AN EXPERIMENTAL INVESTIGATION
OF THE EFFECTS OF BOUNDARY LAYER SUCTION
ON THE PERFORMANCE OF AN AEROTHERMOPRESSOR

by

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Abstract

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Submitted to the Department of Mechanical Engineering on May 21, 1956 in partial fulfillment of the requirements for the degree of Master of Science.

An investigation of the effects of boundary layer suction on the performance of a medium-scale, variable-area Aerothermopressor -- a device for increasing the stagnation pressure of a high-temperature high-velocity gas stream -- is reported.

The specific problems approached are:

i) Supersonic start-up
ii) Shock stability
iii) Diffuser efficiency

The boundary layer suction satisfactorily solves the start-up problem. The removal of the low energy fluid along the walls ahead of the geometric throat in the evaporation section allows the cooling-drag throat associated with water injection to initiate supersonic flow ahead of the minimum area.

The shock stability problem is considerably more involved. The end effect is a re-location of the shock in a stable position ahead of minimum area where it is tripped by the boundary layer suction slot.

Diffuser efficiency is given but slight attention since the problem seems to be associated with wall roughness due to carbon deposits rather than flow separation at the diffuser entrance. Suction is of little consequence on the former, its value being more pronounced on the dynamics of the flow.

An overall increase in Aerothermopressor performance is realized. The experimental results are compared with theoretical analyses obtained by the use of the Whirlwind Digital Computer.

Thesis Supervisor: Kenneth R. Wadleigh
Title: Associate Professor of Mechanical Engineering

FOREWORD

This thesis reports an interim activity in the development of the Aerothermopressor. It is an attempt to provide a more complete understanding of the physical processes occuring in an existing apparatus before the apparatus is subjected to major changes. At the same time, it is intended to provide some indication of improvements which might be incorporated into the proposed modification.

Throughout this report it is assumed that the reader has some previous knowledge of the character and behavior of the Aerothermopressor. Much of the material presented depends upon the understanding of foregone investigations before full value can be attached to this work. The ambitious newcomer to the device will find a wealth of background available in the reference list.

The project for the development of the Aerothermopressor is sponsored by contract between the Office of Naval Research and the Division of Industrial Cooperation at the Massachusetts Institute of Technology. The test facilities are located in the Gas Turbine Laboratory of the Mechanical Engineering Department, M.I.T.

The assistance which many individuals have contributed to this undertaking, and without which it would have been impossible to reach this point, is yet to be acknowledged. It is a pleasure to take this opportunity to express due thanks to each and all.

I am particularly grateful to Professor Kenneth R. Wadleigh, my thesis advisor, for his cooperation and guidance throughout this work. It has been a most rewarding experience for me to have been able to complete this phase of my education under his capable supervision.

To Professor Alve J. Erickson goes special thanks, not only for the time and effort which he gave in assisting with the experimental runs and the theoretical analysis, but also for his many contributions to the process of my learning.

I am indeed indebted to Mr. Donald Haraden for the long laborious hours which he gave to the construction and testing of the apparatus, and for the many contributions of his ambition and his ingenuity which often resulted in improvement of the situation or easement of the task.

Thanks are also due to the staff and employees of the Gas Turbine Laboratory and of the Fuels Research Laboratory who cooperated to make the testing of this device possible.

Finally, to my wife, Faith, goes by far the deepest gratitude for her endurance throughout my graduate studies and for her patience and care in typing this report.

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NOMENCLATURE

A	Area
D	Diameter (O.D. - Outside Diameter, I.D. - Inside Diameter
f	Friction factor
k	Ratio of specific heats
M	Mach Number
p	Static Pressure
P_o	Mixture Stagnation Pressure - Gas and Liquid Phases
p_o	Stagnation Pressure of Gas Phase
T	Absolute Temperature
T_o	Absolute Stagnation Temperature
W	Molecular Weight of Gas Phase
w	Mass Rate of Flow
y	Ratio, Velocity of Injected Liquid to Velocity of Gas
Z	Distance Along Evaporation Section from Inlet Plane
η_o	Diffuser Efficiency
ω_1	Inlet Humidity
Ω_o	Water - Air Ratio -- w_l/w_g

Subscripts

a	Upstream of Entrance Nozzle
bls	Boundary Layer Suction
g	Gas
l	Liquid
1	At Evaporation Section Entrance (Nozzle Exit)
2	At Diffuser Entrance (Evaporation Section Exit)
3	At Diffuser Exit

I Introduction

Prior Development

The Aerothermopressor is, basically, a device designed to increase the stagnation pressure of a high-temperature, high-speed gas stream. The original theory of this device resulted from an analysis by Shapiro and Hawthorne (2)[1] in 1947. The formula which they presented showed that the cooling of a gas stream would result in a stagnation pressure rise if, and only if, the cooling were accomplished by the favorable interplay of thermodynamic and dynamic processes in the evaporation of a volatile liquid into the stream.

The theory was first investigated at M.I.T. in 1949 as the topic of student theses. Theoretical and experimental development has continued at M.I.T. since then, being under the sponsorship of the Office of Naval Research since 1952. The first significant development work was reported by Wadleigh (3) in 1953. From the results of his experimentation with a small scale apparatus (2 1/8 in. dia.) it was determined that significant rises in stagnation pressure could be obtained in units of larger scale. Gavril (4) performed an extensive theoretical analysis of the device, including computations which compared favorably with the experimental results of Wadleigh, and substantiated the conclusions as to size and performance.

An Aerothermopressor of medium scale, (11 in. dia., 25 lb/sec. air flow) intended to be large enough to demonstrate

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1. Numbers in parentheses correspond to the numbers in the list of references appearing at the end of this report.

an appreciable stagnation pressure rise, was built in 1953-54. Extensive experimentation with this unit using a constant area test section and one with variable area accomplished by the use of internal plugs was reported by Fowle (5)[1]. The stagnation pressure rise obtained was of the order of 3.5% for the constant area section and 5% for variable area.

The same unit was next investigated by Erickson (6)[1] using a test section with a suitable area change accomplished by varying the duct diameter. The pressure rise reported for this operation was of the same order as had been obtained by Fowle.

Before another modification of the apparatus was undertaken it was decided to further explore the existing rig in various ways. It was hoped that these studies would result in a) increased performance, b) some concrete experimental and theoretical basis for the proposed modification, and c) a better corrolation between predicted performance and that actually obtainable. One of the exploratory studies which was suggested was the application of boundary layer suction. Numerous considerations, treated below, made this proposal inviting.

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1. Since references 5 and 6 report the major analytical and experimental work thus far performed on the medium-scale Aerothermopressor they will be frequently cited in this thesis.

Inception of the Problem

In references 4, 5, and 7 one of the interesting physical phenomena of Aerothermopressor operation is discussed -- the transition from subsonic flow to supersonic flow without the occasion of a geometric throat, i.e., in a constant area duct. This unusual occurance is a result of the combined effects of drag and cooling associated with the injection of water into the air flow. In a constant area Aerothermopressor with the water injected at the exit plane of the entrance nozzle, this transition occurs within 6 inches of the plane of injection.

In Aerothermopressor operation it is desirable to control the level of the flow Mach No. as well as its longitudinal variation. In the above case the lengthwise variation is a function of the processes occuring in the flow, such as cooling, friction, or droplet drag, rather than external influences. The length downstream at which supersonic flow can exist is somewhat controllable in that it is a function of the duct inlet and exit pressure levels, the inlet temperature, the water injection rate, etc. However, there is a value of each of these beyond which any change may result in instability and reversion of the flow to subsonic. The initial level of the Mach No. for supersonic flow is uniquely determined in that it is the critical Mach No. for the system.

The basic equation for Aerothermopressor action, as derived from (2),

$$\frac{dp_o}{p_o} = -\frac{kM^2}{2}\left[\frac{dT_o}{T_o} + 4f\frac{dz}{D} + 2(1-y)\frac{dw}{w} - \frac{dW}{W}\right] \qquad \text{(Eq.1)}$$

shows how the change in stagnation pressure depends upon the value of the Mach No. quite predominantly. Reference 7 explains that at subsonic speeds evaporative cooling tends to reduce the Mach No. such that the potential increase of stagnation pressure due to the cooling cannot be realized (simply because the $kM^2/2$ term in equation 1 becomes too small). Furthermore, it is shown that at supersonic speeds the cooling tends to drive the Mach No. higher, thereby forfeiting pressure rise by a reduction in the evaporation rate (due to the rapid drop of gas temperature).

The most obvious means of accomplishing Mach No. control is by adjustment of the cross-sectional area with length along the duct. Analysis has shown that the most favorable variation involves first a decrease in the area, then a gradual increase to the point where diffusion is predicated and a constant rate of area increase is maintained. This converging - diverging area variation results in favorable subsonic performance but it presents an unusual problem to operation at supersonic speeds where the Aerothermopressor performs best.

The geometry of a test section as described above is of the same nature as a nozzle used to accelerate a flow to Mach Nos. greater than 1. It therefore presents no problem to obtaining supersonic flow downstream of the minimum area. The flow ahead of the throat will remain subsonic, and at the throat Mach No. unity will exist. But effective Aerothermopressor action calls for exactly the opposite situation -- Mach No. greater than 1 initially, decreasing to 1 at the minimum area, and less than 1 thereafter! The process of obtaining supersonic flow in the constant area duct is not always adequate in the present circumstance since the choked-flow condition at minimum area reduces the number of operating variables by 2, mass flow rate and exit pressure. If the minimum area were increased sufficiently to eliminate the supersonic starting problem then the desired area variation would no longer be present. A flexible section which would allow temporary adjustment of the area would be unreasonable from the standpoint of design and of cost. A supersonic entrance nozzle could be used, but the losses associated with its application would be a detriment to the overall pressure rise since once supersonic flow is established the flow processes tend to maintain it. Even with such a nozzle a starting problem would still exist, though of a different nature than the problem above.

If the low energy fluid along the wall could be removed at some point just ahead of the minimum area in the converging - diverging duct, the remaining high velocity flow would "see" a larger area in the throat. This increased area would allow more flow to pass through. The increased flow would mean higher velocities upstream of the point where the boundary layer was removed. The higher velocities could, in themselves, cause supersonic flow to be established or, at the least, assist the drag and cooling processes in driving the Mach No. above 1. The process described need be applied just during the start-up since not only would the flow tend to be self-maintaining, but the undesirable low energy fluid would be a smaller percentage of the total flow.

The removal of the low velocity fluid implies boundary layer suction, wherein the flow near the wall which is retarded because of wall friction is sucked off through a suitable slot, or holes. Since a portion of the mass flow, small that it may be, is removed it too will help to increase the entrance velocity and initiate supersonic flow.

Once supersonic flow is established in the test section another problem develops. The possibility exists that the conditions at the entrance to the section may not be compatible with the conditions at minimum area -- inlet temperature, mass rate of flow of air and of water, and inlet pressure may determine a flow which will not match the back pressure and flow conditions at the throat. In such a situation either the entire operation would become subsonic or a shock, or series of discontinuities, would exist ahead of the minimum area which would tend to match the required throat conditions. In either case, Aerothermopressor action would not be optimum since, in the first instance, subsonic operation in this region is less potent than supersonic, and, in the second, not only would the stagnation pressure loss across the shock substract directly from the desired result, but the consequent Mach No. variation would not be as desired.

Here again the application of boundary layer suction might be of value in that it would help the stream swallow any discontinuity or bring it through the minimum area to stabilize the flow. Once the stream became stable the suction might be removed without affecting the situation.

A third bit of information which the application of boundary layer suction might supply is concerned with diffuser[1] efficiency. In the design of the basic unit used in this investigation Fowle had more or less arbitrarily specified the diffuser cone angle at 5° (5). This angle was not experimentally verified as optimum, although Fowle reports efficiencies of 80 to 90%, based upon the enthalpy change from the state entering the diffuser to the state at actual leaving pressure but at entering entropy divided by the actual enthalpy change from entrance to exit. Add to this the fact that the manner in which the evaporation section was merged with the diffuser resulted from considerations other

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[1] In a variable area Aerothermopressor, such as previously described, the geometry of the test section, or more properly termed, the evaporation section, results in no true line of demarcation between nozzle and evaporation section or evaporation section and diffuser. The flow may accelerate or decelerate and the pressure fall or rise in portions of what is known as the evaporation section. For the purpose of this report the nozzle will be defined arbitrarily as the

than maximum efficiency of transition (5,6) and investigation of this possible source of stagnation pressure loss seems worthwhile.

The use of boundary layer suction to study the diffuser efficiency becomes possible since, again, the removal of low energy fluid along the walls eliminates one of the important causes of irregularities, tubulences, possibly back flows, and the like in the transition region at the entrance to the diffuser.

The final, and perhaps most all encompassing, reason for applying boundary layer suction arises from its potential aid to overall performance and to improving the correlation between theoretical analysis and experimental results for the unit at hand. The first three considerations above involve better performance by nature. The general "cleaning up" of the flow, and the improving of velocity and stagnation pressure profiles to more closely approach one-dimensional flow; stabilizing the downstream shock nearer to minimum area so that it will occur at a Mach No. nearer to 1; essentially reducing wall friction effects; removing the water on the walls which is introduced near the nozzle exit but whose value further downstream is questionable, especially

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Footnote 1, page 7, cont. -- portion of the apparatus converging with constant radius of curvature and the diffuser, likewise arbitrarily, as the portion of the apparatus diverging with constant (5°) cone angle. The evaporation section then lies between these two.

since it may be reaccelerated to some degree at the minimum area or diffuser entrance and thereby cause a loss in stagnation pressure; these and other indefinable advantages could be effected by boundary layer suction and result in performance improvement and/or closer comparison of theory and experiment.

II Test Apparatus and Measurements

The Aerothermopressor Flow System

The basic physical Aerothermopressor unit used in this investigation is the same as specified and reported by Fowle (5)[1] but employing the variable area evaporation section as investigated by Erickson (6).[1] The flow system is pictured in Figure 1 for reference. Figure 2 is a photograph of a portion of the test apparatus and control panel.

The air was supplied by two positive displacement 2-stage opposed-piston reciprocating compressors in amounts up to 27 pounds per second at pressures up to 22 psig, the upper limit on pressure being imposed by the strength of the equipment and insured by a safety relief blow-out assembly. Heat was supplied up to 30,000,000 BTU per hour in a combuster fired with number 2 fuel oil.

The heated air passed through insulated ducting to the test apparatus. Here the air was accelerated by the entrance nozzle. Filtered city water, 0-60 gallons per minute, was injected at the exit plane of the nozzle. Water was also introduced along the duct walls near the nozzle exit at a rate of 0-6 gallons per minute. The stream next passed through the evaporation section, 83 inches long and varying in inside diameter from 11 inches at entrance to approximately 10 inches (16% area reduction) at the minimum area. From the evaporation section the flow entered the diffuser,

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1. References 5 and 6 should be consulted for complete equipment specification and description.

222 1/8 inches long and cone angle of nearly 5°.

At the outlet of the test apparatus a system of quench-water sprays and a water eliminator were installed. The former was intended to provide ultimate cooling of the stream, and the latter to prevent any water drops from being discharged to atmosphere with the gas. Lastly, the flow passed through a back pressure valve and out through a sound muffler.

Control of the system was, for the most part, automatic and remote through the use of electrical, mechanical, and hydraulic mechanisms. Operation was complex enough that 2 moderately well trained personnel were required for test runs. It is to be emphasized, however, that this situation, as well as much of the equipment described or shown in Figure 1, are unique to an experimental Aerothermopressor. Neither would be necessary in a commercial installation.

The Boundary Layer Suction System

Figure 3 shows a schematic diagram of the boundary layer suction equipment. A slot, 1/4 inch wide and chamfered at 45° in the main flow direction, was cut in the Aerothermopressor evaporation section 8 inches ahead of the minimum area. A manifold was placed around the slot and suction was applied to the manifold in 2 places. The suction was supplied through valves and piping from a 6 inch stream ejector whose flow - pressure characteristic is shown in Figure 5.

A more complete description of the construction of the suction facility appears in Appendix A. Figure 4 is a photograph of the boundary layer suction apparatus as mounted on the Aerothermopressor. Figure 6 is a detailed design of the manifold.

Measurements

The following properties of the Aerothermopressor system were determined: (after Fowle (5) and Erickson (6))

i) The mass flow of gas entering
ii) The stagnation temperature at nozzle entrance
iii) The stagnation pressure at nozzle entrance
iv) The stagnation pressure at evaporation section inlet
v) The inlet Mach No.
vi) The stagnation pressure at diffuser exit
vii) The static pressure distribution along the length of the test apparatus
viii) The total amount of injected water

In addition, the radial distribution of stagnation pressure at the inlet to the diffuser was measured by horizontal traverses with a special impact probe for selected runs. The mass flow removed by boundary layer suction was also approximately determined. Exact measurement of this quantity would be possible only by the use of complex equipment since the flow consists of liquid water, water vapor, air, and products of combustion.

III Aerothermopressor Operation
Without Boundary Layer Suction

Previous Theoretical and Experimental Results with Internal Area Variation

It seems worthwhile to review some previous Aerothermopressor results, at least qualitatively, and somewhat quantitatively, so that adequate comparison to the tests herein under consideration can be made. This section will treat the relevant results obtained by Fowle (5).

An Aerothermopressor with variation of cross-sectional area achieved by the use of internal plugs in a constant area duct was realized at the outset not to be the ideal way to better performance through area control. Parasitic losses such as additional plug wall friction, drag due to mounting and traversing hardware, and impingement and reentrainment of injected water were sure to be introduced. However, the information which could be obtained quickly and economically justified such a program.

Tests were made with plugs which gave maximum area variation of 12, 16, and 20%. The most suitable of these sizes was the 16% maximum change. Since the external area variation section discussed later used an area adjusted in the same proportions (approximately), the results obtained with the 16% variation only will be reviewed.

First, consideration will be given to the supersonic starting problem. Inherent in the method of area change employed, and associated with the consequent losses mentioned above, supersonic starting was difficult to attain for the geometry with the plug at its best operating position. At a temperature of 800° the plug had to be traversed almost all the way into the diffuser to allow the usual drag and cooling processes to initiate supersonic operation. Once it was established, if the plug were traversed foreward instability resulted and the flow dropped subsonic. No successful supersonic runs at 800°F were ever taken.

At 1000° stable supersonic operation was possible since the increased temperature allowed more evaporative cooling. Cooling always tends to drive the Mach No. away from unity. Because of the resultant higher Mach No. the stream was less susceptible to small disturbances which otherwise might cause it to become unstable or subsonic. The starting procedure still necessarily involved removing the plug at least half way from the evaporation section and then relocating it at best operating position. It may be argued that this procedure was most unusual only for the apparatus employed. Nonetheless, the starting problem of interest to boundary layer suction application is certainly well illustrated.

With reference to losses due to irregularities in the stream ahead of minimum area, the results reported (for the best stagnation pressure rise attainable) exemplify the problem. Figure 7 presents relevant data. The Mach No. is shown to decrease ahead of the minimum area from 1.28 to .92, then increase to 1.06 just beyond minimum area and shock to subsonic thereafter. The stagnation pressure as measured rises until the point is reached where the Mach No. first goes below 1, then falls until the shock occurs, and finally rises slowly until the stream enters the diffuser. From the effects of area decrease, friction and drag, and evaporation on Mach No. it can be shown that it is impossible for the above described Mach No. variation to occur without a discontinuity such as a shock being present. The stagnation pressure change seems to substantiate the existance of this phenomenon. Therefore, either the shock(s) exist and a potential source of improvement can be associated with their removal, or the measured values of stagnation pressure (which was used with measured static pressure to determine Mach No.) are faulty.[1]

Diffuser efficiency for the operation with 16% maximum internal area variation was reported to range between 80 and 87%, depending on entering Mach No. Since these figures did not exclude the losses suffered because of hardware mounted in the diffuser for plug operation it is reasonable to assume that 85 to 90% should be obtainable in a clean diffuser. (Whether it was or not will be revealed in the next section.) Since there is little ground for comparison here, the potential gain through boundary layer suction will be neglected.

Typical Aerothermopressor performance for the runs

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1. See Footnote 1 next page.

treated in this section, the theoretically determined performance for the same conditions, and the theoretically determined performance for the same conditions and same area change using external variation rather than internal, are all shown inFigure 7. Reasonable comparison of the theoretical and experimental results for internal variation, except for p_o/p_{o_1} initially,[1] is to be noted. The Aerothermopressor action, as shown, is 4.7% for the experimental run.

Previous Theoretical and Experimental Results with External Area Variation

The operating measurements which could be taken with the external area variation evaporation section were restricted by the design of the section. It had been decided that in order to expide construction of a new apparatus, the design should be kept as simple as possible. At the same time, to achieve best performance the interior of the new section should be "clean" so that the parasitic losses due to roughness, irregularities, etc., would be reduced.

With the previous ideals in mind, a new entrance nozzle was designed and fabricated which allowed for differ-

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[1] There is reason to believe that the stagnation pressure as measured was in error or was misinterpreted. The measurements were made with a special probe which supposedly indicated p_o for the gas phase only. The data, however, agrees more closely with the theoretically computed mixture stagnation pressure (as shown in Figure 7). Analysis has shown that the probe could indeed be measuring P_o rather than p_o . Fowle suggested this possibility but immediately discarded it. Studies are being undertaken at present to resolve the question since a significant advance in the understanding and analysis of Aerothermopressor action would result.

ential thermal expansion in order to eliminate local buckling. The joint where the nozzle, boundary water ring, and evaporation section bolted together (see Figure 1) was machined to close tolerance to obtain the most favorable matching of the internal diameters. The evaporation section was spun over hard wood forms and welded into one piece to avoid flanged joints. All welds were ground inside so that the wall would be as free from roughness as possible. No access ports, for insertion of measuring probes, were provided since they generally caused irregularities in the inside wall in previous installations. Only static pressure taps were added to the section. The diffuser was not changed, except that all extraneous hardware associated with plug traversing was removed. Select points for measurement were available in the diffuser since it had 4 access ports spaced along its length. Static pressure taps were also present.

In light of the above consideration, static pressure data and select points of stagnation pressure are the only basis for analysis of operation in this section of the report and in the section to follow where operation with boundary layer suction applied to this same test apparatus is discussed.

It was intended that the area variation in the present unit be the same as had resulted from the 16% internal plug. Difficulties in the fabrication of such a design resulted in a slight change in the end product. Although the maximum variation remains 16%, the overall contour is but a close approximation of the desired parabolic area change, which had been the basis for the plug design.

The relevant results which Erickson reports (6) will be briefly summarized in the following. Figure 8 presents typical operation as discussed.

In operation of the Aerothermopressor with area change accomplished by varying the duct dismeter, the same general problems were encountered as have been presented above. It was generally impossible to obtain continued supersonic operation below 850°F. In order to initiate supersonic flow in this temperature range it was necessary to 'bounce' it in by temporary temperature change or sudden flow rate changes. Once supersonic, the stream was quite unstable, i.e., only slight adjustment of back pressure, water rate, or inlet temperature, for example, would cause it to become subsonic.

At 1000° or above it was usually only necessary to adjust the water rate and decrease the back pressure in order to obtain the desired operation. At this higher temperature the flow remained stable enough so that the downstream shock could be brought within 2 or 3 in. of the minimum area without causing reversion to subsonic operation.

It was again suspected (as indicated by the measured static pressure curve in Figure 8) that some shock or discontinuity was occuring ahead of minimum area. The estimated stagnation pressure loss for the discontinuity, obtained through extrapolation of theoretical results, was of the order of 2 or 3%. Though small, this loss constitutes a noteworthy variation from the theoretical run shown in Figure 8 which shows no loss in this region. It is also a significant portion of the overall pressure rise obtained.

The desired increase in diffuser efficiency was not realized. On the contrary, from the limited data available, a loss of about 10% was added to previously reported values for the diffuser without plug hardware. The data reported at this time shows efficiency ranging between 76 and 83% as M at the diffuser entrance was varied from .80 to .50 . Further measurements to validate this data are necessary.

The drop in diffuser efficiency seems contributable to two sources. First is the possibility thatthe flow separates at the diffuser entrance. This separation might be due either to poor transition from the evaporation section or to the higher Mach Nos. at the diffuser entrance caused by the area change in the evaporation section. Back flows at the wall at entrance and turbulences washed downstream could result from the separation. The principal effect of these phenomena is an inefficient dissipation of energy.

The second possible source of diffuser loss, and one which definitely is worthy of serious consideration, is carbon deposits on the diffuser walls. It has been experienced that in ordinary Aerothermopressor operation, where 2 to 3 gallons per minute of fuel oil are burned, poor efficiency of the combustion can result in considerable carbon formation.

The combustion process is largely controllable by the operator in that he is able to regulate the quantity of air supplied for atomizing the oil, as well as the percentage of the total air flow passing through the combustion chamber. Disregard or injudicious adjustment of these controls in even one days' operation could cause carbon formation which, by the nature of the system, would tend to be deposited in the diffuser.[1] An effective increase in wall friction would result from this random and uneven deposition.[2]

The curves of Figure 8 show a typical static pressure plot for operation with external area variation and the results from the theoretical analysis for equivalent conditions.

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[1] At the conclusion of the experimental runs for boundary layer suction the diffuser was inspected and gross carbon deposits were discovered. The surface was wavy and uneven and had many sudden irregularities due to flaking away of the heavier deposits. It cannot be assumed that these deposits were present in the runs treated here although evidence of their effect in the low diffuser efficiencies may suggest this conclusion aposteriori. A study of the change in efficiency with the removal of the deposits has been undertaken by Erickson.

[2] Aerothermopressor action is directly affected by a change in diffuser efficiency. The formula for η_D, derived from the definition on page 7, is:

$$\eta_D = \frac{\left(1 + \frac{k-1}{2} M_2^2\right)\left(\frac{p_{03}}{p_{02}}\right)^{\frac{k-1}{k}} - 1}{\frac{k-1}{2} M_2^2}$$

(using nomenclature specified in the beginning of this thesis). Applying this equation to typical operation Mach Nos., a decrease of 10% in the efficiency will result in a decrease of 3 to 4% in the stagnation pressure ratio across the diffuser.

Because of considerations treated above, stagnation pressure and Mach No. plots cannot be shown for the experimental run. The stagnation pressure at entrance and exit is, however, indicated since an analysis by Fowle (5) shows that these data can be inferred from the static pressures to within 1% accuracy. The discrepancies in the static pressure curves, caused by the suspected discontinuity ahead of minimum area and by inefficient diffusion as treated above, are to be noted. Aerothermopressor action of about 3 1/2% is shown, although slightly higher values were obtained in maximum performance runs.[1]

Comparison of the theoretical runs of Figures 7 and 8 indicates that the present test section does not exhibit the same characteristics as were predicted for the 16% plug variation extrapolated to external area change. The discrepancies can be attributed only to the fact that the present section, though an approximation, is not an exact equivalent of the plug variation, and/or, diffuser efficiency is considerably worse in the present situation.

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1. In order to provide some basis for comparison, all data plotted in Figures 7, 8, and 9 are for operation of the various apparatus at a given set of inlet conditions. The theoretical analyses are based upon identical specifications. Consequently, the runs shown do not necessarily exemplify best performance although the results may be considered typical.

IV Aerothermopressor Operation
With Boundary Layer Suction

General Effects on Operation

A series of exploratory runs was made to determine the effects, if any, which the boundary layer suction slot would have on the flow. Typical results at 800° and 1200°F are reported graphically in Figures 10 and 11. The Figures show static pressure plots for a run taken before the test section was cut, a run taken with the slot but with no suction applied, and a run with full boundary layer suction applied. The plots are not typical operating performance, but rather are an extreme of operation where supersonic flow after minimum area is allowed in order to better illustrate the point in question. At operating conditions, the downstream shock is moved up to approximately minimum area by an adjustment of back pressure. This characteristic plot would not accurately present the desired comparison since shock effects would confuse the picture.

From the figures it can be reasonably concluded that the effects of the slot alone are negligible. The variation in static pressure is less than the margin of error in the measurements and within the accuracy possible in the duplicating of flow conditions with the apparatus. The effect of full suction is predominant only in the region immediately downstream of the slot. Because the flow is not decelerated as much, due to the effective increase in the throat area, slightly higher Mach Nos. are maintained after minimum area as indicated by the lower static pressure. These effects gradually die out and whatever differences might remain are eliminated, to all practical methods of measurement, by the shock.

In usual operation, where best performance is sought, other criteria make the influences of boundary suction desirable, as will be pointed out in following sections.

Improvement to Supersonic Start-Up

The supersonic start-up problem was virtually eliminated by the use of boundary layer suction. Whereas temperatures of 850°F or over and considerable manipulation of controls were necessary to initiate supersonic operation prior to the use of suction, temperatures of only 830°F and no spasmodic adjustments were necessary when suction was used.

As the temperature was increased from low temperatures, if sufficient air flow and approximately correct water injection were supplied, the back pressure reduced to a minimum, and full boundary layer suction on, it could be noticed that the pressure at nozzle exit was reduced much faster than at minimum area. This indicated that the Mach No. at nozzle exit was increasing faster than at other points in the system due to nozzle action and droplet drag. As the temperature approached 800°F the driving force for evaporative cooling became great enough to counterbalance droplet drag and cause the flow to become supersonic. Hence the previous situation, of Mach No. reaching one and subsequent choking occuring in the area throat rather than at the drag-cooling throat, no longer existed.

Once Mach Nos. greater than 1 were established it was possible to turn off boundary layer suction completely. If temperature, water flow, or back pressure happened to be slightly misadjusted and the flow became subsonic, opening the suction control valve was all that was necessary to reinstall supersonic operation. The necessary adjustment to flow conditions could then be made and suction removed. Caused possibly by the effect of the suction slot on shock stability (treated below), stable supersonic operation at 830° was experienced (See Figure 12, Runs No. 560419 -1, -2, -9, -10) and stagnation pressure rises of the order of 3% without suction were recorded.

Though supersonic flow had been reasonably simple to attain at temperatures of 1000°F or over with no boundary layer suction, one advantage of suction still applied. Should the stream happen to revert to subsonic from, say, the introduction of a probe, adjustment of one of the variables, usually back pressure, had previously been necessary to return the flow to its prior position. This change, and the delay accompanying its accomplishment, usually propagated a change in inlet conditions -- specifically inlet temperature. Consequently it took a matter of a few minutes for the stream to again become stable and some fudging with controls often was necessary in order to re-establish previous conditions. Under present circumstances an immediate opening of the suction control valve would return the stream to its former state without changing any operational controls. Subsequent removal of the boundary layer suction resulted in immediately stable and identical previous conditions.

Shock Stability

Boundary layer suction was never given a chance at proving its effectiveness in removing the shock(s) ahead of minimum area. First, a more complete analysis of what really was happening in this region resulted from the discovery that previous stagnation pressure measurements were most likely in error.[1] This analysis indicated that the experimentally determined Mach No. variation shown in Figure 7 was questionable. The suspected shock from supersonic to subsonic ahead of minimum area and the re-acceleration to $M = 1$ at the throat was now considered to be a normal deceleration to M of approximately 1 (as indicated in the theoretical curve of Figure 7) caused by the interaction of area change and friction with evaporative cooling.[2] This determination

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[1] See footnote 1, page 16.

[2] "The Behavior of Stream Properties Under Influence of Area Change, Evaporation, Wall Friction, and Droplet Drag", appears as Table V in reference 5. It should be consulted for a complete summary of various effects frequently cited herein.

indicated that the discontinuities which suction was supposed to attack did not in fact exist.

Secondly, but of equal significance, the slot in the evaporation section by itself contributed to the frustration of boundary layer suction. Since the slot was located in an essentially transonic region, i.e., a region of Mach No. near to one where instability is inherent, and, since the area change between the slot and minimum area was virtually nil, the slot tripped a shock ahead of minimum area which was experimentally of comparable value to a consolidated shock just downstream of the minimum area. That is to say, it was the intent of boundary layer suction to assist the stream in swallowing what was suspected to be a shock ahead of the minimum area. It was thought possible thereby to form a single shock which could be favorably positioned near the throat by adjustment of the back pressure. The suction slot, however, succeeded in accomplishing practically the reverse. Instead of bringing the suspected shock from ahead of minimum area to a position after minimum area, the slot provided sufficient disturbance to allow the downstream shock to be brought forward and suitably stabilized ahead of minimum area.

The final effect of these two considerations is much simpler to describe. In operation at temperatures of 830°F or higher, where supersonic flow could be stably maintained, adjustment of the back pressure resulted in locating a stable, nearly normal shock precisely at the boundary layer suction slot. This location was obtained regardless of the presence of boundary layer suction or the lack thereof. Quantitatively this shock position resulted in a more favorable stagnation pressure rise[1] than had previously been experimentally obtained, the value now being 5.2% without suction and 7.8% with suction, as compared with 3.2% for a previous run at similar conditions. (Compare Figures 8 and 9.)

The theoretical analyses for these two cases present an interesting result. The conditions obtaining at the diffuser entrance, and consequently at exit, are identical to within 1% or less. This means that the shock positions essentially exchange stagnation pressure loss across the shock for stagnation pressure rise via more favorable Mach No. variation or evaporative cooling, and vice-versa. But, as indicated above, the experimentally obtainable rise is much more favorable with the shock farther forward.

Thus the value of boundary layer suction contributed little true value to shock stability whereas the boundary layer suction slot was of important consequence. Further experimentation with simpler shock tripping devices may be called for, but, obviously, a point will be reached where

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[1] Throughout this thesis reference to stagnation pressure rise or Aerothermopressor action has been meant to indicate the ratio $(p_{o3} - p_{o1})/p_{o1}$ (usually expressed in per cent). This ratio is a measure of the % rise in stagnation pressure from the nozzle exit to the diffuser exit using the stagnation pressure at the nozzle exit as reference.

shock loss and Mach No. or cooling gain will not counterbalance.

Diffuser Efficiency

Only two runs comparable to previously reported diffuser efficiency runs are available. The results therefore must be given appropriate weight.

For a Mach No. at entrance of .50 previous diffuser efficiency was reported as 83.2%. With full boundary layer suction and slightly greater initial air flow, in order to achieve an equivalent Mach No., the diffuser efficiency was determined as 87.1%. For an entering Mach No. of .65 the efficiency for prior runs is recorded as 76% and for the similar conditions with suction 82%.

The only conclusion derivable from these data is that although an increase of a few percent may be realized with boundary layer suction, the range of efficiencies is still much less than desired. This consideration tends to suggest either that boundary layer suction applied so far upstream from the transition region is only partially effective in reducing the losses due to separation, or, more likely, the carbon deposits[1] in the diffuser have increased the wall friction appreciably, a situation which boundary layer suction cannot remedy.

In Figures 8 and 9 the high friction factor of .019

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1. See footnote 1, page 20.

was used in the theoretical runs and, even at that, the nature of the diffuser static pressure distribution seems more favorable than the experimental distribution.

Summary

In conclusion, the application of boundary layer suction can claim positive advantage in the problem of supersonic start-up. This is of particular value to operation of the experimental apparatus. For a commercial installation an Aerothermopressor would probably be designed for a much smaller range of operation. The area variation might, therefore, be designed so as to accomodate the particular range. Other means, such as auxiliary water injection or a variable throat using sleeves or sliding blocks, are devisable which could accomplish a similar result. The whole problem may be solved con-currently with the change in the length of the converging portion as dictated by the considerations of shock stability.

It seems of little consequence to Aerothermopressor performance just how or where, within limits of course, the transition from supersonic flow to subsonic occurs. Experimentation or theoretical analyses to determine the maximization of this process, stagnation pressure-wise, seems worthwhile.

Boundary layer suction has supplied some basis for conclusion that the transition from the evaporation section to the diffuser could be improved. It seems to show more conclusively that either the diffuser is basically of inefficient design (which is somewhat disproved by the values reported by Fowle (5) for diffuser efficiency prior to his mounting of plug equipment), or that the carbon deposits must be the cause of inefficiency.[1]

Finally, notice may be called to the increased Aerothermopressor performance due, in part, to the effect of boundary layer suction on the above problems. Before further modification is undertaken it could prove beneficial to analyze more thoroughly the zones of improvement by providing access ports on the present section so that stagnation pressure traverses may be taken.

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1. It is to be noted that an Aerothermopressor attached to a gas turbine, as intended for commercial application, should hardly be faced with the carbon problem since combustion is considerably better.

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3. Wadleigh, K. R., "An Experimental Investigation of a Small-Scale Aerothermopressor - A Device for Increasing the Stagnation Pressure of a High-Temperature, High-Velocity Gas Stream by Evaporative Cooling." Sc.D. Thesis, Department of Mechanical Engineering, M.I.T., Cambridge, Mass., 1953.

4. Gavril, B. D., "A Theoretical Investigation of the Thermodynamic and Dynamic Effects of Water Injection into High-Velocity, High-Temperature Gas Streams." Sc.D. Thesis, Department of Mechanical Engineering, M.I.T., Cambridge, Mass., 1954.

5. Fowle, A. A., "An Experimental Investigation of an Aerothermopressor Having a Gas Flow Capacity of 25 Pounds Per Second." Sc.D. Thesis, Department of Mechanical Engineering, M.I.T., Cambridge, Mass., 1955.

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7. Shapiro, A. H., Wadleigh, K. R., Gavril, B. D., and Fowle, A. A., "The Aerothermopressor -- A Device for Improving the Performance of a Gas Turbine Power Plant." Transactions A.S.M.E., Vol. 78, No. 3, 1956.

8. Schlichting, H., "Boundary Layer Theory." Translated by Kestin, J., McGraw-Hill Book Co. Inc., New York, 1955.

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Appendix A

Test Apparatus

Figure 1, showing the Aerothermopressor flow system, indicates the placement of the boundary layer suction apparatus. Figure 3 is a more detailed schematic of the apparatus. Figures 2 and 4 are photographs of the Aerothermopressor and the boundary layer suction equipment respectively.

To modify the existing variable area evaporation section to allow boundary layer suction a slot was cut in the section 8 inches ahead of minimum area, i.e., 39 inches downstream of the plane of injection. This dimension was rather arbitrarily chosen but consideration was given to two factors. The suspected disconinuities in the flow, as discussed in Section I, consistantly appeared in the vicinity of 36 inches from the nozzle exit or injection plane. In order for suction to be able to help the stream swallow the shock(s) it would have to be placed downstream of the region of occurance. At the same time, to be effective in the start-up problem the suction had to be applied far enough ahead of the minimum area to allow the stream to expand to the new area that it would "see". Since the placement required by these two restrictions was still only qualitative, the final decision was, in part, based upon the physical specifications to be met, that is, the placing of piping, the position with respect to pressure taps, etc.

The section was cut by hand and then ground to desired dimensions. Since the slot was to be chamfered 45° in the direction of the flow its axial width was only 1/8 in. The chamfer was ground by hand and, being that the test section wall was 1/8 in. thick, a 1/4 in. wide slot normal to suction flow resulted. Here again, slot width was arbitrarily determined. Some restriction was imposed by the flow-pressure characteristic of the ejector which supplied the suction. Enough flow had to be removed to accomplish the objectives, of course, but this too was indeterminate. In order to allow some flexibility, should 1/4 inch have been wrong, the design incorporated changeable spacers, as described below, to adjust the width.

Two rings, 15 1/2 inches in outside diameter and with inside diameter to fit the duct (10.5 in. approximate), were made of 304 stainless. (See Figure 6 for full details of all manifold parts.) These were welded to the duct, each at 2 3/4 inches from the slot centerline.

A cover, made in 2 pieces, was rolled from 1/4 in. stainless stock. Four bolts were allowed to locate the cover over the side rings but a clamping arrangement was devised to provide firm seating of the cover on the ring O.D.

In assembly the halves of the evaporation section were first bolted to the nozzle and to the diffuser, gap allowance being assured by an adjustment on the expansion joint downstream of the diffuser. Eight spacers, of 3/4 in. double extra heavy stainless pipe, each 5 1/2 inches long, were placed between the rings. Bolts, 3/8 - 16 stainless, were passed through the rings and spacers. The expansion joint was released, the spacer length now determining the slot width, and the rings were bolted fast. The cover, with gaskets, could now be placed over the rings completing the manifold.

Calculations to determine the number and size of bolts and spacers and the required stiffness of the side rings and welds were made on the basis of the axial load and the bending moment which the manifold had to endure in operation. No mislocation resulted, even at operating extremes.

Two four inch pipe elbows were welded to the manifold. Flexible metal hose, 4 in. I.D., was brazed to the elbows and connected by means of a 10 in. length of 4 inch supported rubber hose to flanges. The flanges bolted to a fabricated 6 x 4 x 4 reducing Y. The six inch line was valved with a Walworth 719F flanged gate valve. A two inch line bypassed the larger valve and was provided with a Walworth 95 globe valve. This latter arrangement was included to allow the fine control at low flow rates which was not available with the 6 inch valve. The six inch line continued after the valve and was connected to the Gas Turbine Laboratory steam ejector line. Figure 5, the ejector characteristic, is included for reference.

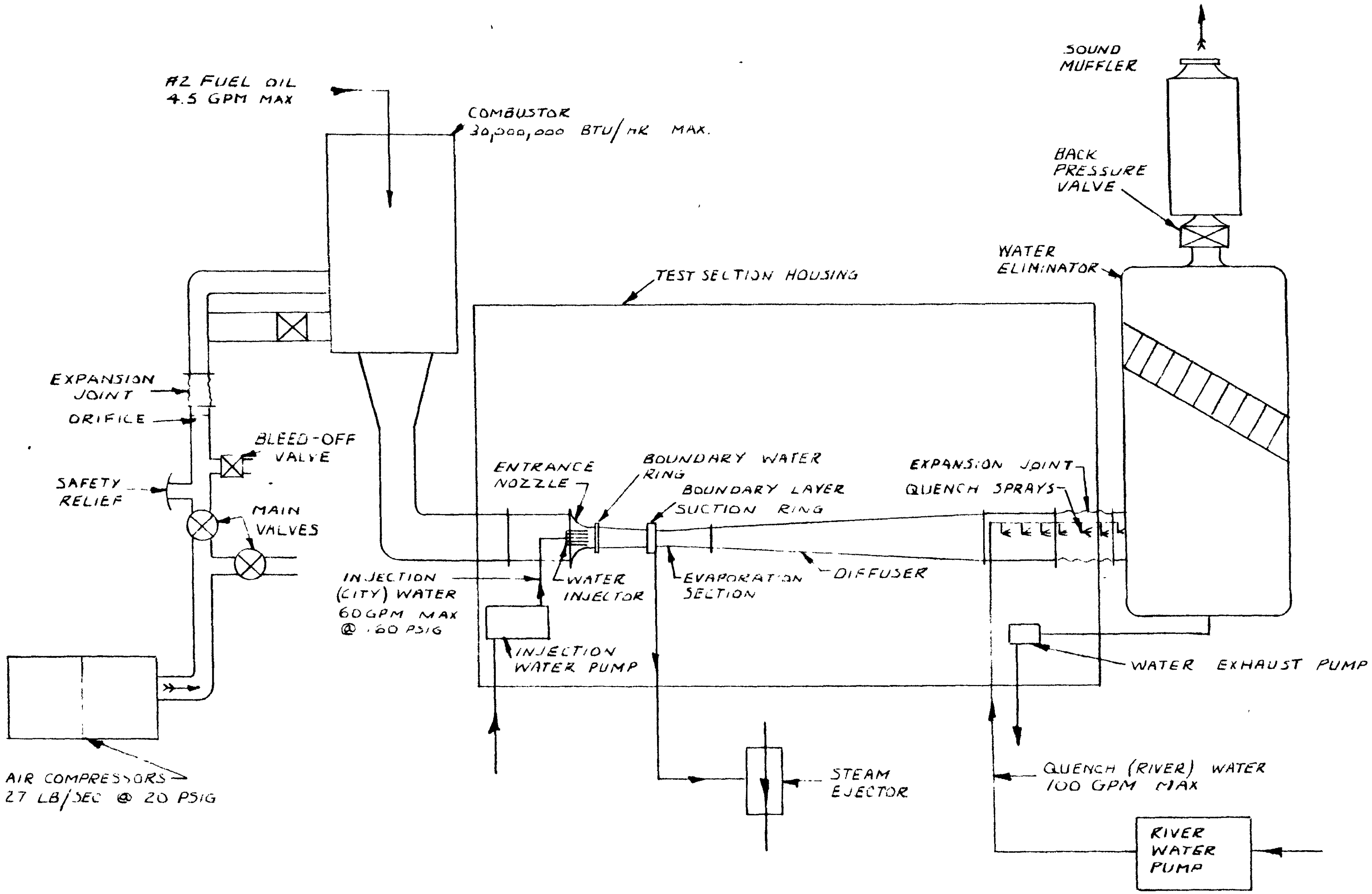

FIGURE 1 AEROTHERMOPRESSOR FLOW SYSTEM

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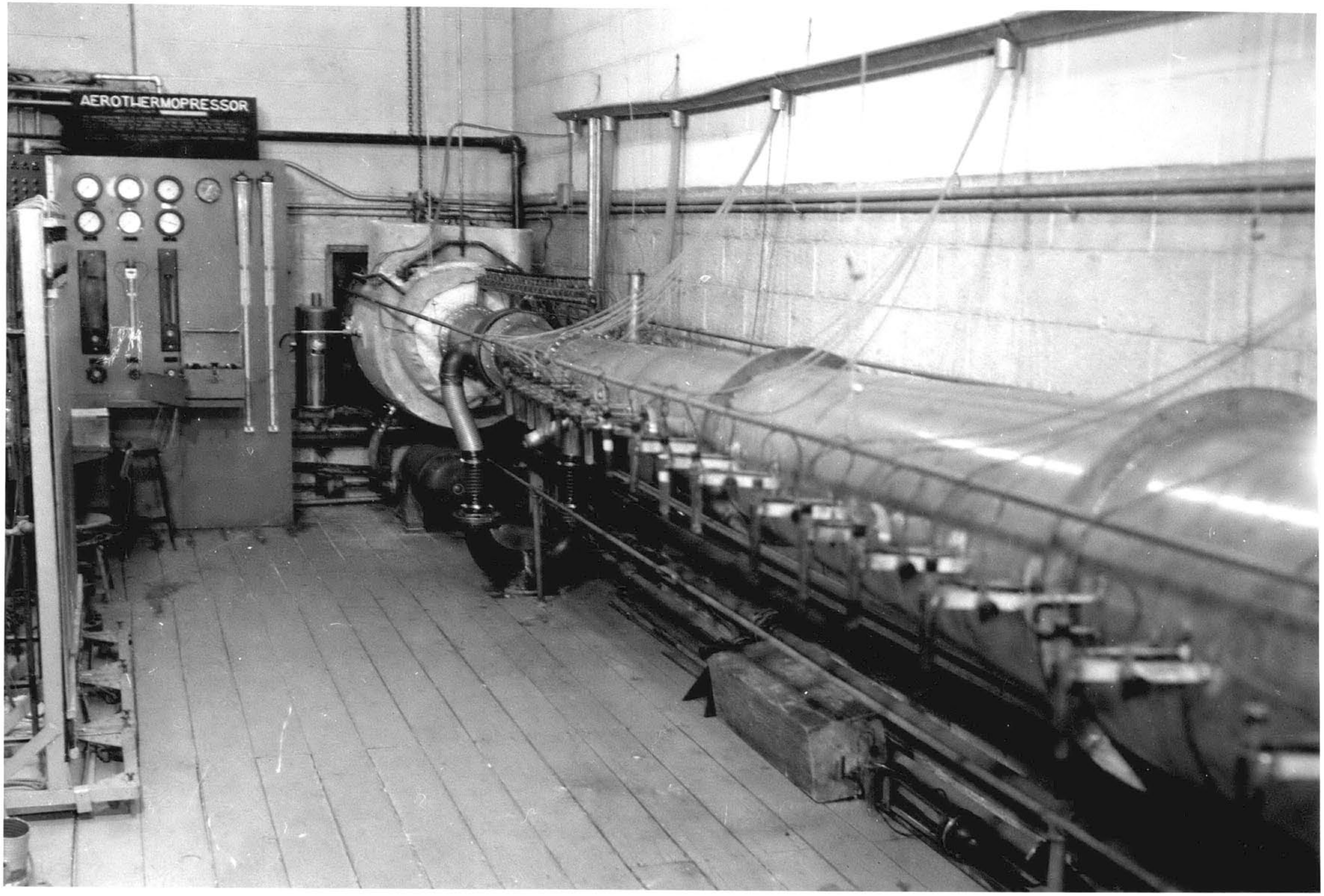
FIGURE 2 AEROTHERMOPRESSOR TEST APPARATUS AND CONTROL PANEL


AEROTHERMOPRESSOR

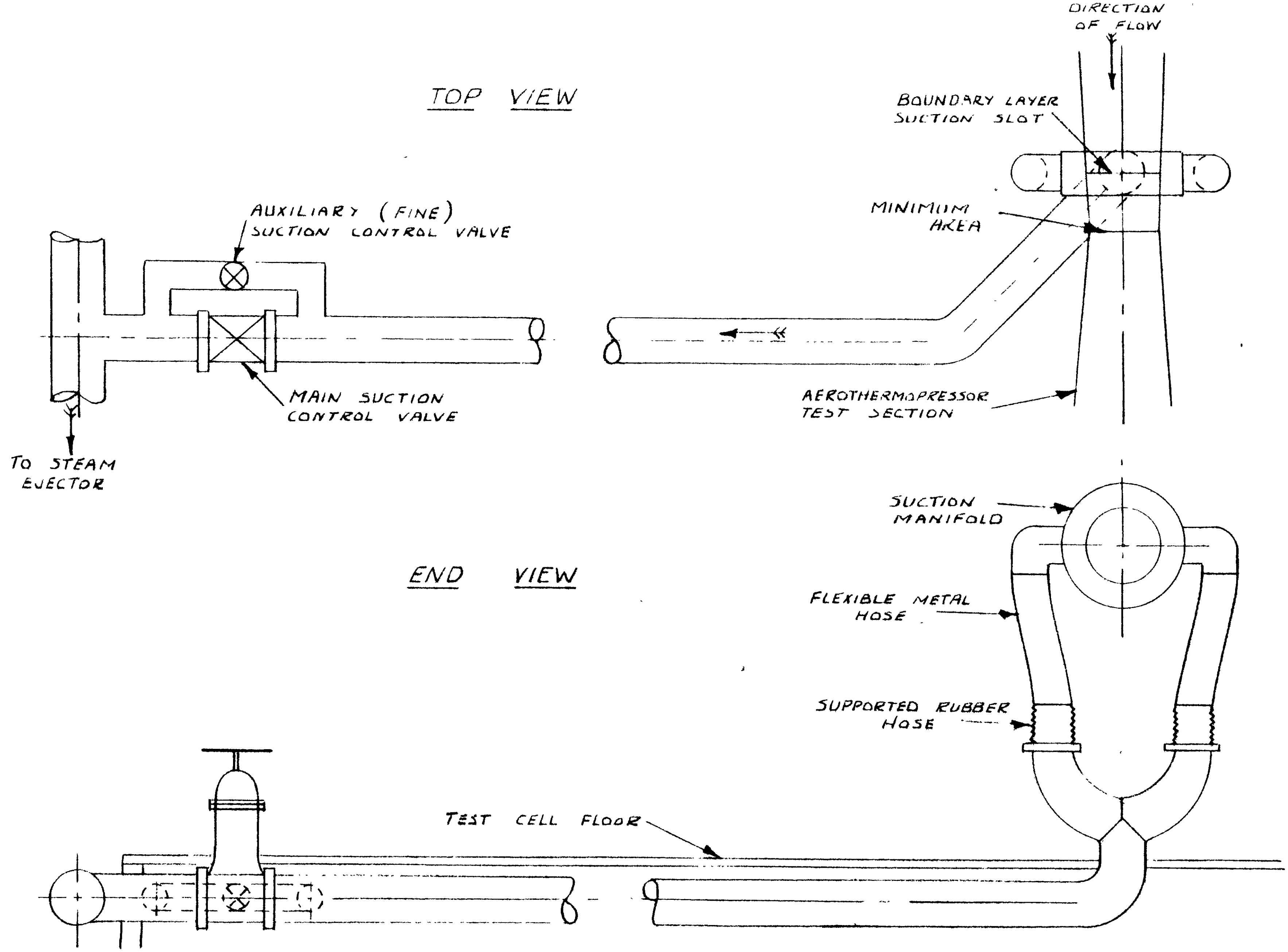


FIGURE 3 BOUNDARY LAYER SUCTION SYSTEM

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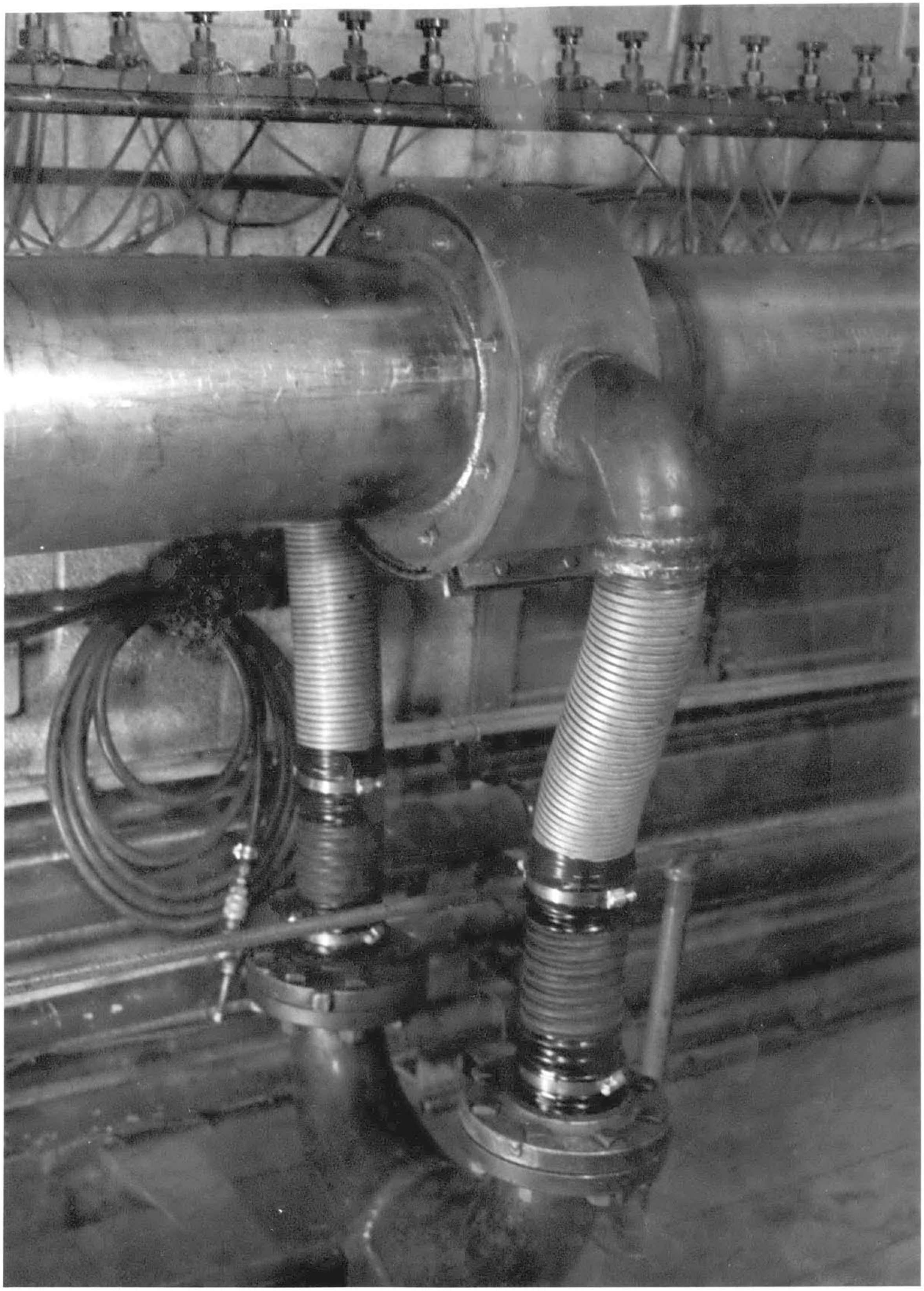
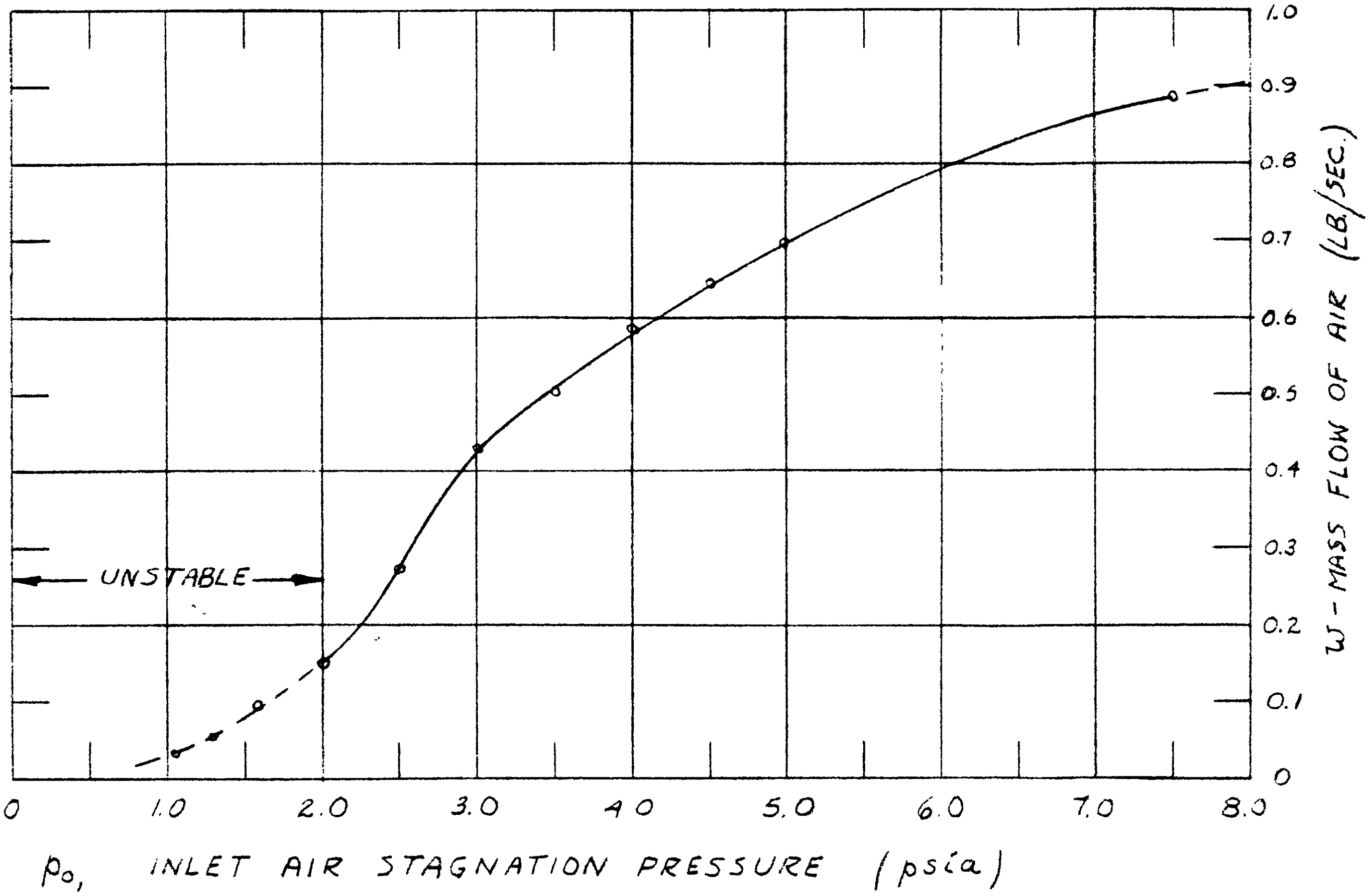
FIGURE 4 BOUNDARY LAYER SUCTION SYSTEM





EJECTOR DISCHARGE STATIC PRESSURE = 14.7 psia.

EJECTOR INLET AIR STAGNATION TEMPERATURE = 75 °F

STEAM PRESSURE = 185 psia (SATURATED)

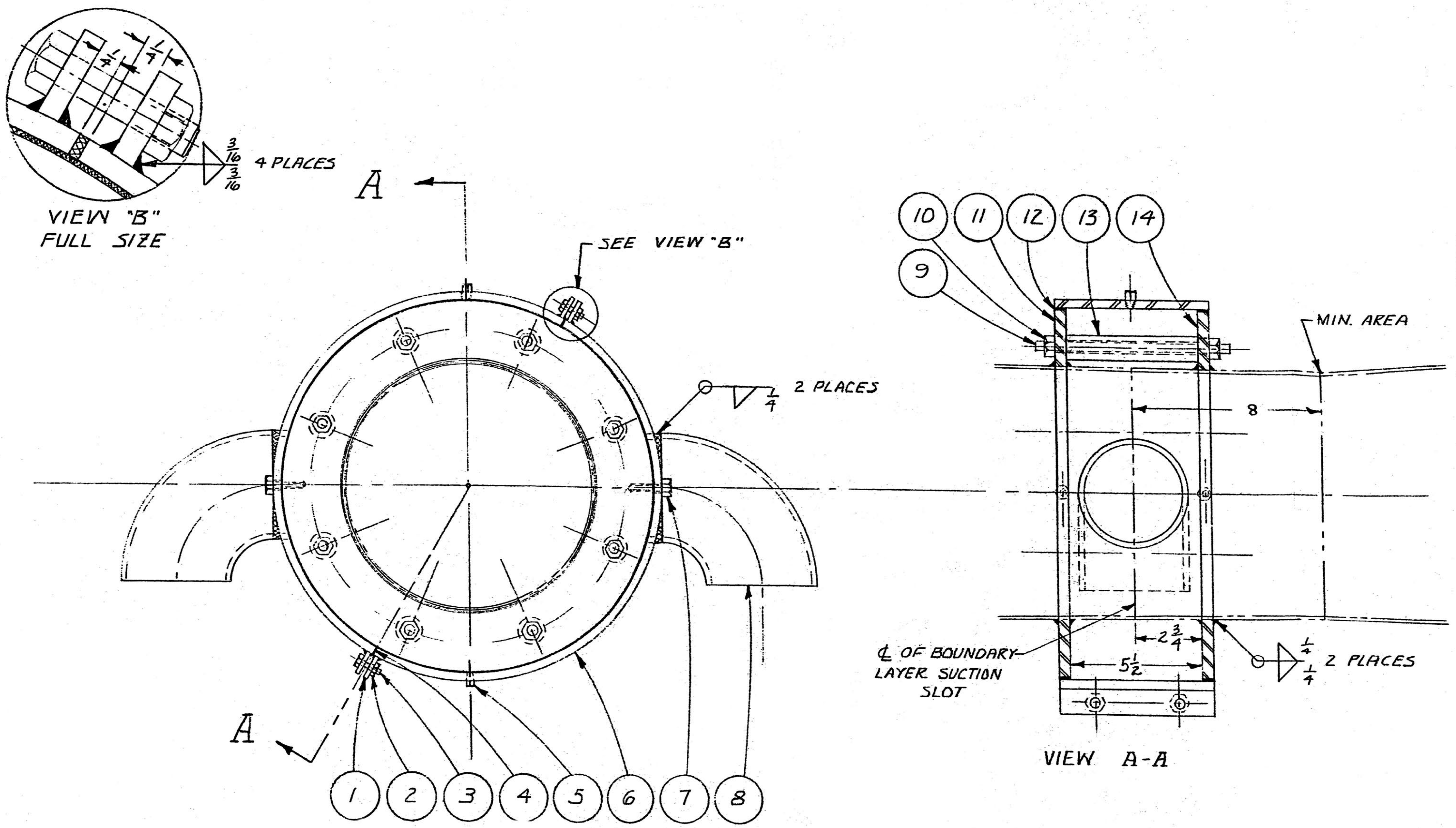
STEAM CONSUMPTION ≈ 4000 LBM/HR.

FROM: A RESEARCH GUIDE –
GAS TURBINE LABORATORY
M.I.T., SEPT. 1954

FIGURE 5 STEAM EJECTOR FLOW - PRESSURE CHARACTERISTIC

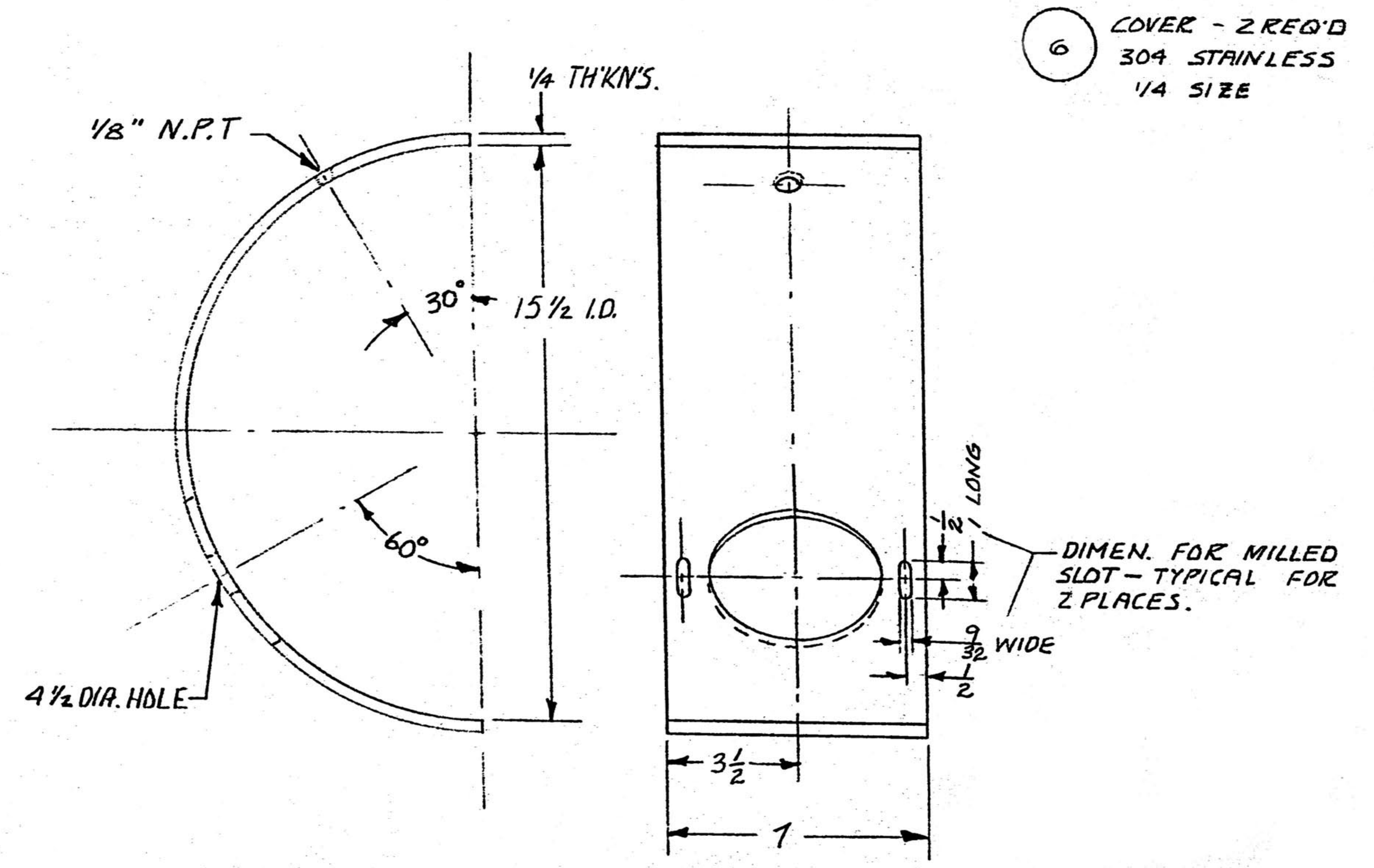
FIGURE 6 MANIFOLD DESIGN

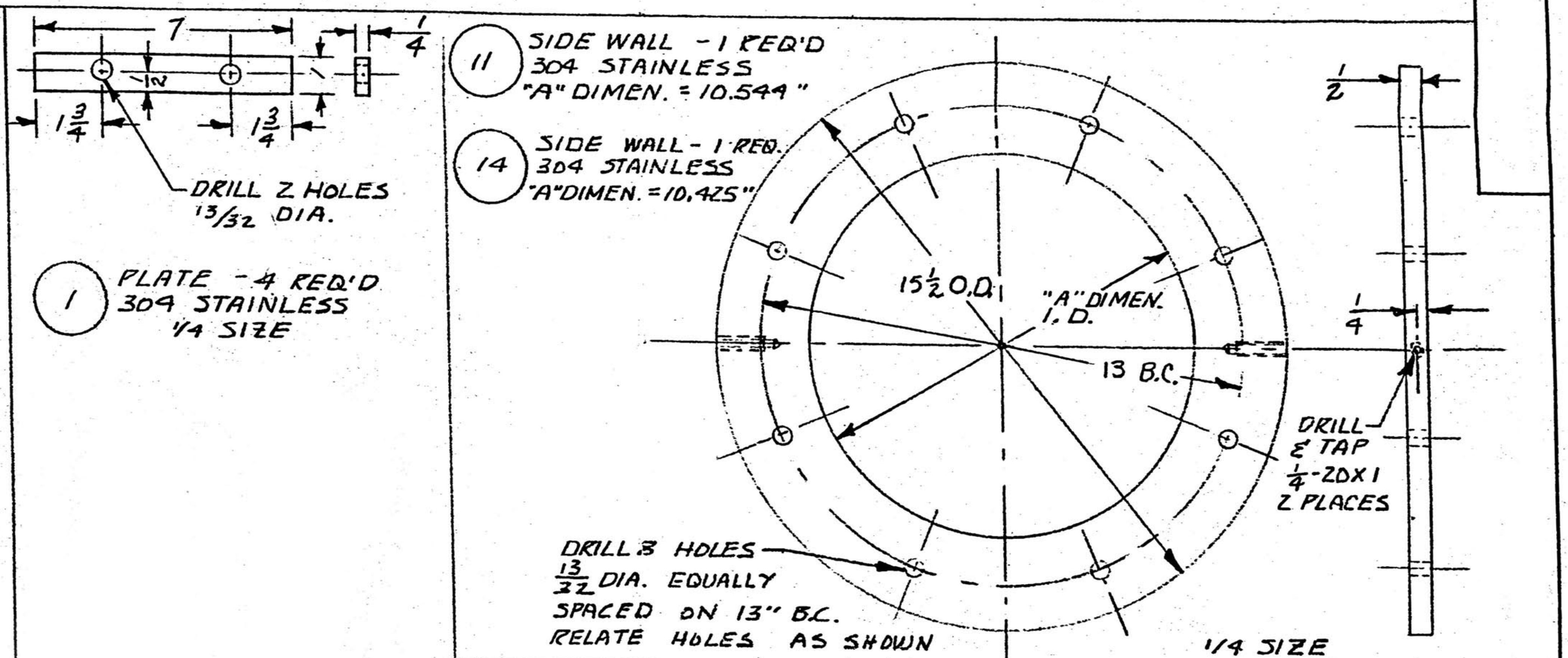
REVISIONS			
SYM.	DESCRIPTION	DATE	APPROVAL



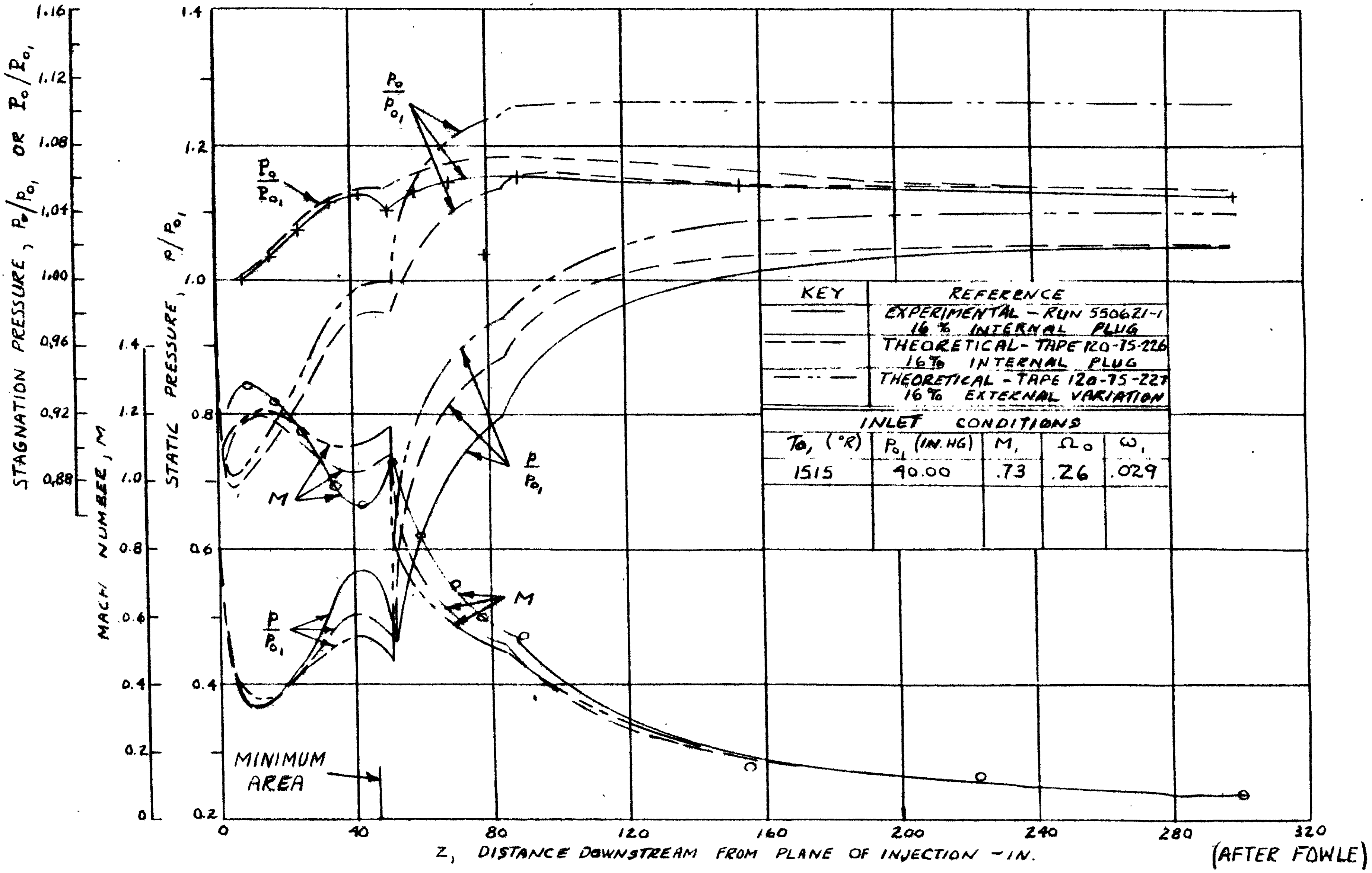
PART NO.	NO. REQ'D.	DESCRIPTION	MAT'L.
1	4	PLATE	304 STAINL'S
2	4	NUT 3/8-16	" "
3	4	BOLT 3/8-16 x 1 1/4	" "
4	2	GASKET - 1/8" LIVE RUBB.	RUBBER
5	2	1/8" N.P.T. PIPE PLUG	304 STAINL'S
6	2	COVER	" "
7	4	BOLT 1/4-20 x 1	" "
8	2	4" S.R WELD EL.	COMM.
9	8	THREADED ROD 3/8-16 x 8	304 STAINL'S
10	16	NUT 3/8-16	" "
11	1	SIDE WALL	" "
12	2	GASKET - 1/16" LIVE RUBB	RUBBER
13	8	PIPE - 3/4" DBL. EXT. HEAVY	304 STAINL'S
14	1	SIDE WALL	" "

ASSEMBLY - 1/4 SIZE





ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCE ON FRACTIONAL DIMENSIONS ±1/64 TOLERANCE ON DECIMAL DIMENSIONS ±.005 TOLERANCE ON ANGULAR DIMENSIONS ±½° BREAK SHARP CORNERS UNLESS OTHERWISE SPECIFIED	WEIGHT APPROX. 10#	DR: J.F.F. DATE 3/31/56	CKD. DATE 4-3-56	APPD. DATE
	SCALE: NOTED	MATERIAL: SEE PARTS LIST	FINISH:	
USED ON	FOR: **AEROTHERMOPRESSOR D.I.C. 6985**			
	NAME: BOUNDARY LAYER SUCTION MANIFOLD			
DO NOT SCALE THIS DRAWING	**MASS. INST. OF TECH.** CAMBRIDGE, MASS.	A-D-01-JF		



(AFTER FOWLE)

FIGURE 7 EXPERIMENTAL AND THEORETICAL RESULTS FOR INTERNAL AREA VARIATION AND THEORETICAL RESULTS FOR SIMILAR EXTERNAL VARIATION

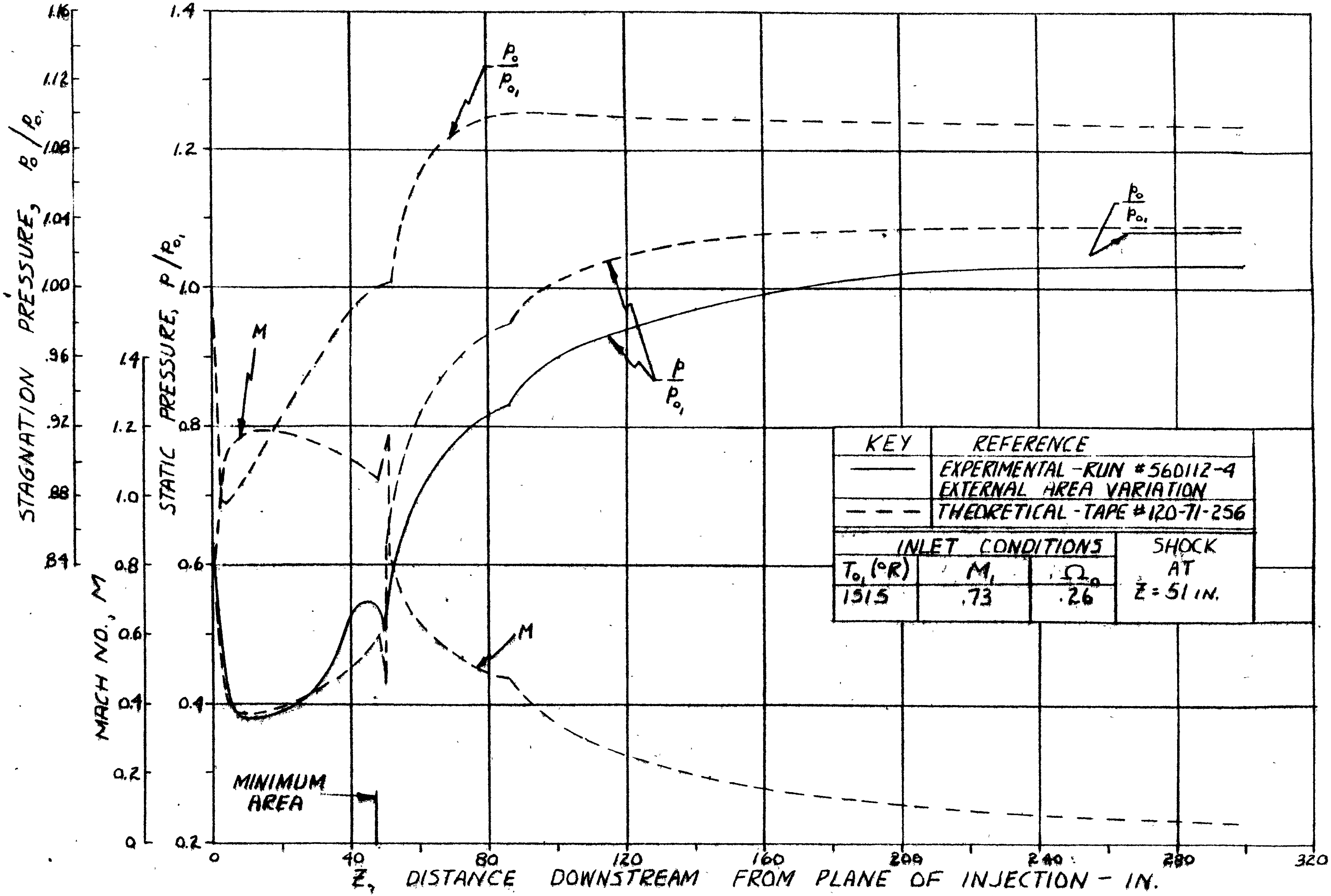


FIGURE 8 EXPERIMENTAL AND THEORETICAL RESULTS FOR EXTERNAL AREA VARIATION

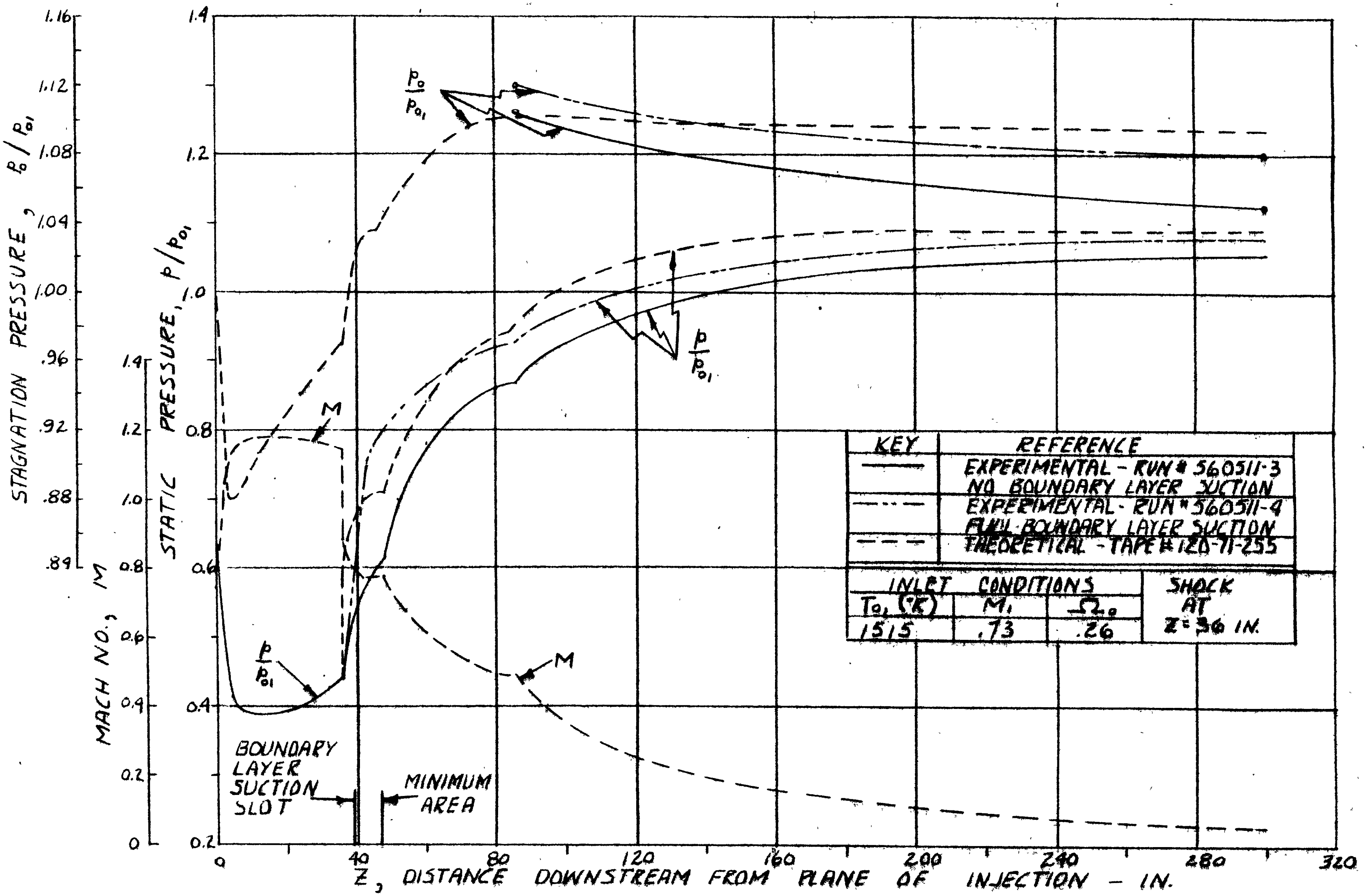


FIGURE 9 EXPERIMENTAL AND THEORETICAL RESULTS FOR BOUNDARY LAYER SUCTION RUNS

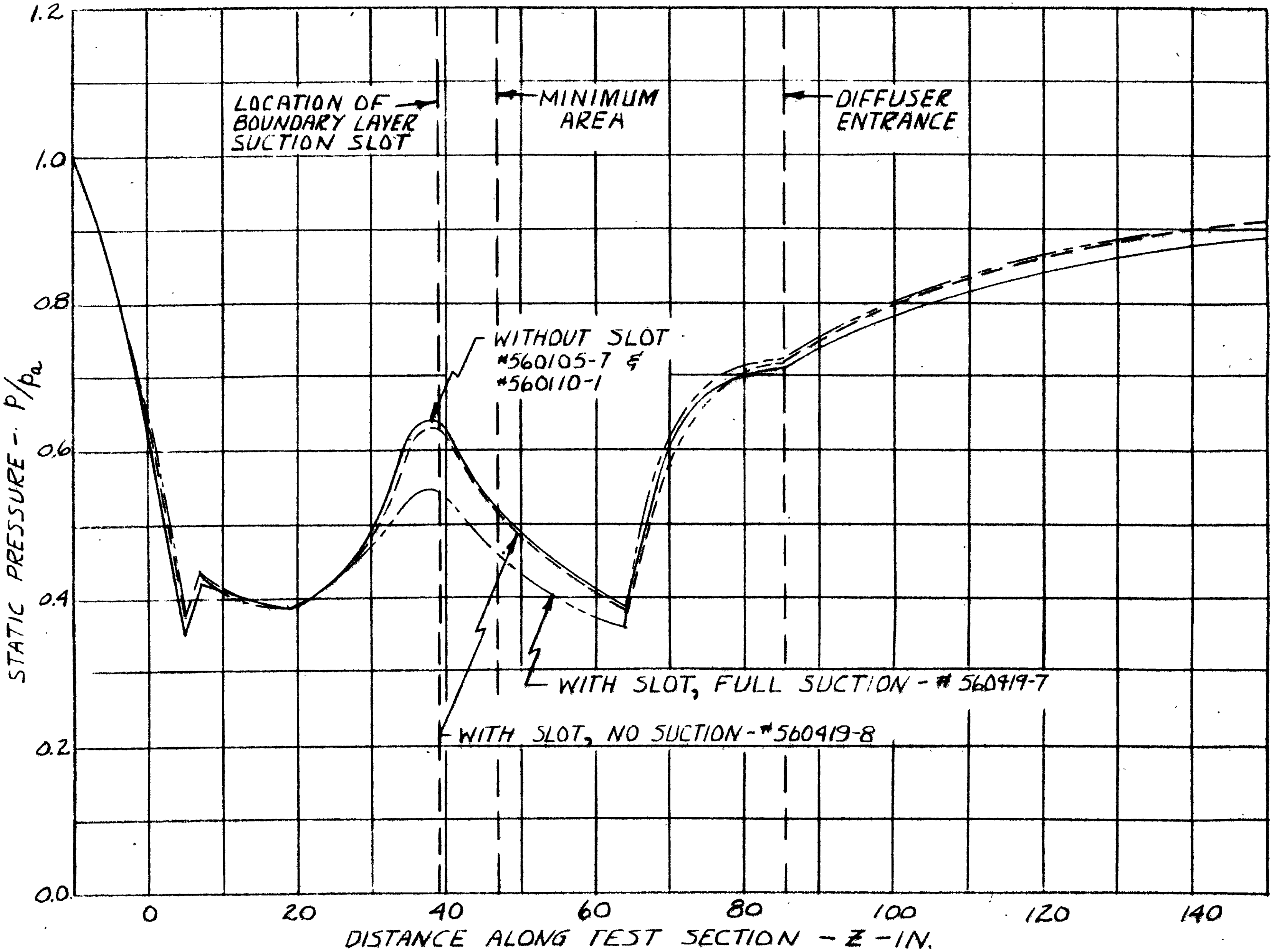


FIGURE 10 - EFFECT OF BOUNDARY LAYER SUCTION SLOT - 800 °F RUNS

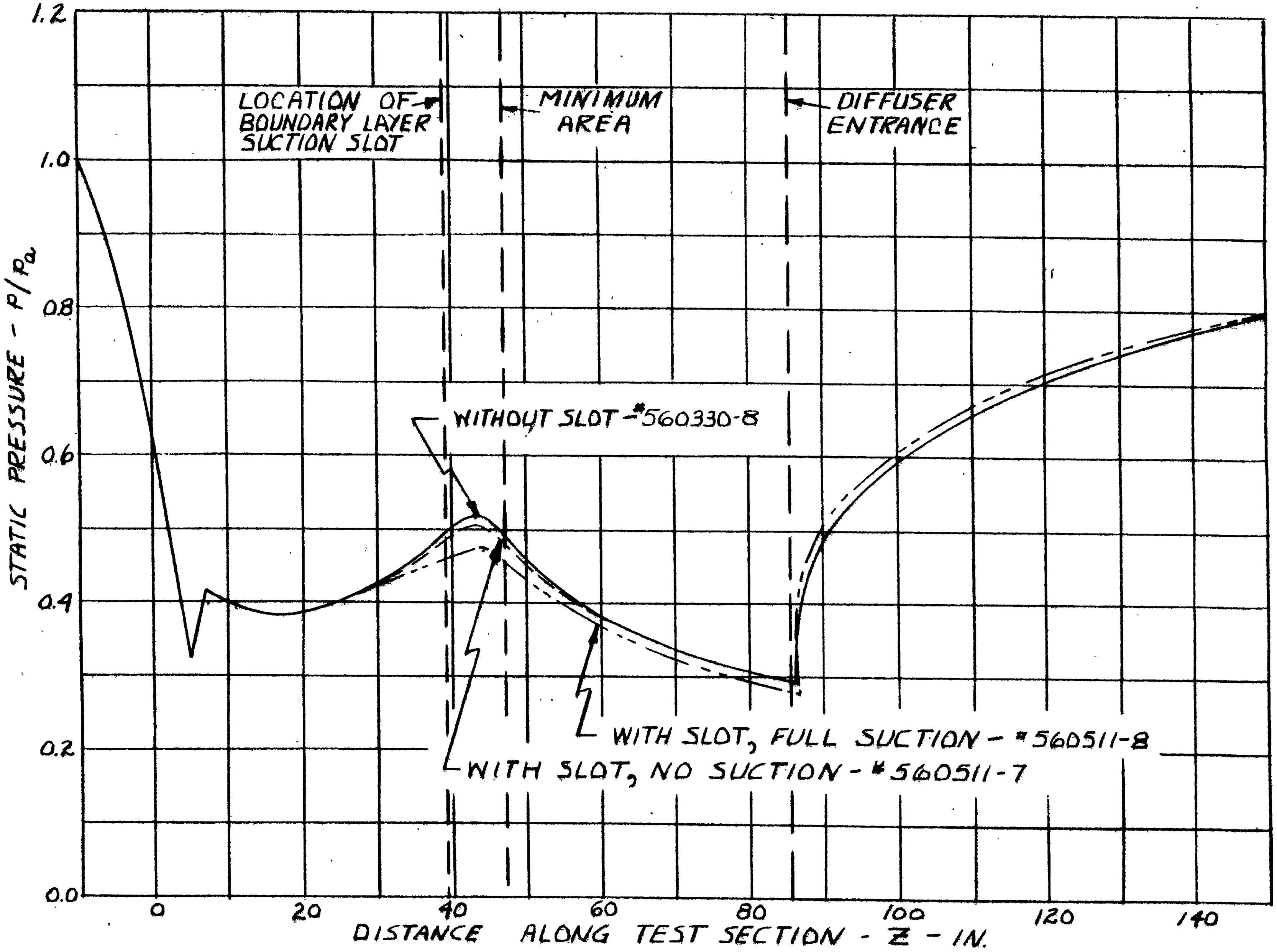


FIGURE II - EFFECT OF BOUNDARY LAYER SUCTION SLOT - 1200°F RUNS

FIGURE 12

TABLE OF SIGNIFICANT BOUNDARY LAYER SUCTION RUNS

Run No.	T_{o_1} (°R)	p_{o_1} (in. Hq.)	Ω_o	$\frac{p_{o_s} - p_{o_1}}{p_{o_1}}$	w_{bls} lbm/sec
560419-1	1290	31.78	.25	.058	.78
560419-2	1280	29.82	.24	.060	.73
560419-3	1410	32.98	.31	.067	.76
560419-4	1410	32.98	.31	.044	0
560419-9	1290	31.87	.26	.056	.75
560419-10	1290	31.31	.26	.029	0
560511-1	1465	30.50	.30	.046	0
560511-2	1465	30.50	.30	.074	.77
560511-3	1521	33.05	.28	.052	0
560511-4	1518	32.92	.28	.078	.80
560511-5	1665	34.42	.36	.057	0
560511-6	1665	34.48	.36	.082	.76

Run No.	T_{o_1} (°R)	Suction
560419-5	1410	None
560419-6	1410	Full
560419-7	1290	Full
560419-8	1290	None
560511-7	1665	None
560511-8	1665	Full

Notes:

$M_1 = M_{cr} = .73$ for all runs.

Runs 560425-5 to -8 and 560507-4 were invalid due to troubles with the water injector and collapsing of flexible suction lines.

Runs 560425-1 to -4 and 560507-1 to -3 were used to calculate diffuser efficiency since the above factors were considered to have negligible effect on this measurement.