A-37: COMPARISON OF THRUST PER UNIT VOLUME OF PULSE REACTOR VS THRUST

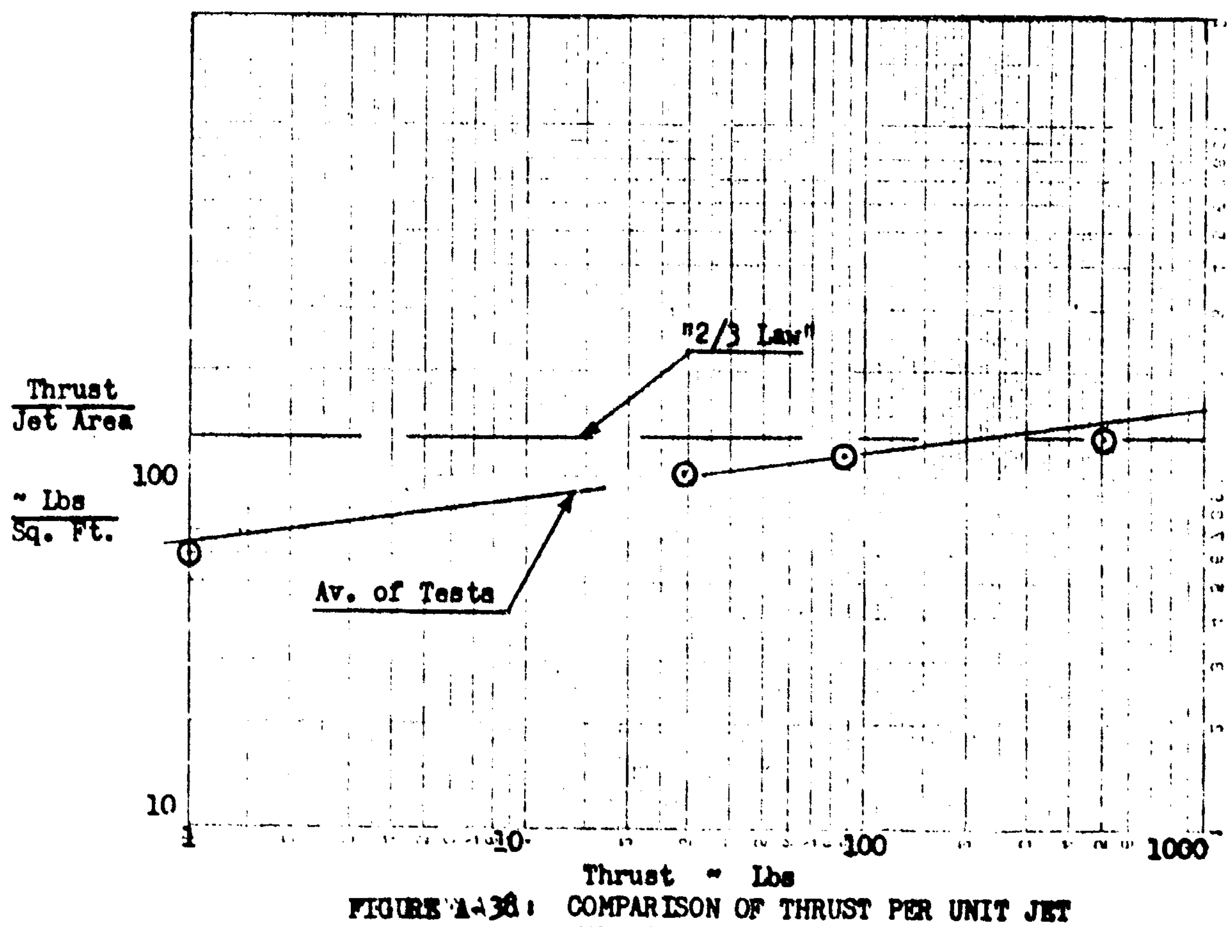


FIGURE A-38: COMPARISON OF THRUST PER UNIT JET WAKE AREA VS THRUST