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TECHNICAL NOTE

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A VISUAL TECHNIQUE FOR DETERMINING QUALITATIVE AERODYNAMIC HEATING RATES ON COMPLEX CONFIGURATIONS

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A VISUAL TECHNIQUE FOR DETERMINING QUALITATIVE AERODYNAMIC HEATING RATES ON COMPLEX CONFIGURATIONS

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SUMMARY

An experimental investigation was conducted at a test-section Mach number of 4.95 and a stagnation temperature of 400° F to evaluate a visual technique for obtaining qualitative aerodynamic heat-transfer data on complex configurations. This technique utilized a temperature-sensitive paint which exhibited the characteristic that a pronounced color change occurred at a known temperature.

The visual results obtained with the temperature-sensitive paint indicated that this technique was satisfactory for determining qualitative heat-transfer rates on various bodies, some of which exhibited complex flow patterns. The results obtained have been found useful to guide the instrumentation of quantitative heat-transfer models, to supplement quantitative heat-transfer measurements, and to make preliminary heat-transfer studies for new configurations.

INTRODUCTION

The design of hypersonic vehicles which are exposed to high aerodynamic heat fluxes requires detailed knowledge of local heat-transfer parameters. Many of the proposed hypersonic configurations are composed of components which result in complex flow patterns for which no reliable analytical analysis is available and for which the measurement of heat-transfer data is often difficult. In order to help simplify the collection of heat-transfer data on complex configurations, a visual technique for obtaining qualitative heating rates has been investigated. This technique employs a temperature-sensitive paint which exhibits a pronounced color change at a known temperature. The early development, use, and evaluation of this paint is discussed in reference 1.

Descriptions of the use of temperature-sensitive paint are given in references 1 to 3; these references indicated that the paint has been used extensively for various heat-transfer investigations. The present investigation, however, applied the method to a heat-transfer problem by utilizing a technique which apparently had not been considered previously.

The purpose of this report is to discuss the general characteristics of the paint and the technique used to obtain qualitative aerodynamic heating rates and to present some of the results obtained with this
technique. The investigation was conducted at a nominal Mach number of L
4.95 and a stagnation temperature of 400° F. The test-section unit 6
Reynolds numbers were 3.39×10^6 and 15.19×10^6 per foot. 6
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SYMBOLS

q aerodynamic heat-transfer rate

q' aerodynamic heat-transfer rate at $\frac{s}{R} = 2.02$ and $\alpha = 0^\circ$

s distance along model measured from the stagnation point at $\alpha = 0^\circ$

R body radius of model

α angle of attack of model center line

θ circumferential distance around model; $\theta = 0$ at most windward generator

DISCUSSION OF TECHNIQUE

Models

In order to evaluate the temperature-sensitive-paint technique, the following models were constructed and tested: (1) an X-15 airplane, (2) a Project Mercury reentry capsule, and (3) a 79.5° swept delta wing.

The models were made from Paraplex and fiberglass by forming in a suitable mold. Paraplex was used as a base material because of its desirable working and acceptable insulating qualities. Since a transient heating technique was employed to test the models, it was important to use a material with a low thermal diffusivity in order to reduce the heating time (testing time) and the effects of lateral conduction.

Short testing times are necessary so that the model heating characteristics will be similar to those of a semi-infinite slab. This condition insures that each point on the model surface is heated at a rate which is independent of the local model thickness. Lateral conduction should be small to prevent the temperature at a given point in the model from being influenced by the temperature at adjacent points.

Description of Temperature-Sensitive Paint

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The visual technique used for obtaining qualitative aerodynamic heat-transfer rates employed a temperature-sensitive paint* which exhibited the characteristics that a pronounced color change occurred at a known temperature. A large group of paints which exhibit either single- or multiple-color changes are available. The temperatures at which these paints change color range from approximately room temperature to about 3,000° F. The multiple-color-change paint has the characteristic that successive changes occur at discrete temperatures as the paint is heated. The color changes for most paints are permanent; however, a few paints exhibit color changes that are temporary. It should be noted that, in general, the temperature at which the temperature-sensitive paints change color is time dependent; the shorter the time required for a color change to occur, the higher the indicated temperature.

For the present investigation, a multiple-color-change paint was used. It was initially believed that the color changes in the lower temperature ranges would be the easiest to note and record for this paint. Also, when the investigation was being contemplated, little was known about the temperature-sensitive paints; therefore, it was deemed desirable to use a multiple-color-change paint which would be useful in the temperature range available with the facility to be used. Calibration curves (from ref. 4) for the paint are presented in figure 1. A more detailed description of this paint may be obtained from the distributor.

Because of the short testing time and the low stagnation temperature used, only the first color change was obtained. The following discussion therefore is limited to the characteristics of the paint and its first

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*The temperature-sensitive paint, which carried the trade name "Thermocolor" (presently sold under the label "DetectoTemp"), was procured from the Curtiss-Wright Corporation, Princeton Division.

color change. The color changes for the paint used in the present investigation are permanent; however, if the paint was exposed to room conditions for long periods prior to or after testing, the color would tend to fade. The amount of fading appeared to be a function of the light intensity and the humidity of the air. The fading of the colors would not necessarily destroy the evidence of a color change after testing or prevent a color change from occurring on a model which had been painted for a long period prior to testing. This fading, however, destroyed much of the contrast between the two colors and the photographic recording of the colors was sometimes difficult, if not impossible, to obtain on black and white film. (A red filter was used with some success to photograph the models which had faded.) Inasmuch as this fading characteristic of the paint was not noted until near the end of the present investigation, the photographs presenting the results are not very satisfactory. For future tests, it is recommended that the paint used should be recently mixed and applied to the model and directly thereafter tested and photographed.

The influence of variable paint thickness on qualitative heat-transfer results is unknown but it is believed that the effects are small for normal variations in paint thickness. For this investigation, every effort was made to obtain a smooth, thin uniform coating that would permit photographic recording of a color change and yet eliminate the effects of paint thickness and paint surface conditions on the results. The paint was applied to the models with an artist's air brush. If the sprayed surface was rough, it was smoothed either by hand rubbing or by brushing with a cotton swab. Even with these procedures, it was sometimes difficult to obtain a perfectly smooth, uniform coating on models with sharp edges or corners. The paint surface, so obtained, was soft and "powdery" and could not be used for aerodynamic testing. In order to overcome this difficulty, a high-temperature silicone lacquer, available from the paint distributor, was sprayed over the painted surfaces to bond the paint pigment to the model surface. The bonding provided by the lacquer proved to be satisfactory except in the stagnation regions.

Test Procedure

Testing of the models was conducted in the Gas Dynamics Branch of the Langley Research Center in a 9-inch axially symmetric blowdown jet at a nominal Mach number and stagnation temperature of 4.95 and 400° F, respectively. The test-section unit Reynolds numbers were 3.39×10^6 and 15.19×10^6 per foot.

Testing was performed by the transient heating method. This was accomplished by bringing the jet to the desired operating conditions with the model outside the test section. After steady operation was obtained, a vertical door in the test section was retracted and the isothermal model, which was mounted on a second door actuated by a horizontal pneumatic cylinder, was inserted into the test section. The model remained in the test section until the desired color change occurred. The minimum testing time, governed by the time response of the actuating mechanism, was about 1.5 seconds. The maximum testing time was governed by the time required to obtain the desired color change; this time never exceeded 8.0 seconds.

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The testing time was measured by recording the output of a dynamic-pressure gage, which measured test-section static pressure, on a multi-channel recorder. This method could be employed since the opening and closing of the doors in the test section resulted in a static-pressure change within the test section. The transient time required to inject the model into and to retract it from the test section was about 0.1 second. This time was assumed to have a negligible effect on the color change of the paint since the time was less than 10 percent of the total heating time for the minimum testing time employed.

DISCUSSION OF RESULTS

The results of the present investigation are presented in figures 2 to 5. In figures 2 to 4, the first part of the figure shows the model prior to testing. The subsequent photographs present the model after testing at various conditions. The dark areas in the photographs indicate regions where the temperature-sensitive paint changed color (from pink to blue); therefore, the dark regions represent areas with higher heating rates than the light areas. Although the paint used throughout this investigation was a multiple-color-change paint, only one color change was experienced as a result of the short testing times employed and the low stagnation temperature used.

Recording the color change of the paint on black and white film was complicated by the fact that the gray tone values of the two colors were very similar, especially when the paint had faded. A color change was sometimes obscured by highlights and shadows; this condition could lead to possible ambiguity in interpreting the black and white film records. This difficulty does not occur when the results are examined visually or when recorded on color film. An example of the results recorded on color film is presented in figure 5. In this figure the model shown in figure 2(e) is repeated in color.

The boundary between the light (pink) and dark (blue) areas on the photographs represents lines of constant temperature; however, the exact temperatures of these isotherms are unknown since a sufficiently accurate time scale was not available. Care should be exercised when comparing the results of one photograph with those of another since a difference in testing time can alter any conclusions that might be deduced from the comparison as a result of the time dependency of the color change of the paint.

The results obtained with the X-15 are presented in figures 2(b) to 2(f). Several areas with higher heating rates than the general level were evident as shown by the dark areas emanating from the canopy, wing-fuselage junction, and the vertical and horizontal stabilizer-fuselage junction. Also, the high heat-transfer rates associated with the apex of three-dimensional bodies and leading edges of wings are shown. (Sometimes the color change in the vicinity of the apex was obscured in the photographs as a result of highlights in this region.)

Figure 2(b) presents the results obtained in the shortest testing time used with the X-15 model at an angle of attack of 0°. From this figure it is evident that the primary high heat-transfer regions occurred at the apex of the fuselage and the leading edges of the wing and tail assembly. As the testing time was increased (see fig. 2(c)), other high heat-transfer regions are indicated. These secondary high heat-transfer regions have lower heating rates than the areas shown in figure 2(b) as evidenced by both the longer time required to obtain the color change and the known time dependency of the color change of the paint. Still longer testing times (see fig. 2(d)) reveal high heating rates of tertiary importance. It should be noted that the actual magnitudes of the differences between the heating rates noted above were unknown and the arbitrary notation of primary, secondary, and tertiary was used for discussion purposes only. The changes in the temperature-sensitive-paint pattern at successive times suggest the use of a motion-picture camera to map the isotherms on a complex configuration at known times. This information could be used for quantitative evaluation of heat-transfer rates. An evaluation of the quantitative use of the paint was considered beyond the scope of this investigation. Several methods can undoubtedly be devised to reduce the time and temperature data to heat-transfer coefficients. All of these methods will involve the difficulties common to any heat-transfer measurements; for example, an evaluation of the material properties of the model and the avoidance or accounting for conduction and losses must be made. In addition, the fact that the temperature at which the color change occurs depends on the time rate of temperature change will require further study of the paints themselves to determine accurate calibrations over the range of heating rates to be studied on a model.

The upper surface of the X-15 model in figure 2(d) is particularly interesting since it indicates the existence of a very complex flow pattern around the canopy which resulted in higher localized heating rates on the fuselage than the general level. There probably is no other simple testing device which could reveal these results so vividly and in such detail. Figure 2(f) is of interest since it indicates that a shock, apparently from the apex of the fuselage, crossed the wing at the location indicated by the dark lines near the wing tips.

Quantitative heat-transfer measurements (unpublished) have been made on a model of the X-15 at approximately the same Mach number as the present investigation. The qualitative pattern of relative heating rates indicated by the temperature-sensitive paint was consistent with the quantitative measurements. However, the temperature-sensitive paint indicated details of the heat-transfer pattern that could not be shown by the thermocouple spacing used on the quantitative model.

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The results obtained with the Project Mercury reentry capsule are presented in figure 3. The results presented reveal, in addition to the high heating rate on the forward portion of the capsule, high heat-transfer regions on the capsule afterbody. (In fig. 3 the nose of the capsule sometimes appears to be much lighter than the base area. This effect was due to highlights on the model and to the white material from which the model was made showing through the damaged painted surface.) As a result of the indicated high heat-transfer rate to the base of the capsule, the NASA Space Task Group fabricated and tested a quantitative heat-transfer model.

A representative plot of the measured heat-transfer data is presented in figure 3(e) for $\alpha = 10^{\circ}$. A comparison between figures 3(d) and 3(e) can be made by dividing the heating rates of 3(e) into two regions as determined from the qualitative results presented in figure 3(d). The region above a certain heating rate will represent areas on the model for which a color change was experienced; the area below will represent areas where the color did not change. This division is noted in figure 3(e) by the line at $\frac{q}{q'} = 0.44$ which was chosen to fit the location of the color change on the 180° meridian. The comparison made in this manner indicated that the temperature-sensitive paint revealed a detailed variation of the heating rate on the afterbody that was in good agreement with the thermocouple data. The line of demarcation would, of course, have been at a different value of q/q' for a different testing time or choice of paint.

The results obtained with a 79.5° swept delta wing are presented in figure 4. These results indicated high heating regions at the apex and the leading edges of the model. Two high heating regions were also noted in the upper surface which were apparently caused by vortices formed by the model apex. An interesting result is presented in figure 4(c). For this test a single roughness element apparently tripped the boundary layer and resulted in a high heat-transfer region indicated by the dark "wedgelike" region in the photograph.

CONCLUDING REMARKS

An experimental investigation was conducted at a test-section Mach number of 4.95 and a stagnation temperature of 400° F to evaluate a visual technique for obtaining qualitative aerodynamic heat-transfer data on complex configurations. The technique utilized a paint which has the characteristic that a pronounced color change occurs in the paint at a known temperature.

The results indicated that qualitative heat-transfer rates to various bodies, some of which exhibited complex flow patterns, could be obtained with the temperature-sensitive-paint technique with relative ease.

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The results obtained have been found useful to guide the instrumentation on quantitative heat-transfer models, to supplement quantitative heat-transfer measurements, and to make preliminary heat-transfer studies for new configurations.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., February 23, 1960.

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2. Stepka, Francis S., and Hickel, Robert O.: Methods for Measuring Temperatures of Thin-Walled Gas-Turbine Blades. NACA RM E56G17, 1956.

3. Petrick, Ernest N.: Metal Temperature Measurement With Detectotemps. Tech. Rep. No. 3-57-1, Curtiss-Wright Corp., Princeton Div., Mar. 1957.

4. Anon.: Calibration Curves for Temperature Indicating Colors, Detectotemp and Thermochrom. Rep. No. R-4a, Curtiss-Wright Corp., Princeton Div., July 1959.

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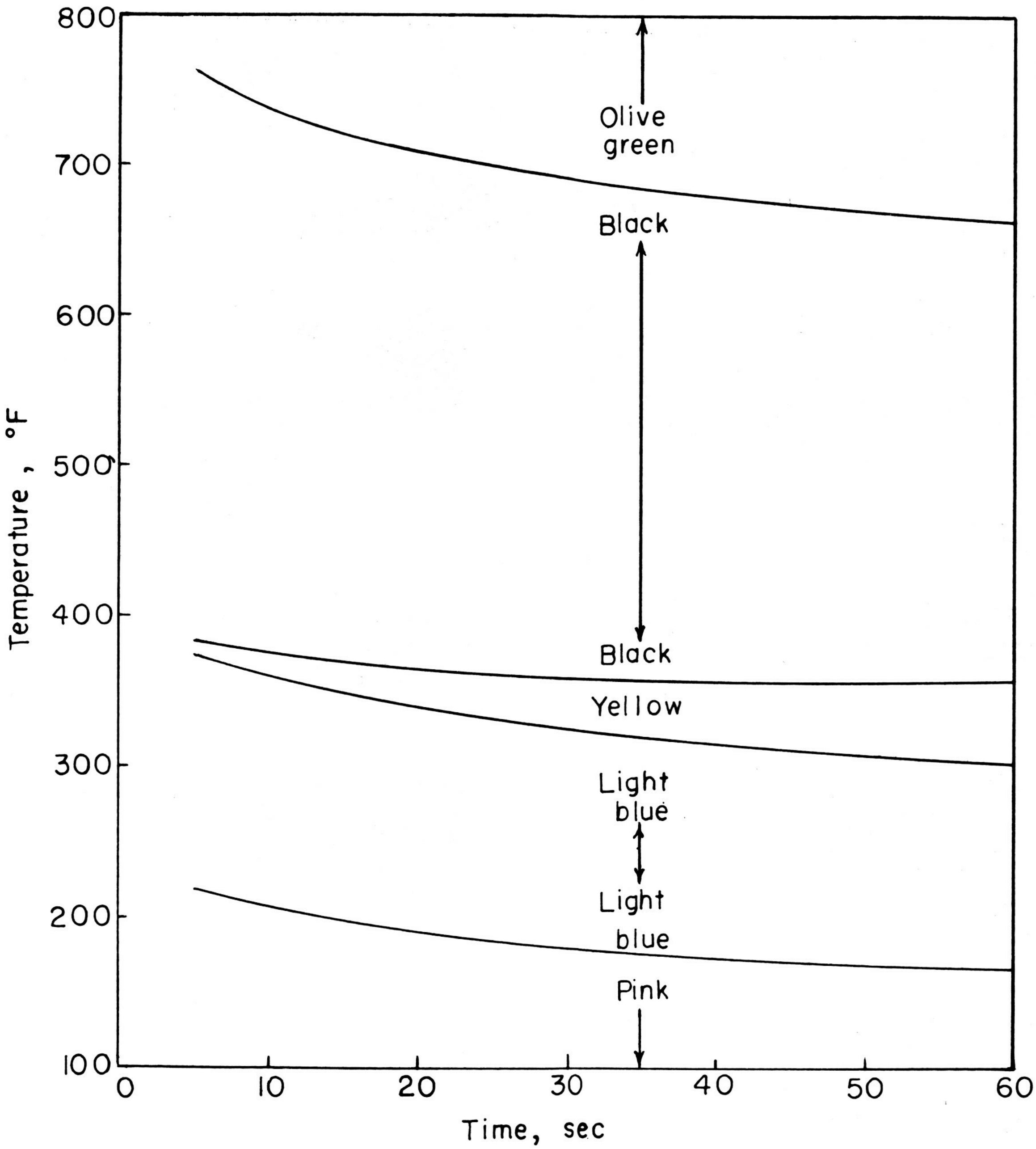
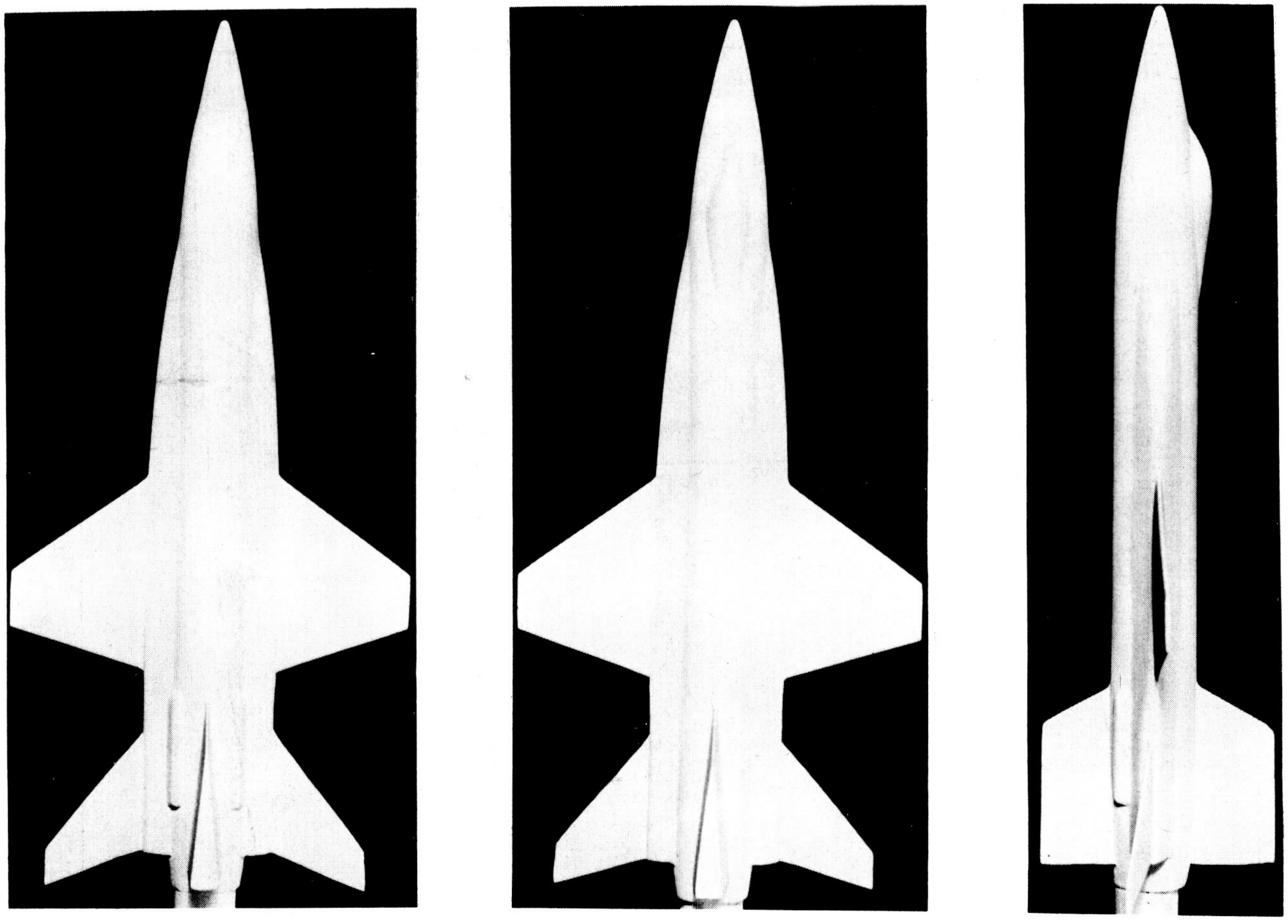


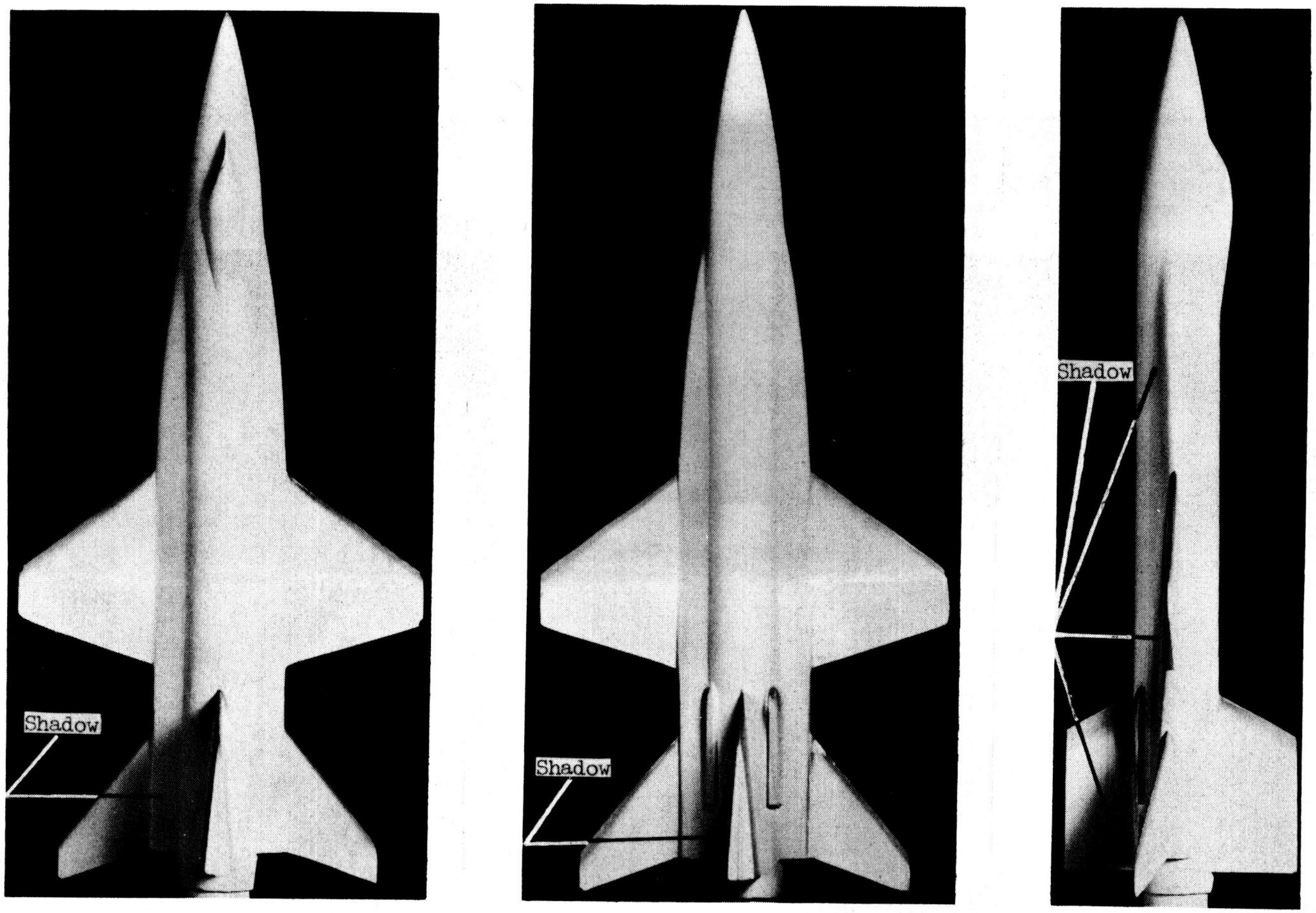
Figure 1 .- Calibration curve (from ref. 4) for the temperature-sensitive paint.



Bottom L-59-3793 Top L-59-3792 Side L-59-3790

(a) Model painted with temperature-sensitive paint prior to testing.

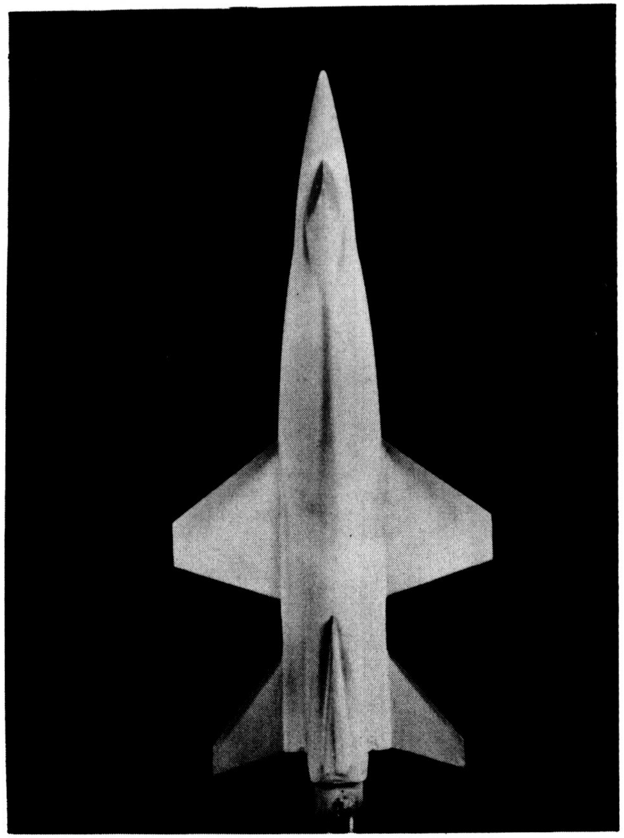
Figure 2 .- Results of temperature-sensitive paint investigations with X-15 model.



Top Bottom Side L-60-271

(b) Mach number, 4.95; angle of attack, 0°; Reynolds number (based on body length), 2.02×10^6; testing time, 3.78 sec; color change, pink to blue.

Figure 2 .- Continued.

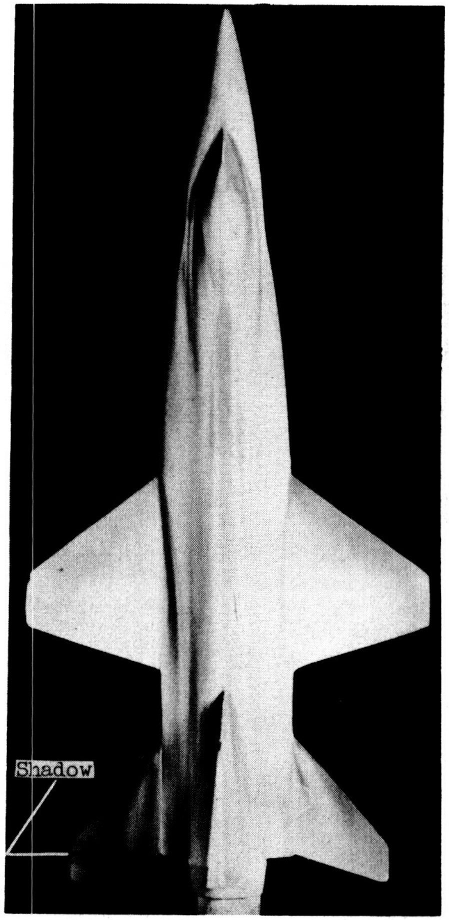


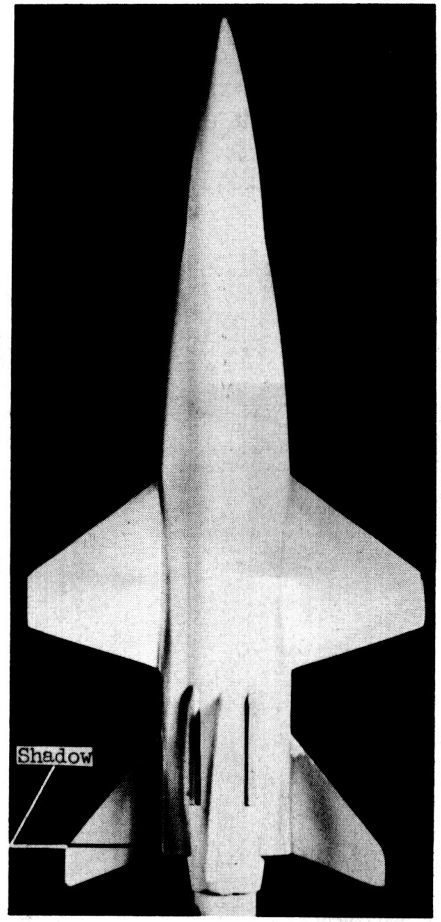
Top

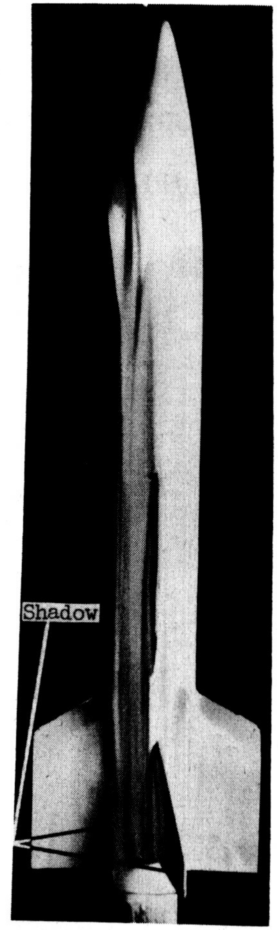
Bottom L-60-272

(c) Mach number, 4.95; angle of attack, 0°; Reynolds number (based on body length), 2.02×10^{6}; testing time, 6.00 sec; color change, pink to blue.

Figure 2 .- Continued.



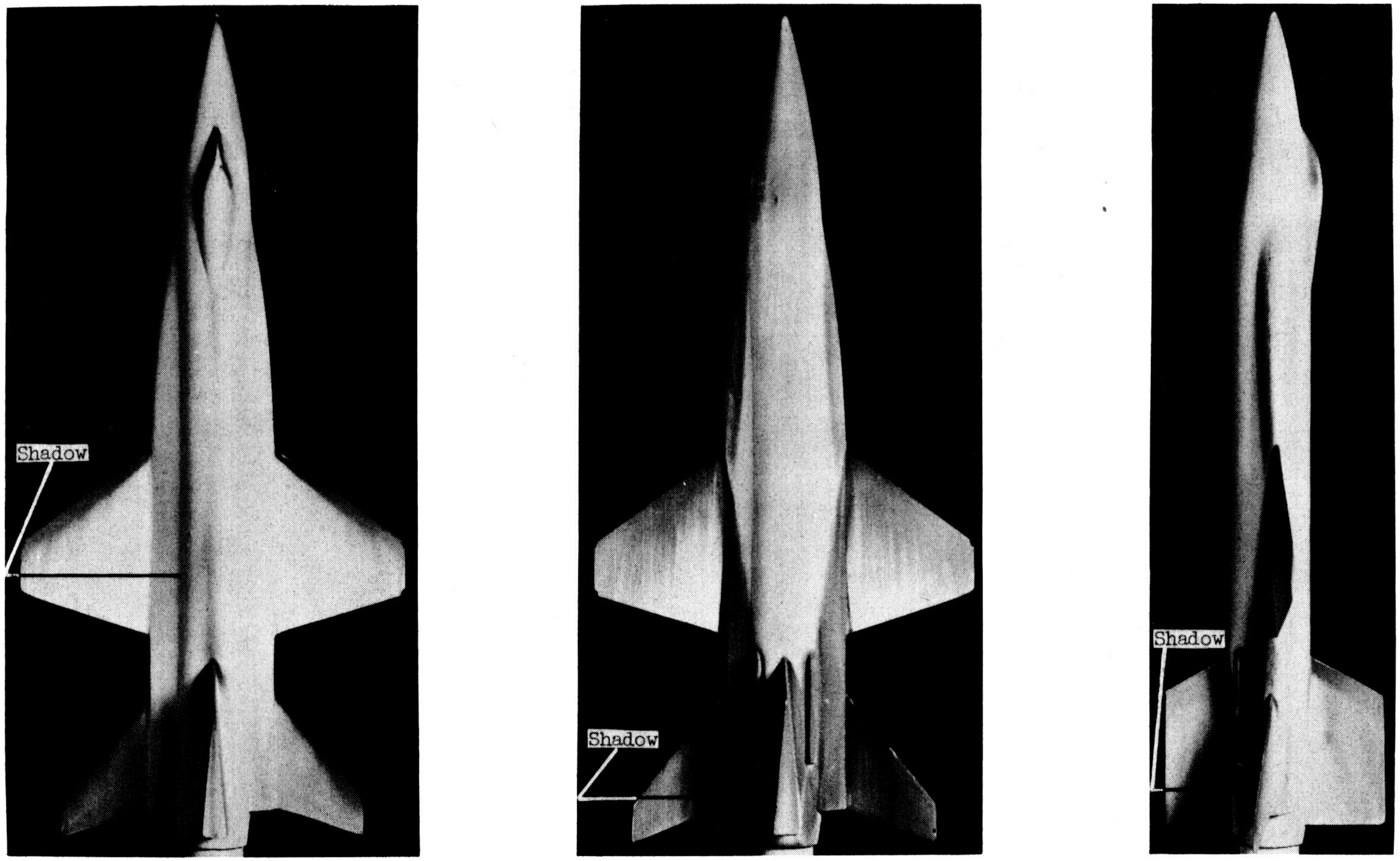




Top Bottom Side L-60-273

(d) Mach number, 4.95; angle of attack, 0°; Reynolds number (based on body length), 2.02×10^{6}; testing time, 7.06 sec; color change, pink to blue.

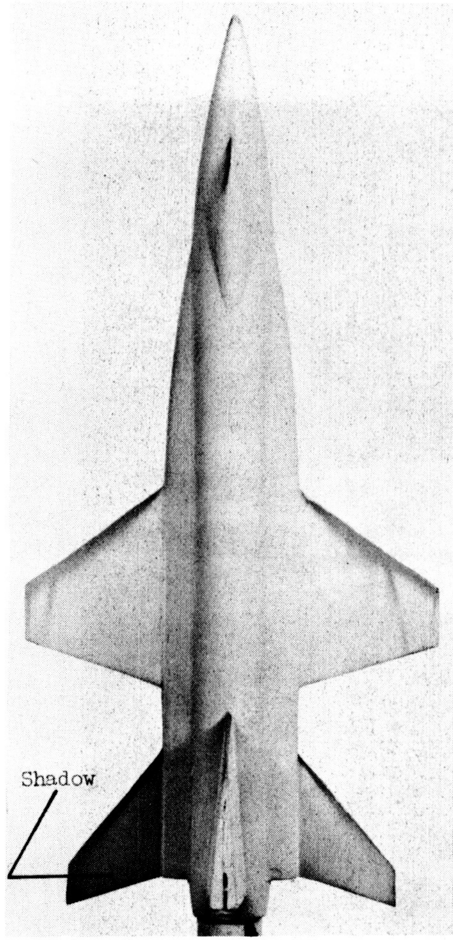
Figure 2 .- Continued.



Top Bottom Side L-60-274

(e) Mach number, 4.95; angle of attack, 10°; Reynolds number (based on body length), 2.02×10^6; testing time, 7.50 sec; color change, pink to blue.

Figure 2 .- Continued.



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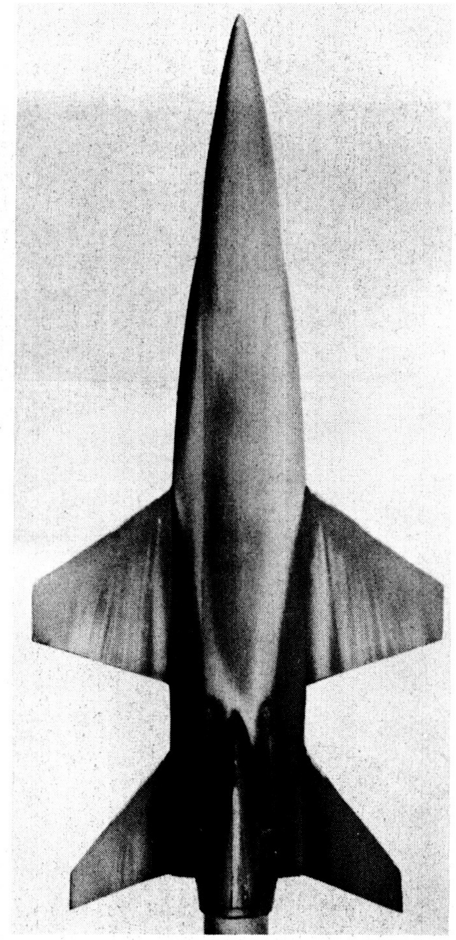

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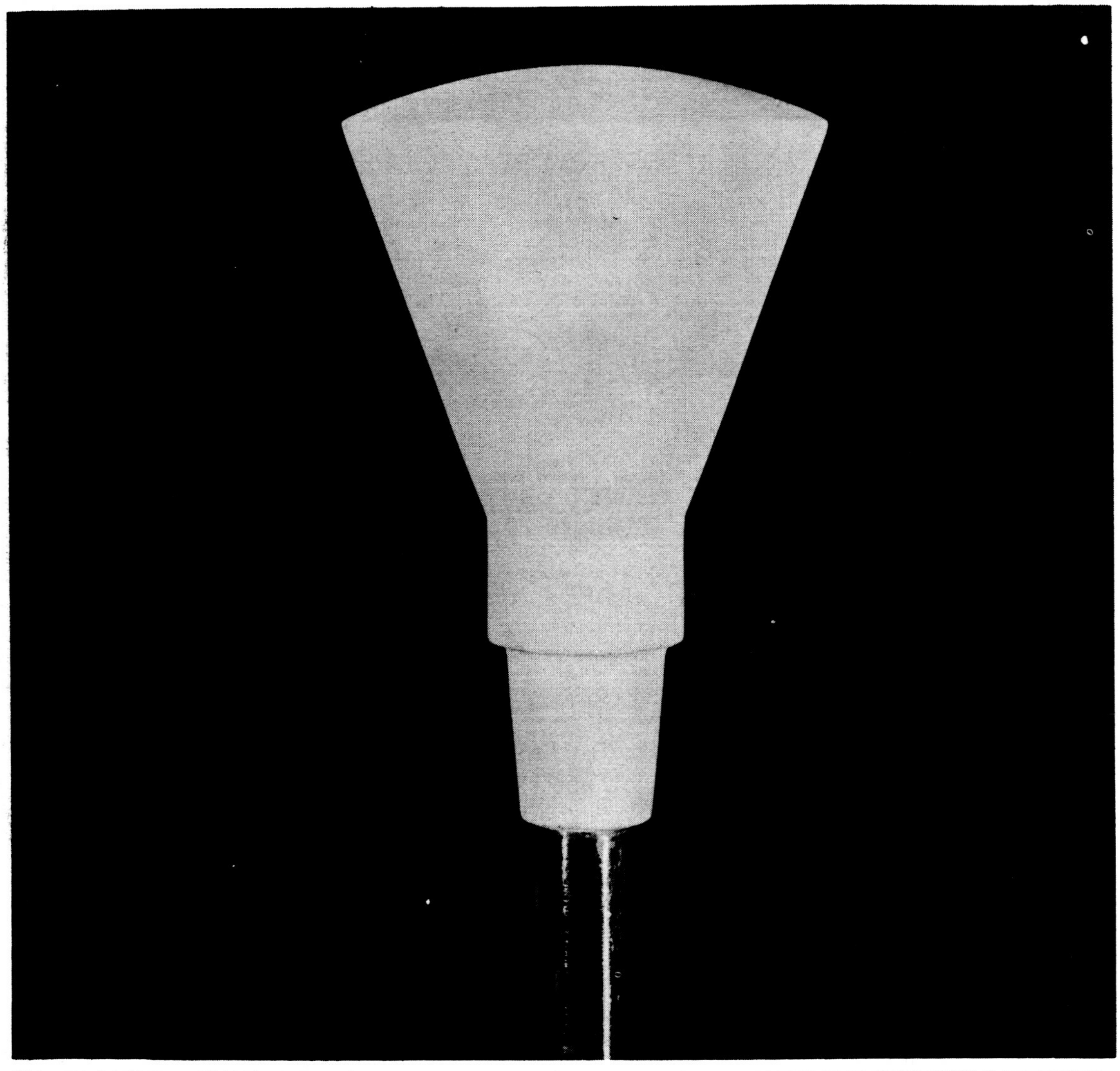
L-60-275

(f) Mach number, 4.95; angle of attack, 20°; Reynolds number (based on body length), 2.02×10^6; testing time, 6.07 sec; color change, pink to blue.

Figure 2 .- Concluded.



L-60-564

(a) Model painted with temperature-sensitive paint prior to testing.

Figure 3 .- Results of temperature-sensitive-paint investigations with the NASA Project Mercury reentry capsule.

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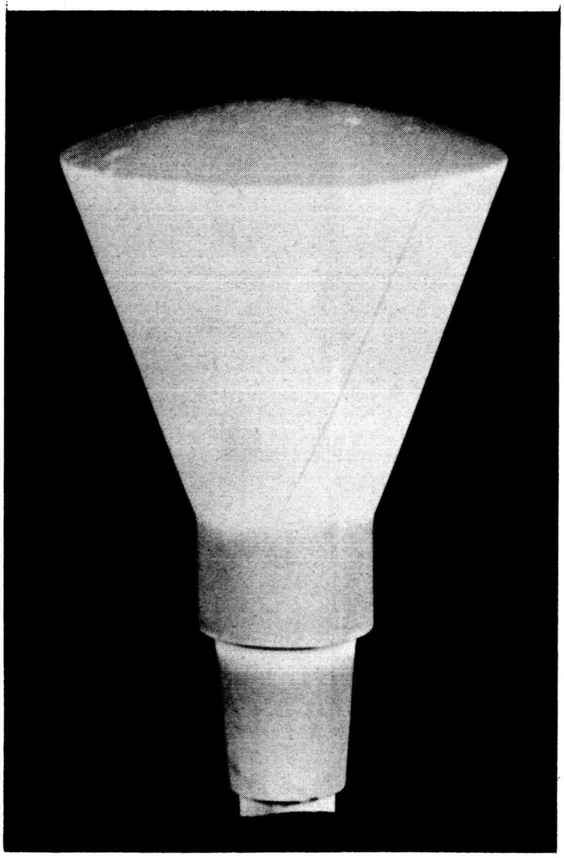
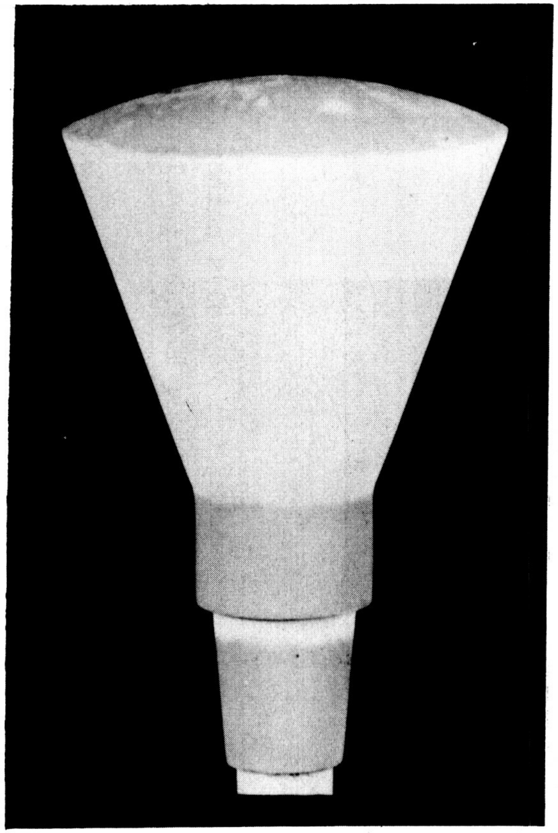


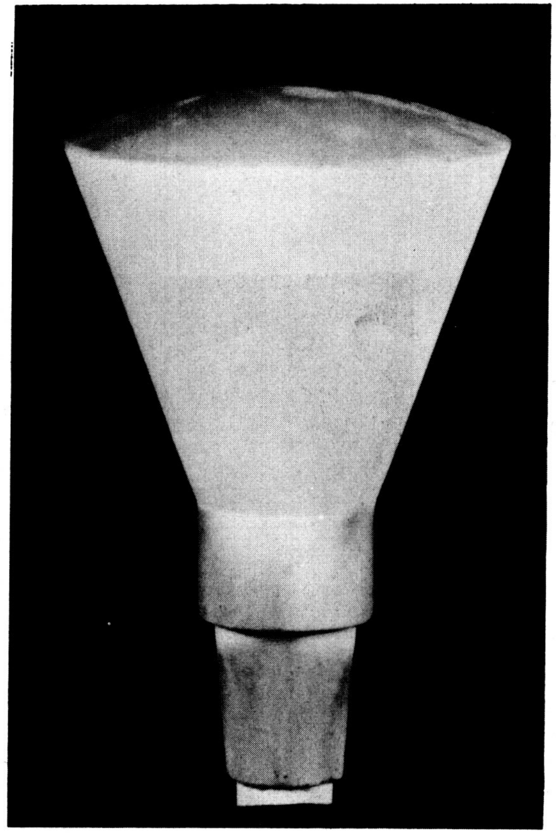
L-59-3166

(b) Mach number, 4.95; angle of attack, 0°; Reynolds number (based on body diameter), 2.22×10^{6}; testing time, 1.75 sec; color change, pink to blue.

Figure 3 .- Continued.



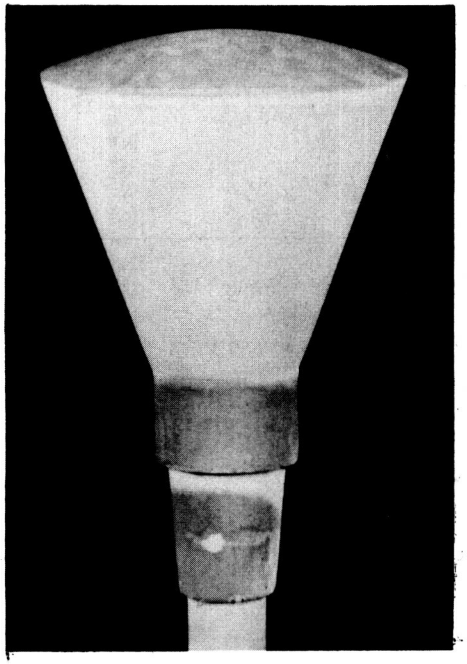
View - Most windward L-59-3171



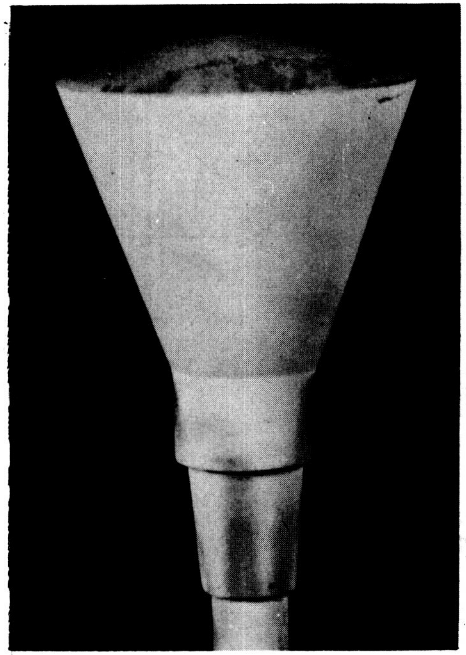
View - most leeward L-59-3172

(c) Mach number, 4.95; angle of attack, 5^{o}; Reynolds number (based on body diameter), 2.22×10^{6}; testing time, 2.35 sec; color change, pink to blue.

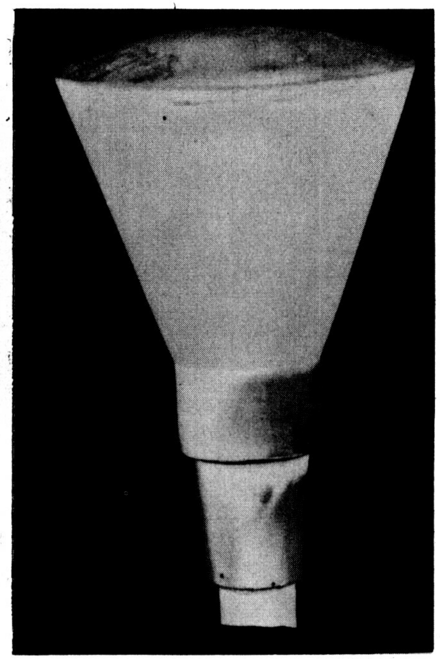
Figure 3 .- Continued.



L-59-3175
View - most windward



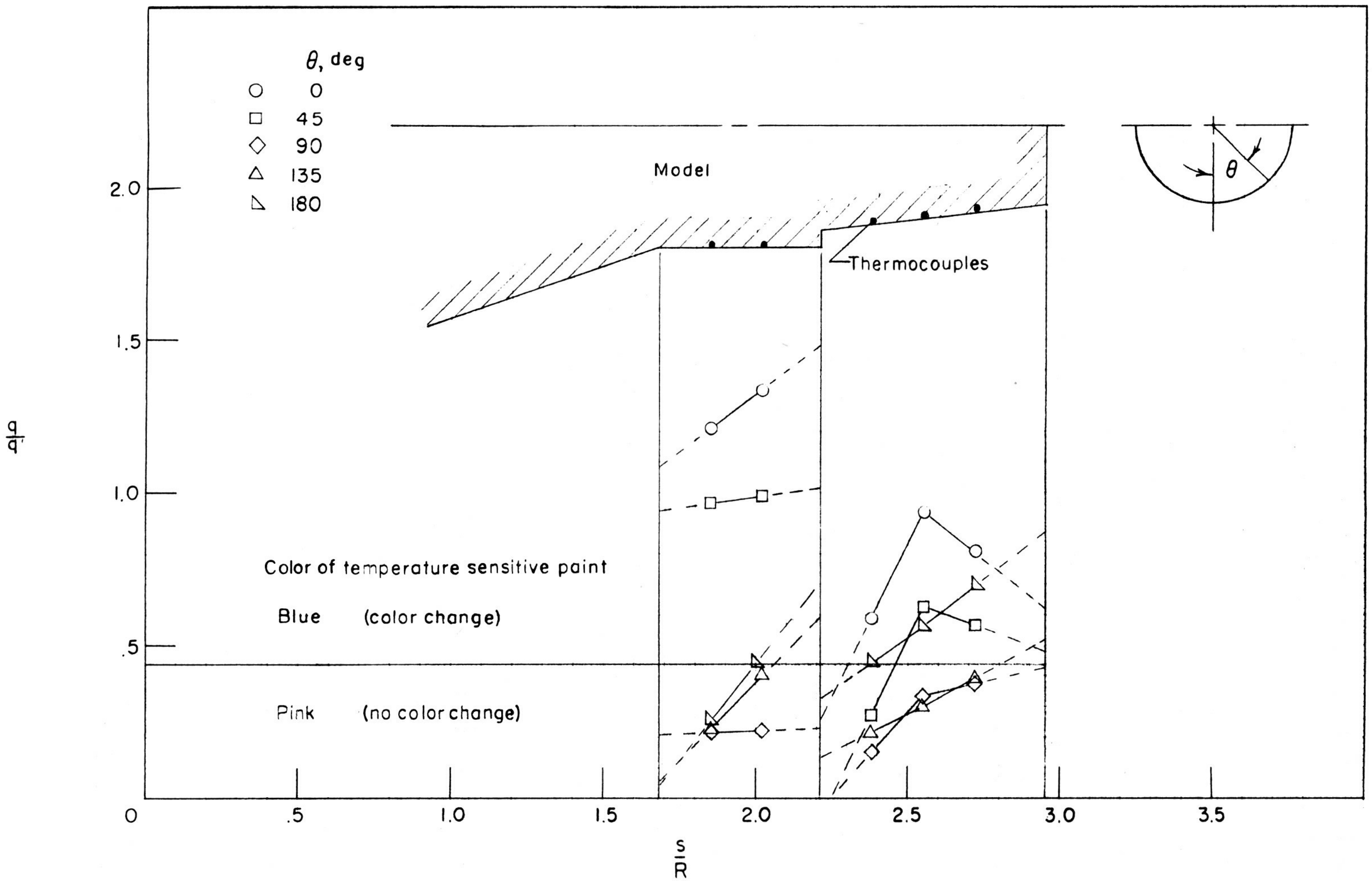
L-59-3176
View - most leeward



L-59-3174
View - 90° from most windward

(d) Mach number, 4.95; angle of attack, 10°; Reynolds number (based on body diameter), 2.22×10^6; testing time, 2.45 sec; color change, pink to blue.

Figure 3 .- Continued.



(e) Heat-transfer rate to capsule afterbody at $\alpha = 10^{\circ}$.

Figure 3 .- Concluded.

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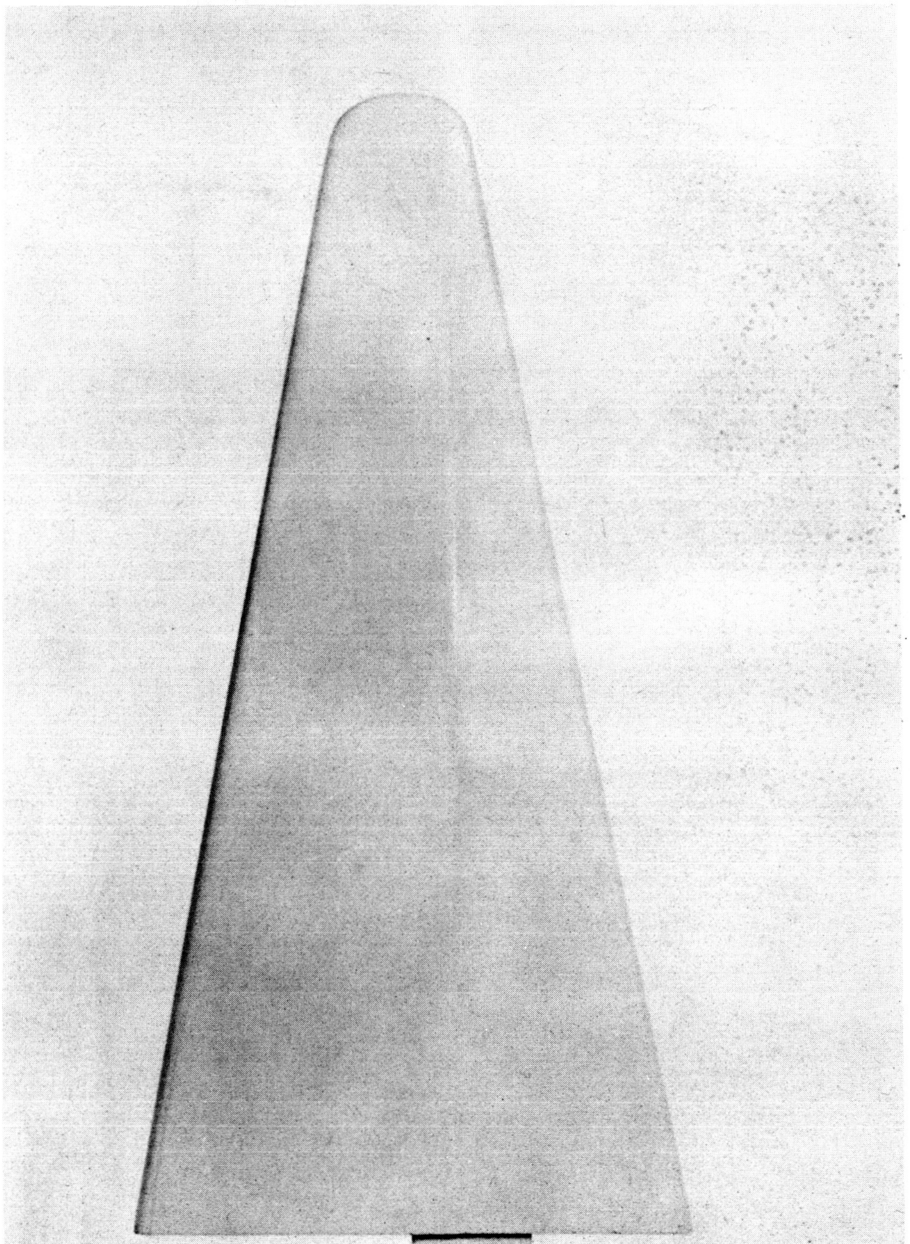
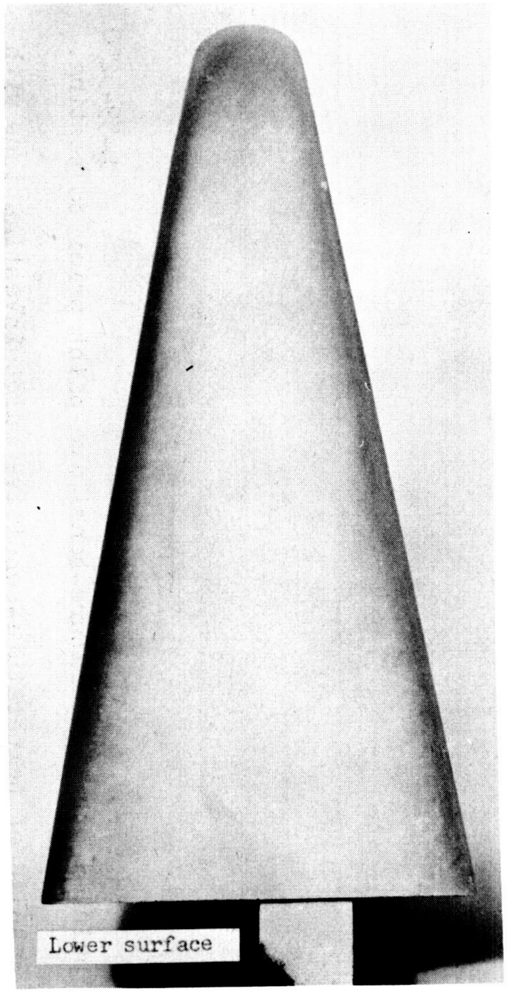


L-59-3250

(a) Model painted with temperature-sensitive paint prior to testing.

Figure 4 .- Results of temperature-sensitive paint investigations with 79.5° swept delta wing.



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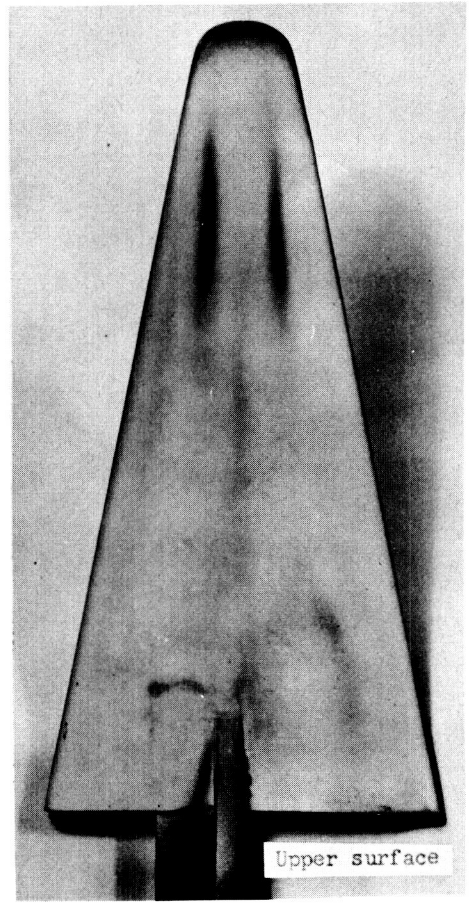

L-59-2706

(b) Mach number, 4.95; angle of attack, 14.5°; Reynolds number (based on body length), 1.84×10^6; testing time, 6.80 sec; color change, pink to blue.

Figure 4 .- Continued.

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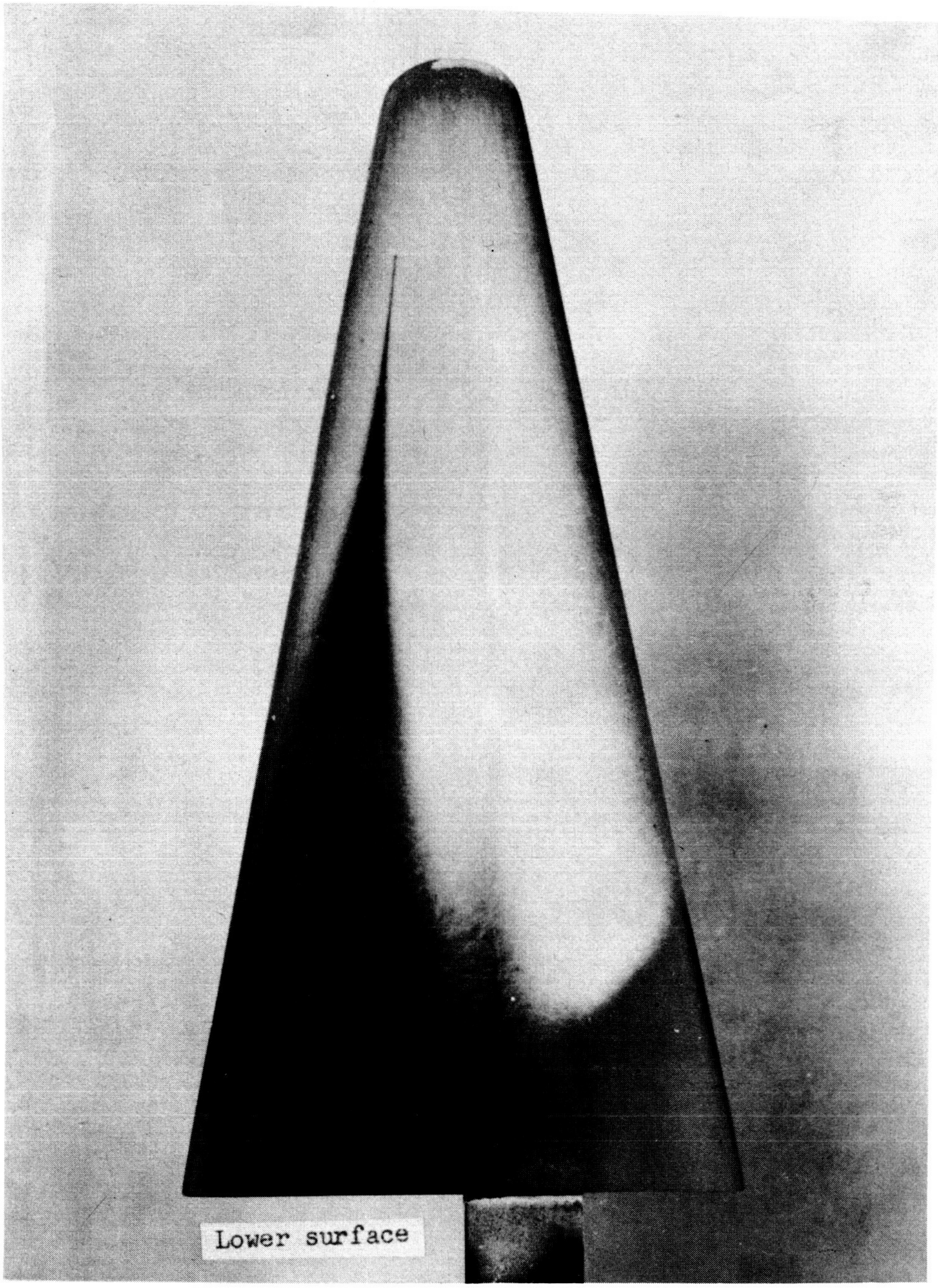
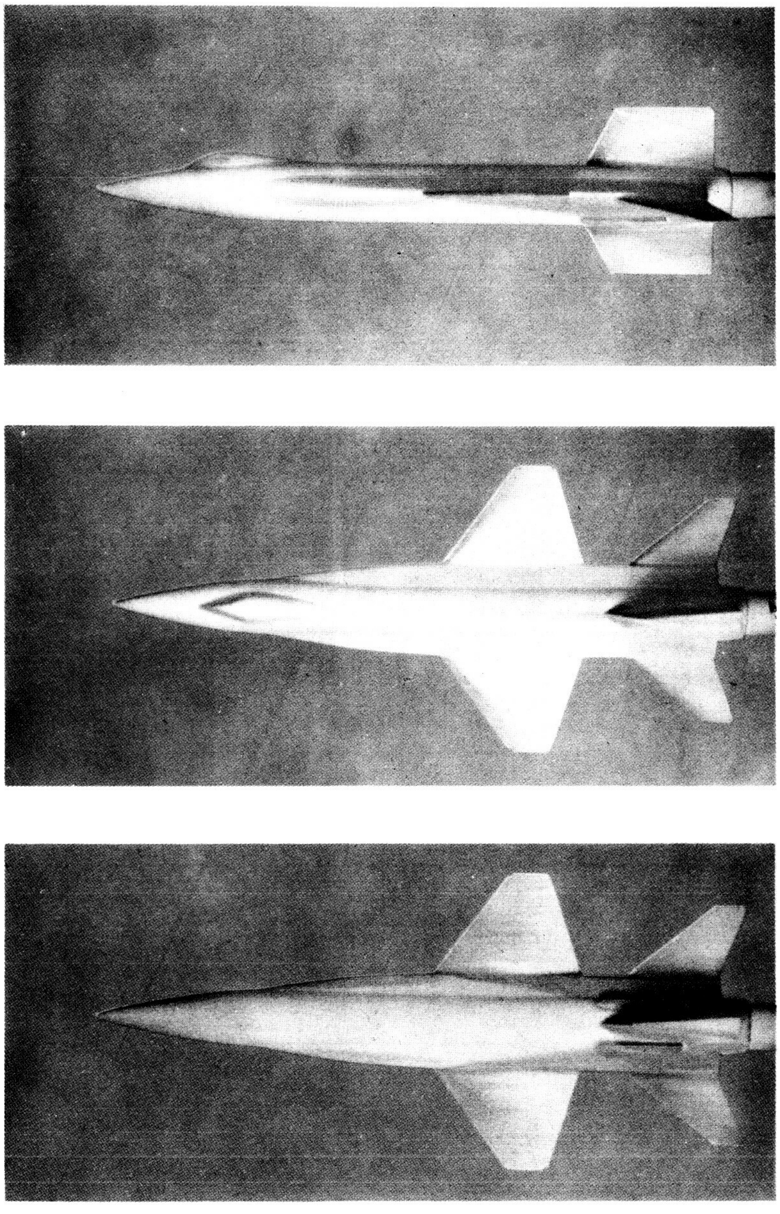


L-59-2705

(c) Mach number, 4.95; angle of attack, 20°; Reynolds number (based on body length), 1.84×10^6; testing time, 3.00 sec; color change, pink to blue.

Figure 4 .- Concluded.



Side

Top

Bottom

Figure 5.- Color photographs of results obtained with temperature-sensitive paint on X-15 model. (Conditions same as for fig. 2(e).)