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Technical Report

ON MENARD INSERTS IN SUPERSONIC NOZZLES

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ABSTRACT

The usefulness of Ménard inserts in conjunction with low and high Mach-number nozzles of fixed contour is discussed and supported by experimental data.*

OBJECTIVE

The purpose of the study was to investigate the possibility of using Ménard inserts as a simple and extremely economical technique of changing the Mach number of a set of fixed nozzle blocks.

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INTRODUCTION

Intentional changes of the design Mach number in a nozzle with fixed contours by means of movable sidewall inserts were first reported by Ménard.[1] His work formed the starting point for studies in the Aerodynamics Laboratory of The University of Michigan concerning the potential usefulness of such inserts at low and high Mach numbers. The study was motivated by the possibility of using Ménard inserts as a simple and extremely economical technique of changing the Mach number of a set of fixed nozzle blocks.

DISCUSSION

Consider a given two-dimensional symmetric nozzle with a uniform exit flow of Mach number M_0; add to the plane walls of this nozzle properly shaped and located half bodies so that a new uniform flow of Mach number $M_1 = M_0 + \Delta M$ results. The determination of the contours of these inserts and of their location relative to the basic nozzle cannot be carried out by any of the usual design procedures for two-dimensional or axisymmetric nozzles. Only the simple one-dimensional area-ratio theory or the cumbersome technique of characteristics for general three-dimensional supersonic flows appear applicable. The latter method, however, requires such excessive computational work that its use, in general, cannot be justified for this problem.

The one-dimensional area-ratio gives, of course, only a first order approximation to the total cross-sectional area distribution of the inserts. The exact shape of the inserts is dependent on additional considerations of the "area-rule" type, i.e., the rate of change of flow area shall be as small and smooth as possible, and strong secondary flows in the boundary layer and local separation must be avoided. The first consideration can be complied with easily, while the latter one depends entirely on experienced judgment or experimental results.

The specific design procedure employed was as follows. The flow-area curve of the original nozzle of a Mach number M_0 was modified as shown in Fig. 1. The new throat area was determined from the isentropic area-ratio for a new Mach number slightly higher than M_1 to account for boundary layer growth. The area distribution of the inserts was obtained by extending upstream the straight-line section, at the point of inflection, of the original flow-area curve; this extension continues into the new throat region having the same curvature as the original one. Finally, the subsonic portion was faired smoothly into the contour of the original nozzle entrance. In this manner a curve of the area distribution for the inserts was determined (Fig. 1) and used to design the insert shapes. Practical considerations make it desirable to construct each insert as one half of a body of revolution, or, at least, a slice of a body of revolution. It was found that this can generally be accomplished without too great a deviation from the desired aerodynamic configuration. The cusp at the downstream end of the insert area corresponds to a conical tip.

RESULTS

LOW MACH NUMBER INSERTS

The technique described above was used to design a set of inserts for the 19-in. x 27.5-in. wind tunnel of the Ordnance Aerophysics Laboratory so that their Mach 1.5 nozzle would give Mach 1.6 flow of acceptable uniformity. The design Mach number of this insert was chosen as 1.63 to allow for the effects of boundary-layer growth. It was also recommended that these inserts be tested at two-off-design positions to determine experimentally the optimum position.

Inserts of the recommended design were manufactured and tested by the Ordnance Aerophysics Laboratory. The results were highly satisfactory and are reported in Reference 2. Briefly, the desired Mach number of 1.6 was achieved with the inserts in design position, and the flow uniformity was no worse than that of the basic Mach 1.5 nozzle. Off-design positions of the inserts, 6 in. upstream and downstream of the design, resulted in usable flows of Mach 1.57 and 1.63, respectively, with the most uniform flow being obtained in the latter position. The centerline variations of the Mach 1.63 flow with inserts and of the Mach 1.5 flow of the basic nozzle immediately upstream of the test-section center are shown in Fig. 2.

According to Reference 2, the cost of these inserts and their installation amounted to approximately 13 percent of the expected cost of a new set of Mach 1.63 nozzle blocks.

HIGH MACH NUMBER INSERTS

After this success at low Mach numbers, the program of designing inserts for the OAL facility became quite ambitious. The first high Mach number inserts were to boost the OAL Mach 2.23 nozzle to Mach 3.0. It was found that no inserts could be designed which would have a reasonable chance of giving acceptable flow at the Mach 3.0 level. The variation in Mach number due to incomplete cancellation of radial flow alone was estimated to be about 4 percent and additional major nonuniformities had to be anticipated in view of the unusual shape of the insert. The details of this study are contained in Reference 3.

Next, a series of inserts were studied to bring the OAL Mach 2.75 nozzle to a Mach number of 3.0. Exploratory tests with models of the proposed inserts were conducted in the Mach 2.84 nozzle of the 8-in. x 13-in. wind tunnel of the University. Both the OAL Mach 2.75 and The University of Michigan Mach 2.84 nozzle are of the Foelsch type and have maximum expansion angles of about 2/3 of the Prandtl-Meyer angle.

The first series of tests were made of so-called "short" inserts, designed in accordance with the procedure outlined previously. The results are given in Reference 4, and, although three insert shapes were tested, no satisfactory test-section flow was achieved, as can be seen in Fig. 3. The shapes of inserts tested are shown in the upper portion of Fig. 4. The unsatisfactory flow of all three short inserts was primarily due to a strong lateral shock believed to originate in local regions of rapid expansion and cross flow just downstream of the effective throat of the nozzle-insert combination. A china-clay pattern of this region is shown in Fig. 5 for the most severe case of transverse expansion and subsequent compression. The shock traces seen are believed to be those of the lateral shock responsible for the poor performance of these inserts.

To alleviate the local expansion, a long cylindrical insert was tested. The model is shown in the lower half of Fig. 4, and the results of this test program are given in Reference 5. The main result is given in Fig. 6 and shows that a flow of reasonable uniformity was obtained, and that the Mach 3.0 level of the basic nozzle was increased by an increment of .20. The lateral shocks mentioned before were now sufficiently weak and were quickly attenuated.

Figure 7 shows the Mach number distribution predicted from these tests for the OAL Mach 2.75 nozzle with cylindrical inserts. However, in case one wants to terminate these cylindrical inserts in a smooth trailing point upstream of the test-section, additional model tests are strongly recommended to assure that the flow uniformity remains acceptable.

CONCLUSIONS

The work with Ménard inserts to date has indicated the following:

1. Ménard inserts are an effective and economical means of increasing the Mach number of an existing two-dimensional nozzle.

2. At low Mach numbers (around 1.5), increments of up to 10 percent of the basic Mach number can be achieved without loss in flow uniformity.

3. The design of inserts for the low Mach number range can be carried out by a modified area-ratio theory. In most cases no model tests will be needed.

4. At high Mach numbers (above 2) increments in Mach number due to inserts will be less than 10 percent, and some deterioration of the uniformity of the flow must be anticipated.

5. The design of inserts for the high Mach number regime should be substantiated by model tests, especially in the case of large increment inserts in short nozzles.

REFERENCES

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3. Amick, J. L., and Liepman, H. P., "Mach 3.0 Inserts for OAL Mach 2.23 Nozzle," University of Michigan Supersonic Wind Tunnel, WTM No. 244, Feb., 1955
4. Amick, J. L., "Preliminary Tests of Ménard Inserts Designed to Produce Mach 3 Flow in a Mach 2.75 Nozzle," University of Michigan Supersonic Wind Tunnel, WTM No. 253, Aug., 1955.
5. Amick, J. L., and Harrington, S. A., "Tests of Long Sidewall Bodies Designed to Give Mach 3 Flow in a Mach 2.75 Nozzle," University of Michigan Supersonic Wind Tunnel, WTM No. 257, Dec., 1956.

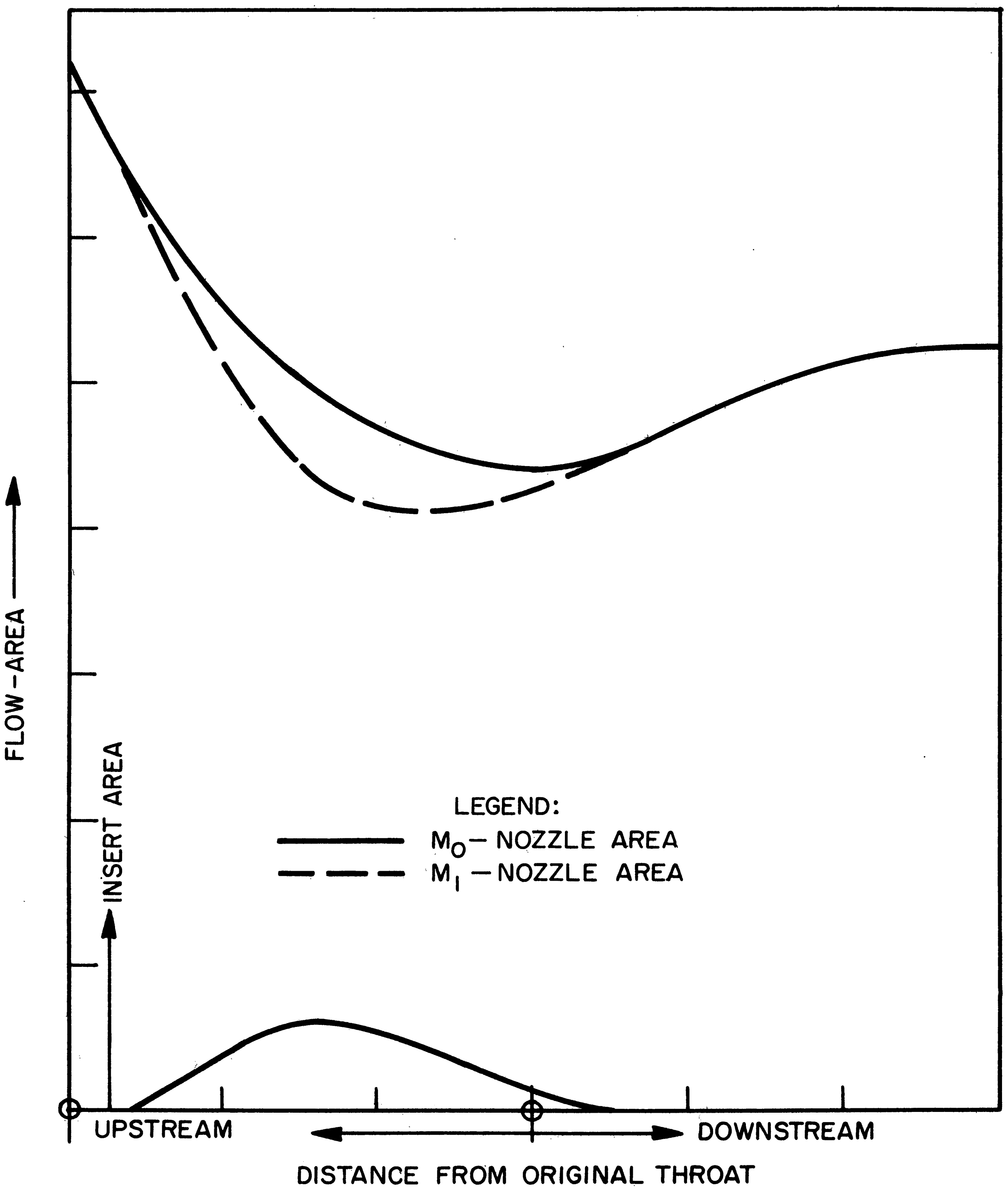

Fig. 1. Typical nozzle area distribution with and without inserts.

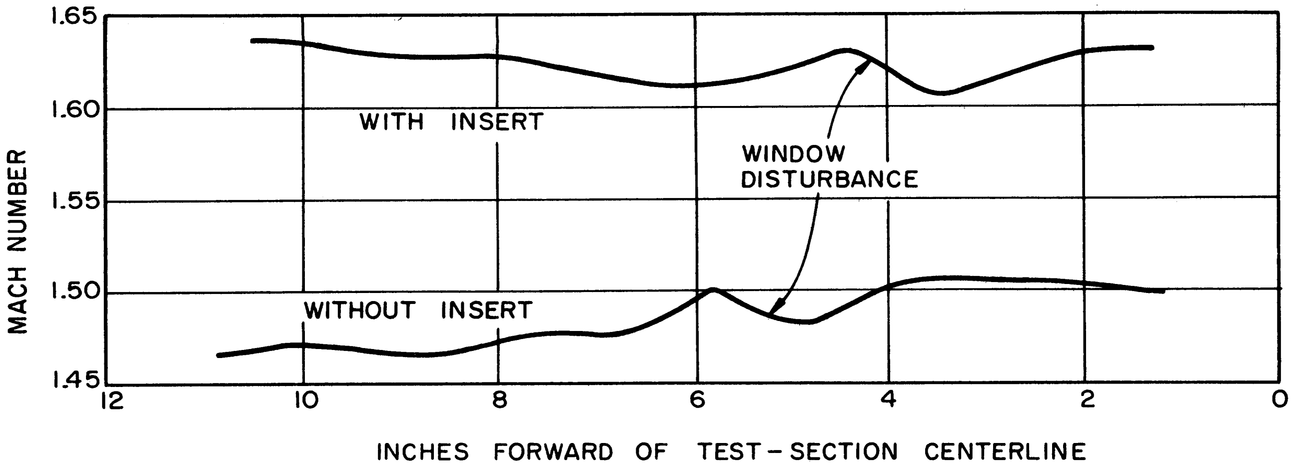

Fig. 2. Centerline Mach number OAL Mach 1.50 nozzle.

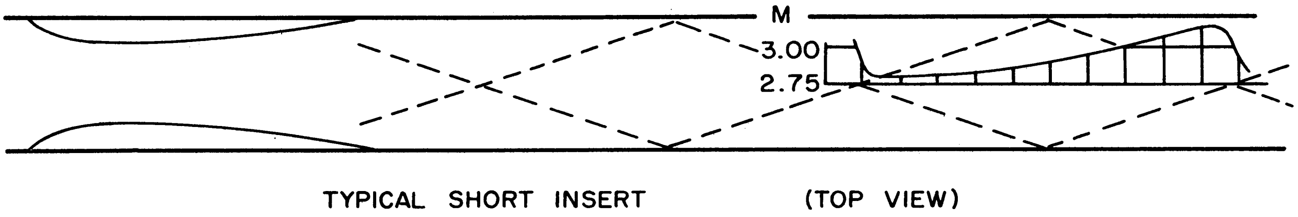

Fig. 3. Predicted centerline Mach numbers in OAL Mach 2.75 nozzle.
(Extrapolated from tests in U. of M. Mach 2.84 nozzle)

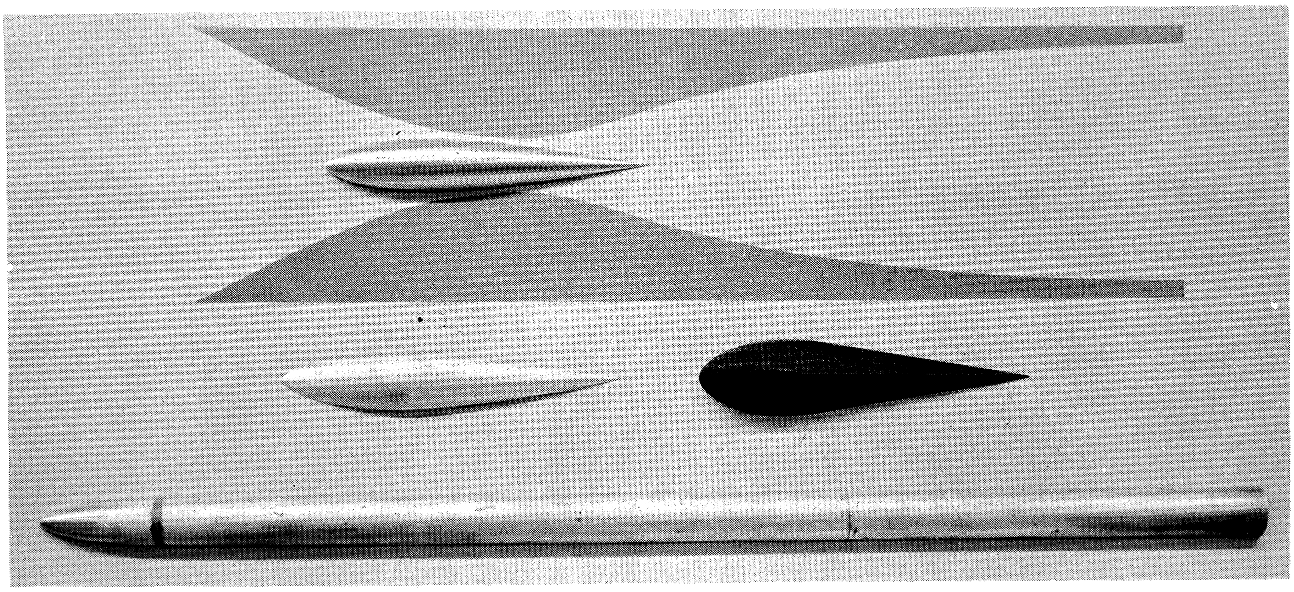

Fig. 4. Models of Ménard sidewall bodies (designed to give M-3 flow in OAL M-2.75 nozzle tested in U. of M. M-2.84 nozzle).

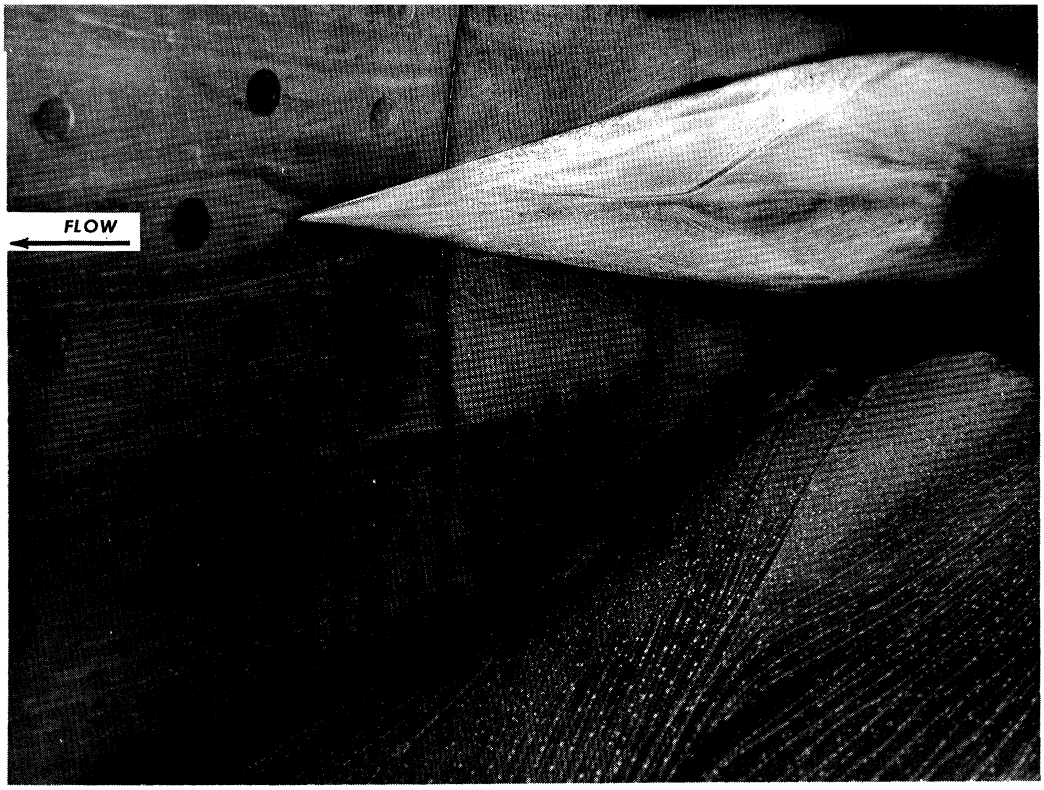

Fig. 5. Boundary-layer streamlines with inserts No. 1 in highest Mach number position in U. of M. 2.84 nozzle.

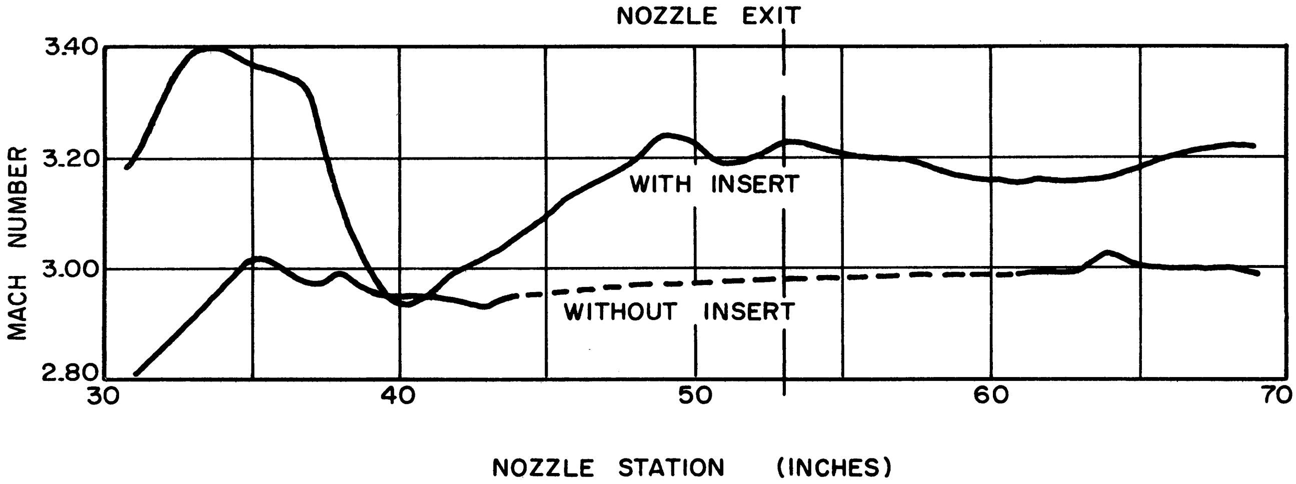

Fig. 6. Effect of cylindrical sidewall body on the centerline Mach number.
(Tests in U. of M. Mach 2.84 nozzle)

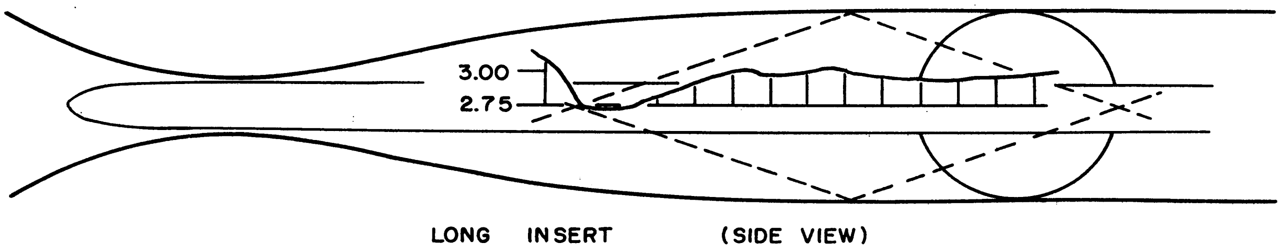

Fig. 7. Predicted centerline Mach numbers in OAL Mach 2.75 nozzle.
(Extrapolated from tests in U. of M. Mach 2.84 nozzle)