

LEVEL II



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**HIGH SPEED FLOW SEPARATION  
AHEAD OF FINITE SPAN STEPS**

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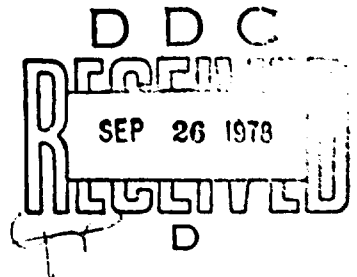
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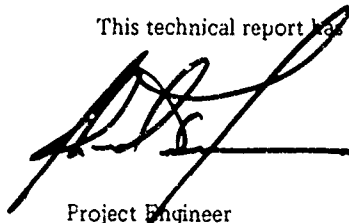
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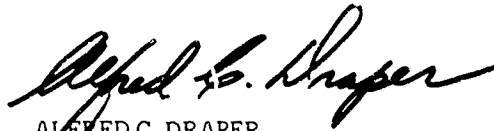
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19 KEY WORDS (Continue on reverse side if necessary, and identify by block number) Separation, Steps, Turbulent Boundary Layer, Supersonic, Hypersonic, Heat Transfer, Flat Plate		
20 ABSTRACT (Continue on reverse side if necessary, and identify by block number) Detailed surface heat transfer data, oil flow, and schlieren photographs are presented for high speed flow separation ahead of finite span, forward facing steps on flat plates. Step spans were varied from three to ten times as large as the step height, and the step heights are three to four times larger than the undisturbed turbulent boundary layer thickness. Reynolds numbers, based on plate length, were approximately 15 million for both Mach 4.75		

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and Mach 5.04 local undisturbed flows over the flat plate surface. For these test conditions, the maximum extent of separation ahead of the step is approximately 4.4 times as large as the step height independent of step span, and peak heating rates were measured that are more than six to eight times larger than the undisturbed flow heating rates. Peak heating on the plate surface occurs slightly upstream and approximately 1/2 step height inboard of the outboard sides of the steps, the increase in peak heat transfer coefficients over the undisturbed flow values decreases with increasing step span. In addition to presenting the detailed surface heat transfer data, a plausible theoretical analysis is presented for calculating the region of turbulent boundary layer separation ahead of these finite span steps.

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## FOREWORD

Results of the experimental and analytical investigation described herein were obtained under Air Force Task 240407 "Aeroperformance and Aeroheating Technology." The Project Monitor was Richard Neumann of the High Speed Aero Performance Branch (FXG), Aeromechanics Division, Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson Air Force Base, Ohio. Mr. Neumann conceived the research program and directed the work. The authors thank him for his guidance and help throughout the program.

The authors also wish to thank James R. Hayes (AFFDL/FXG) for his assistance in supplying details of the experimental apparatus used and for the data, which were obtained during an earlier portion of the program. The current work comprised reducing, analyzing, and presenting the experimental results. This later portion of the program was accomplished by AF Reserve Officers assigned to the Aeronautical Systems Division (ASD) of the Air Force Systems Command (AFSC) under ASD Reserve Project 75-105. LTC Kaufman is a Senior Staff Scientist for Grumman Aerospace Corporation, Bethpage, N.Y., and CAPT Kirchner is a Physical Science Instructor, Chesterfield County, Virginia Public School System. The authors express their gratitude to their fellow ASD Reserve Officers, Myron D. Goldman, MAJ, USAFR and Harold O. Jensen, CAPT, USAFR, for their engineering and drafting assistance in preparing this report.

## TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I INTRODUCTION .....	1
II EXPERIMENTAL APPARATUS, CONDITIONS, AND TEST PROCEDURE .....	2
1 Model .....	2
2 Wind Tunnel .....	3
3 Flow Conditions .....	3
4 Data and Test Procedure .....	5
III EXPERIMENTAL RESULTS .....	8
1 Flows Over Flat Plate Without Steps .....	8
2 $M_1 = 5.04$ Flows Over Flat Plate - Step Models .....	10
3 $M_1 = 4.75$ Flows Over Flat Plate - Step Models .....	11
4 Discussion of Experimental Results .....	12
IV ANALYTIC METHOD .....	14
1 Extent of Separation .....	14
2 Planform Shape of Separated Flow Region .....	16
V CONCLUSIONS .....	18
REFERENCES .....	60

## LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1	Planform and Profile Sketches of Model with Step in Furthest Aft Location ..... 19
2	Coordinate System ..... 20
3	Front View Photograph of Model Mounted on Injection System in Cabin Beneath Tunnel Test Section ..... 21
4	Schlieren Photographs of Flows Over Flat Plate Surface with No Step ..... 22
5	Heat Transfer Coefficient Distributions on Flat Plate Surface with No Step for $M_1 = 5.04$ ( $\alpha = -6.8^\circ$ ) ..... 23
6	Heat Transfer Coefficient Distributions on Flat Plate Surface with No Step for $M_1 = 4.75$ ( $\alpha = -9.0^\circ$ ) ..... 24
7	Distribution of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Flat Plate Surface for $M_1 = 5.04$ , No Step Attached to Surface ..... 25
8	Distribution of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Flat Plate Surface for $M_1 = 4.75$ , No Step Attached to Surface ..... 26
9	Profile Schlieren Photograph of $M_1 = 5.04$ Flow Ahead of 3-Inch Span Step ..... 27
10	Streamwise Distributions of Heat Transfer Coeffi- cient Ratios ( $h/h_{und}$ ) on Plate Surface for $M_1 = 5.04$ Flow Ahead of 3-Inch Span Step .. ..... 27
11	Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 3-Inch Span Step for $M_1 = 5.04$ ..... 28
12	Distribution of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Surface Ahead of 3-Inch Span Step for $M_1 = 5.04$ ..... 29

LIST OF ILLUSTRATIONS (cont'd)

<u>Figure</u>	<u>Page</u>
13 Lines of Constant ( $h/h_{und}$ ) Contours on Surface Ahead of 3-Inch Span Step for $M_1 = 5.04$ .....	30
14 Profile Schlieren Photograph of $M_1 = 5.04$ Flow Ahead of 5-Inch Span Step .....	31
15 Streamwise Distributions of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Plate Surface for $M_1 = 5.04$ Flow Ahead of 5-Inch Span Step .....	31
16 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 5-Inch Span Step for $M_1 = 5.04$ .....	32
17 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 5-Inch Span Step for $M_1 = 5.04$ .....	33
18 Lines of Constant ( $h/h_{und}$ ) Contours on Surface Ahead of 5-Inch Span Step for $M_1 = 5.04$ .....	34
19 Profile Schlieren Photograph of $M_1 = 5.04$ Flow Ahead of 7-Inch Span Step .....	35
20 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for $M_1 = 5.04$ Flow Ahead of 7-Inch Span Step .....	35
21 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 7-Inch Span Step for $M_1 = 5.04$ .....	36
22 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 7-Inch Span Step for $M_1 = 5.04$ .....	37
23 Lines of Constant ( $h/h_{und}$ ) Contours on Surface Ahead of 7-Inch Span Step for $M_1 = 5.04$ .....	38
24 Profile Schlieren Photograph of $M_1 = 5.04$ Flow Ahead of 10-Inch Span Step .....	39
25 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for $M_1 = 5.04$ Flow Ahead of 10-Inch Span Step .....	39



LIST OF ILLUSTRATIONS (cont'd)

<u>Figure</u>	<u>Page</u>
26 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 10-Inch Span Step for $M_1 = 5.04$ .....	40
27 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 10-Inch Span Step for $M_1 = 5.04$ .....	41
28 Lines of Constant $(h/h_{und})$ Contours on Surface Ahead of 10-Inch Span Step for $M_1 = 5.04$ .....	42
29 Profile Schlieren Photograph of $M_1 = 4.75$ Flow Ahead of 3-Inch Span Step .....	43
30 Streamwise Distributions of Heat Transfer Coefficient Ratios $(h/h_{und})$ on Plate Surface for $M_1 = 4.75$ Flow Ahead of 3-Inch Span Step .....	43
31 Distribution of Heat Transfer Coefficient Ratios $(h/h_{und})$ on Surface Ahead of 3-Inch Span Step for $M_1 = 4.75$ .....	44
32 Lines of Constant $(h/h_{und})$ Contours on Surface Ahead of 3-Inch Span Step for $M_1 = 4.75$ .....	45
33 Profile Schlieren Photograph of $M_1 = 4.75$ Flow Ahead of 5-Inch Span Step .....	46
34 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for $M_1 = 4.75$ Flow Ahead of 5-Inch Span Step .....	46
35 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 5-Inch Span Step for $M_1 = 4.75$ .....	47
36 Lines of Constant $(h/h_{und})$ Contours on Surface Ahead of 5-Inch Span Step for $M_1 = 4.75$ .....	48
37 Profile Schlieren Photograph of $M_1 = 4.75$ Flow Ahead of 7-Inch Span Step .....	49
38 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for $M_1 = 4.75$ Flow Ahead of 7-Inch Span Step .....	49

LIST OF ILLUSTRATIONS (cont'd)

<u>Figure</u>	<u>Page</u>
39 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 7-Inch Span Step for $M_1 = 4.75$ .....	50
40 Lines of Constant $(h/h_{und})$ Contours on Surface Ahead of 7-Inch Span Step for $M_1 = 4.75$ .....	51
41 Profile Schlieren Photograph of $M_1 = 4.75$ Flow Ahead of 10-Inch Span Step .....	52
42 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for $M_1 = 4.75$ Flow Ahead of 10-Inch Span Step .....	52
43 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 10-Inch Span Step for $M_1 = 4.75$ .....	53
44 Distribution of Heat Transfer Coefficient Ratios $(h/h_{und})$ on Surface Ahead of 10-Inch Span Step for $M_1 = 4.75$ .....	54
45 Lines of Constant $(h/h_{und})$ Contours on Surface Ahead of 10-Inch Span Step for $M_1 = 4.75$ .....	55
46 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 3-Inch Span Step for $M_1 = 5.04$ .....	56
47 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 5-Inch Span Step for $M_1 = 5.04$ .....	57
48 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 7-Inch Span Step for $M_1 = 5.04$ .....	58
49 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 10-Inch Span Step for $M_1 = 5.04$ .....	59

## LIST OF SYMBOLS

$b$	step span
$c$	specific heat of model wall material
$h$	aerodynamic heat transfer coefficient
$\ell$	extent of separated flow region upstream of step face
$m$	source strength
$M$	Mach number
$p$	pressure
$\dot{q}$	aerodynamic heat transfer rate
$Re$	Reynolds number
$t$	time
$T$	temperature
$U$	stream flow velocity
$w$	density of model wall material
$x, y, z$	orthogonal coordinate system with origin at step face (see Fig. 2)
$\alpha$	angle of attack of flat plate surface
$\gamma$	ratio of specific heats of air (taken as 1.4 herein)
$\delta$	boundary layer thickness
$\epsilon$	flow deflection angle at separation
$\tau$	shock wave angle
$\xi$	dummy variable of integration, Eq. (11)

LIST OF SYMBOLS (cont'd)

$\tau$  thickness of wall at thermocouple location  
 $\psi$  stream function

Subscripts

o stagnation conditions  
l flow conditions over flat plate surface  
 $\infty$  tunnel free stream flow conditions  
awT adiabatic wall conditions for turbulent boundary layer  
sep conditions at the location of flow separation  
und local undisturbed flow conditions (values on the flat plate surface when no step is attached)  
w wall conditions

SECTION I  
INTRODUCTION

Flow separation can substantially alter the anticipated loads and heating rates on high speed aircraft surfaces, and can compromise an aircraft design. The importance of this problem is well recognized and has prompted many investigations of shock-induced separated flows (e.g., Refs. 1-40). Although important to practical aircraft design, three dimensional separated flow problems are quite complex and are not amenable to theoretical solutions at present. The subject work was undertaken to obtain a better understanding of some important three dimensional flow effects for a relatively basic geometry: flow separation ahead of finite span, forward facing steps.

The character of the boundary layer and the ratio of the step height to the undisturbed boundary layer thickness strongly affect the extent of flow separation ahead of steps. These effects have been investigated for high aspect ratio, essentially "two dimensional" steps (Refs. 6, 17, 35, 36, and 38). The subject work complements these existing separated flow investigations and includes finite span effects.

Steps of various spans were mounted on an existing large flat plate model. Flow conditions, step height, model size, and attitude were chosen to ensure turbulent boundary layer flow on the flat plate surface prior to the onset of separation. All steps had the same height, which was chosen to be several times larger than the undisturbed boundary layer thickness. Dense arrays of surface aerodynamic heat transfer rate data were obtained, as well as planform oil film flow and profile schlieren photographs. The data were analyzed, compared with some analytical results, and are presented herein.

## SECTION II

### EXPERIMENTAL APPARATUS, FLOW CONDITIONS, AND TEST PROCEDURE

#### 1 Model

Planform and profile views of the flat plate forward facing step model are sketched in Figure 1. An existing FD-1 flat plate model, which had been used in an earlier experimental program (Ref. 23), was modified for the present experiments. The flat plate portion of the model has a 24-inch span and a 26.5-inch chord. The face of the model forms an angle of  $30.5^\circ$  with the flat plate surface, and the leading edge is ground sharp.

A 10-inch square portion of the flat plate surface, centered mid-span and terminating at the plate trailing edge, is instrumented with thermocouples. Thermocouples are spot welded to the inner surface of thin wall portions of the insert to enable one to obtain aerodynamic heating rates using the thin wall transient temperature technique (Ref. 23). The thermocouples are spaced at 0.50-inch intervals along three chordwise lines, and at 0.25-inch intervals along two chordwise lines. The five chordwise lines are two inches apart.

Forward facing steps of 3-, 5-, 7-, and 10-inch spans were fabricated. The steps have 2-inch chords, heights of 1-inch, and are attachable at different locations near the trailing edge of the flat plate surface. The steps can be shifted forward 0.125-inch from the furthest aft location, and can be shifted spanwise in 0.5-inch intervals. Shifting the step location between tunnel runs permits obtaining thermocouple data at 0.125-inch intervals along chordwise lines 0.5-inch apart. The steps are sealed and insulated from the flat plate surface by a layer of teflon. A step oriented coordinate system

is shown in Figure 2. The origin is centered at the step mid-span where the forward face of the step meets the flat plate surface.

## 2 Wind Tunnel

The subject experiments were conducted in the von Karman Facility Tunnel B at Arnold Engineering Development Center (AEDC). This is a continuous flow, closed-circuit, variable density wind tunnel. It has replaceable, axisymmetric, contoured nozzles to provide either nominally Mach 6 or Mach 8 free stream flows in the 50-inch diameter test section (Ref. 41). A model injection system is located in a cabin directly beneath the test section; the model may be injected into the tunnel flow and then ejected without interrupting the tunnel flow. A front view photograph of the model mounted on the injection system in the cabin beneath the test section is shown in Figure 3. In this photograph, the 10-inch span forward facing step is attached to the model.

## 3 Flow Conditions

In order to provide data for turbulent boundary layer separation, tunnel stagnation pressure ( $p_o$ ) and temperature ( $T_o$ ) values were chosen that result in a relatively high unit Reynolds number ( $Re_x/ft$ ) in the nominal Mach 6 free stream flow. However, when the plate was aligned with the free stream flow, a turbulent boundary layer was not fully developed on the plate surface until further downstream than desired. Therefore, the model was pitched nose downward (flat plate surface in compression), in order to increase the local flow unit Reynolds number and cause boundary layer transition to occur further forward. Two angles of attack were chosen:  $\alpha = -6.8^\circ$  and  $\alpha = -9.0^\circ$ .

The local Mach numbers ( $M_1$ ) of the resulting flows over the flat plate surface were:  $M_1 = 5.04$  and  $M_1 = 4.75$ .

Tunnel flow stagnation conditions, free stream flow static conditions, and local flow conditions over the flat plate surface are listed in Table I. Free stream conditions are denoted by subscript  $\infty$ , local flow conditions over the pitched flat plate surface are indicated by subscript 1. The adiabatic wall temperature for turbulent boundary layer flow over the flat plate surface ( $T_{awT}$ ) is computed using a turbulent recovery factor of 0.89

$$\frac{T_{awT}}{T_o} = \frac{1 + 0.178 M^2}{1 + 0.2 M^2} \quad (1)$$

TABLE I FLOW CONDITIONS

		$\alpha$ (deg)	-6.8	-9.0
$p_o$ (psia)	284	$p_{o1}$ (psia)	262	241
$T_o$ ( $^{\circ}$ R)	850	$T_{o1}$ ( $^{\circ}$ R)	850	850
$M_{\infty}$	5.95	$M_1$	5.04	4.75
$Re_{\infty}/10^6$ ft	5.33	$Re_{a1}/10^6$ ft	7.37	7.78
$p_{\infty}$ (psia)	0.189	$p_1$ (psia)	0.473	0.613
$T_{\infty}$ ( $^{\circ}$ R)	105	$T_1$ ( $^{\circ}$ R)	140	154
$T_{awT}$ ( $^{\circ}$ R)	768	$T_{awT}$ ( $^{\circ}$ R)	772	773



#### 4 Data and Test Procedure

Data were obtained on five basic model configurations (flat plate alone or with any one of four forward facing steps of different spans), at two model angles of attack ( $-6.8^\circ$  and  $-9.0^\circ$ ). Aerodynamic heating rate distributions on the flat plate surface and profile schlieren flow photographs were obtained for all configurations at both angles of attack. As indicated in Table II, planform oil film flow motion pictures were obtained when the steps were attached to the flat plate model at  $\alpha = -6.8^\circ$  ( $M_1 = 5.04$ ), and when the 10-inch span step was attached to the flat plate model at  $\alpha = -9.0^\circ$  ( $M_1 = 4.75$ ). Several tunnel runs were duplicated to ascertain the repeatability of the data.

TABLE 2 DATA

$M_1$	Step Span (Inches)				
	0	3	5	7	10
5.04	h sch	h oil sch	h oil sch	h oil sch	h oil sch
4.75	h sch	h sch	h sch	h sch	h oil sch
h: heat transfer coefficient distribution oil: oil film flow motion pictures sch: schlieren flow photographs					

Aerodynamic heat transfer rates,  $\dot{q}$ , are proportional to the rate at which the surface temperature rises on a thin wall model (Refs. 9, 16, and 23)

$$\dot{q} = wtc(dT_w/dt) \quad (2)$$

where  $w$  is the density of the model wall material,  $\delta$  is the thickness of the wall at the thermocouple location,  $c$  is the specific heat of the model wall material,  $T_w$  is the surface wall temperature, and  $t$  is time. The aerodynamic heat transfer coefficient used herein is

$$h = \dot{q} / (T_{awT} - T_w) \quad (3)$$

To obtain the heating rates, the model is cooled to essentially room temperature (approximately 535°R) and then quickly injected into the tunnel flow. Temperatures measured by each thermocouple are recorded at the rate of 20/sec for several seconds. The model is then ejected from the tunnel flow. Linear portions of curve fits to the temperature time histories are used to calculate the values of  $(dT_w/dt)$ . Errors due to conduction, radiation, and nonuniform flow heating are minimized by using the linear portions of the temperature-time curves; the errors are negligible for the subject experiments (Refs. 9, 16, and 23).

Dense aerodynamic heating rate distributions were obtained by shifting the step location from run to run and injecting the model again into the same tunnel flow. Thus, up to eight runs were used to record temperature data for one step configuration. This effectively increases the thermocouple location density eightfold. Profile schlieren flow photographs were taken while the temperature data were being measured and recorded.

Additional tunnel runs were required to obtain planform oil film flow motion pictures. The flat plate surface was coated

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Full injection from cabin to tunnel centerline takes approximately two seconds. The model passes through the tunnel wall free shear layer and experiences nonuniform flow heating for less than one second.

with a mixture of titanium dioxide and silicone oil and the model injected into the tunnel flow. High resolution motion pictures of the surface oil film flow were obtained using 70 mm film and a framing rate of 10/sec.

## SECTION III

### EXPERIMENTAL RESULTS

Data are presented first for flows over the flat plate model with no step attached. Streamwise distributions of the aerodynamic heat transfer coefficients on the flat plate surface at  $\alpha = -6.8^\circ$  ( $M_1 = 5.04$ ) and at  $\alpha = -9.0^\circ$  ( $M_1 = 4.75$ ), referred to as  $h_{\text{und}}(x)$ , are used to nondimensionalize the heat transfer coefficients measured on the plate surface when various span steps are attached to the model.

#### 1 Flows Over Flat Plate Without Steps

The coordinate system origin, when there is no step, is taken along the flat plate surface centerline, 23.75 inches downstream of the plate leading edge (cf, Figures 1 and 2). Boundary layer thicknesses at  $x = 0$ , scaled from profile schlieren photographs (Figure 4), are approximately: 0.29-inch for  $\alpha = -6.8^\circ$  and 0.27-inch for  $\alpha = -9.0^\circ$ . These values agree closely with those calculated using the Anderson and Lewis (Ref. 42) method. (The local flow running length Reynolds numbers at  $x = 0$  are approximately 14.6 million for  $\alpha = -6.8^\circ$  and 15.4 million for  $\alpha = -9.0^\circ$ .)

Aerodynamic heat transfer coefficients for the flows over the flat plate surface with no step attached are indicated in Figures 5 and 6 for  $M_1 = 5.04$  and 4.75. Measured heat transfer coefficient values are indicated by symbols along the five streamwise lines of thermocouples for both angles of attack (Figures 5 and 6). The measured heating rates agree fairly well with those calculated using the Anderson and Lewis method (Ref. 42), and exhibit no consistent anomaly. The solid lines

that pass through the data points in Figures 5 and 6 were taken to be representative of the heat transfer rate coefficient distributions for the local flat plate flows undisturbed by steps. These  $h_{und}(x)$  distributions were used to nondimensionalize the heat transfer rate coefficient distributions measured at all spanwise stations. The distributions are given by

$$h_{und} = (4.45 - 0.415 x)10^{-3} \quad \text{for } M_1 = 5.04$$

and by

$$h_{und} = (5.40 - 0.0508 x)10^{-3} \quad \text{for } M_1 = 4.75$$

(4)

Nondimensionalizing the data in coefficient form, and using consistent values for the local undisturbed flow heat transfer coefficient distributions, avoids compounding errors caused by minor variations in thermocouple readings or tunnel flow conditions from run to run.

Heat transfer coefficients for the undisturbed local  $M_1 = 5.04$  flow over the flat plate surface, nondimensionalized by values calculated using Eq. (4), are indicated in the "carpet" plot shown in Figure 7. In this figure, the ratio of the heat transfer coefficients is plotted at the corresponding thermocouple locations on the flat plate. The repeatability of the heat transfer coefficient ratios, ascertained by comparing values from repeat tunnel runs, is approximately 3 percent (standard deviation = 2.5 percent). A similar plot of heat transfer rate coefficient ratios, for the  $M_1 = 4.75$  local undisturbed flow over the flat plate surface, is shown in Figure 8.

## 2 $M_1 = 5.04$ Flows Over Flat Plate - Step Models

Photographic and heat transfer rate data were obtained for  $M_1 = 5.04$  ( $\theta = -6.8^\circ$ ) for steps having spans of 3, 5, 7, and 10-inches. A profile schlieren flow photograph for the 3-inch span step is shown in Figure 9. Streamwise distributions of heating rate coefficients on the flat plate surface ahead of the 3-inch step, nondimensionalized using the undisturbed flow heating rate coefficient distribution [Eq. (4)], are plotted in Figure 10 on the same page. Curves are faired through data obtained along the centerline and along lines 1-inch outboard (on either side) of the centerline. The highest heating occurs along the outboard lines, approximately 0.2-inch upstream of the step face.

A frame from the planform oil film flow motion picture shows an oil accumulation line ahead of the 3-inch step indicative of flow separation (Figure 11). This line is superimposed on the carpet plot of the measured heat transfer coefficient ratios shown in Figure 12. The oil accumulation line passes through the region where there is an initial rise in the heat transfer coefficient ratios. Contours of constant values of  $(h/h_{und})$  are drawn in Figure 13. Alternate contours are dashed simply as an aid in distinguishing them. The highest heat transfer coefficient ratio contour ( $(h/h_{und} = 8)$ ), occurs just upstream of the step face between 0.5 and 1.0-inch outboard from the step centerline.

Profile schlieren photograph and streamwise distributions of heat transfer coefficient ratios ahead of the 5-inch span step are shown on the same page in Figures 14 and 15. The oil film flow photograph, carpet plots of heat transfer coefficient ratios,

and contours of constant  $(h/h_{und})$  values are shown in Figures 16-18. Similar data for the 7-inch span step are shown in Figures 19-23. Data for the 10-inch span steps are given in Figures 24-28. In all cases, measured peak heating rates occur approximately 0.2-inch ahead of the step face and approximately 0.5-inch inboard of the outboard edge of the step.

### 3 $M_1 = 4.75$ Flows Over Flat Plate - Step Models

A profile schlieren photograph for  $M_1 = 4.75$  flow ( $\alpha = -9.0^\circ$ ) over the flat plate with a 3-inch span step is shown in Figure 29. Streamwise heat transfer coefficient ratios on the plate surface ahead of the 3-inch span step are plotted in Figure 30 on the same page. Carpet plots of the heat transfer coefficient ratios and contours of constant values of  $(h/h_{und})$  are shown in Figures 31 and 32. Similar data for the 5- and 7-inch span steps are presented in Figures 33-40. Planform oil film flow photographs were not obtained for these configurations (cf. Table II).

A profile schlieren photograph and streamwise distributions of heat transfer coefficient ratios for the 10-inch span step on the flat plate at  $\alpha = -9.0^\circ$  are shown in Figures 41 and 42. A planform oil film flow photograph for this configuration is shown in Figure 43. The oil accumulation line apparent in Figure 43 is superimposed on the carpet plot of the heat transfer coefficient ratios given in Figure 44. Lines of constant  $(h/h_{und})$  contours are shown in Figure 45. Similarly to the model configurations pitched at  $\alpha = -6.8^\circ$ , the highest heating rates on the plate surface pitched at  $\alpha = -9.0^\circ$  occur approximately 0.2 inch upstream of the step face and 0.5-inch inboard of the outboard edge of the step.

As noted earlier, heat transfer data were obtained during several repeat tunnel runs. For the 10-inch step on the flat plate at  $\alpha = -9.0^\circ$ , the average deviation in the heat transfer coefficient ratio value is 0.025, the standard deviation is 0.037.

#### 4 Discussion of Experimental Results

The apparent boundary layer thickness immediately upstream of flow separation  $\delta_{sep}$ , and the apparent length of separated flow upstream of the step face,  $l_{sep}$ , scaled from the profile schlieren flow photographs, are listed in Table III. For these experiments, the boundary layer thickness and maximum extent of separation are independent of the step span. The apparent boundary layer thickness just upstream of separation is slightly less for  $\alpha = -9.0$  than for  $\alpha = -6.8^\circ$ . The extent of separation, apparent in the profile schlieren flow photographs, is approximately the same for both angles of attack. The separation lengths listed in the table match closely the distances from the step faces to the oil accumulation lines scaled from the planform oil film flow photographs. Apparent in the planform oil film flow photographs, and indicated in the heat transfer coefficient ratio carpet plots, the streamwise extent of separation generally

TABLE 3 APPARENT BOUNDARY LAYER THICKNESS AT SEPARATION AND EXTENT OF SEPARATED FLOW REGION

$M_1$	$\delta_{sep}$ (in.)	$l_{sep}$ (in.)
5.04	0.26	$4.35 \pm 0.15$
4.75	0.24	$4.35 \pm 0.15$



is greatest near the centerline and diminishes outboard. The streamwise thickness of the oil accumulation line is comparable to or smaller than the local boundary layer thickness.

For all test cases, the highest heating on the plate occurs approximately 0.2-inch forward of the step face and 0.5-inch inboard from the outboard edge of the step. The peak heat transfer coefficient ratio values are largest for the smallest step spans, and decrease monotonically with increasing step span for both angles of attack. The peak heat transfer coefficients exceed 6 to 8 times those for the local undisturbed flows, depending on step span. Average values of the heat transfer coefficients in the separated flow region are approximately 2.5 times as large as those for the undisturbed flows over the flat plate surfaces.

SECTION IV  
ANALYTIC METHOD

An analytic method was devised for calculating the extent and shape of the separated flow region upstream of finite span steps. The method gives results in good agreement with the subject data but, because of several assumptions, must be considered empirical until better rationale are developed for the derivation of the method. Its application to different flow conditions is not warranted until more extensive empirical verification is provided or until a rational proof of the validity of the derivation of the method is established.

The method for estimating the extent of separation is based on the observation that the difference between the shock wave angle and the effective flow deflection angle at the onset of separation is a minimum when turbulent boundary layer separation occurs ahead of a forward facing step. The shape of the separation line on the plate surface follows from the assumption that hypersonic, turbulent boundary layer separation is driven by flow conditions in the outer, inviscid flow and that the subsonic separated flow region can be approximated by a linear source distribution with its strength dependent upon the extent of separation along the centerline.

1 Extent of Separation

The extent of separation along the centerline ahead of a forward facing step depends on the step height and the effective angle of the streamline dividing the separated flow from the outer, inviscid flow. The oblique shock wave,  $\theta$ , and inviscid flow deflection angle,  $\epsilon$ , are related by (Refs. 43 and 44)

$$\tan(\psi - \epsilon) = \frac{(\gamma-1)M_1^2 \sin^2 \epsilon + 2}{(\gamma+1)M_1^2 \sin^2 \epsilon} \tan \psi \quad (5)$$

Rewriting the equation as

$$\tan(\psi - \epsilon) = \frac{\gamma-1}{\gamma+1} \tan \psi + \frac{4}{(\gamma+1)M_1^2 \sin^2 2\epsilon} \quad (6)$$

and setting the partial derivative of  $\tan(\psi - \epsilon)$  with respect to  $\epsilon$  equal to zero yields

$$\frac{\gamma-1}{8} M_1^2 = \frac{\cos^2 \psi \cos 2\epsilon}{\sin^2 2\epsilon} \quad (7)$$

which may be simplified for computational purposes to

$$\frac{\gamma-1}{2} M_1^2 = \frac{1 - 2 \sin^2 \epsilon}{\sin^2 \epsilon} \quad (8)$$

For the subject experiments, flow separation occurs where  $[\tan(\psi - \epsilon)]$  is a minimum. Equation (8) may be used to relate the upstream Mach number and shock wave angle at the onset of turbulent boundary layer separation ahead of the steps tested in this program. (In these experiments the step height is larger than the boundary layer thickness, but not so large that a strong detached shock wave forms ahead of the step.)

Once  $\theta$  is determined for  $M_1$ , the flow deflection angle ( $\epsilon$ ) can be determined using other oblique shock relations, such as (Refs. 43 and 44)

$$\tan \epsilon = 2 \frac{M_1^2 \sin^2 \theta - 1}{M_1^2 (\gamma + \cos 2\theta) + 2} \cot \theta \quad (9)$$

Assuming that the dividing streamline for the separated flow re-attaches essentially at the top of the forward face of the step

$$l_{\text{sep}} = \frac{h}{\tan \epsilon}$$

therefore

$$l_{\text{sep}} = \frac{M_1^2 (\gamma + \cos 2\epsilon) + 2}{2(M_1^2 \sin^2 \epsilon - 1)} h \tan \epsilon \quad (10)$$

Equations (8) and (10) may be used to calculate the extent of separation,  $l_{\text{sep}}$ , upstream of forward facing steps.

## 2 Planform Shape of Separated Flow Region

The region of separated flow ahead of finite span steps on a plate surface is calculated assuming that a line source distribution exists along the step, perpendicular to the flow. The line source distribution is expressed by the relationship

$$\zeta = \frac{m}{2\pi b} \int_{-b/2}^{b/2} \tan^{-1} \left( \frac{y - \xi}{x} \right) d\xi \quad (11)$$

where  $b$  is the step span and  $m$  is the source strength. Integrating this expression and superimposing it upon a uniform free stream function gives

$$\psi = U_1 y + \frac{m}{2\pi b} \left\{ \left( y + \frac{b}{2} \right) \tan^{-1} \left( \frac{y + \frac{b}{2}}{x} \right) - \left( y - \frac{b}{2} \right) \tan^{-1} \left( \frac{y - \frac{b}{2}}{x} \right) + \frac{x}{2} \ln \left[ \frac{x^2 + \left( y - \frac{b}{2} \right)^2}{x^2 + \left( y + \frac{b}{2} \right)^2} \right] \right\} \quad (12)$$

The strength of the source ( $m$ ), established from boundary conditions, is a function of the separation length  $l_{sep}$  [given by Eq. (10)]

$$m = \pi b U_1 \left[ \tan^{-1} \left( \frac{b/2}{l_{sep}} \right) \right]^{-1} \quad (13)$$

Using zero as the constant value of the stream function  $\psi$  along the separation line and the value for the source strength given by Eq. (13), the separation line shape can be calculated from

$$0 = 2 y \tan^{-1} \left( \frac{b/2}{l_{sep}} \right) + \left( y + \frac{b}{2} \right) \tan^{-1} \left( \frac{y + \frac{b}{2}}{x} \right) - \left( y - \frac{b}{2} \right) \tan^{-1} \left( \frac{y - \frac{b}{2}}{x} \right) + \frac{x}{2} \ln \left[ \frac{x^2 + \left( y - \frac{b}{2} \right)^2}{x^2 + \left( y + \frac{b}{2} \right)^2} \right] \quad (14)$$

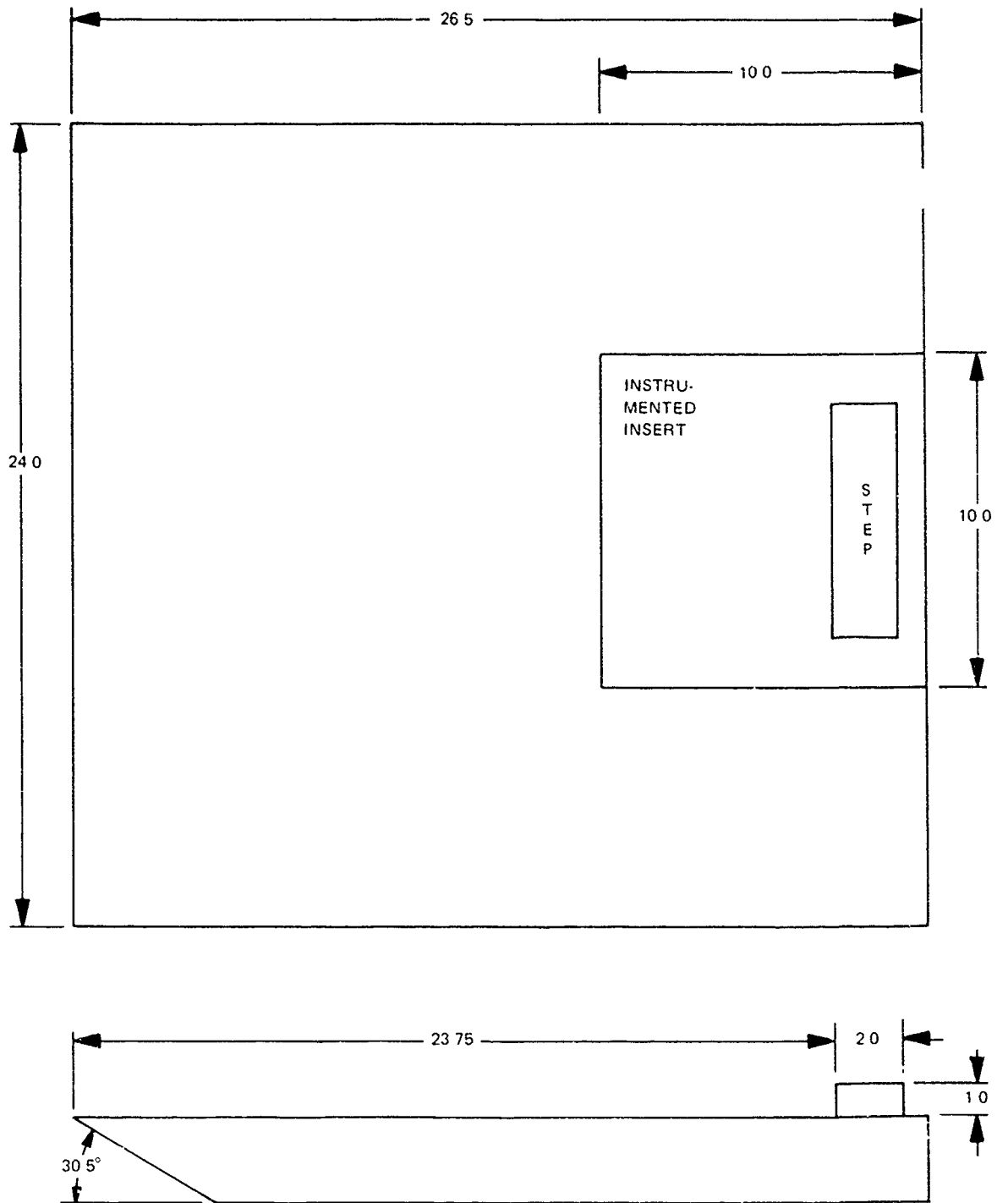
Sample plots of separation lines calculated in this manner are compared with the observed oil accumulation line shapes in Figures 46-49 for  $M_1 = 5.04$ . For these cases, there is generally good agreement between the experimental and analytical separation lines calculated as described above.

## SECTION V

### CONCLUSIONS

These conclusions pertain to turbulent boundary layer separation ahead of finite span, forward facing steps on flat plate surfaces. The step spans tested were three to ten times as large as the step height, and the step height is three or four times as large as the undisturbed boundary layer thickness. The results discussed were obtained for local undisturbed flow Mach numbers of 4.75 and 5.04 and Reynolds numbers of approximately 15 million, based on plate length upstream of the steps.

The maximum extent of flow separation upstream of the steps varies approximately from 4.2 to 4.5 times as large as the step height, independent of the step spans tested. The average heat transfer to the surface in the separated flow region is approximately 2.5 times larger than for the undisturbed flows over the flat plate surfaces. Local regions of peak heating occur slightly upstream of the step face at locations approximately  $\frac{1}{2}$  step height inboard from the side edges of the steps. The amplification of the heat transfer coefficients in these local regions of peak heating approaches nine for the three-inch span steps. The peak heating amplification factor diminishes somewhat with increasing step span. However, the location of peak heating to the plate surface, with respect to the face and side edges of the steps, does not vary with step span. Results of derived analytical expressions for the maximum extent of separation and for the shape of the separation line on the plate surface agree with the experimental results for these test conditions.



NOTE ALL LINEAR DIMENSIONS IN INCHES

Figure 1 Planform and Profile Sketches of Model with Step in Furthest Aft Location

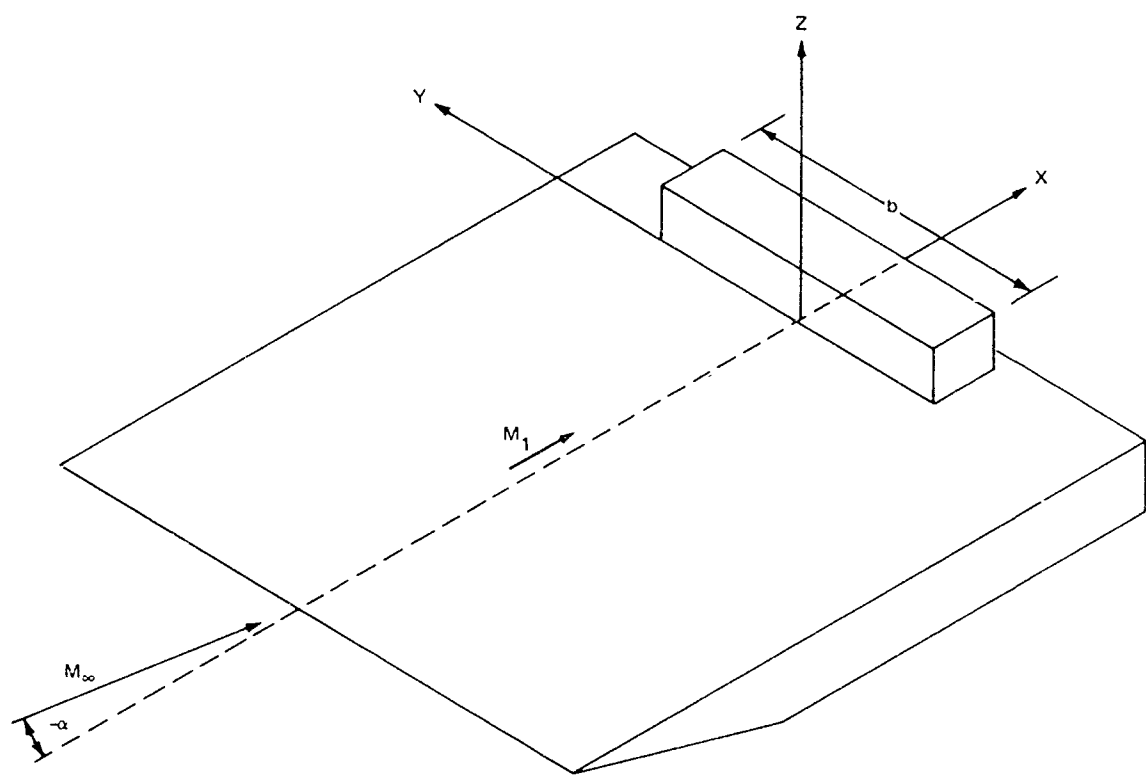


Figure 2 Coordinate System



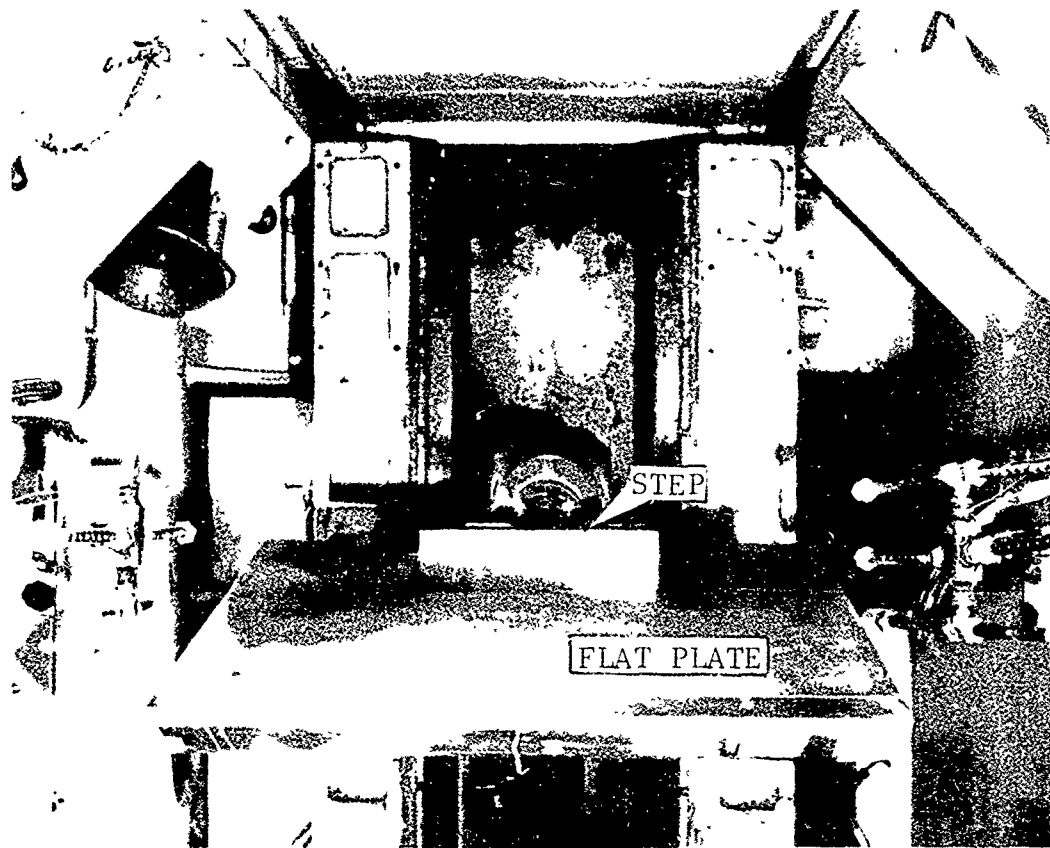
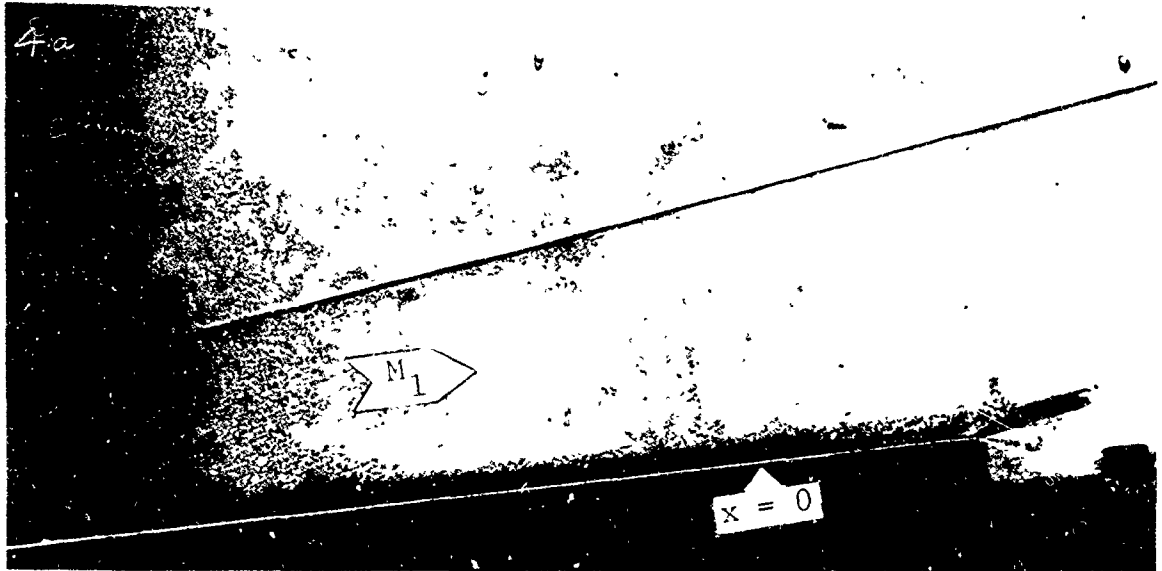
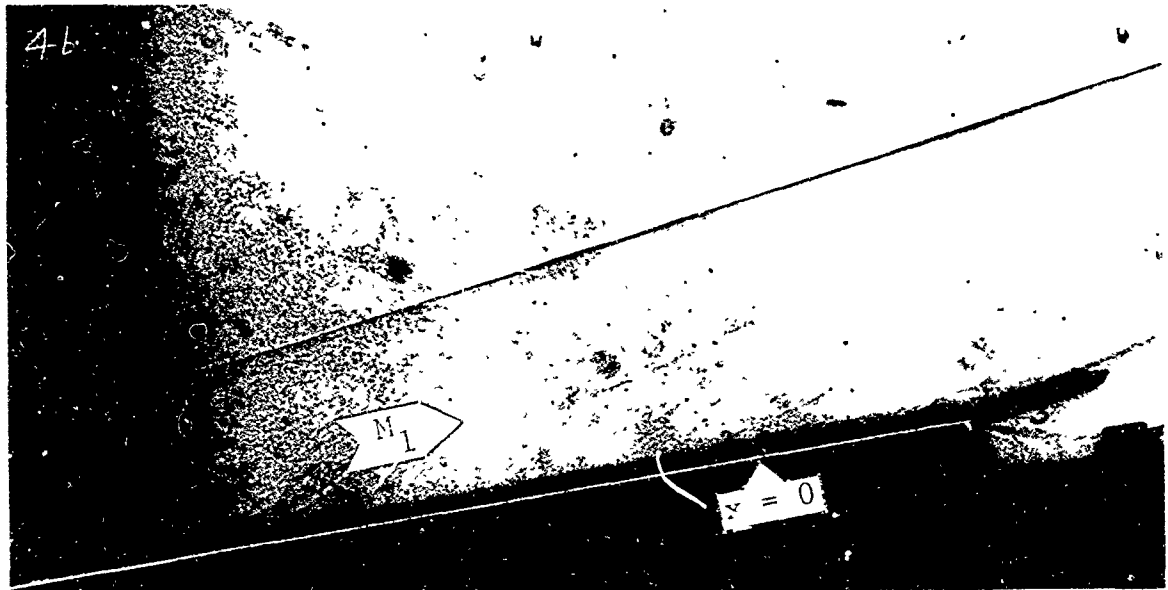


Figure 3 Front View Photograph of Model Mounted on Injection System in Cabin Beneath Tunnel Test Section



a)  $M_1 = 1.504$



b)  $M_1 = 4.75$

Figure 4 Schlieren Photographs of Flows over Flat Plate Surface with no Step

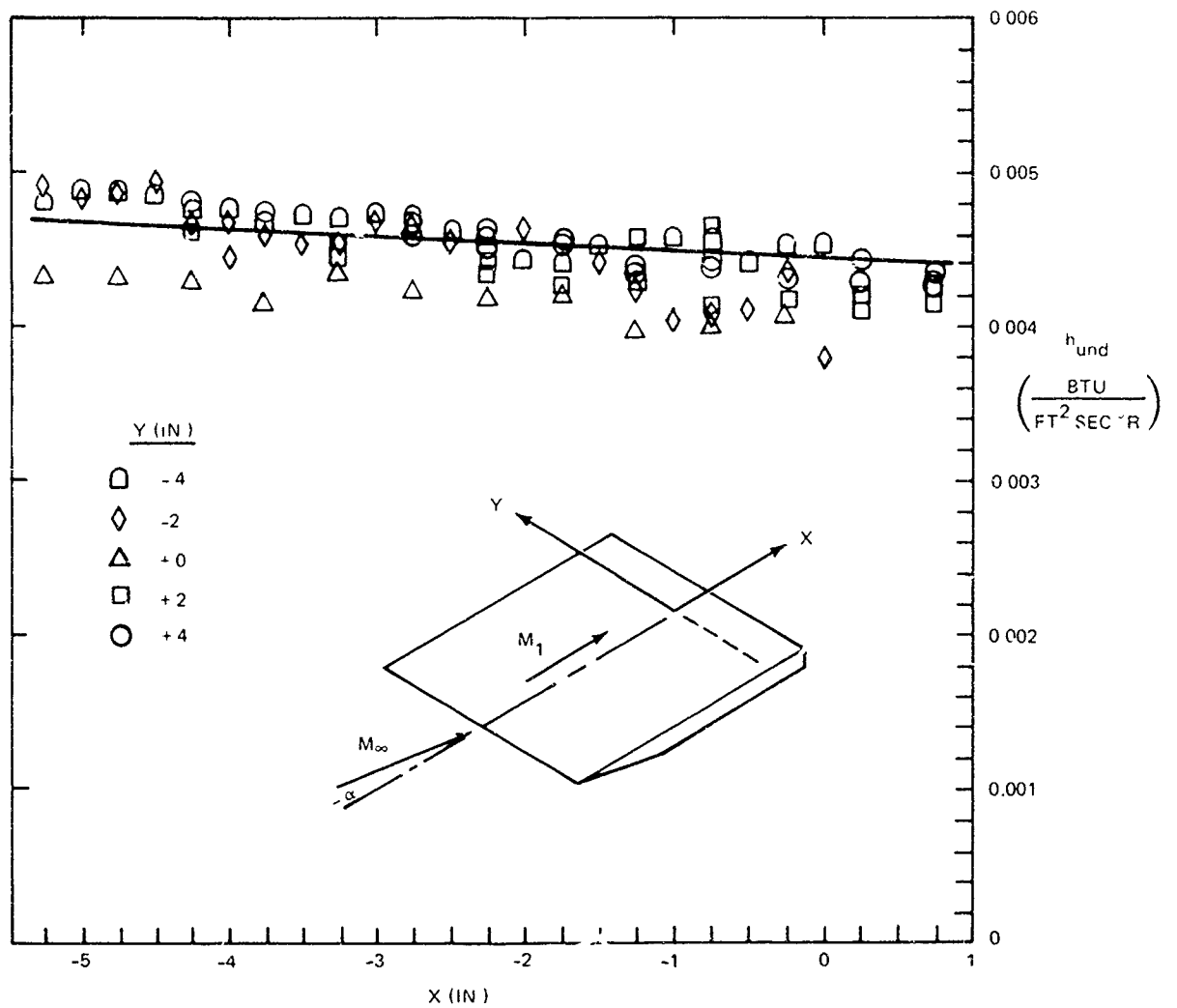


Figure 5 Heat Transfer Coefficient Distributions on Flat Plate Surface with no Step for  $M_1 = 5.04$  ( $\alpha = -6.8^\circ$ )

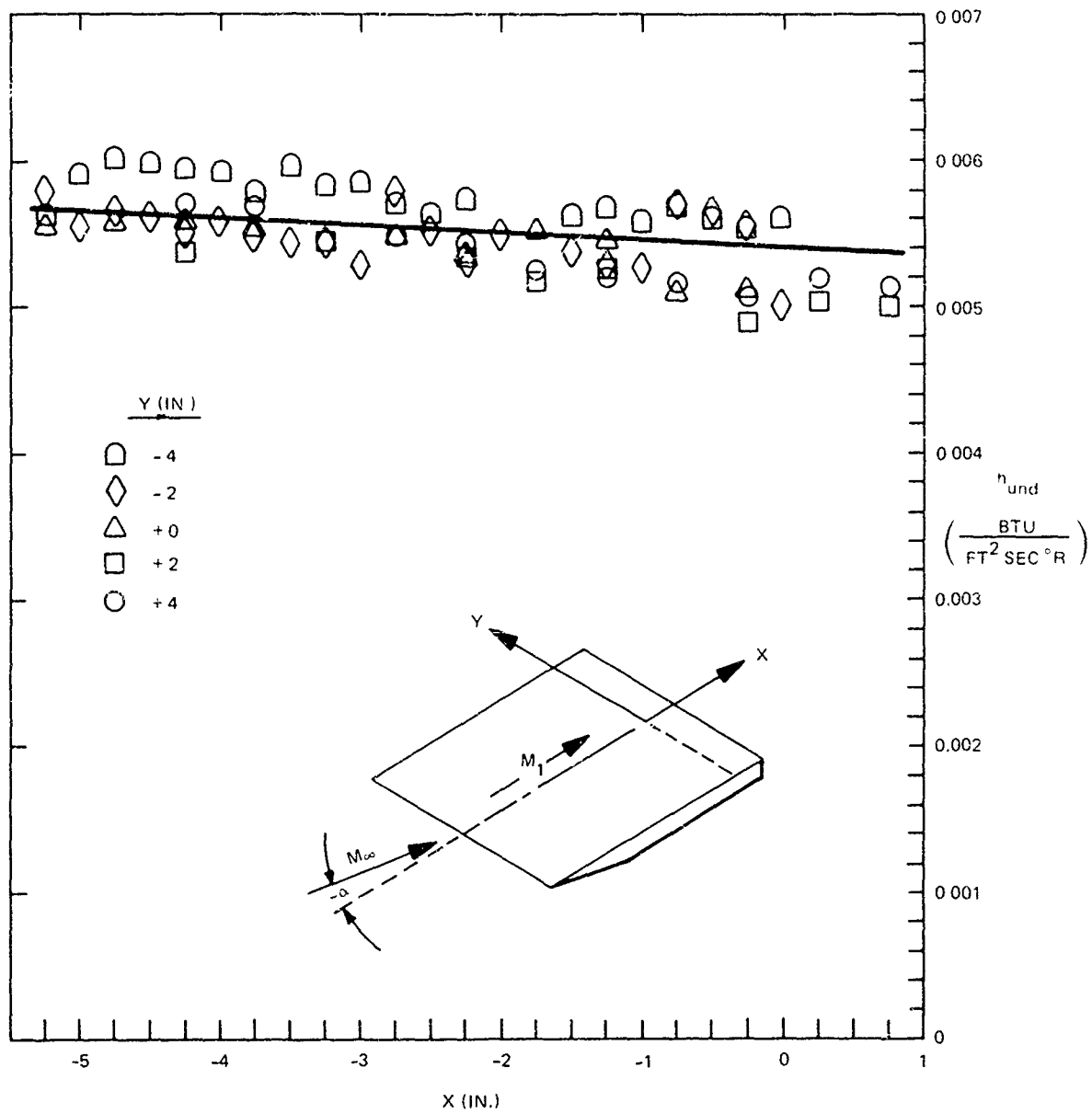


Figure 6 Heat Transfer Coefficient Distributions on Flat Plate Surface with no Step for  $M_1 = 4.75$  ( $\alpha = -9.0^\circ$ )

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X	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.0	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0	-3.5	-4.0	-4.5	-5.0	-5.5	-6.0	
0.75						0.95					0.92																	
0.50						0.96					0.92																	
0.25						0.96					0.92																	
0.00						0.93					0.90				0.94													
-0.25						0.95					0.88				0.44													
-0.50						0.95					0.86				0.93													
-0.75						0.95					0.96				0.93													
-1.00						0.95					0.93				0.81													
-1.25						0.98					0.96				0.96													
-1.50						0.98					0.96				0.96													
-1.75						0.98					0.96				0.96													
-2.00						0.98					0.96				0.96													
-2.25						0.98					0.96				0.96													
-2.50						0.98					0.96				0.96													
-2.75						0.98					0.96				0.96													
-3.00						0.98					0.96				0.96													
-3.25						0.98					0.96				0.96													
-3.50						0.98					0.96				0.96													
-3.75						0.98					0.96				0.96													
-4.00						0.98					0.96				0.96													
-4.25						0.98					0.96				0.96													
-4.50						0.98					0.96				0.96													
-4.75						0.98					0.96				0.96													
-5.00						0.98					0.96				0.96													
-5.25						0.98					0.96				0.96													



Figure 7 Distribution of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Flat Plate Surface for  $M_1 = 5.04$ , No Step Attached to Surface

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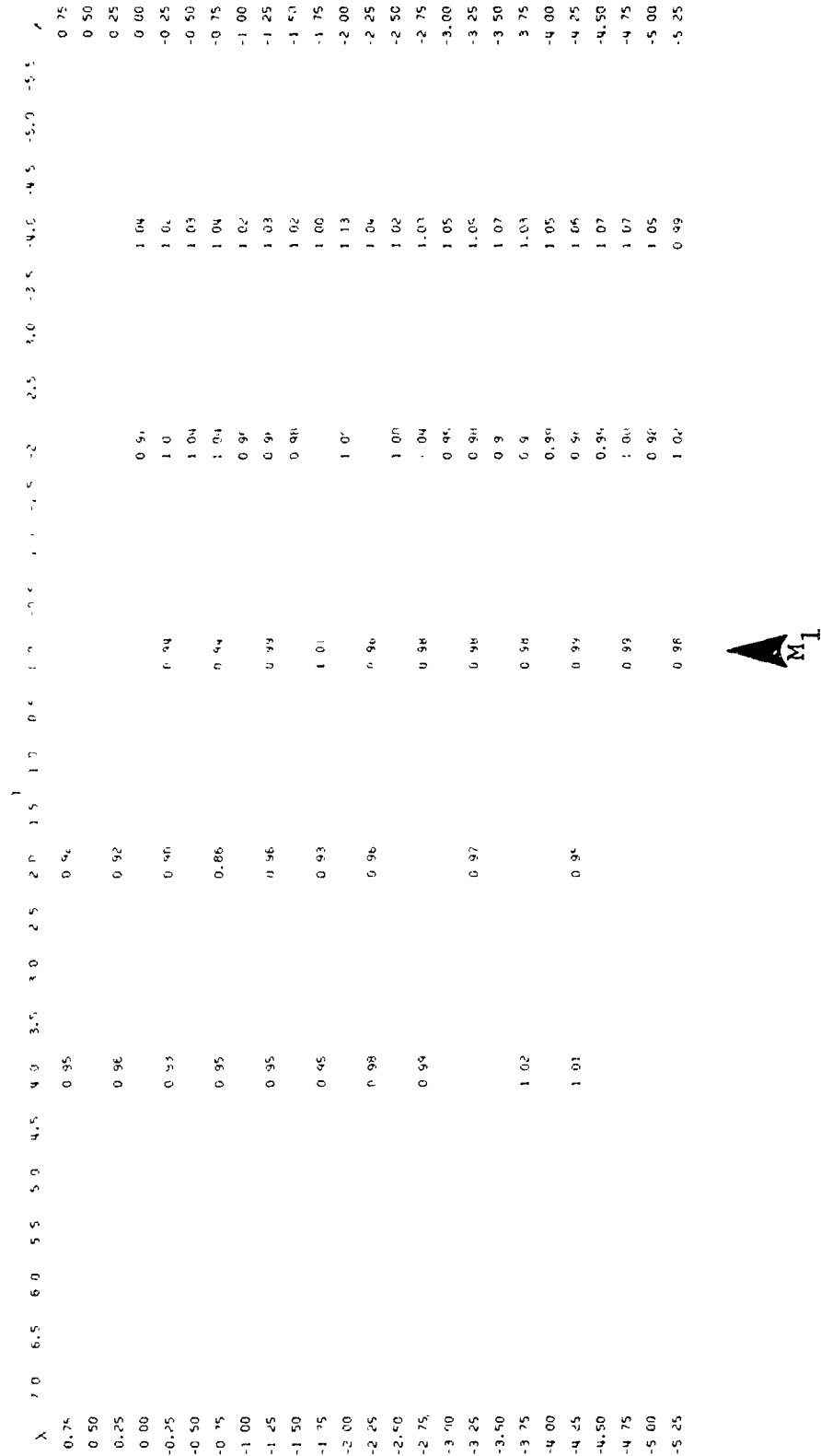


Figure 8 Distribution of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Flat Plate Surface for  $M_1 = 4.75$ , No Step Attached to Surface



Figure 9 Profile Schlieren Photograph of  $M_1 = 5.04$  Flow Ahead of 3-inch Span Step

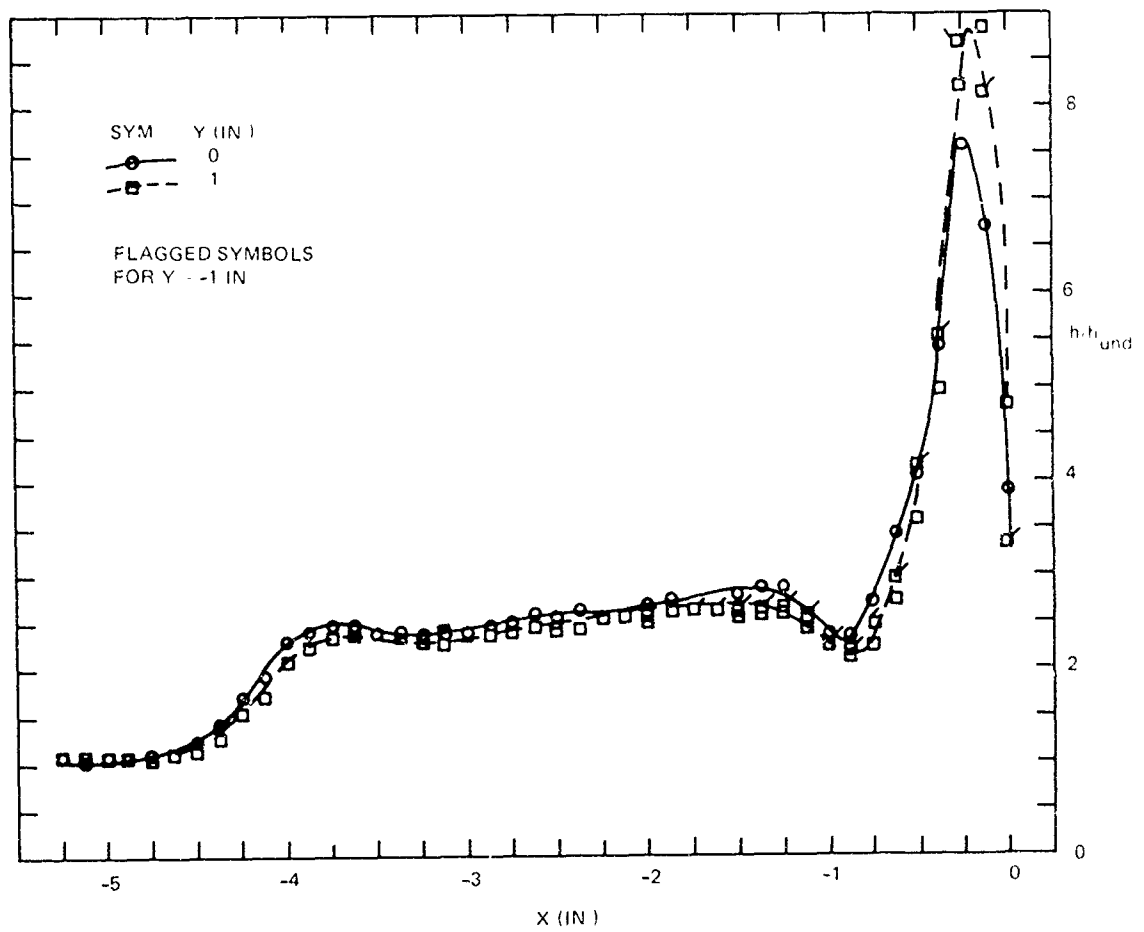


Figure 10 Streamwise Distributions of Heat Transfer Coefficient Ratios ( $h/h_{und}$ ) on Plate Surface for  $M_1 = 5.04$  Flow Ahead of 3-inch Span Step



Figure 11 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 3-inch Span Step for  $M_1 = 5.04$



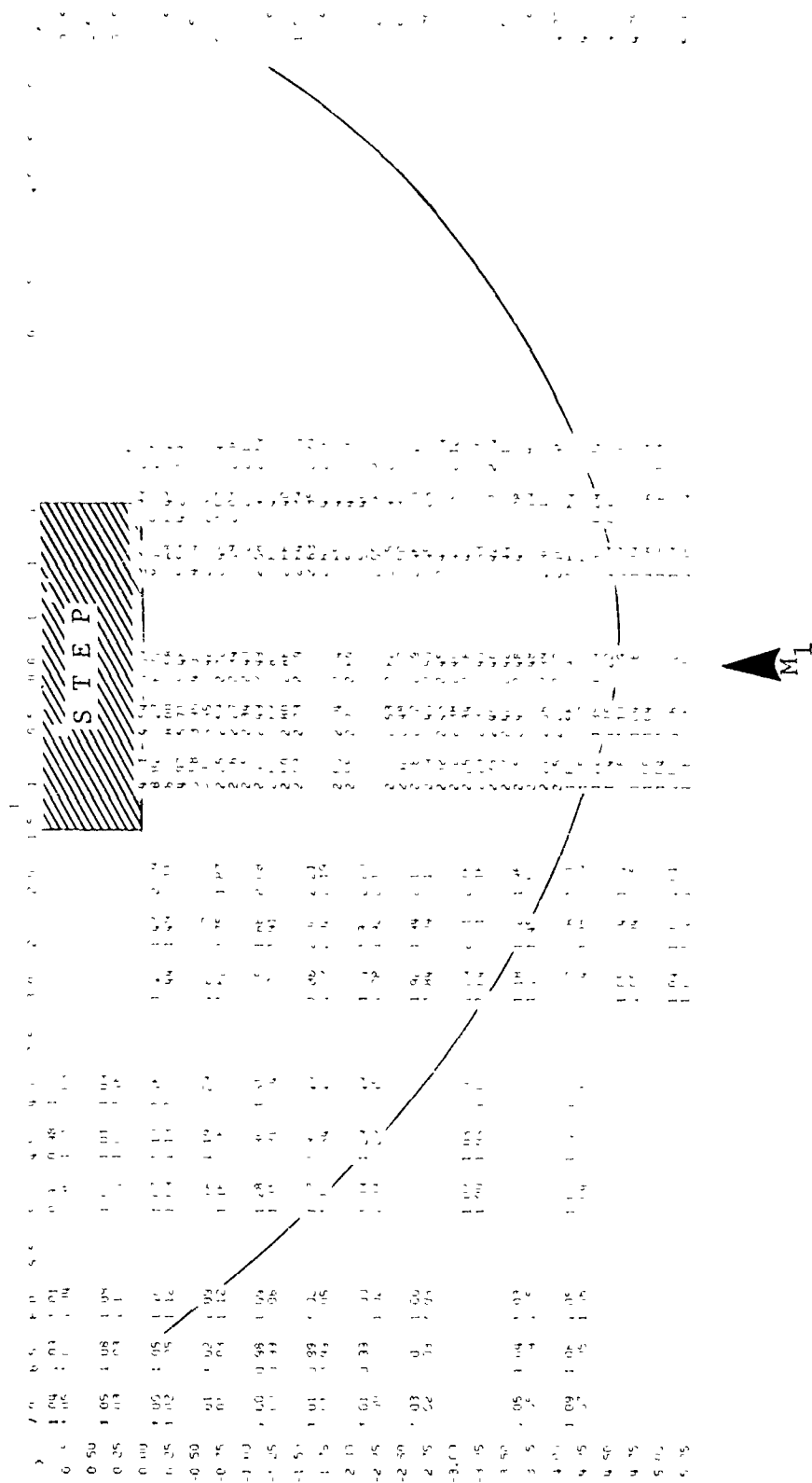


Figure 12 Distribution of Heat Transfer Coefficient Ratios ( $h/h_{\infty}$ ) on Surface Ahead of 3-inch Span Step for  $M_1 = 5.04$

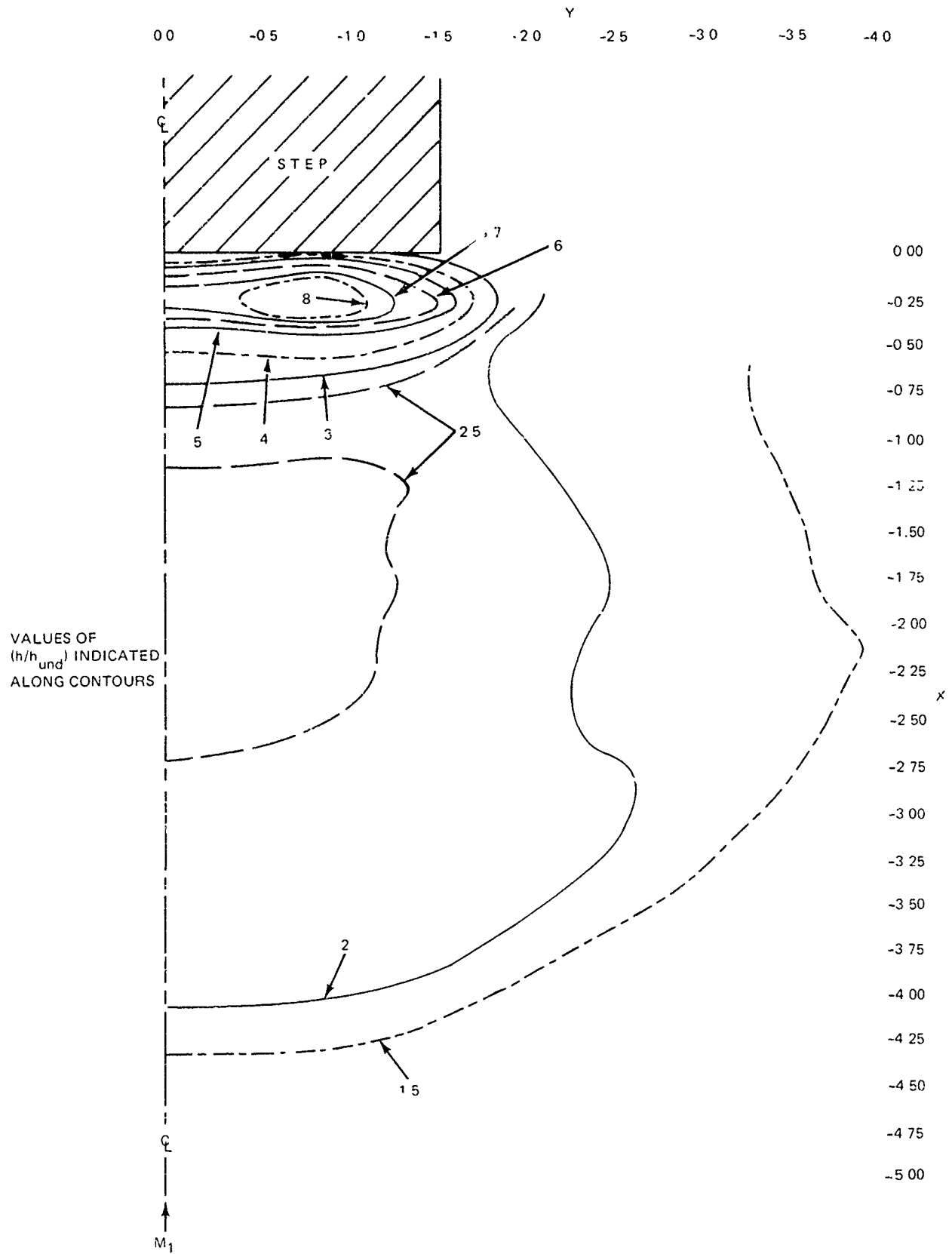


Figure 13 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 3-inch Span Step for  $M_1 = 5.04$

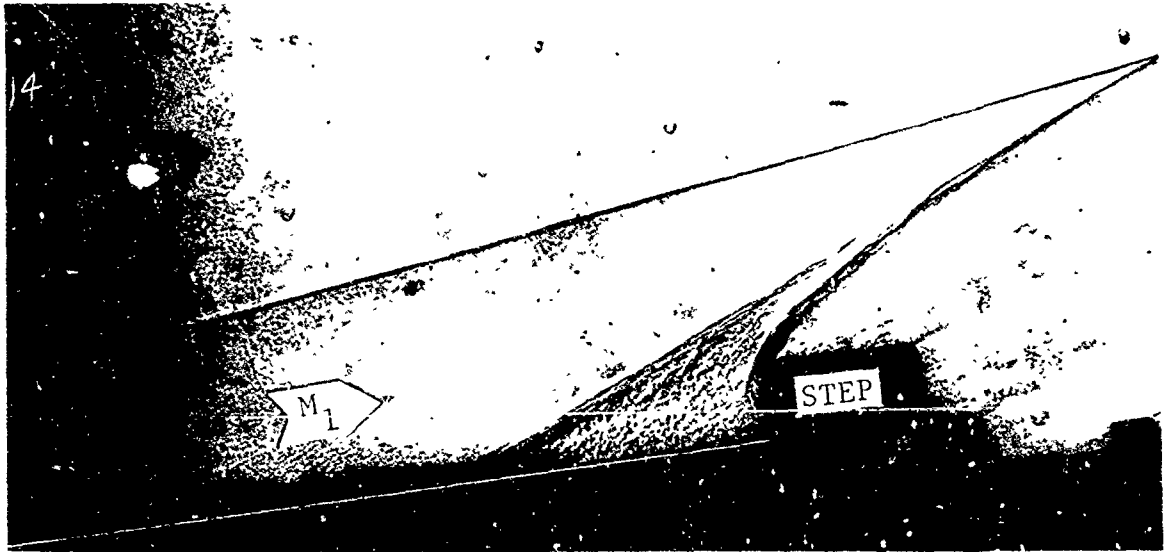


Figure 14 Profile Schlieren Photograph of  $M_1 = 5.04$  Flow Ahead of 5-inch Span Step

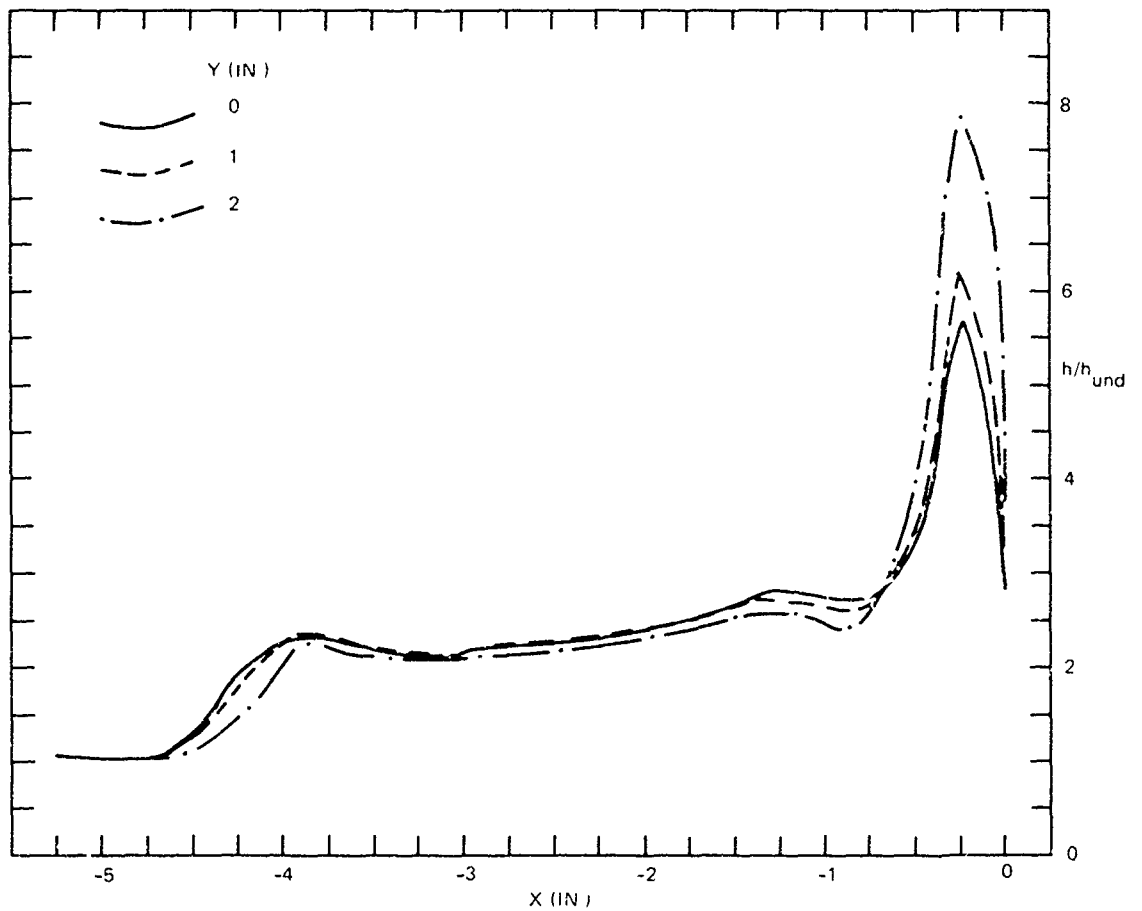


Figure 15 Streamwise Distributions of Heat Transfer Coefficient  $R$  ( $h/h_{und}$ ) on Plate Surface for  $M_1 = 5.04$  Flow Ahead of 5-inch Span Step



Figure 16 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 5-inch Span Step for  $M_1 = 5.04$

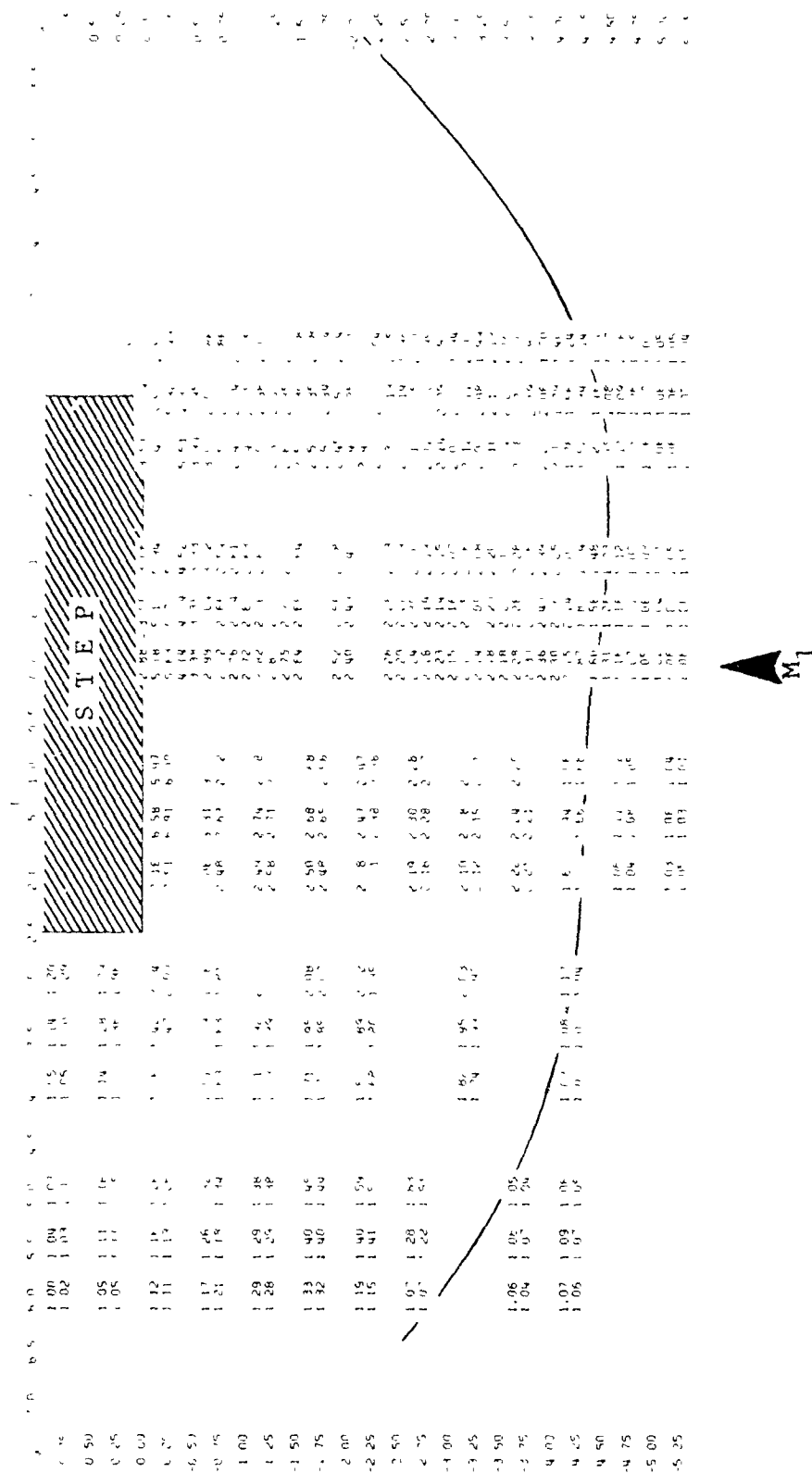


Figure 17 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 5-inch Span Step for  $M_1 = 5.04$

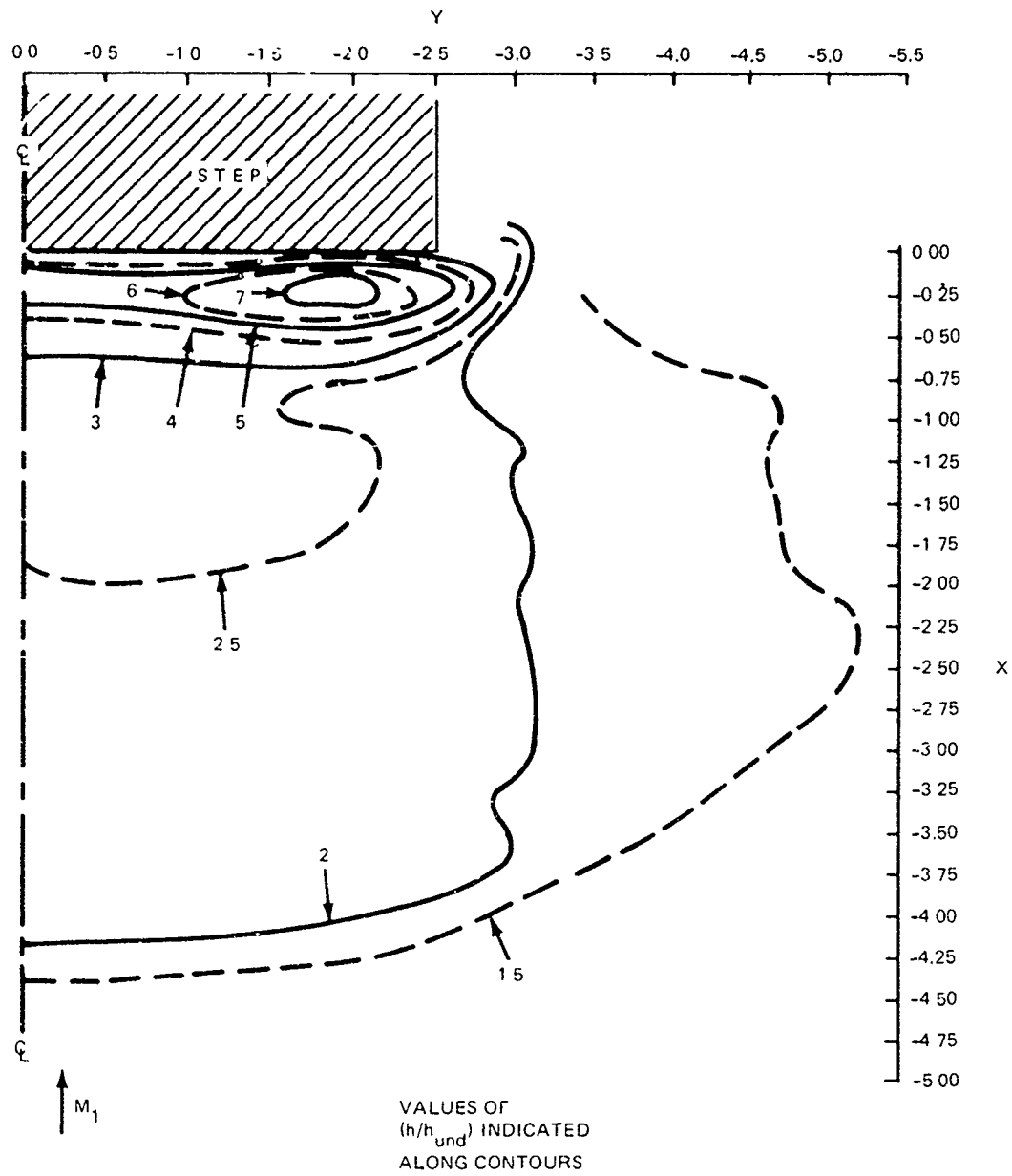


Figure 18 Lines of Constant ( $h/h_{und}$ ) Contours on Surface Ahead of 5-inch Span Step for  $M_1 = 5.04$

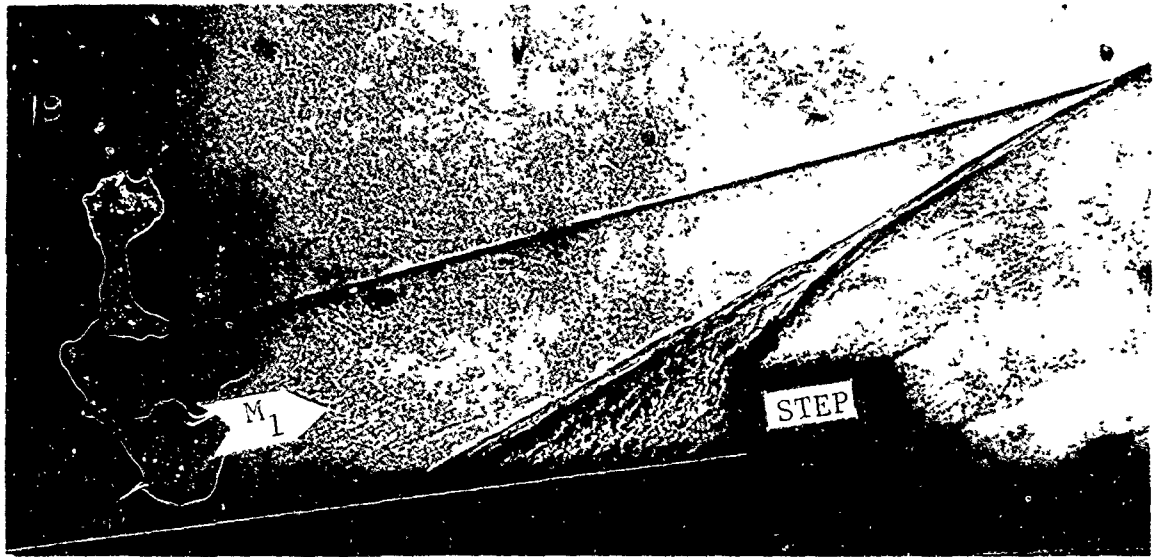


Figure 19 Profile Schlieren Photograph of  $M_1 = 5.04$  Flow Ahead of 7-inch Span Step

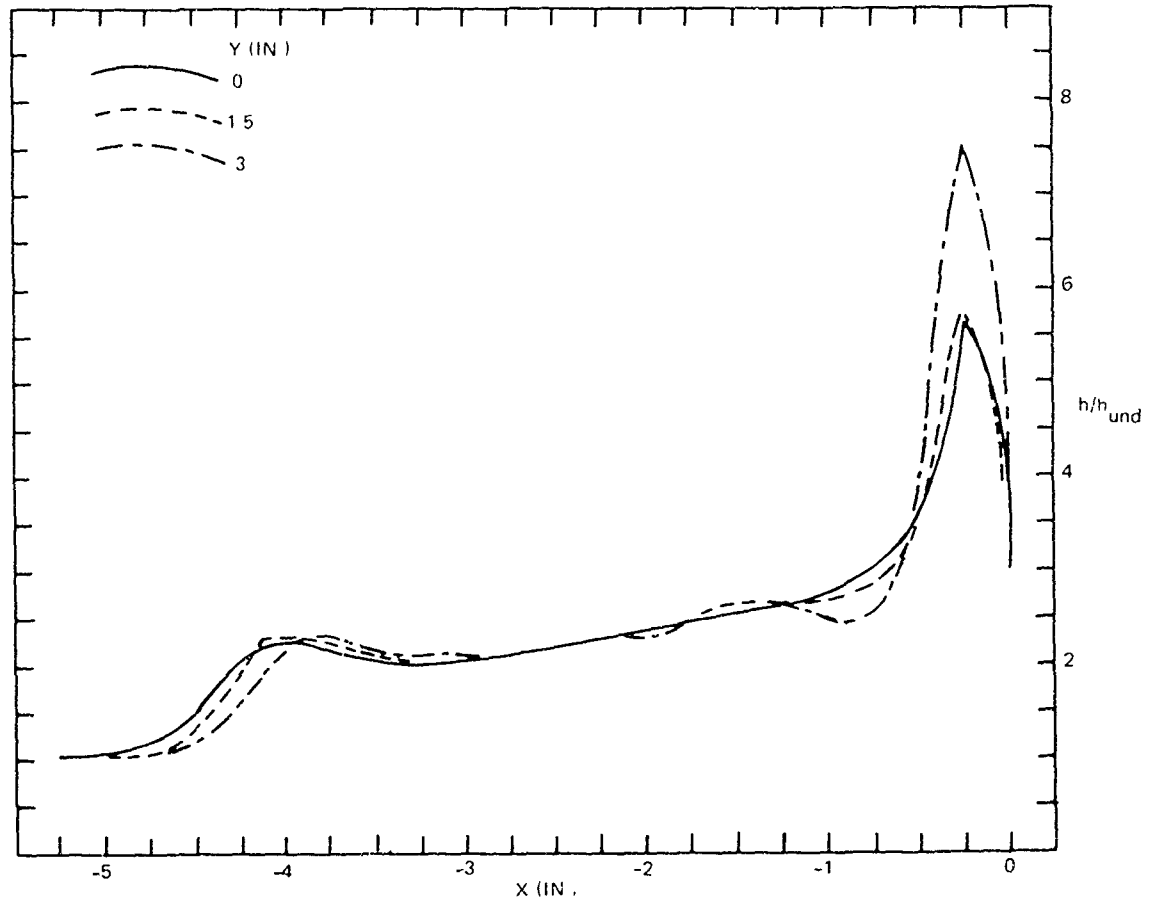


Figure 20 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for  $M_1 = 5.04$  Flow Ahead of 7-inch Span Step

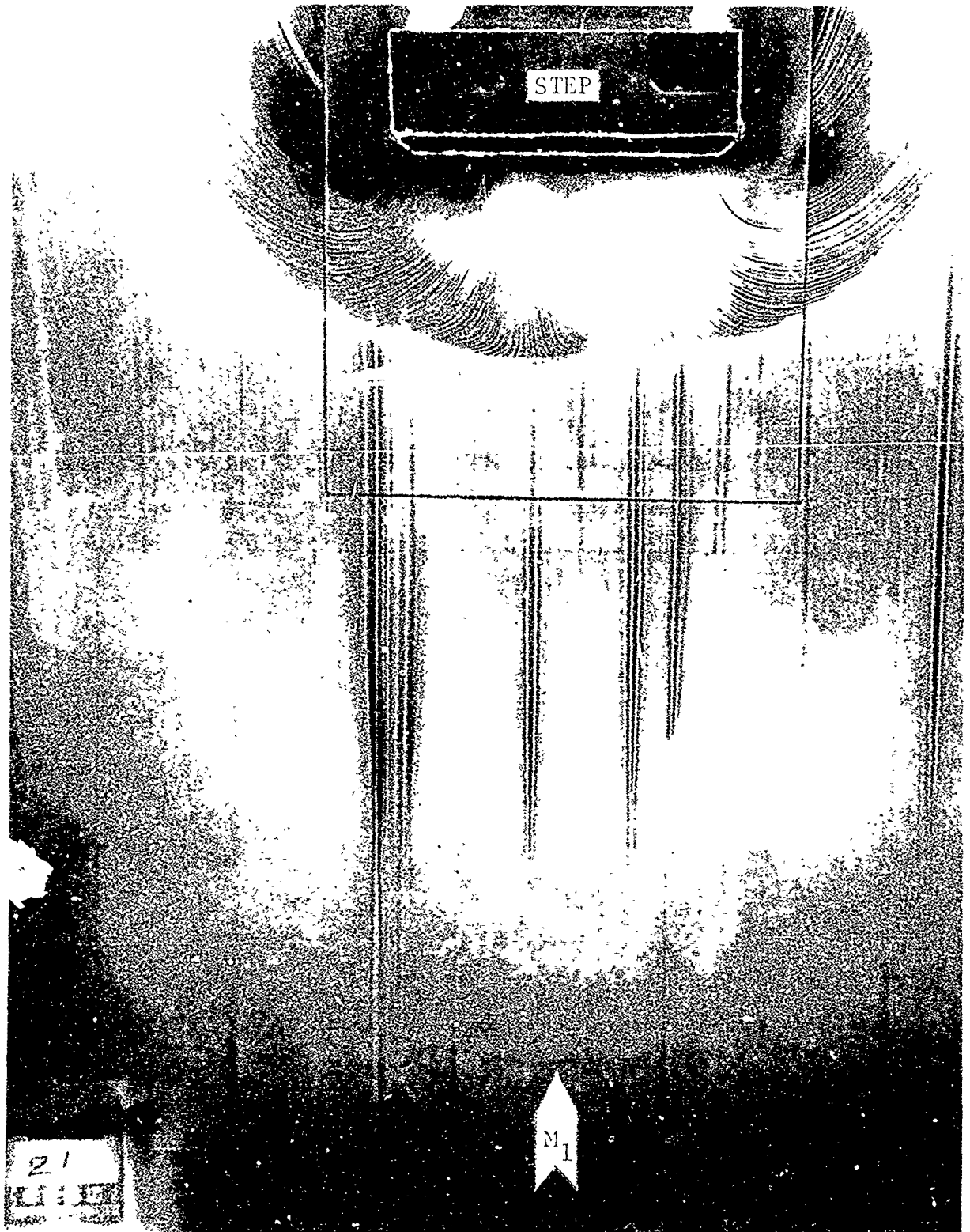


Figure 21 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 7-inch Span Step for  $M_1 = 5.04$



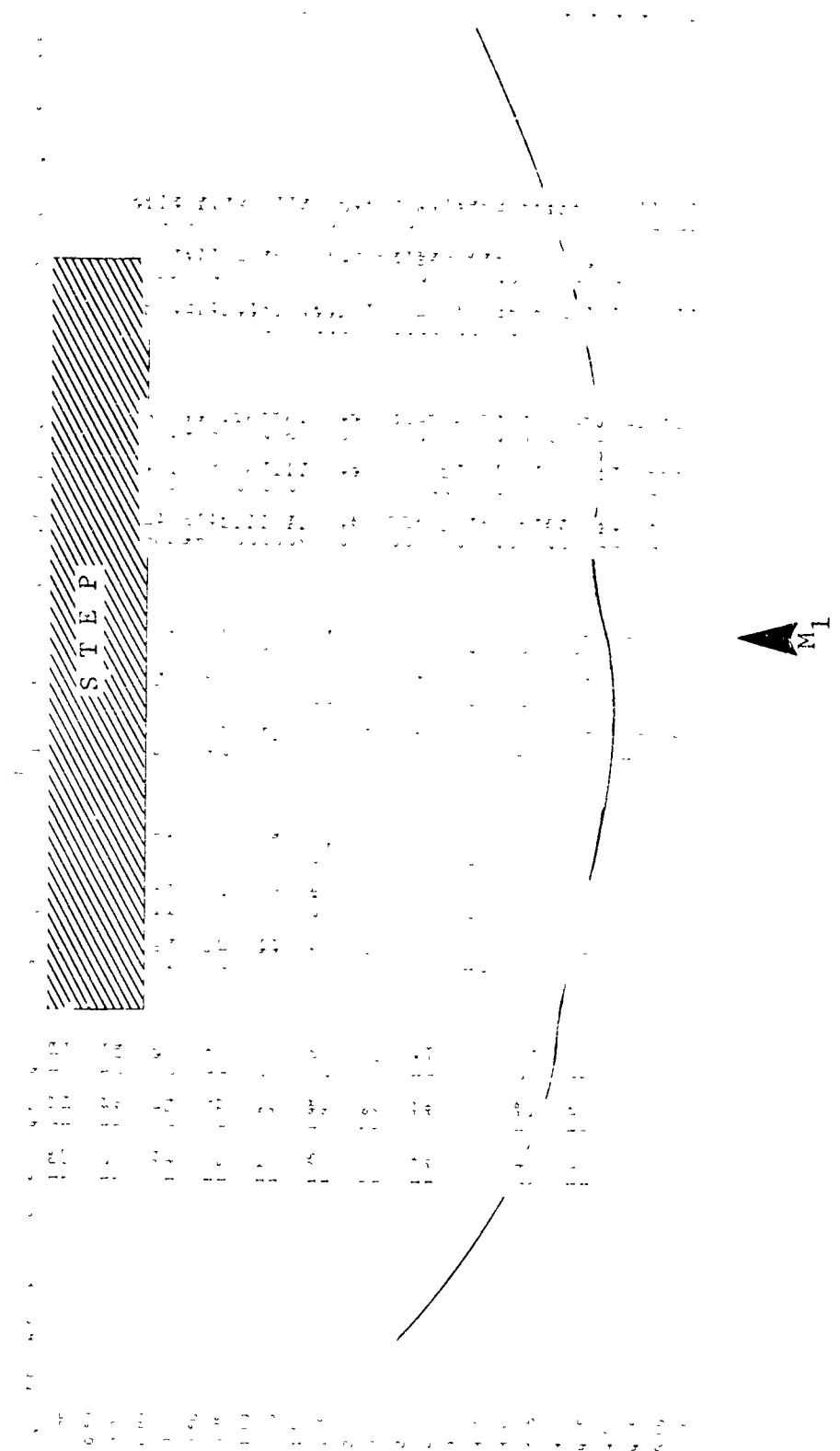


Figure 22 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 7-inch Span Step for  $M_1 = 5.04$

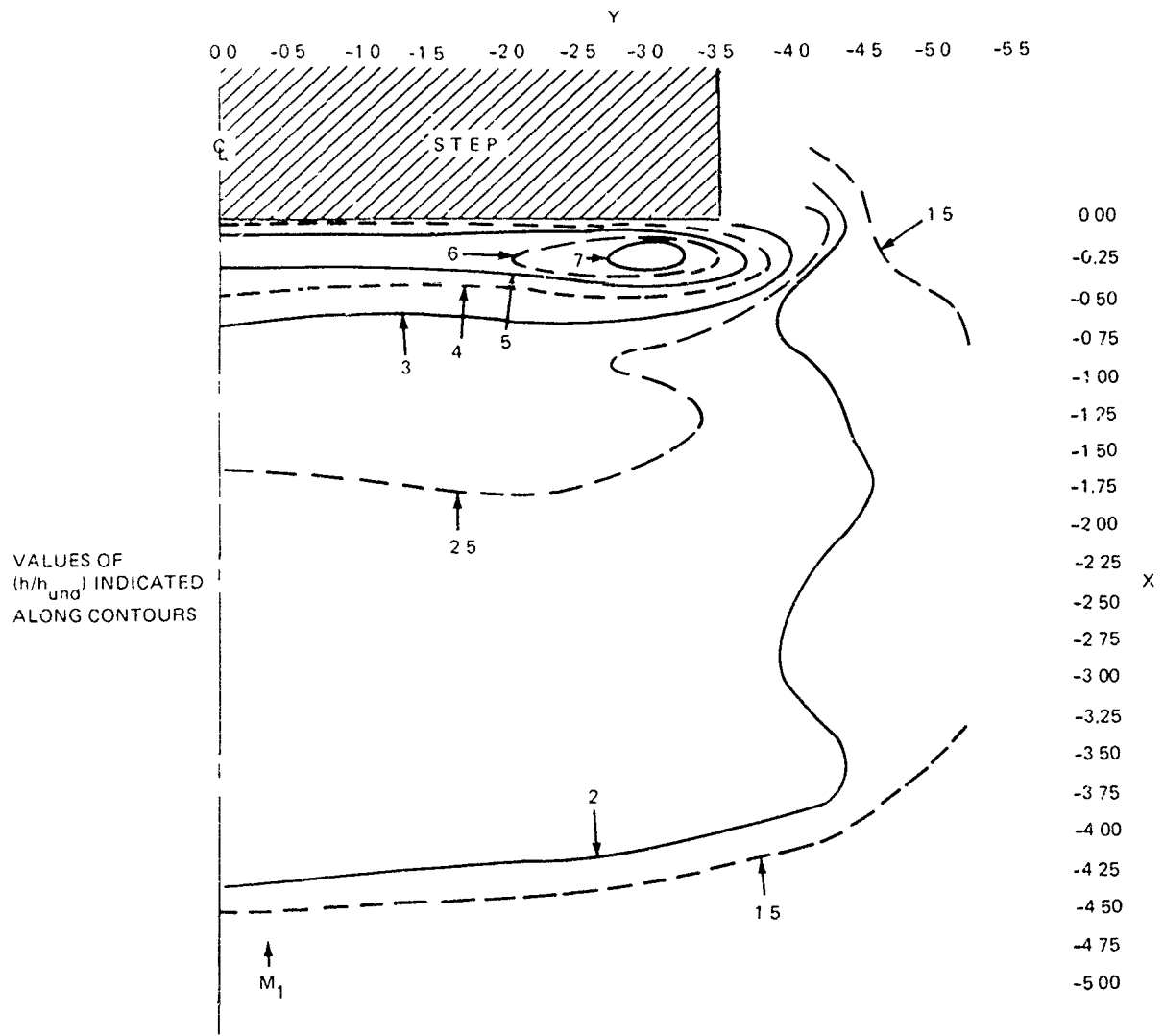


Figure 23 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 7-inch Span Step for  $M_1 = 5.04$

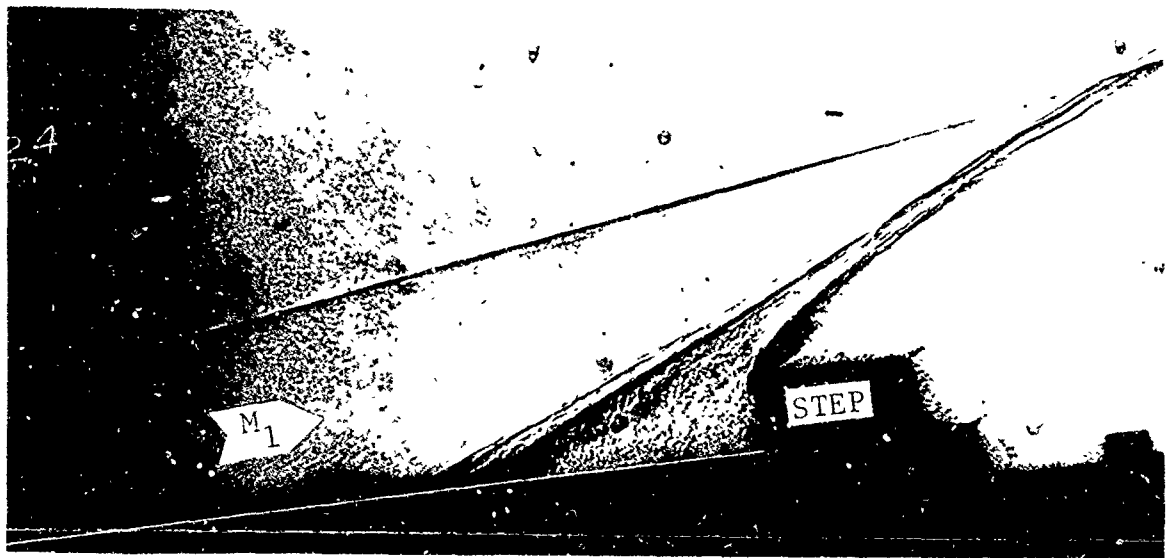


Figure 24 Profile Schlieren Photograph of  $M_1 = 5.04$  Flow Ahead of 10-inch Span Step

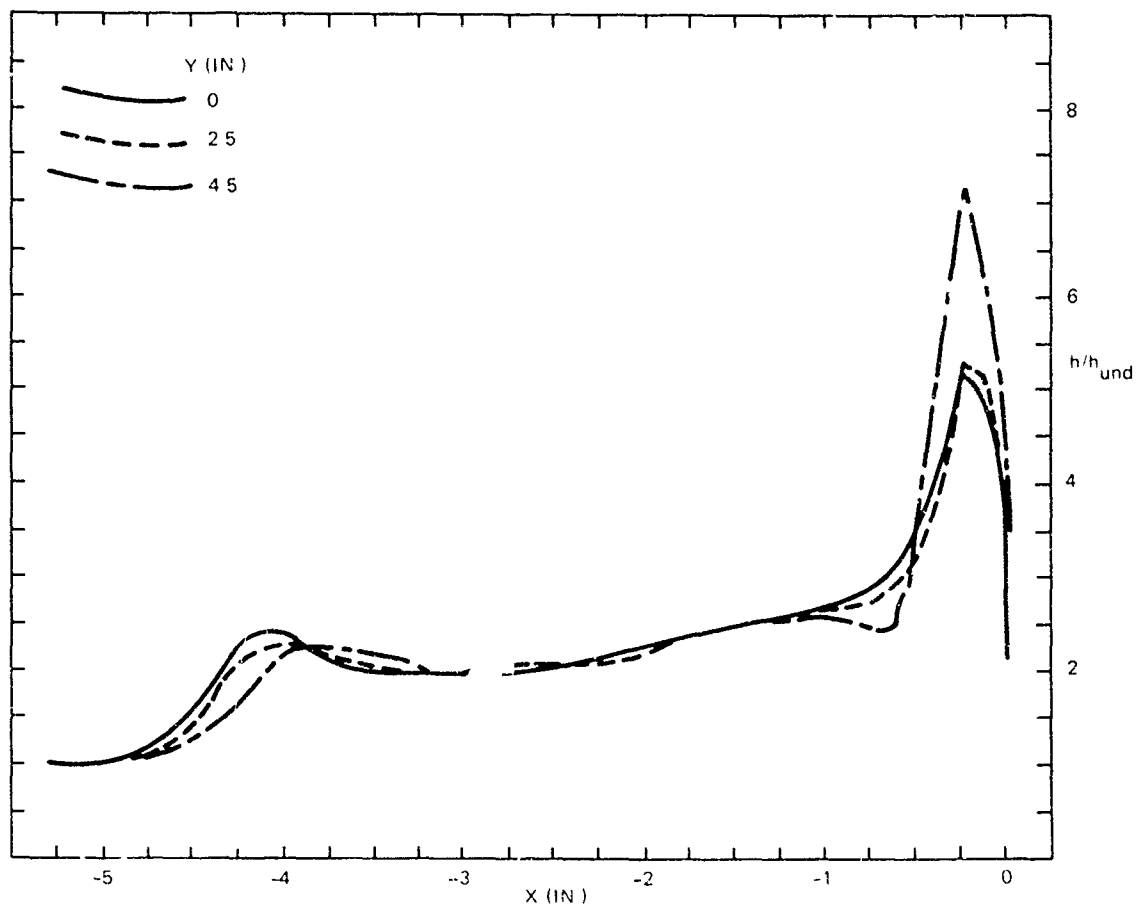


Figure 25 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for  $M_1 = 5.04$  Flow Ahead of 10-inch Span Step

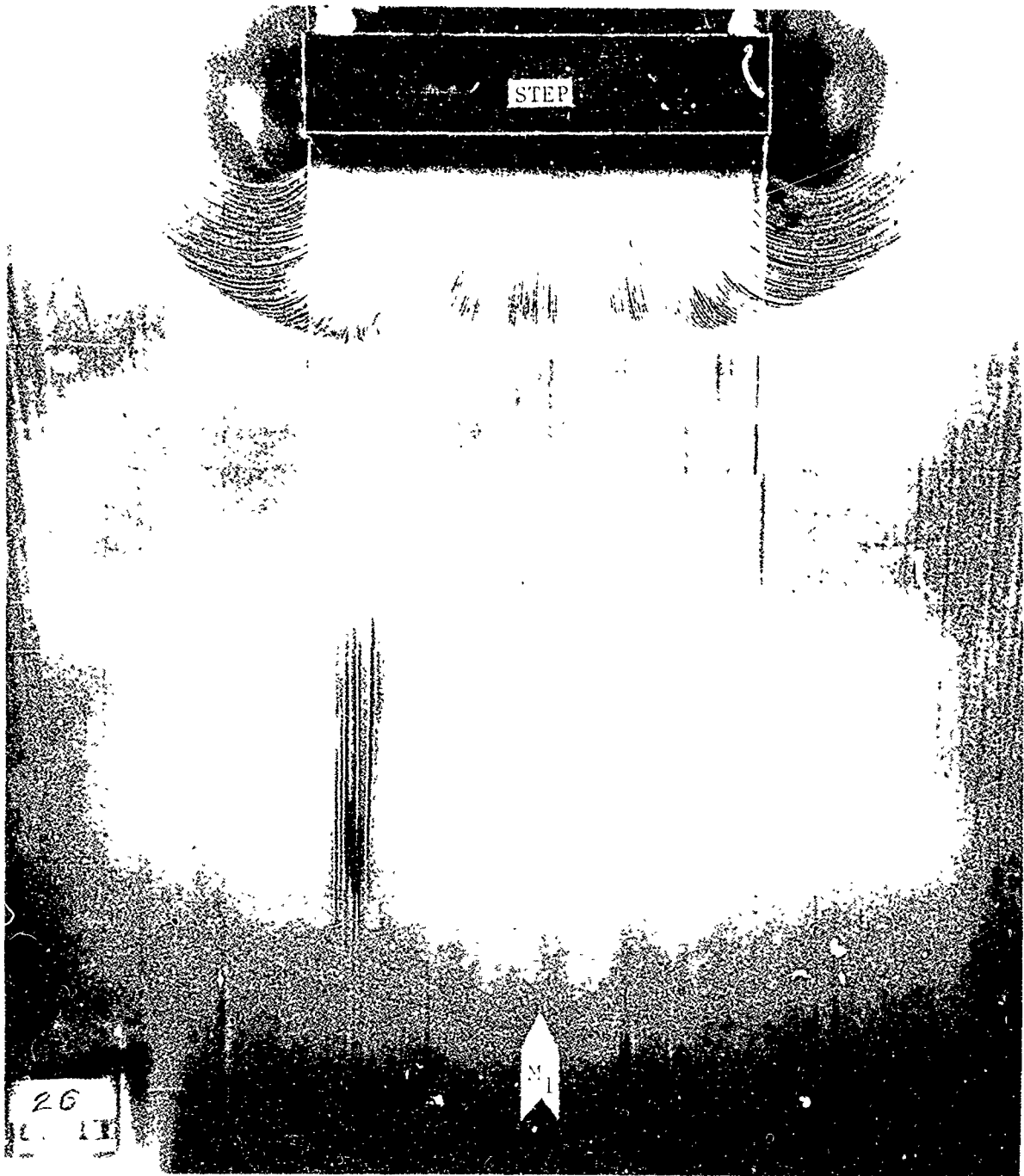


Figure 26 Frame from Motion Picture Showing Oil Film Flow on Surface Ahead of 10 inch Span Step for  $M_1 = 5.04$

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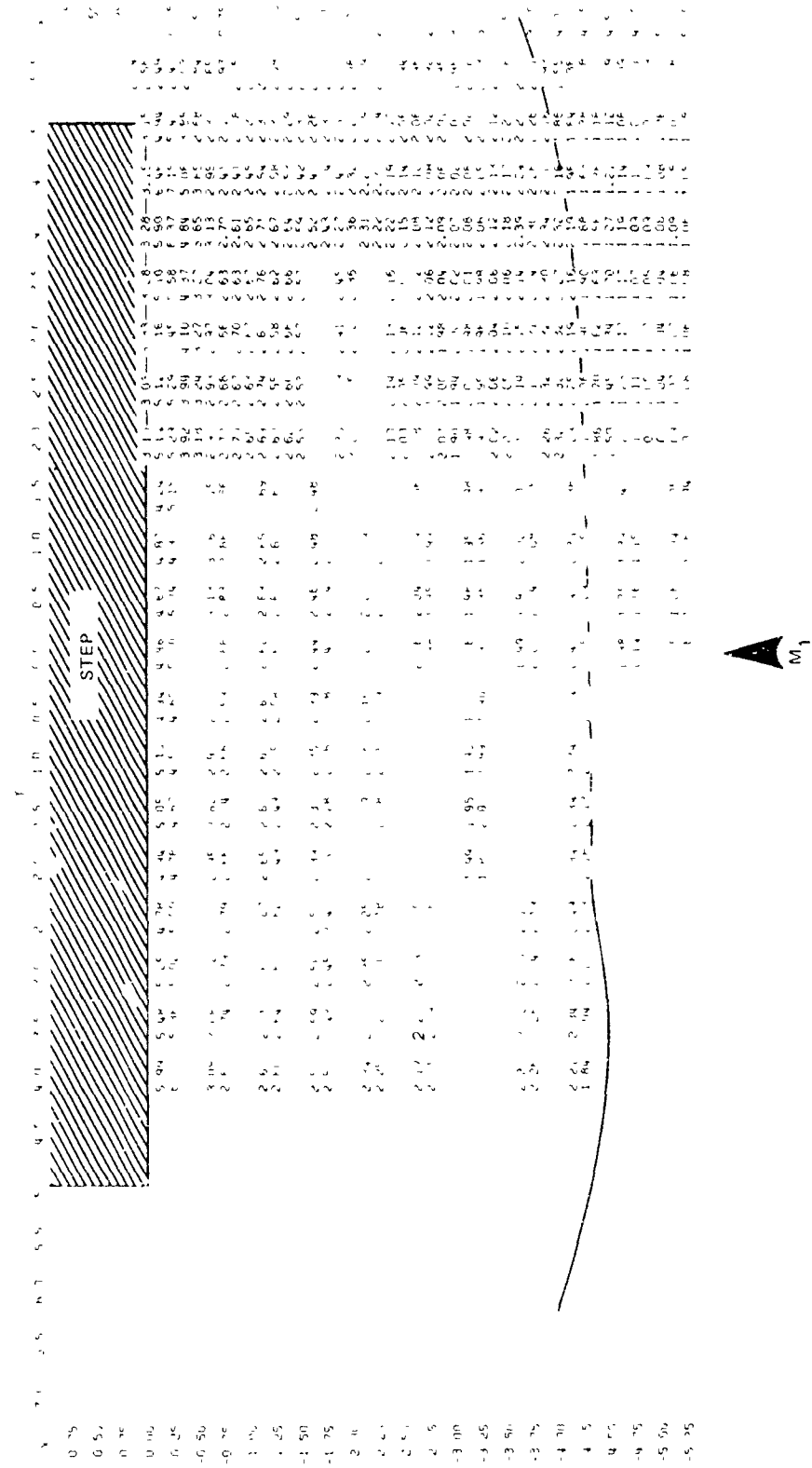


Figure 27 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 10-inch Span Step for  $M_1 = 5.04$

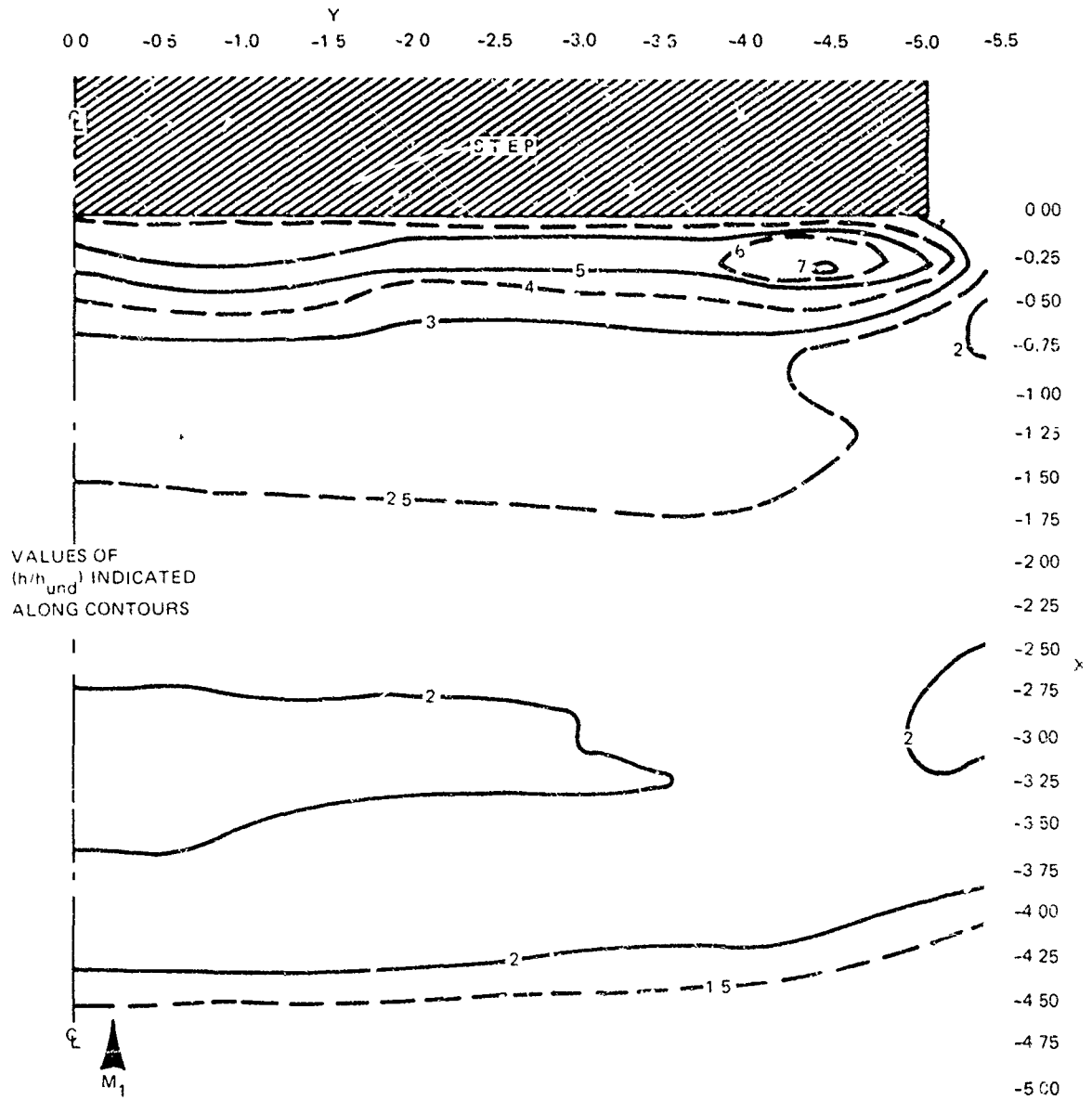


Figure 28 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 10-inch Span Step for  $M_1 = 5.04$

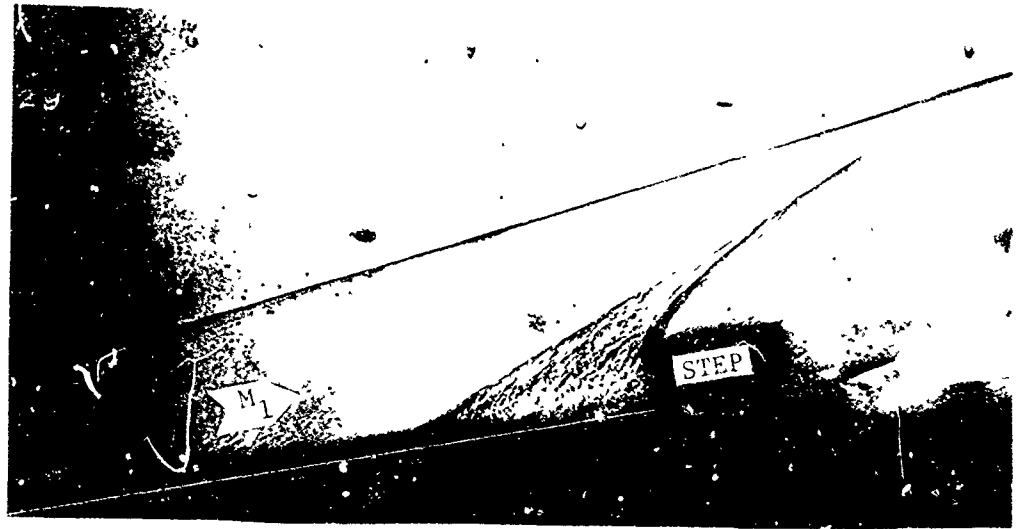


Figure 29 Profile Schlieren Photograph of  $M_1 = 4.75$  Flow Ahead of 3-inch Span Step

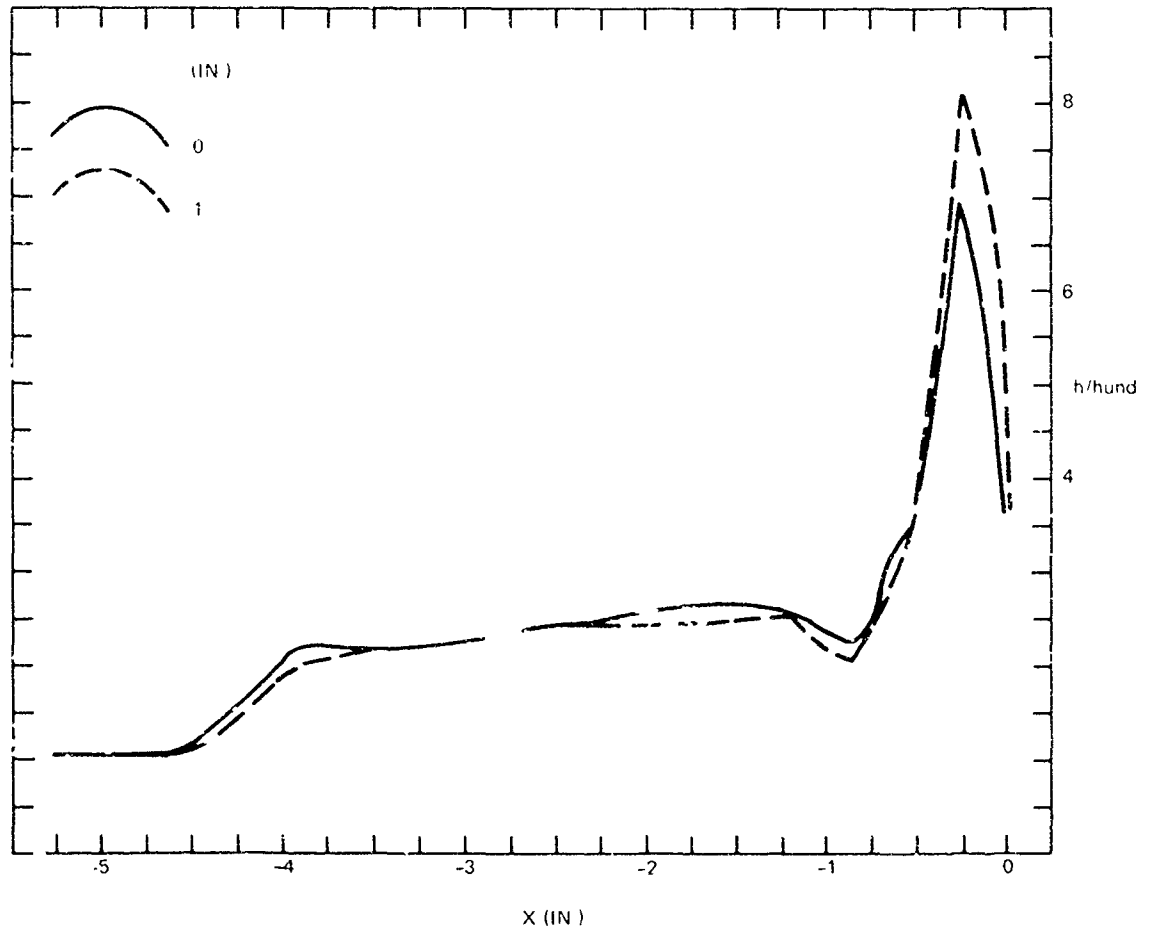


Figure 30 Streamwise Distributions of Heat Transfer Coefficient Ratio ( $h/h_{und}$ ) on Plate Surface for  $M_1 = 4.75$  Flow Ahead of 3-inch Span Step

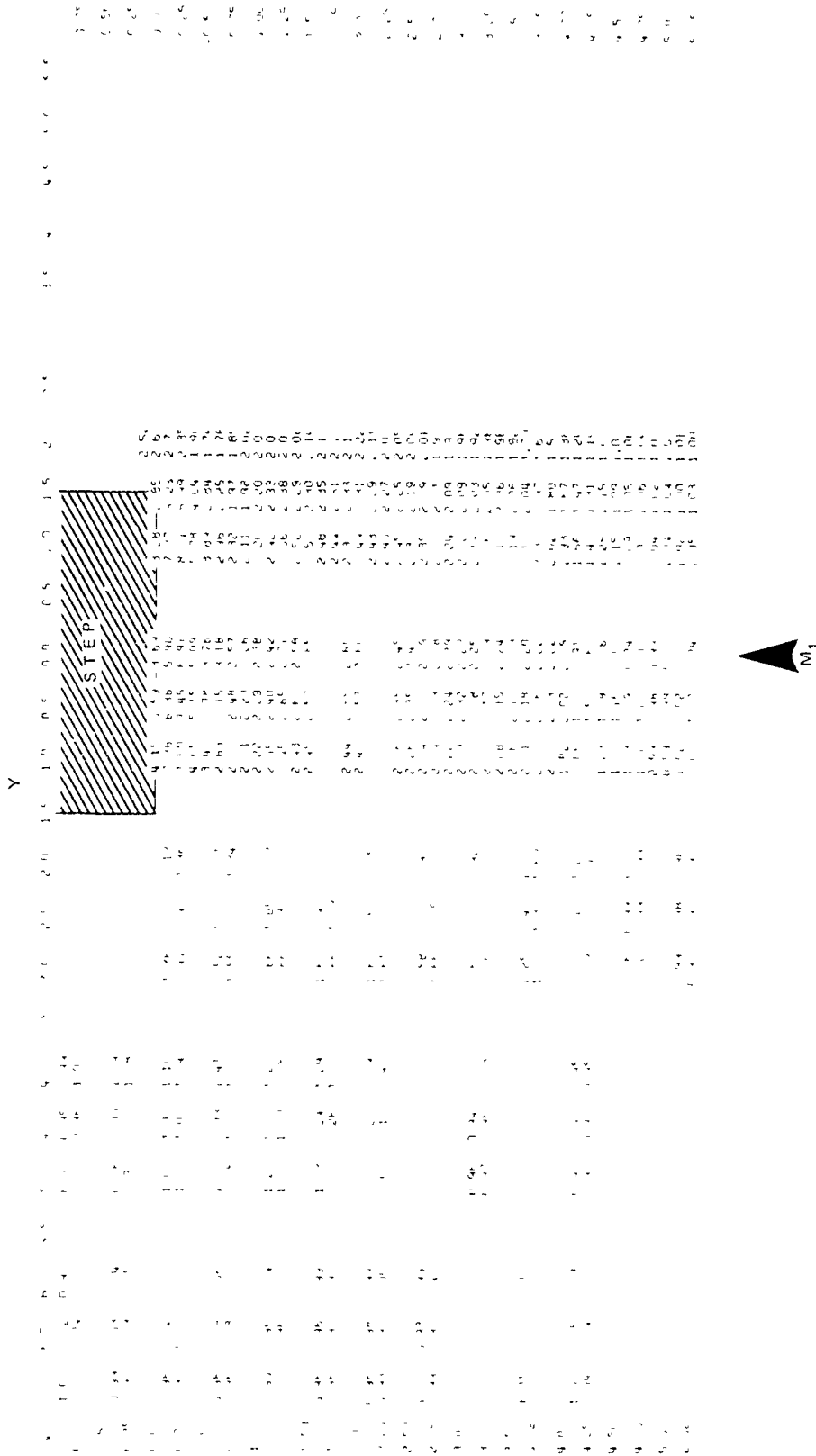


Figure 31 Distribution of Heat Transfer Coefficient Ratios  $(h/h_{und})$  on Surface Ahead of 3-inch Span Step for  $M_1 = 4.75$



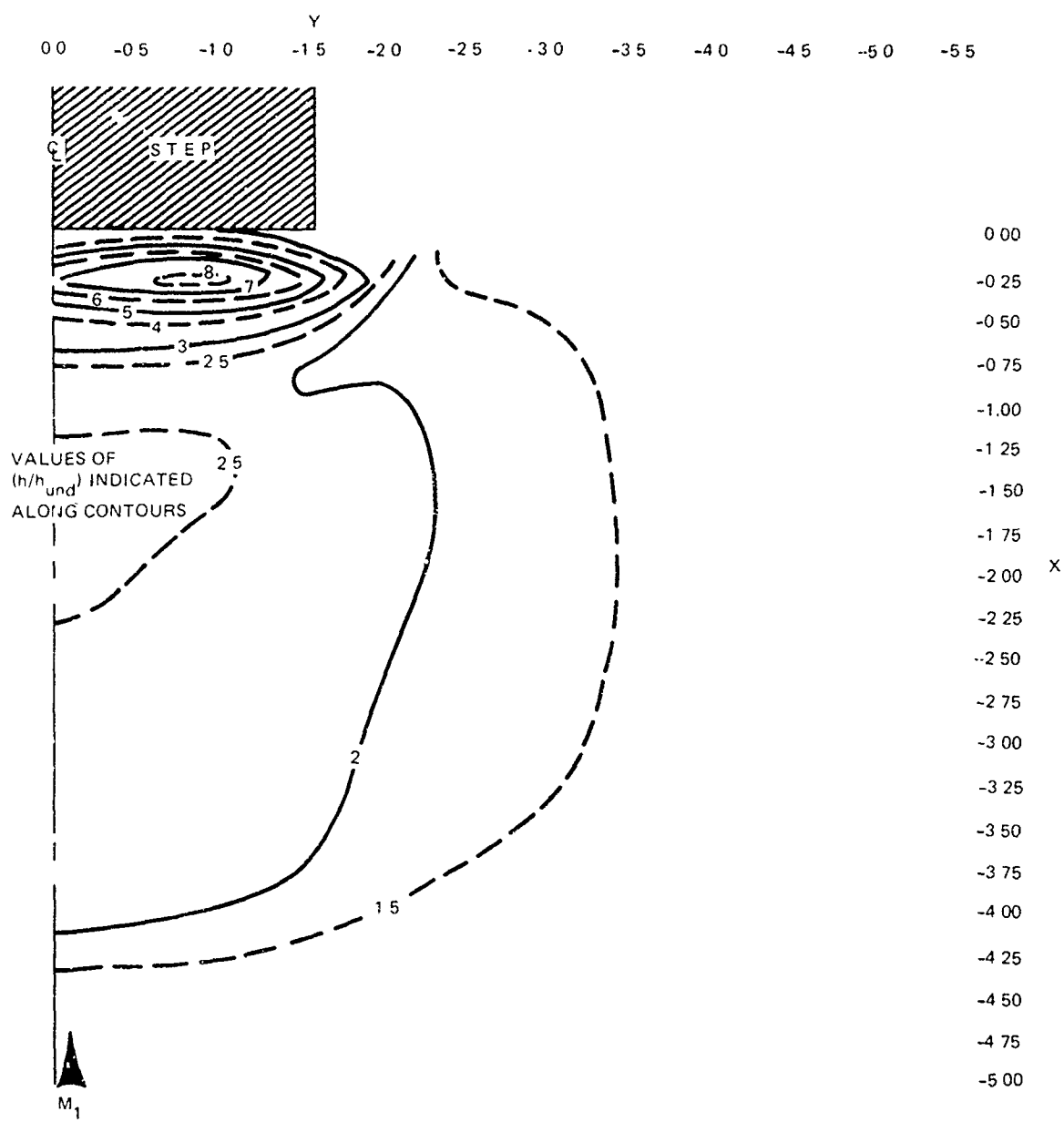


Figure 32 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 3-inch Span Step for  $M_1 = 4.75$



Figure 33 Profile Schlieren Photograph of  $M_1 = 4.75$  Flow Ahead of 5-inch Span Step

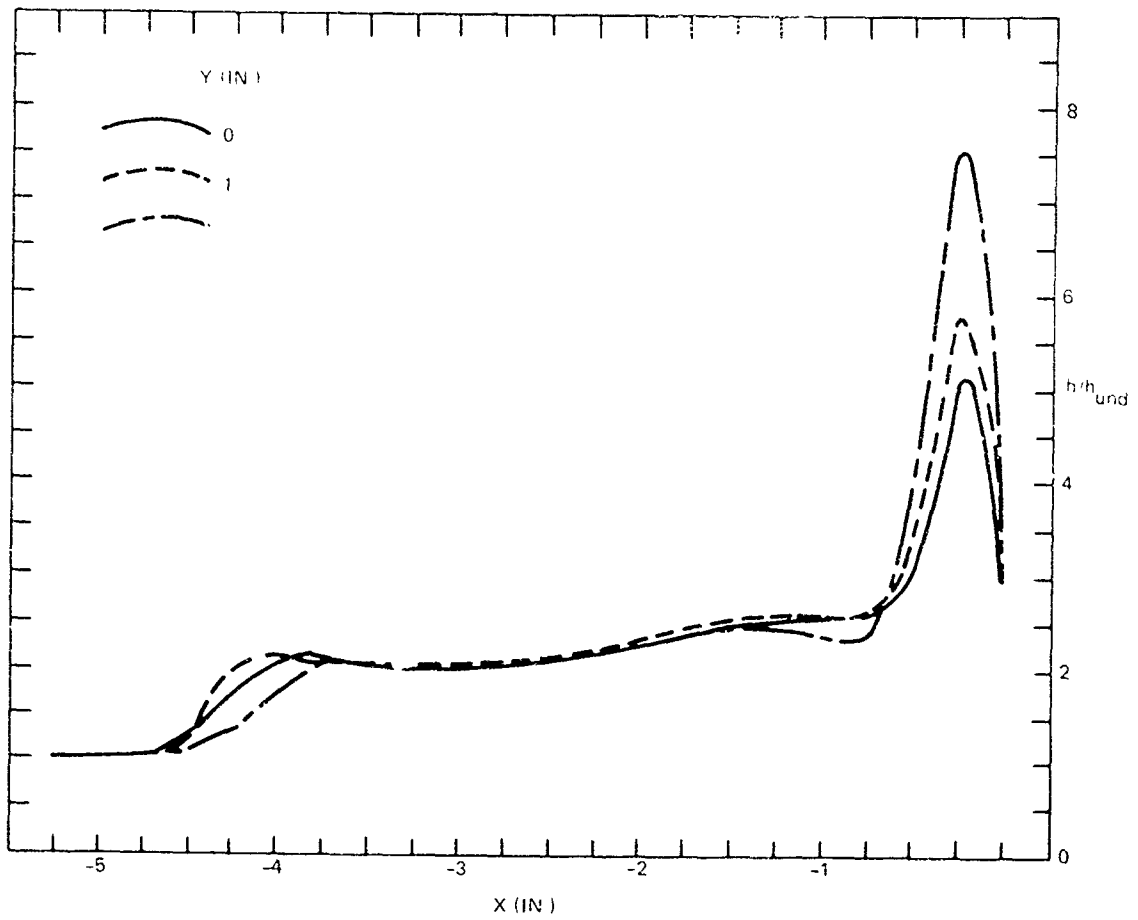


Figure 34 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for  $M_1 = 4.75$  Flow Ahead of 5-inch Span Step

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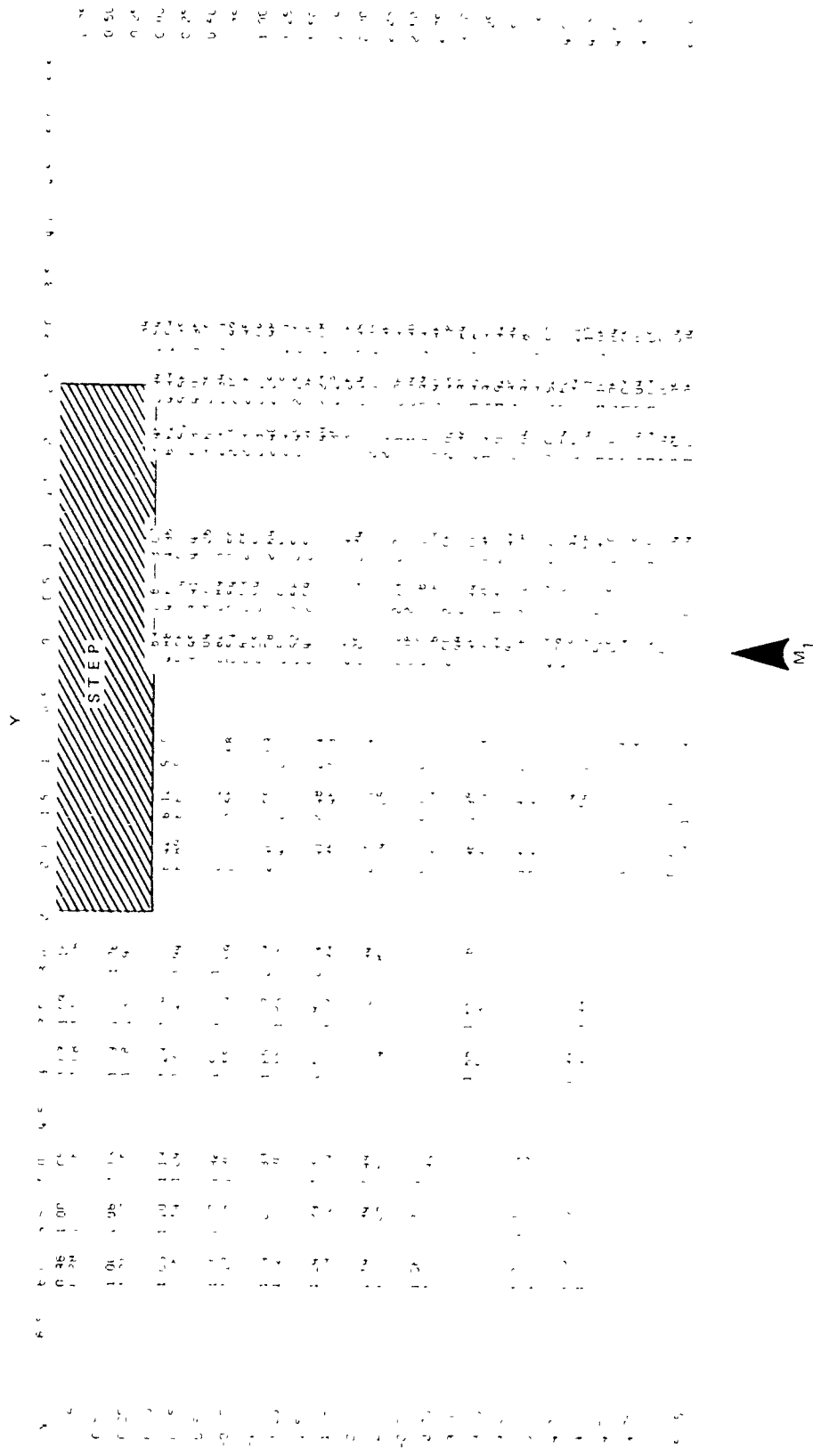


Figure 35 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 5-inch Span Step for  $M_1 = 4.75$

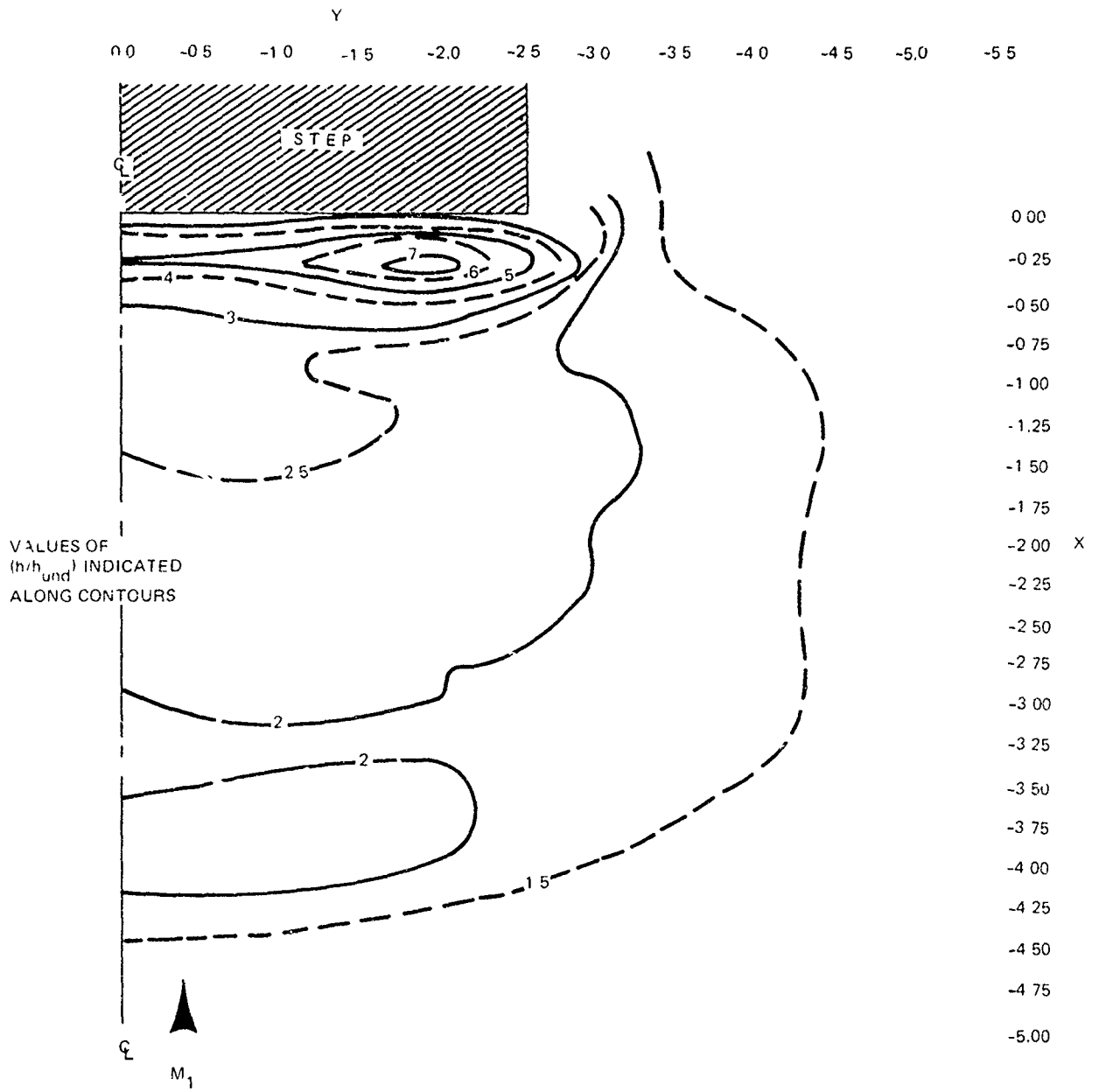


Figure 36 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 5-inch Span Step for  $M_1 = 4.75$



Figure 37 Profile Schlieren Photograph of  $M_1 = 4.75$  Flow Ahead of 7-inch Span Step

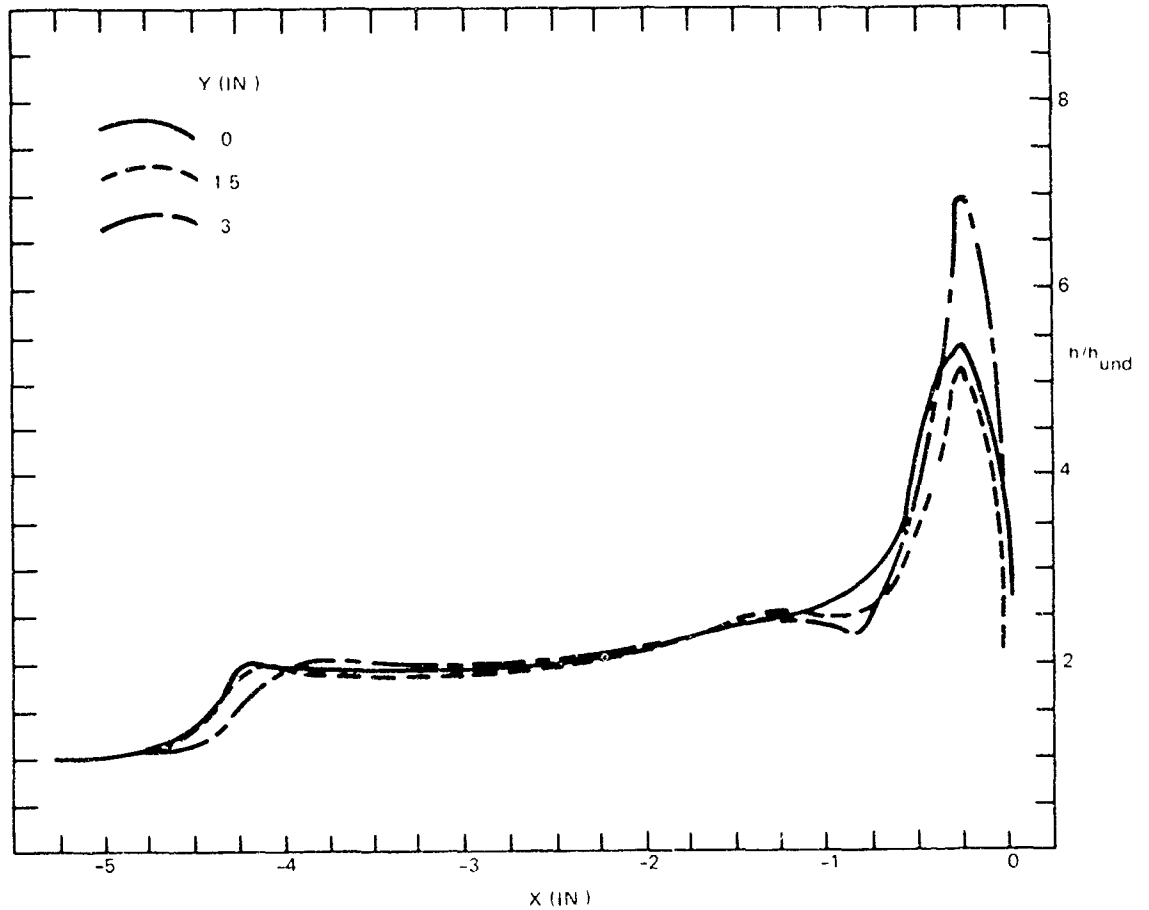


Figure 38 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for  $M_1 = 4.75$  Flow Ahead of 7-inch Span Step.

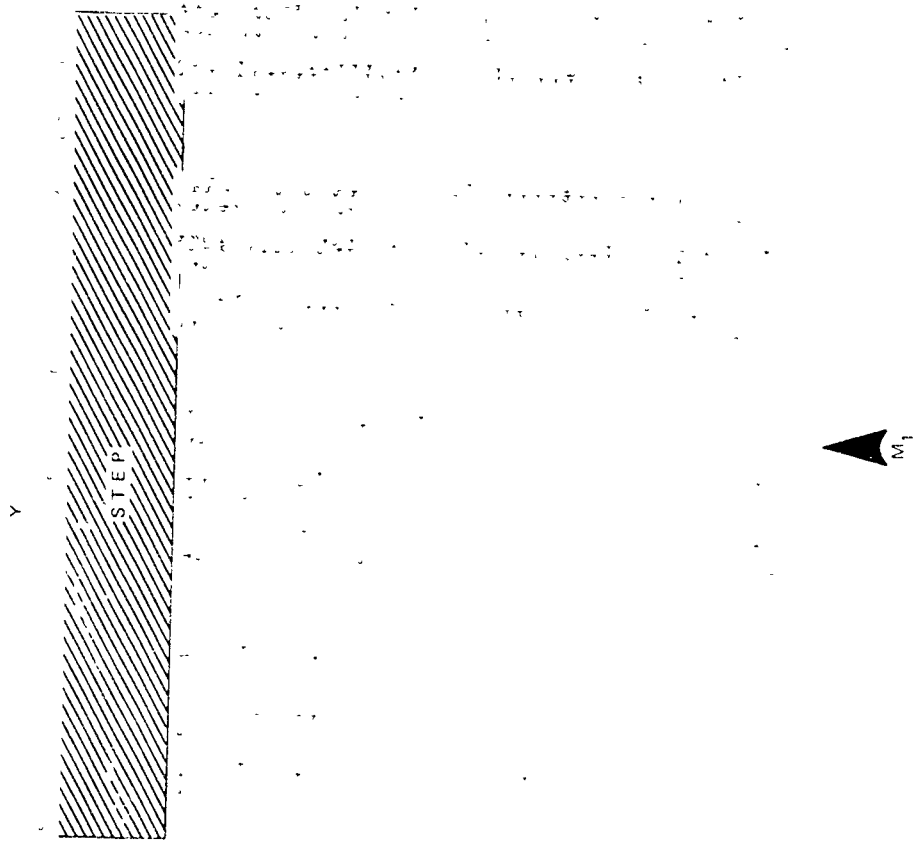


Figure 39 Distribution of Heat Transfer Coefficient Ratios on Surface Ahead of 7-inch Span Step for  $M_1 = 4.75$

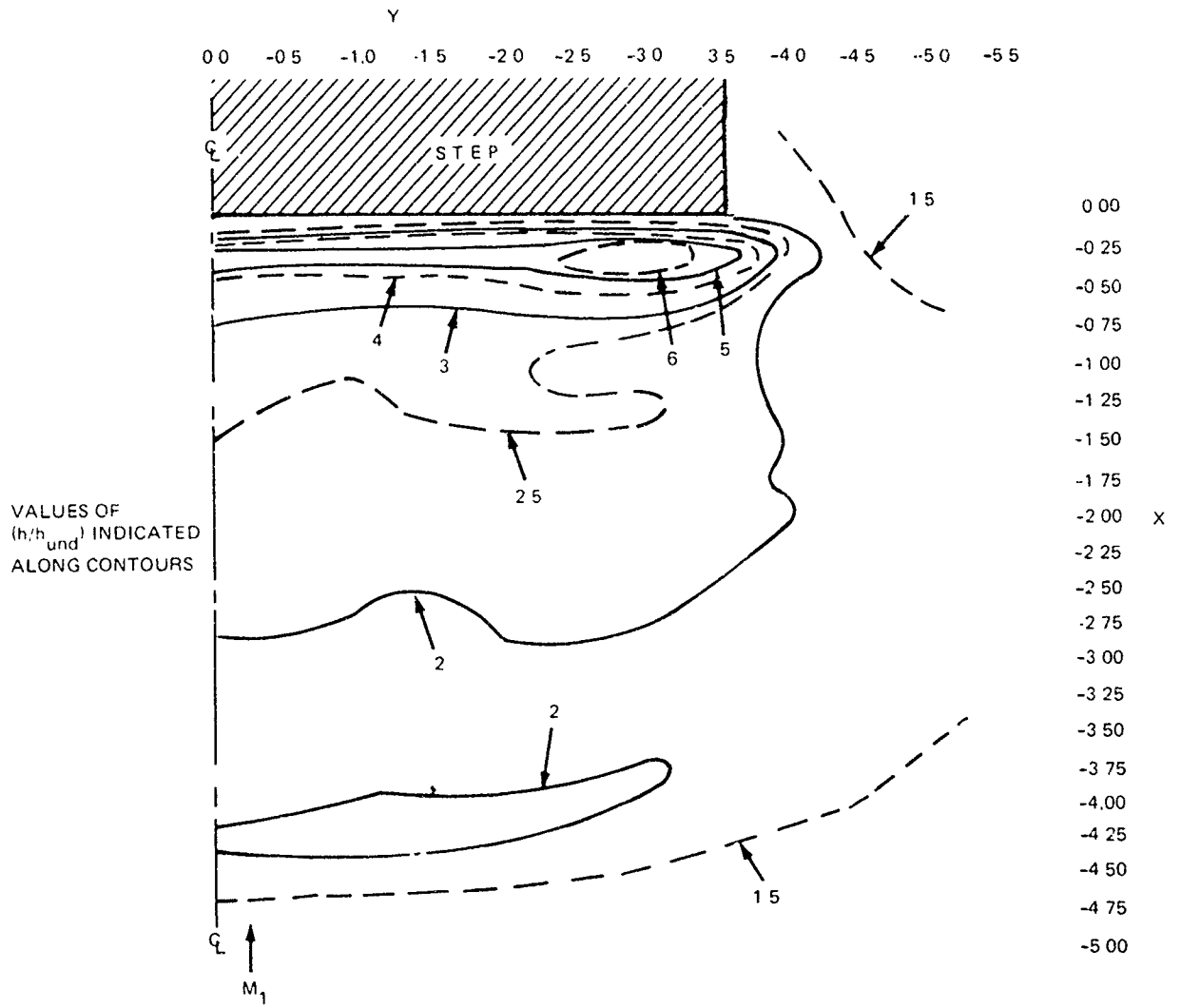


Figure 40 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 7-inch Span Step for  $M_1 = 4.75$



Figure 41 Profile Schlieren Photograph of  $M_1 = 4.75$  Flow Ahead of 10-inch Span Step

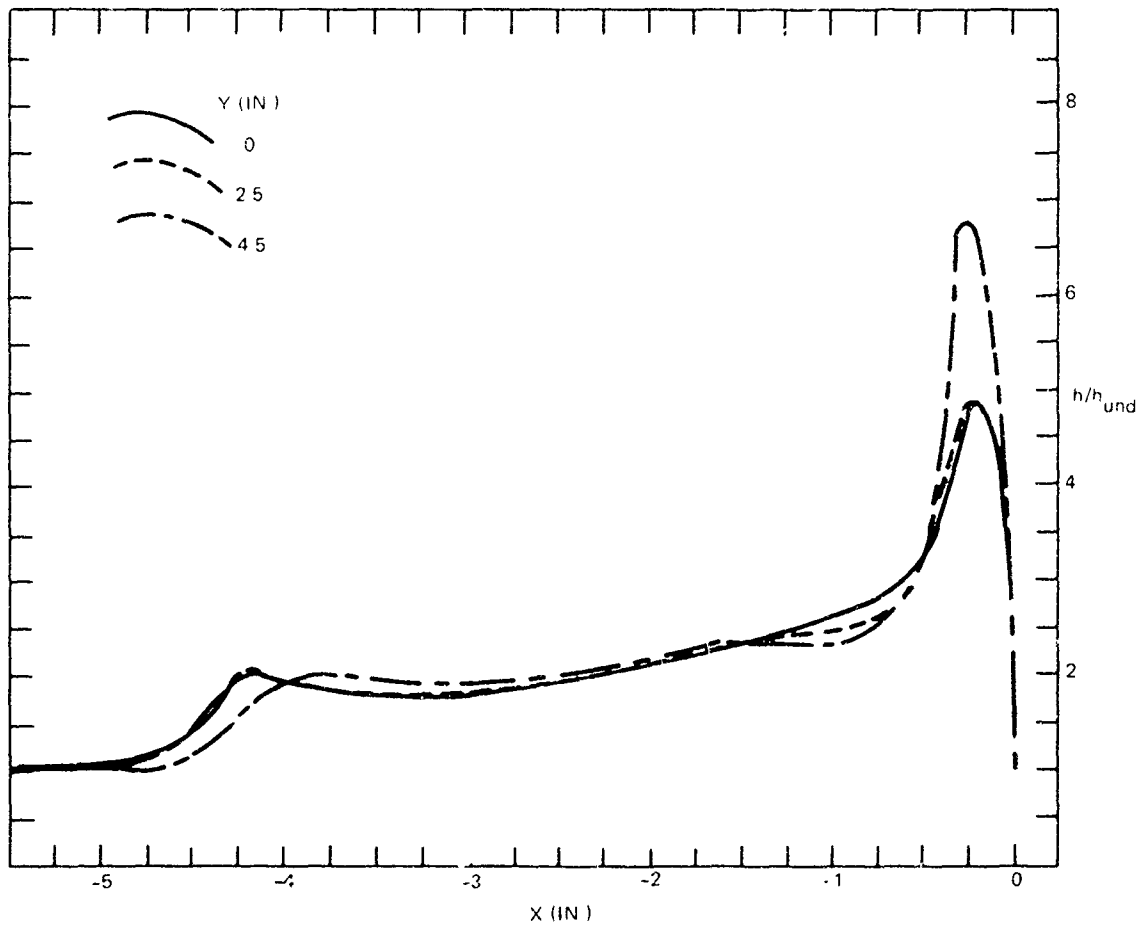


Figure 42 Streamwise Distributions of Heat Transfer Coefficient Ratios on Plate Surface for  $M_1 = 4.75$  Flow Ahead of 10-inch Span Step



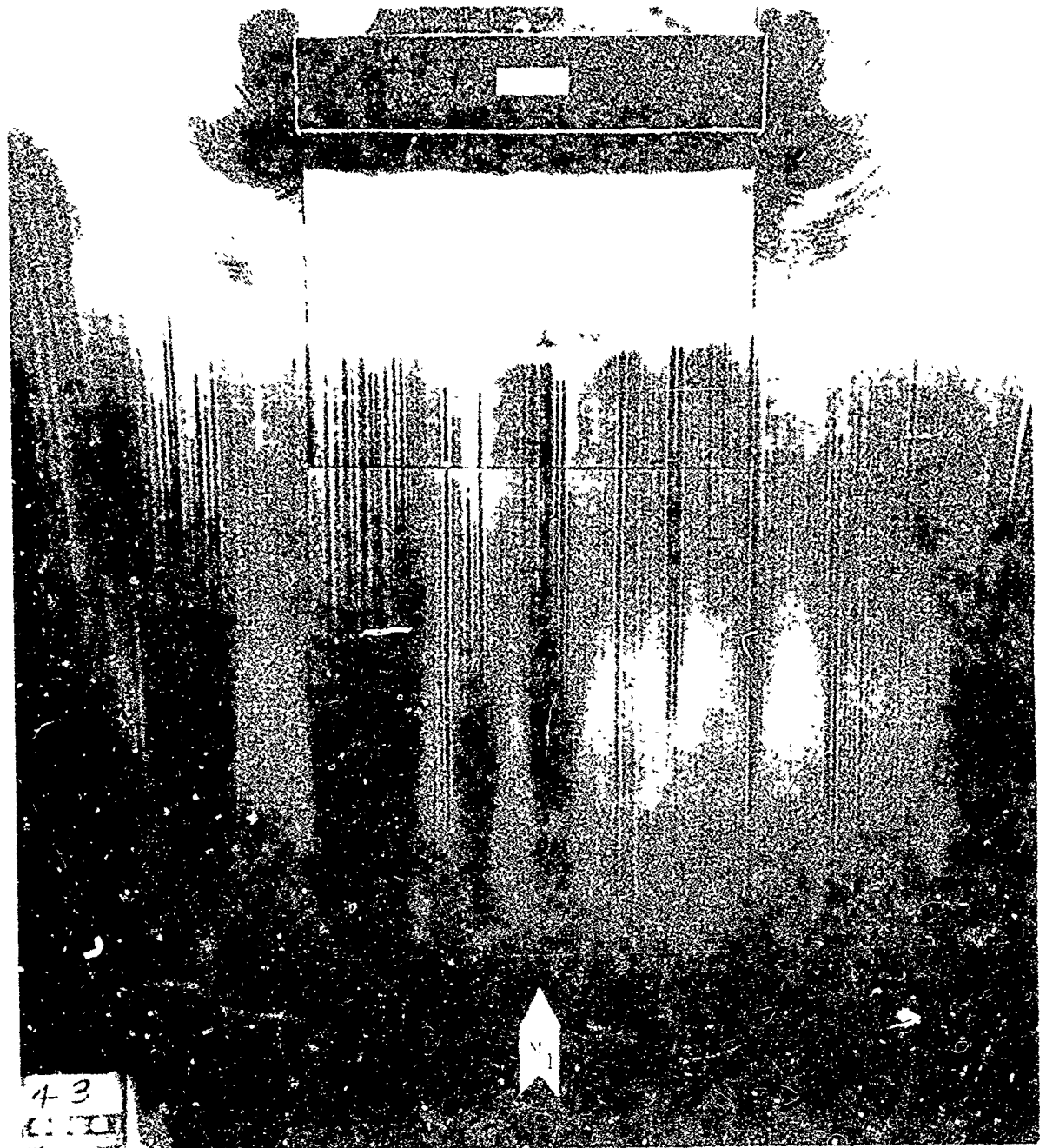


Figure 43 Frame from Motion Picture Shazam! (1941) showing Surface Area of the Window Spacing for M<sub>1</sub> 4.75

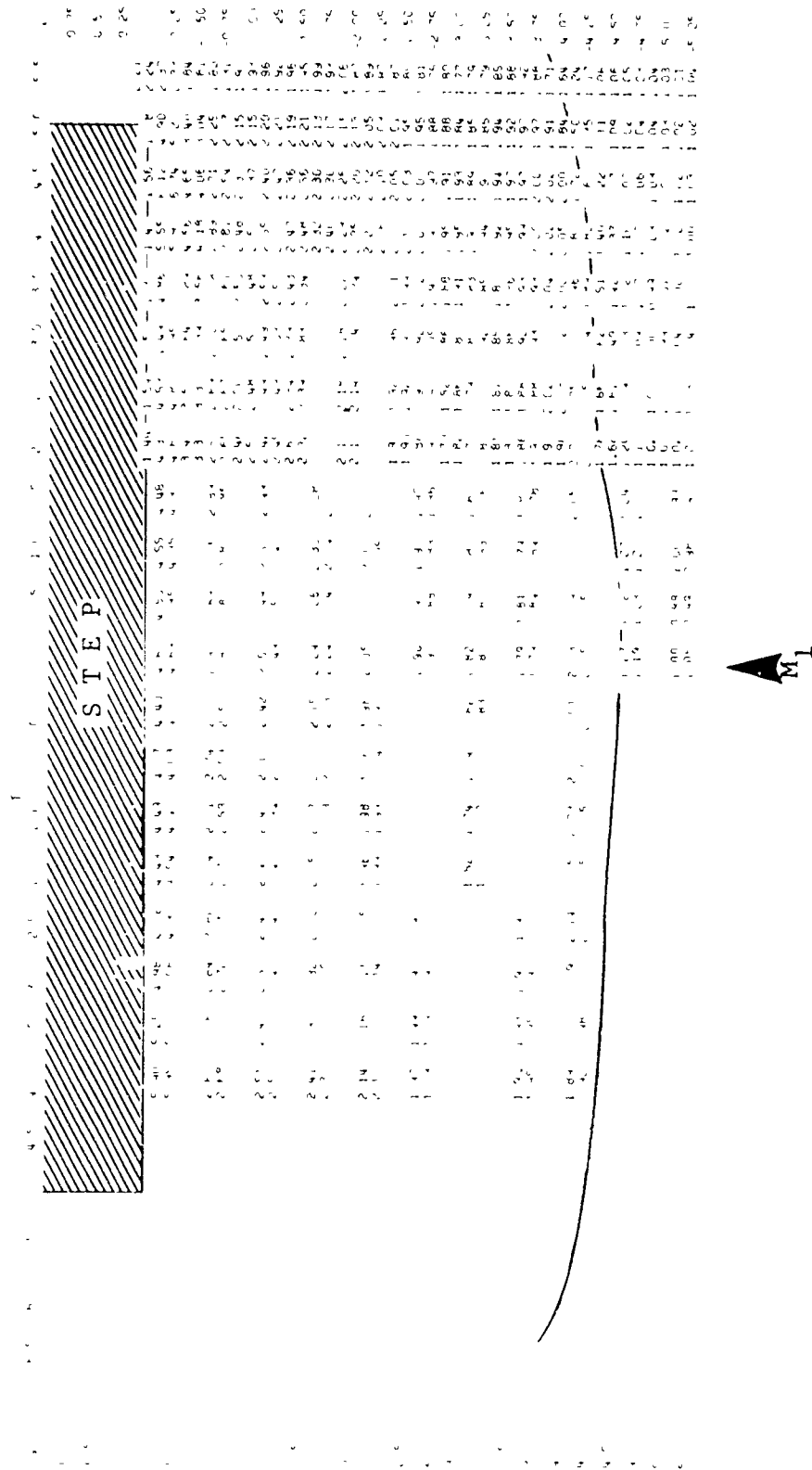


Figure 44 Distribution of Heat Transfer Coefficient Ratios  $(h/h_{und})$  on Surface Ahead of 10-inch Span Step for  $M_1 = 4.75$

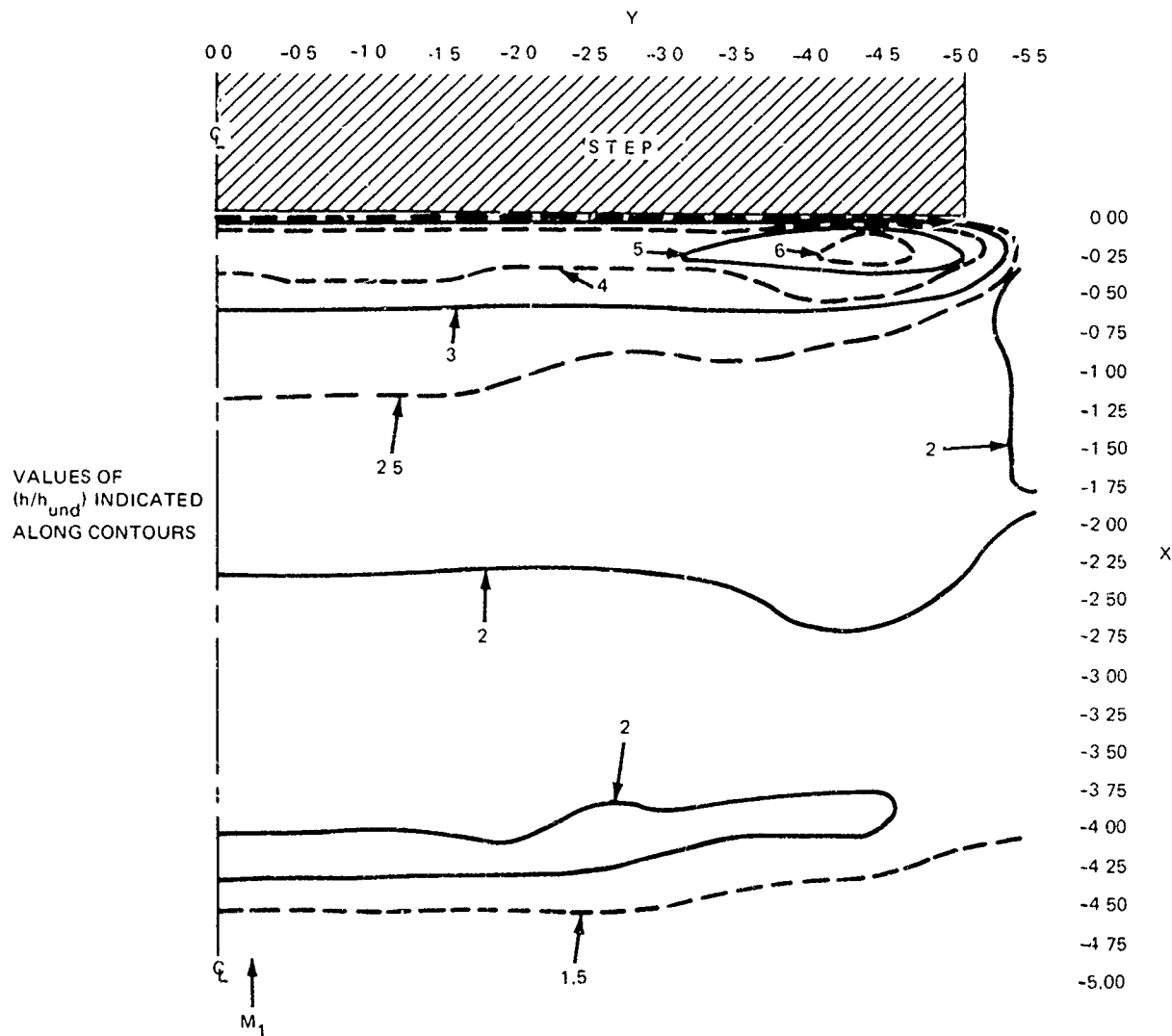


Figure 45 Lines of Constant  $(h/h_{und})$  Contours on Surface Ahead of 10-inch Span Step for  $M_1 = 4.75$

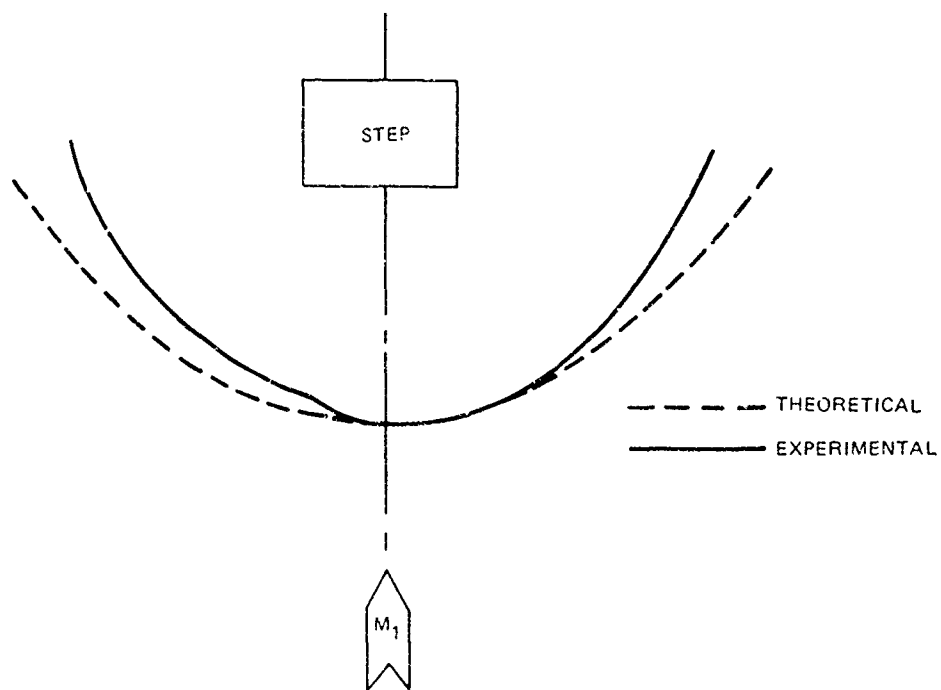


Figure 46 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 3-inch Span Step for  $M_1 = 5.04$

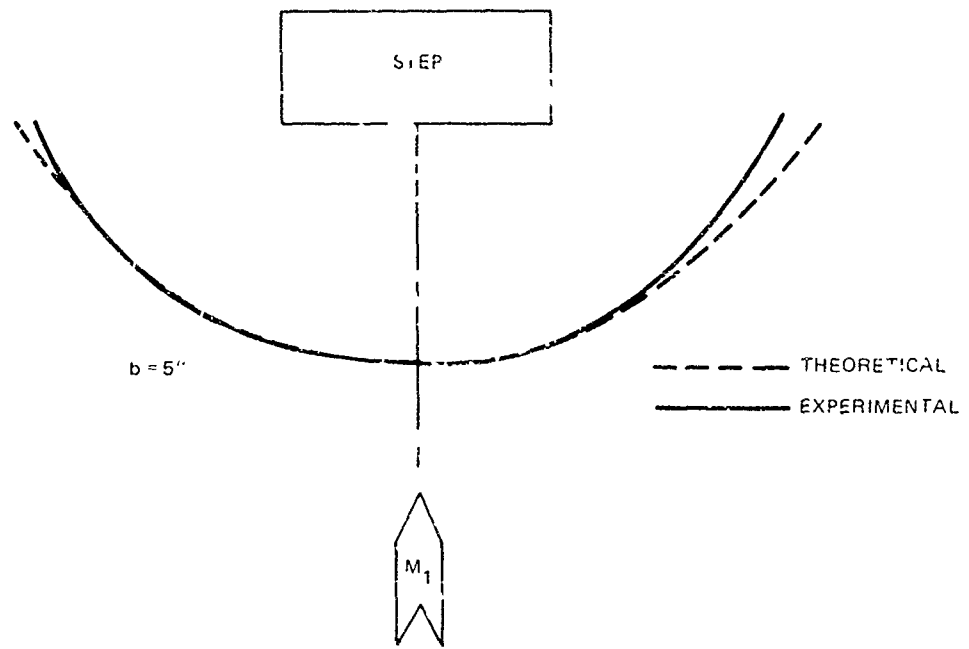


Figure 47 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 5-inch Span Step for  $M_1 = 5.04$

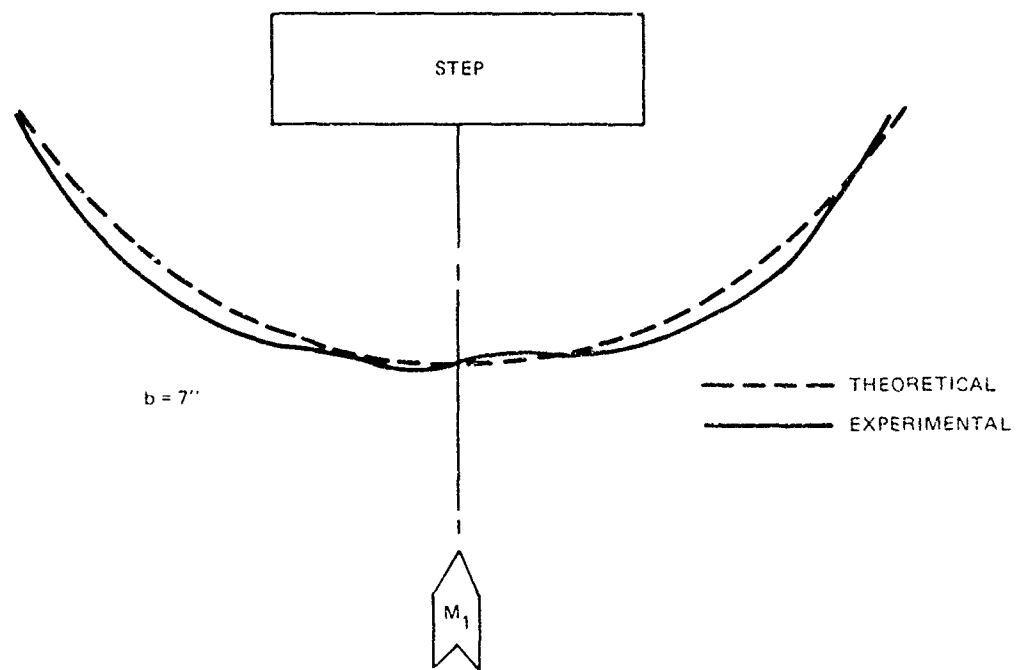


Figure 48 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 7-inch Span Step for  $M_1 = 5.04$

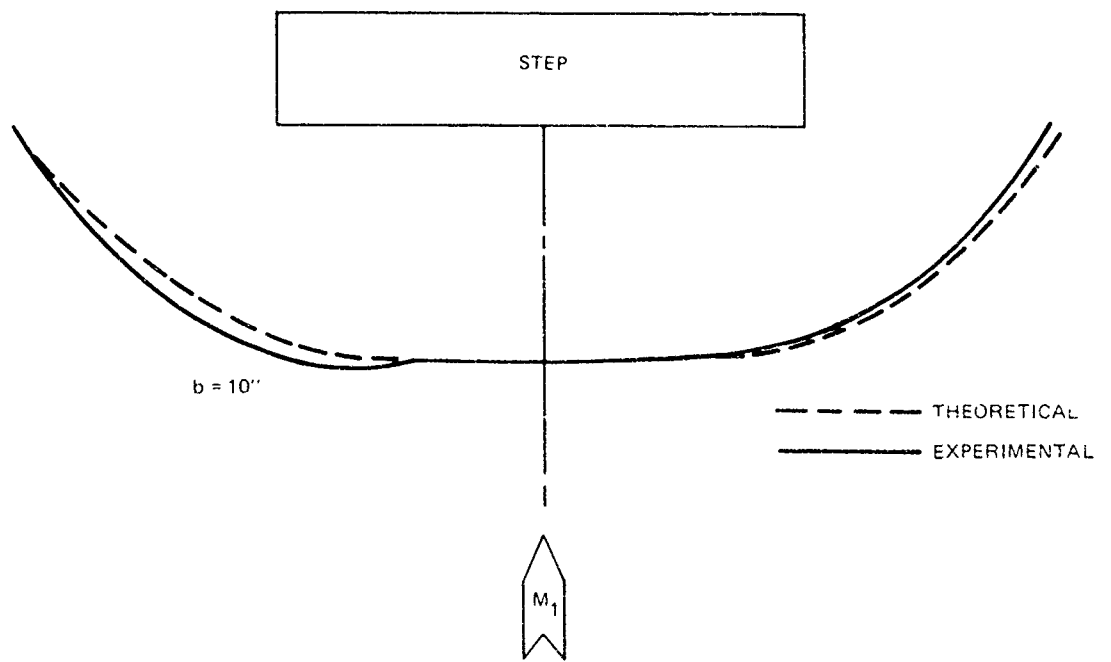


Figure 49 Comparison of Predicted and Experimental Separation Lines on Surface Ahead of 10-inch Span Step for  $M_1 = 5.04$

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