THE UNIVERSITY OF MICHIGAN

COLLEGE OF LITERATURE, SCIENCE, AND THE ARTS
Department of Astronomy

COLLEGE OF ENGINEERING
Department of Aeronautical and Astronautical Engineering

Final Reports

ORA PROJECTS 03941 AND 03942

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under contract with:

DEPARTMENT OF THE NAVY
BUREAU OF WEAPONS
CONTRACT NO. NOrd-16595
WASHINGTON, D.C.

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

December 1963

ORA PROJECT 03941

STUDIES OF VARIATIONS IN THE EARTH'S MAGNETIC FIELD DUE TO SOLAR ACTIVITIES

Final Report

November 1, 1955, to September 30, 1963

NOVEMBER 1, 1955, TO SEPTEMBER 30, 1963

Since November 1, 1955 the McMath-Hulbert Observatory of The University of Michigan has been the grateful recipient of continuous support from the Applied Physics Laboratory of The Johns Hopkins University for studies concerned with "variations in the earth's magnetic field due to solar activity." Each year the contract provided enough money to pay one technical or research assistant if a suitable assistant could be obtained. In addition, two important instruments were made available to the observatory: (a) a total field variometer that recorded changes in the magnitude of the earth's magnetic field at Lake Angelus; (b) a field intensity receiver for recording the 5 Mc/s WWV signal from Fort Belvoir.

PERSONNEL

Throughout the years in which this support has been provided, practically all members of the observatory staff have carried as a continuing purpose, improvement in the understanding of solar-terrestrial relations through better observations or deeper insight in the problems. The professional members of the observatory staff including Drs. McMath, Mohler, Dodson Prince, Teske and Miss Hedeman have all contributed directly to the observatory's studies of geophysics. Funds from the contract have been used to pay the salaries of a number of persons including students, both graduate and undergraduate, who have assisted for short intervals of time in the geophysical research programs. Since March, 1959, Mr. Frederic Stewart has been employed continuously on this contract as Research Assistant. He has contributed greatly to the observation of solar activity and has assisted significantly in the research programs based on these observations.

INSTRUMENTS

The magnetometer made available to the observatory under this contract and in use through 1959 provided immediate and hence valuable information regarding disturbances in the earth's magnetic field for the years covering maximum in the recent solar cycle. In spite of our best efforts, the instrument was not stable and in the first quarter of 1960 it was returned to the Applied Physics Laboratory at Silver Springs. However, it had demonstrated the great assistance that immediate geomagnetic information can provide (a) in distinguishing between sun-associated and geomagnetically-associated disturbances in the ionosphere, and (b) in efforts to recognize the solar causes of geomagnetic phenomena. On the basis of this experience, the observatory took steps to secure a more stable magnetometer.

The 5 Mc WWV recorder has proved to be a trustworthy instrument on which the observatory staff has come to depend for information relating to the ionizing radiation from flares. The ionospheric disturbances recorded on this instrument have been used each month as part of the world-wide ionospheric "patrol" organized by the Central Radio Propagation Laboratory of the National Bureau of Standards. Our experience in studying the ionizing radiation from flares depends so heavily on data from this recorder that we have requested that the instrument be made available to the observatory after termination of this contract. It is our understanding that the recorder is being transferred, through other governmental contracts, to the equipment held by The University of Michigan's Office of Sponsored Research and can thus continue in service at the McMath-Hulbert Observatory.

STUDIES

Throughout all the years of this contract, the McMath-Hulbert Observatory has conducted research programs directed towards a better understanding of the geophysical effects of solar activity. When these programs gave results that seemed worthy of sharing with others they have been described, at least in part, in the Quarterly Reports for this contract. When it seemed suitable, more detailed accounts of the research results were sent directly to Dr. A. J. Zmuda at the Applied Physics Laboratory. Some of the studies have been published in professional journals or reported at professional meetings; others are still "in progress."

The subjects included in these investigations have been numerous and the approaches to the problem of solar-terrestrial relationships varied. We summarize below, a few of the studies. A number of the ideas given in the Quarterly Reports for this contract, though new at the time of the reports, now seem like "old friends."

1956

FLARES AND SUBSEQUENT GEOMAGNETIC STORMS

The Quarterly Report for April-June, 1956 included a "Study of Occurrence of Geomagnetic Storms Following Flares With Major Early Bursts at Radio Frequencies $\leq$ 200 Mc/s 1949-1956." This investigation served to call attention to the geophysical effects of flares with certain types of radio frequency emission at a time when the role of flares in solar-terrestrial relationships was at a low ebb. In addition, the study, especially as published in the Journal of Geophysical Research, gave evidence for an <u>average</u> interval of 2 - 2-1/2 days between flare and start of storm rather than the then generally accepted 17^h-24^h.

1957

ABSORPTION ON 18 Mc RIOMETER

In our Quarterly Report for July-September 1957 we report the occurrence, at the time of certain geomagnetic storms, of absorption on the newly-installed 18 Mc/s "cosmic noise recorder," the instrument now called a riometer. This absorption was of course, that which is now well known as "auroral absorption." Detailed relationships between the magnetic variations and the absorption effects were included in the report for the first quarter of 1958. This material has never been published, and it should not be, until it has been extended to more cases and with the new magnetic records, however, excellent observational material exists for detailed studies of "auroral absorption" at 18 Mc and variations in the local magnetic field.

From 1957 to 1963 there have been examples of daytime absorption at 18 Mc that fail to fit into the categories of either flare or aurora-associated events. Perhaps they represent a "low latitude" aspect of Polar Cap Absorption—or some currently unrecognized type of ionospheric event.

1958

CROCHETS

A study of flares associated with crochets was completed and published.

FLARE SPECTRA

Spectra of many flares were secured in the summer of 1958. They still defy theoretical interpretation (1963), but they indicate that "flares" exhibit many different kinds of spectra; that flares with very wide emission lines are not always associated with significant terrestrial effects, and that flares with known, great terrestrial effects (August 22, 1958) do not always have wide flare emission.

1959

McMATH-HULBERT OBSERVATORY WORKING LISTS OF FLARES

In order to evaluate the most probable causes of geomagnetic distur-

bances during the IGY, we prepared for our own use at the McMath-Hulbert Observatory a list of "flare events" during the IGY, based on the world-wide compilation of reports of flares from each observatory in the Quarterly Bulletin of Solar Activity. It was requested that this list be made available to other investigators. Accordingly it was published as part of the IGY Solar Activity Series. In subsequent years similar working lists of flares have been prepared and published. The series ends with 1962 because the Quarterly Bulletin of Solar Activity will publish flare data in a similar form starting in January, 1963.

SYSTEMATIC EFFECT IN WORLD-WIDE FLARE DATA

Studies of flares in the Working List for the IGY revealed the existence of a serious inhomogeneity in world-wide flare data. According to the data, between the hours 05^h-16^h UT, the rate of flare occurrence was more than twice as great as for the other hours of the Universal Day. This systematic effect stemmed, primarily, from differences between reports from visual and cinematographic flare patrol stations. A systematic difference of this type persists through 1962 and introduces an extra problem in statistical studies of flares and possibly associated geophysical phenomena.

STUDIES OF FLARES ASSOCIATED WITH TYPE IV RADIATION AND PROTON EVENTS

The report for the last quarter of 1959 contained a copy of a paper that was presented at the October, 1960 Cosmic Ray Conference in Iowa City. It stated that flares associated with Type IV radiation and proton events do not appear to differ from other flares by greater size and brightness, more sudden rise to maximum, or wider Hα emission. A search for a possibly distinctive characteristic led us to report that for the flares studied (1958 Feb. 9, 1958 Aug. 22, 1959 July 16) the Hα flare emission covered major sunspot umbrae at the time of the strong Type IV emission.

1960

CHARACTERISTICS OF FLARES WITH POLAR CAP ABSORPTION

Continuing studies of flares associated with PCA showed further evidence for covering of spot umbrae, and indicated that PCA flares differed from other flares with very strong 10 cm emission by (a) higher concentration towards center of solar disk and (b) the atypical relationship of 10 cm maximum after Hα flare maximum.

COMPARISON OF FORBUSH DECREASES WITH GEOMAGNETIC DATA

In the Quarterly Report for October-December, 1960, we described detailed comparison of neutron counts with geomagnetic indices and reported that there were serious departures from the standard relationship of a Forbush decrease at the time of a severe geomagnetic storm. There were "storms" without diminution of neutrons, and there were diminutions of neutrons without seemingly adequate storm conditions. It was suggested that some of these differences might be of assistance in distinguishing between geomagnetic storms that were flare-associated and those that were recurrent. This work is still in progress.

1961

RECURRENT GEOMAGNETIC STORMS

Evidence for recurrent geomagnetic storms in 1960 was presented and a relationship pointed out between these storms and the great Forbush decrease that started on March 31, 1960.

AGE OF REGION RELATED TO OCCURRENCE OF PCA

In the Quarterly Report for April-June, 1961 we gave an account of our contribution to the June 23, 1961 meeting in Boulder, called by NASA to discuss the prediction of flares associated with PCA. We reported that the flares associated with proton events had occurred in calcium plages in their second or later rotations, not in their first rotation. This relationship continues to hold (1963) and is of assistance in efforts to recognize proton producing flares.

1962

NEUTRON COUNTS VERSUS GEOMAGNETIC INDICES, Kp

Daily values of neutron counts (Deep River) were compared with Kp for January 1, 1958-December 31, 1961. In this interval there were 174 "events." These included 57 geomagnetic storms with concomitant diminutions in neutron counts, 98 storms without such diminution in neutron records, 4 cases of marked diminution of neutron count with only very minor geomagnetic disturbance, and 15 instances when the relationships were not clear.

FLARES ASSOCIATED WITH PCA

Survey of the optical characteristics of the 52 flares associated with PCA 1957-1961 confirmed the relationships reported in earlier studies. For this investigation, the PCA events were ranked according to the estimated "magnitude" of the proton event. The greatest PCA events were all associated with Hα flares of importance 3 or 3+ located within 60° of the central meridian. Within the limitations of observational data, all major PCA flares were accompanied by Type IV radio frequency emission and covered major sunspot umbrae.

SURVEY OF THE GEOPHYSICAL EFFECTS OF FLARES FOR THE YEARS 1957-1962

At the request of Dr. C. W. Allan, Chairman of the Inter-Union Commission on Solar and Terrestrial Relationships, we prepared a review article on the "Problems of differentiation of flares with respect to geophysical effects." The study included consideration of the effects of flares on the earth's ionosphere and geomagnetic field and efforts to distinguish between flares with and without such effects. The study will be published in the 10th Report on Solar-Terrestrial Relations, and the abstract has been included in the Quarterly Report for June-September, 1963.

PUBLICATIONS

We list below, publications of research for which the funds of this contract have provided partial support:

The Relation Between Observed Solar Features and Solar Radio Emission. Helen W. Dodson. Proc. Nat'l. Electronics Conf. XI, 498-505, 1955.

Resume of Visually and Photographically Observed Solar Activity at Time of 200 Mc/s Noise Storms Near 1954 Solar Minimum. Helen W. Dodson and E. Ruth Hedeman. ApJ 125, 827, 1957.

Motion Pictures and Photometric Studies of Solar Flares. Helen W. Dodson. Trans. I.A.U., 9, 650, 1957.

Relation Between Optical Solar Features and Solar Radio Emission. Helen W. Dodson. I.A.U. Symposium, 4, Radio Astronomy, 327-333, 1957.

Studies at the McMath-Hulbert Observatory of Radio Frequency Radiation at the Time of Solar Flares. Helen W. Dodson. Proc. of the IRE, Vol. 46, 149-159, 1958.

Geomagnetic Disturbances Associated With Solar Flares With Major Premaximum Bursts at Radio Frequencies $\leq$ 200 Mc/s. Helen W. Dodson and E. Ruth Hedeman. J. of Geophys. Res. 63, 77, 1958.

Crochet-Associated Flares. Helen W. Dodson and E. Ruth Hedeman. ApJ. 128, 636, 1958.

Survey of Number of Solar Flares Observed During the International Geophysical Year. Helen W. Dodson and E. Ruth Hedeman, J. of Geophys. Res., 65, 123, 1960.

A Study of a Solar Active Region Using Combined Optical and Radio Techniques. W. N. Christiansen, D. S. Mathewson, J. L. Pawsey, S. F. Smerd, A. Boischot, J. F. Denisse, P. Simon, T. Kakinuma, Helen Dodson Prince, John Firor. Ann. d'Ap., 23, 75, 1960.

Flares of July 16, 1959. Helen W. Dodson and E. Ruth Hedeman. ApJ. 65, 51, 1960.

McMath-Hulbert Observatory Working List of IGY Flares. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series No. 12, 1960.

Flare Index for Each Day of IGY. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series No. 14, 1961.

McMath-Hulbert Observatory Working List of Flares and Daily Flare Index for IGC-1959. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series No. 15, 1961.

Observations of Loop-Type Prominences in Projection Against the Disk at the Time of Certain Solar Flares. Helen W. Dodson. Proc. NAS, 47, 901-905, 1961.

Photographic Observations of Certain Flares Associated With Polar Cap Absorption. Helen W. Dodson and E. Ruth Hedeman. Arkiv for Geofysic, 3, 469-470, 1961.

Selected High-Resolution Strip Scans of the 10.7 cm Sun. Arthur E. Covington, Gladys A. Harvey and Helen W. Dodson. ApJ. 135, 531-546, 1962.

McMath-Hulbert Observatory Working List of Flares and Daily Flare Index for 1960. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series No. 18, 1962.

The Hα Line in the Flare of November 12, 1960. Richard G. Teske. ApJ. 136, 534, 1962.

Studies of Flares Associated With Polar Cap Absorption. Helen Dodson Prince and E. Ruth Hedeman. Astronomical Journal, 68, 290, 1963.

Characteristics of Flares Associated With Polar Cap Absorption. Helen W. Dodson and E. Ruth Hedeman. Transactions of the I.A.U. (Proc. of 11th Gen'l. Assembly, Berkeley, 1961) XIB, 474, 1962.

Problems of Differentiation of Flares With Respect to Geophysical Effects. Helen W. Dodson and E. Ruth Hedeman. 10th Report on Solar-Terrestrial Relations of the Inter-Union Commission of Solar and Terrestrial Relationships. In press.

Moving Material Accompanying the Flare of 1959 July $16^{d}21^{h}14^{m}$. Helen W. Dodson and E. Ruth Hedeman. Report of Goddard AAS Symposium on Physics of Solar Flares, October, 1963. In press.

McMath-Hulbert Observatory Working List of Flares and Daily Flare Index for 1961. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series No. 21, 1963.

McMath-Hulbert Observatory Working List of Flares and Daily Flare Index for 1962. Helen W. Dodson and E. Ruth Hedeman. IGY Solar Activity Report Series (in press).

APPENDIX

QUARTERLY REPORT

July 1 to September 30, 1963
Contract NOrd-16595—Project 03941

"Studies of Variations in the Earth's Magnetic Field
Due to Solar Activity"

PERSONNEL

Mr. Frederic Steward was employed half-time on this contract for two months and full-time for one month in this quarter. Miss Hedeman and Dr. Prince spent almost the entire quarter preparing the invited review article on "Problems of Differentiation of Flares With Respect to Geophysical Effects" for the 10th Report on Solar-Terrestrial Relations of the Inter-Union Commission on Solar and Terrestrial Relationships.

INSTRUMENTS

The APL-5 Mc WWV recorder continues to supply records of interest and value.

STUDIES

Solar and terrestrial data for the five-year interval 1957-1961 were examined and analyzed in the course of preparation of the manuscript on "Problems of Differentiation of Flares With Respect to Geophysical Effects." The abstract of this article is given below, and provides a summary of the results of the investigation:

Systematic Effects in Flare and Ionospheric Data

Diminution in the visibility of Hα flares from center to limb, and differences between flare reports for 05^h-16^h UT and the remainder of the Universal Day, introduce systematic effects in flare data that lead to special problems in the differentiation of flares with respect to terrestrial phenomena. In addition, the number of known sudden ionospheric disturbances, 1957-1961, depends strongly on Universal Time.

Sudden Ionospheric Disturbances

Comparisons of world-wide flare and ionospheric data for the IGY and 1957-1961 show that fewer than 15% of flares reported as of importance ≥ 1 were accompanied by SWF's, but special studies of well monitored intervals indicate ionospheric disturbances with more than 45% of flares, importance ≥ 1. Although intense Hα emission, sudden rise to maximum, proximity of flare to spots, and strong centimeter radiation favor the occurrence of severe ionospheric disturbances, these circumstances do not appear to be necessary for the emission of ionizing radiation in the flares. Severe ionospheric disturbances have occurred primarily with major Hα flares within 60° of the center of the solar disk, with events evaluated as less important Hα flares more than 60° from the center, and with limb activity without concomitant disk flares. A small number of confirmed SWF's 1957-1961, appear to refer to disturbances of the ionosphere caused by geomagnetic phenomena rather than by solar flares.

Geomagnetic Storms

Consideration of flare-associated radio frequency emission, especially Types IV and II, has greatly improved the statistical association between certain Hα flares and subsequent onset of geomagnetic storms. Nevertheless, a relatively large proportion of the geomagnetic storms, 1957-1961, were not preceded within suitable time intervals by flares with radio frequency events of these types. Evidence exists for possible recurrence-type storms even near maximum in the solar activity cycle. Attention is drawn to two storms with K-9 which may have been related to central meridian passage of regions with proton flares in the preceding rotation.

The flares associated with strong Type IV emission and severe geomagnetic storms generally have been important Hα events, rather highly concentrated towards the central part of the solar disk, covering or impinging upon major spot umbrae, and accompanied by loop-type prominences in the post maximum phase.

Polar Cap Absorption

Flares associated with major Polar Cap Absorption have emitted various types of strong Type IV radiation, have occurred over umbrae in spot groups with members of opposite polarity in close proximity, and the associated calcium plage has been in its second or later rotation.

This study is based on the reports of many investigators for which the needed references will be found in the body of the text.

ORA PROJECT 03942

JET INTERACTION

Final Report

November 1, 1955, to September 30, 1963

NOVEMBER 1, 1955, TO SEPTEMBER 30, 1963

INTRODUCTION

This report summarizes the work done under Contract NOrd-16595 during the period November 1, 1955 to September 30, 1963, with emphasis on the final quarterly period. Aerodynamic work under this contract consisted of two parts:

(1) Development of Menard inserts for increasing the Mach number of the flow in the OAL supersonic wind tunnel, and

(2) Investigation of the interaction between a side jet and a supersonic main stream.

That part of the work having to do with jet interaction is continuing under APL subcontract. Future progress of this work will be reported in the regular APL progress reports.

MENARD INSERTS

The Mach number of a supersonic wind tunnel can be increased somewhat by mounting appropriately-shaped inserts on the nozzle sidewalls in the throat region, as first reported by Menard. The University of Michigan work on Menard inserts was directed toward increasing the Mach number of the Ordnance Aerophysics Laboratory wind tunnel at Daingerfield, Texas. A pair of inserts was designed to raise the Mach number of the OAL Mach 1.5 nozzle to 1.6. Tests at OAL showed that these inserts performed quite well. However, subsequent efforts to design Menard inserts for higher Mach number nozzles were not as satisfactory.

Tests of short inserts designed for a 0.25 Mach number increase in The University of Michigan Mach 2.84 nozzle indicated unsatisfactory flow for aerodynamic test purposes. Long cylindrical inserts extending into the test section were found to give fairly uniform flow over part of the test rhombus, with a Mach number increase of 0.20.

JET INTERACTION

The jet interaction investigation consisted chiefly of force measurements on various configurations having jets issuing laterally into main air streams of Mach number 2.4 to 4.0. Some theoretical analysis was also performed.

The configurations tested were ogive-cylinders (with or without fins) and a flat-plate delta wing. For the body with fins or the flat plate, interaction of the jet with the main flow caused a doubling or tripling of the jet reaction force. On the other hand, for a body without fins the increase in force was smaller, and the helpful interaction force became still less if the jet were moved forward of the base. For a jet near the nose, large negative interaction forces were measured.

Preliminary tests have been made of the jet interaction effects on a finless body-of-revolution at angle of attack. Changes of about 30% in the incremental forces and moments due to the jet were observed in the angle of attack -12° to +12°. A separate report on this work is planned, after some additional confirmatory tests have been made.

In order to investigate the predicted larger interaction effects at hypersonic speeds, a Mach 8 extension to The University of Michigan high speed facilities was begun. It was decided to include in the design of this facility special features which would enable the boundary layer to remain laminar throughout the length of the nozzle, thereby providing a unique capability for tests under low-turbulence conditions. This increase in complexity and cost of the Mach 8 facility was elected with the expectation that the University would be able to pay for the additional cost of the laminar flow features. After most of the design work had been completed, however, it was found that University funds were unavailable. Additional funds are being sought from other sources for completion of the heater, nozzle, diffuser, and downstream piping. The present state of the Mach 8 nozzle design is described in the remainder of this report.

Calculations of the flow in the Mach number 8.0 nozzle are essentially complete. Preliminary calculations of laminar boundary layer development in the nozzle for an intermediate stagnation pressure have also been made. Results of these calculations are shown in Figures 1 through 5.

The inviscid flow calculations were begun by assuming an axial distribution of area ratio parameter as shown in Figure 1. (The area ratio parameter was used rather than Mach number because this permitted the use of the Friedrichs method to solve the transonic flow.) The particular area ratio parameter distribution chosen is the simplest distribution that has zero first and second derivatives at the beginning of the uniform flow region. The centerline Mach number distribution that results from this area ratio parameter distribution is also shown in Figure 1.

Two possible nozzle shapes that result from the centerline flow given in Figure 1 are presented in Figure 2. The short nozzle shown is the one favored for use in the present high speed tunnel system. The long nozzle is shown for comparison, as being more nearly typical of conventional hypersonic nozzles. The flow characteristics of these two nozzles are compared in Figures 3 through 5.

The short nozzle has an unusually large maximum flow deflection angle. From Figure 4 that angle is seen to be about 23°.7 for the short nozzle, compared with 11°.5 for the long nozzle. Conventional practice is to limit the maximum flow angle to about 12°, for fear that larger angles may lead to local separation. But boundary layer separation cannot occur unless the inviscid flow contains an adverse pressure gradient. Adverse pressure gradients are possible if the shape of the transonic portion of the nozzle is arbitrarily determined. In the present design method, however, the transonic contour is accurately calculated by the Friedrichs method.

The nozzle shapes shown in Figure 2 have favorable pressure gradients throughout their lengths, as indicated in Figure 3. Extrapolation of the flow calculations gives a limiting flow angle of about 26°, beyond which adverse pressure gradients would be found, for the prescribed axial flow. This compares with a theoretical limit of one-quarter of the Prandtl-Meyer expansion angle, or 23°.9, for source flow transformed to uniform parallel flow without adverse pressure gradients.

Laminar boundary layer growth on each of the nozzles of Figure 2 was calculated by the approximate method of Cohen and Reshotko. The resulting values of the displacement thickness were added to the inviscid contours to obtain the actual wall contours shown in Figure 2. In addition, the boundary layer Reynolds number based on momentum thickness Re_θ, was calculated (see Figure 5). The short nozzle has a much lower peak value of Re_θ than does the long nozzle, indicating a lesser likelihood of transition from a laminar to a turbulent boundary layer. The possibility of transition occurring at the throat is further decreased in the short nozzle by the very favorable pressure gradient.

BIBLIOGRAPHY

Menard Inserts

1. Amick, J. L. and Liepman, H. P.: Mach 3.0 Inserts for the OAL Mach 2.23 Nozzle. Univ. of Mich. WTM 224, Feb. 1955.

2. Amick, J. L.: Preliminary Tests of Menard Inserts Designed to Produce Mach 3.0 Flow in a 2.75 Nozzle. Univ. of Mich. WTM 253, Aug. 1955.

3. Amick, J. L. and Harrington, S. A.: Tests of Long Sidewall Bodies Designed to Produce M = 3.0 Flow in a 2.75 Nozzle. Univ. of Mich. WTM 257, Feb. 1957.

4. Amick, J. L., Harrington, S. A., and Liepman, H. P.: On Menard Inserts in Supersonic Nozzles. Bumblebee Report CF-2656, May 1957. (Also J. Aero Sci., 24, 707-708, Sept. 1957).

Jet Interaction

1. Hays, P. B.: Stability Tests on a Bleed Simulator at Mach 2.43. Univ. of Mich. WTM 264, May 1959. (Also in Q. Review of Bumblebee Activities, Vol. II, April-June, 1959.)

2. Liepman, H. P.: On the Use of Side Jets as Control Devices. ARS Journal, 29, 443, June 1959.

3. Liepman, H. P.: Interaction Effects of Side Jets With Supersonic Streams—Experimental Results and Wind Tunnel Techniques. Paper presented at joint meeting of AGARD Wind Tunnel Panel and the Supersonic Tunnel Association, Marseille, France, Sept. 1959.

4. Carvalho, G. F. and Hays, P. B.: Jet Interference Experiments Employing Body-Alone and Body-Fin Configurations at Supersonic Speeds. Bumblebee Report CM-979, Dec. 1960.

5. Carvalho, G. F.: Experimental Investigation of Jet-Simulated Flare Stability of an Ogive-Cylinder at Supersonic Speeds. Bumblebee Report CF-2949, Jan. 1962.

6. Amick, J. L. and Carvalho, G. F.: Interaction Effects of a Jet Flap on a 60° Delta Wing at Mach Number 4, and Comparison With Two-Dimensional Theory. Bumblebee Report CM-1031, Feb. 1963.

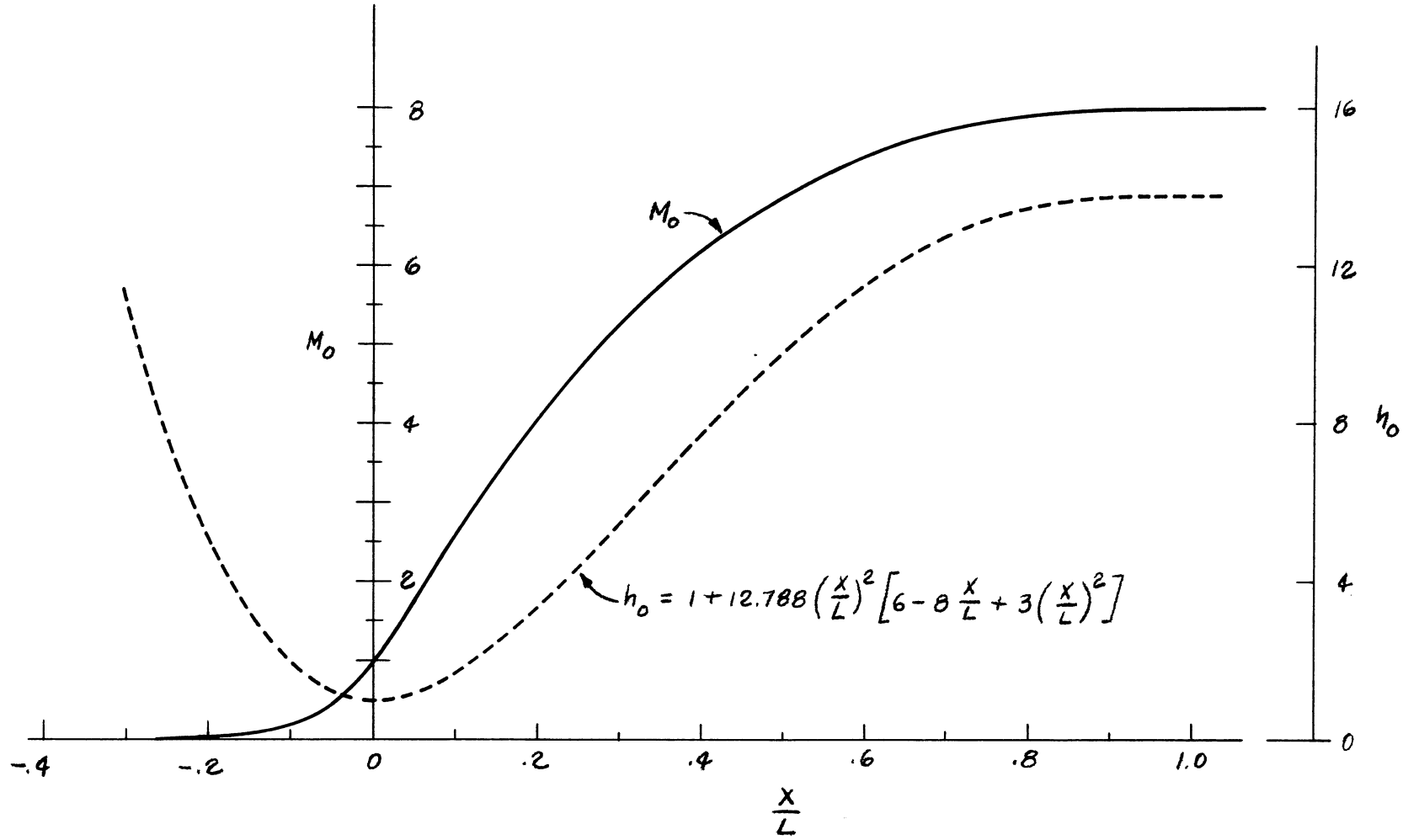

Fig. 1. Prescribed distribution of area ratio parameter, h_o ($\equiv \left[(M_o^2 + 5)^3/216M_o\right]^{\frac{1}{2}}$), along nozzle centerline, and resulting centerline distribution of Mach number, M_o.

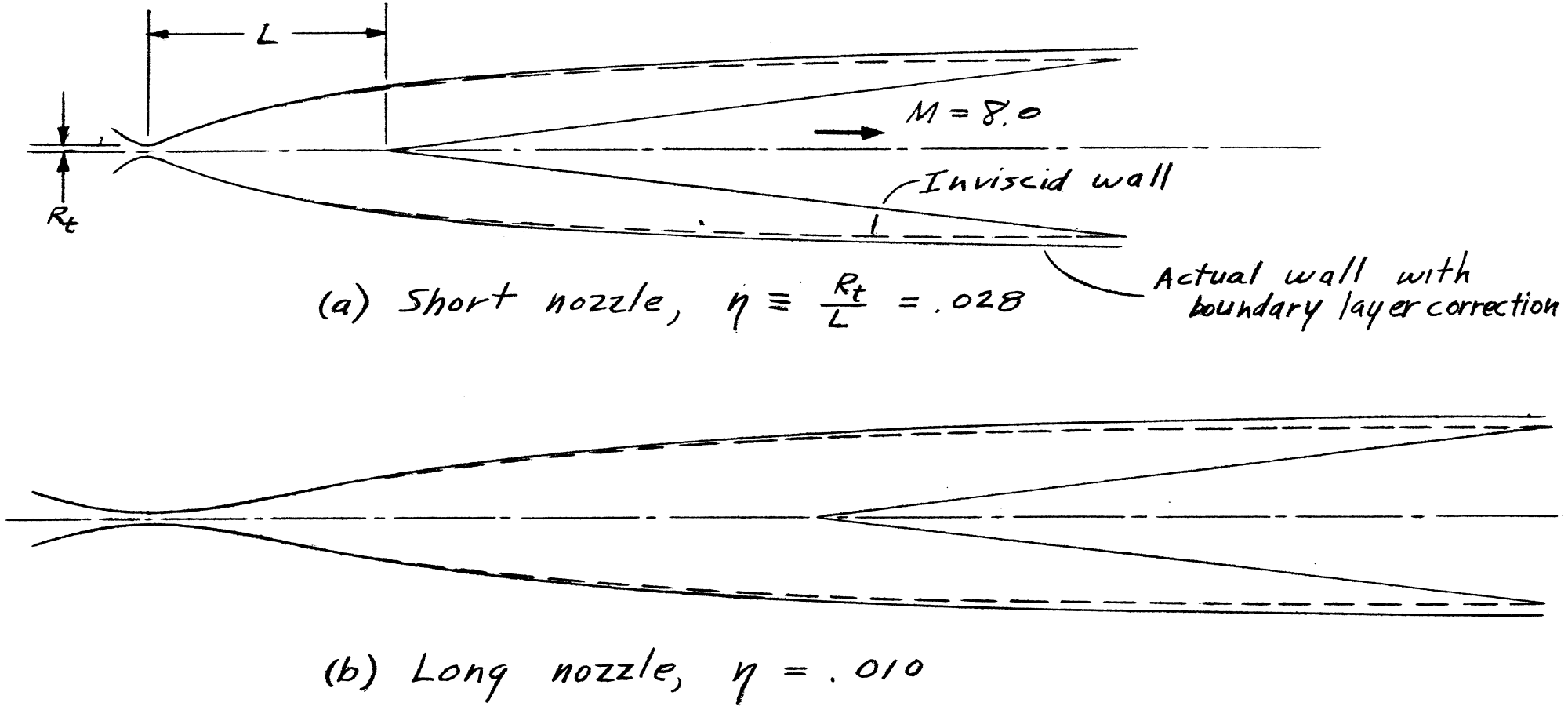

Fig. 2. Nozzle contours calculated from the distribution of Fig. 1, corrected for boundary layer by adding the calculated laminar displacement thickness to the inviscid wall coordinates. Stagnation pressure 400 psia, stagnation temperature 850°F, wall temperature 326°F, 3 inch inviscid exit radius. One-fifth size.

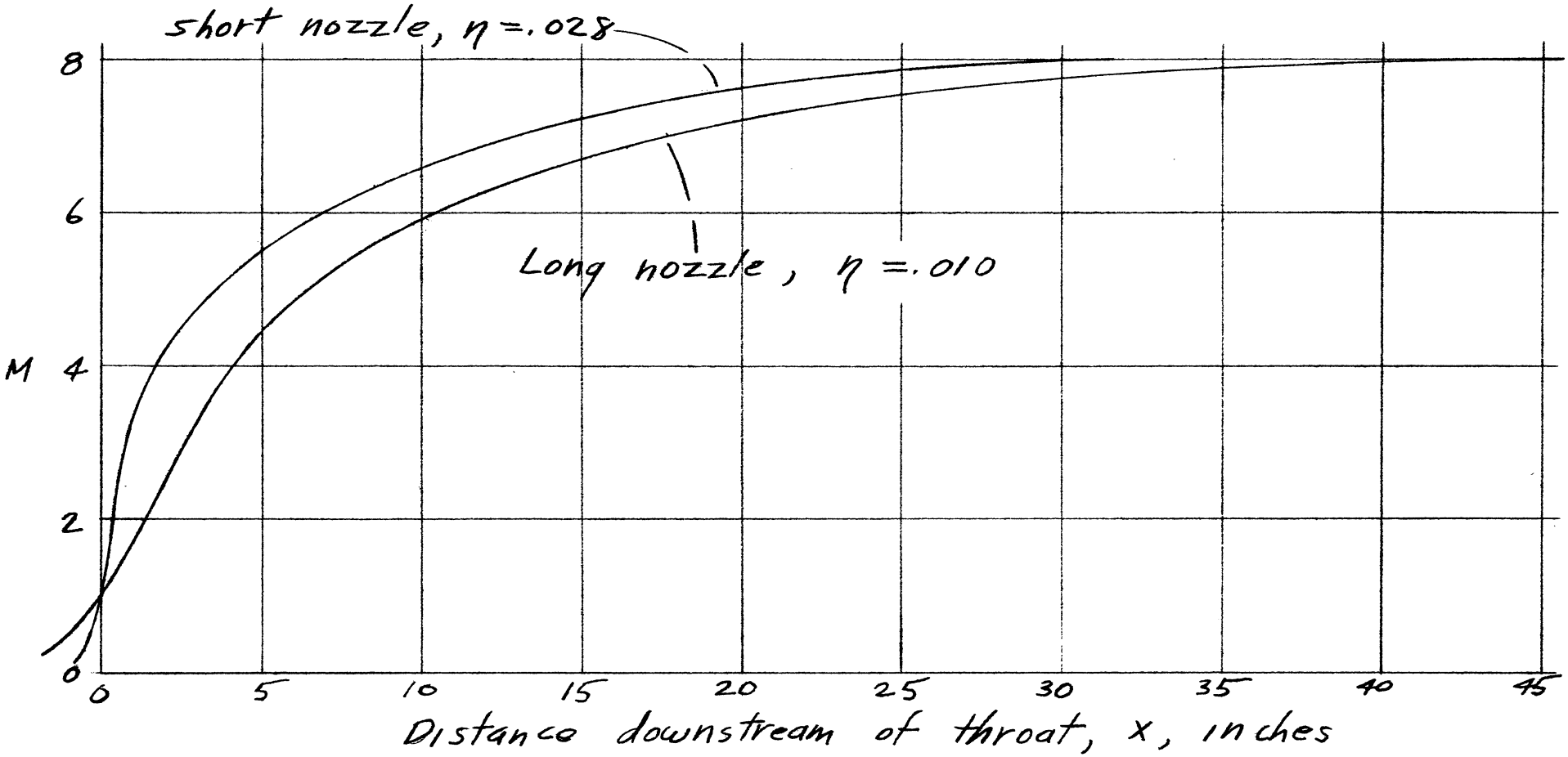

Fig. 3. Mach number distribution along the wall for each of the nozzles of Fig. 2.

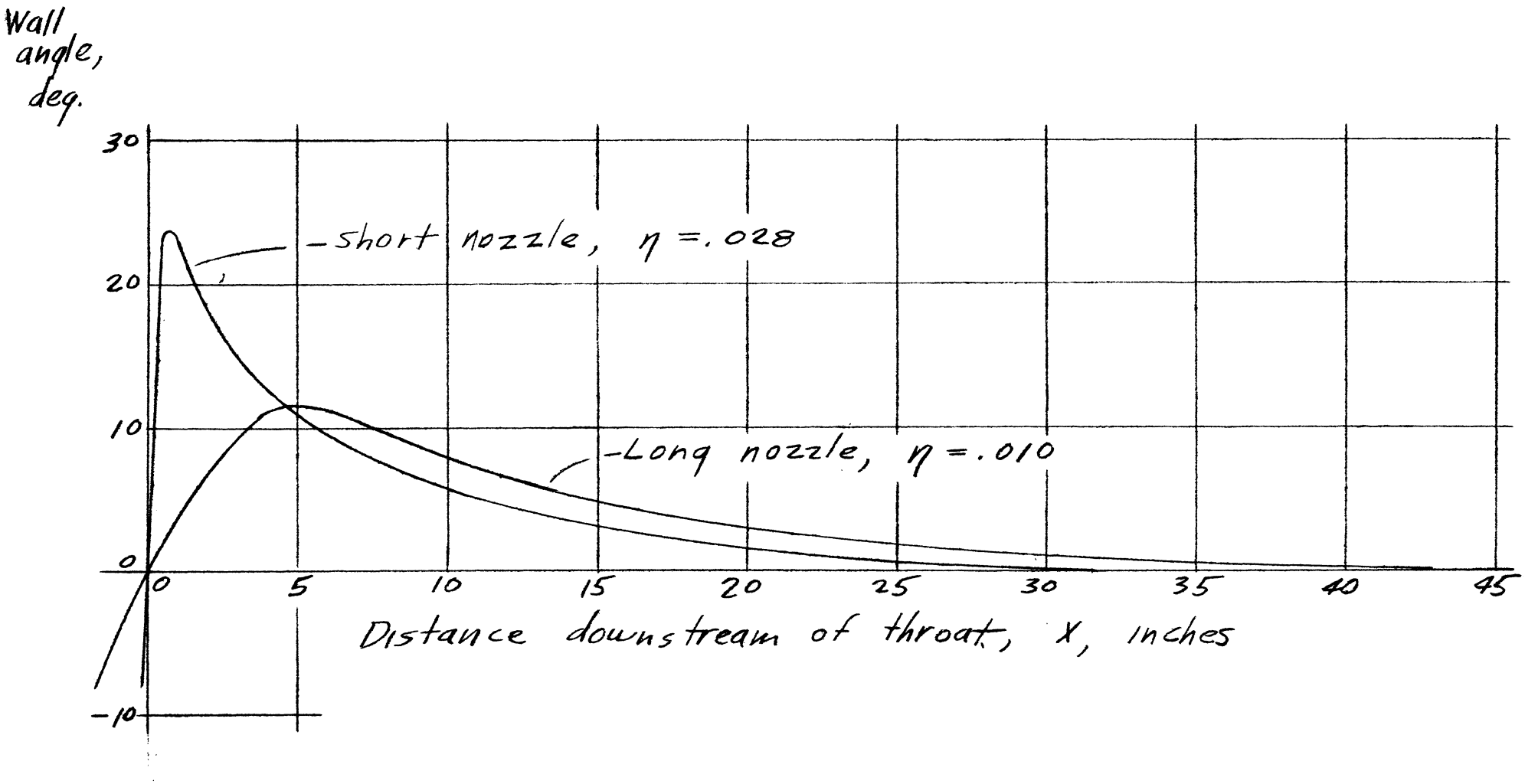

Fig. 4. Flow angle distribution along inviscid wall for each of the nozzles of Fig. 2.

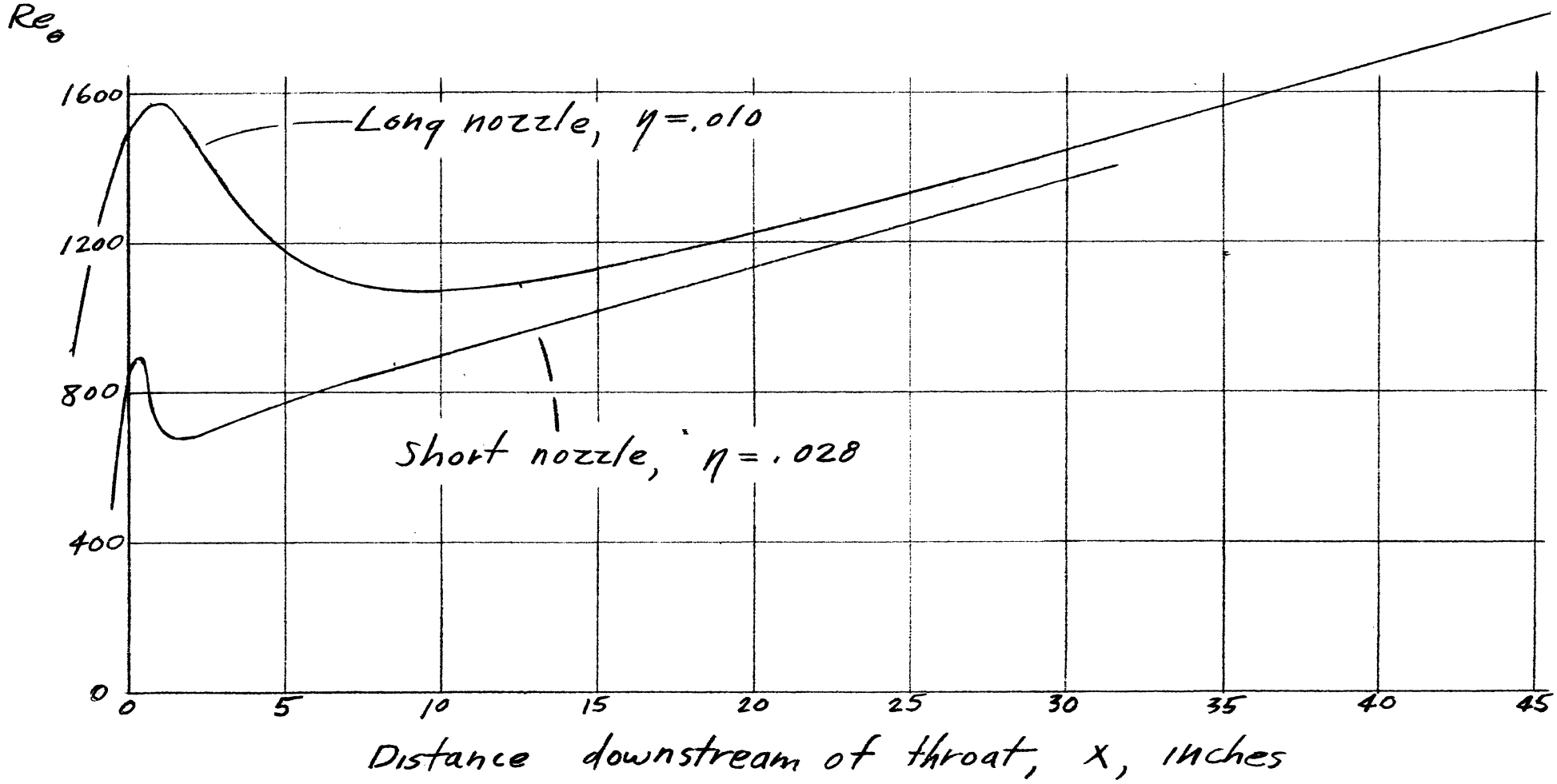

Fig. 5. Reynolds number based on boundary layer momentum thickness for each of the nozzles of Fig. 2.