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INVESTIGATION OF FLOW-FIELD DEVELOPMENT FOR A SERIES OF SONIC-BOOM WIND-TUNNEL MODELS

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16. Abstract

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SUMMARY

A wind-tunnel experiment has been conducted at a Mach number of 2.7 to study the growth of the pressure field as a function of distance from sonic-boom models. Six models were tested: two delta planforms and four rectangular planforms including one model with side plates. The measured sonic-boom pressure signatures are compared with calculated signatures based on theories for two- and three-dimensional flows.

The results indicated a rapid transition from two-dimensional flow characteristics, known to exist near the model lower surfaces, to the three-dimensional characteristics measured in the tests. In general, good agreement was obtained between the measured pressure field and the pressure field calculated by use of conventional techniques for analysis of three-dimensional flow.

These results suggest that three-dimensional flow about the models is established very rapidly – for most cases, in about 1 body length. The results also serve as a reminder that minimum or zero boom concepts based on two-dimensional reasoning can be very misleading and that the development of three-dimensional flow is predominant and must be taken into account.

INTRODUCTION

Considerable effort has been directed toward the establishment of sonic-boom prediction techniques, and various studies have attacked the problem of minimization of the sonic boom through airplane design. Extensive wind-tunnel test programs, beginning some 10 years ago, have treated a great variety of models, including rather basic research shapes, airplane components, and complete airplanes. (See refs. 1 and 2.) In addition, the investigations in the wind tunnel have provided data for evaluation of certain minimum-boom and minimum-drag shapes and for evaluation of a number of unconventional airplane concepts as well.

In the studies, it has been shown that linearized theory (with appropriate corrections) provided reasonably accurate predictions of the sonic-boom pressure signatures. The fundamental concept in the theoretical treatment is the replacement of a three-dimensional aircraft or other complex shape by an equivalent body of revolution. It is presumed that the three-dimensional flow field can be adequately represented locally (within a specified sector of the flow field and at reasonably large distances) by the axially symmetric flow field of a properly defined body of revolution. Definition of the body of revolution, which requires a consideration of both volume and lift effects, is provided by application of area-rule principles outlined by Hayes (ref. 3). The subsequent calculation of the flow field including shocks follows the method introduced by Whitham (ref. 4). The results of wind-tunnel programs indicate the applicability of the simplified approach at distances as close as 1 or 2 body lengths for shapes that approximate axial symmetry and at somewhat larger ratios for more complex configurations.

The work of reference 2 extended these tunnel studies and established the adequacy of the theoretical methods of reference 4 to a body shape which departed drastically from a body of revolution. This particular configuration was rectangular in planform and had a flat upper surface and a lower surface made up of several steps. On the basis of two-dimensional flow concepts, lifting pressures would be created on the lower surface for a small distance behind the shock wave. The flow would then be expanded to the original free-stream direction, and thereby a shock-canceling expansion is created. These events would be repeated for each step on the model. The test indicated that the lower surface two-dimensional flow pattern changes rapidly and becomes predominantly three dimensional in character within about 5 body lengths for this nonaxisymmetrical configuration.

In addition to the study performed in reference 2, six other nonaxisymmetrical model configurations were constructed and tested in the wind tunnel to study the growth of the pressure field as a function of distance from the models. The models were two 40° delta and four rectangular planforms including one model with side plates to force two-dimensional flow to exist within the confines of the side plates. These six models were tested in the Langley Unitary Plan wind tunnel at their design Mach number of 2.7. Sonic-boom pressure signatures were obtained at distances of 12.7, 25.4, and 50.8 cm (5, 10, and 20 inches) below the models, corresponding to 1.25, 2.5, and 5 body lengths, respectively.

The purpose of this report is to present the results of the wind-tunnel tests in the form of measured sonic-boom pressure signatures at three distances below the models at a Mach number of 2.7. Comparison is made of these experimental data with theoretical signatures determined by use of theories for two- and three-dimensional flows.

SYMBOLS

Measurements and calculations were made in U.S. Customary Units and are presented in the International System of Units (SI) and parenthetically in U.S. Customary Units.

h	perpendicular distance from model to measuring probe
M	Mach number
Δp	incremental pressure due to flow field of airplane or model
p	wind-tunnel free-stream static pressure
Δx	distance from bow shock measured along probe center line

MODELS, APPARATUS, AND TESTS

Models

The six models used in the present study are shown in the photographs of figure 1. All models were constructed of stainless steel and had a width of from 5.1 to 10.2 cm (2 to 4 inches) and an overall length of 30.5 cm (12 inches), 10.2 cm (4 inches) of which was considered the effective body length. The remaining 20.3 cm (8 inches) of the model was of constant cross-sectional area to provide for the sting support. Detail drawings of these models giving dimensions and angles are presented in figure 2. One model-sting adapter was used for all models, and the details of this adapter are given in figure 3. The characteristics of the models are as follows:

Model 1.- Model 1, shown in figures 1 and 2(a), has a 40° delta planform, is wedge shaped in profile, and has a lower lifting surface angle of 5°.

Model 2.- Model 2, shown in figures 1 and 2(b), is a "stepped" version of the basic 40° delta wedge (model 1). Three "steps" were incorporated; each consisted of a 5° lifting surface angle followed by a straight section in order to create compression and expansion shocks.

Model 3.- Model 3, shown in figures 1 and 2(c), is rectangular in planform and wedge shape in profile. The lower lifting surface angle is 5°.

Model 4.- Model 4, shown in figures 1 and 2(d), is a stepped version of the basic rectangular 5° wedge (model 3). Three steps were incorporated; each step consisted of a 5° lifting surface angle followed by a straight section. Model 4 is similar to the model

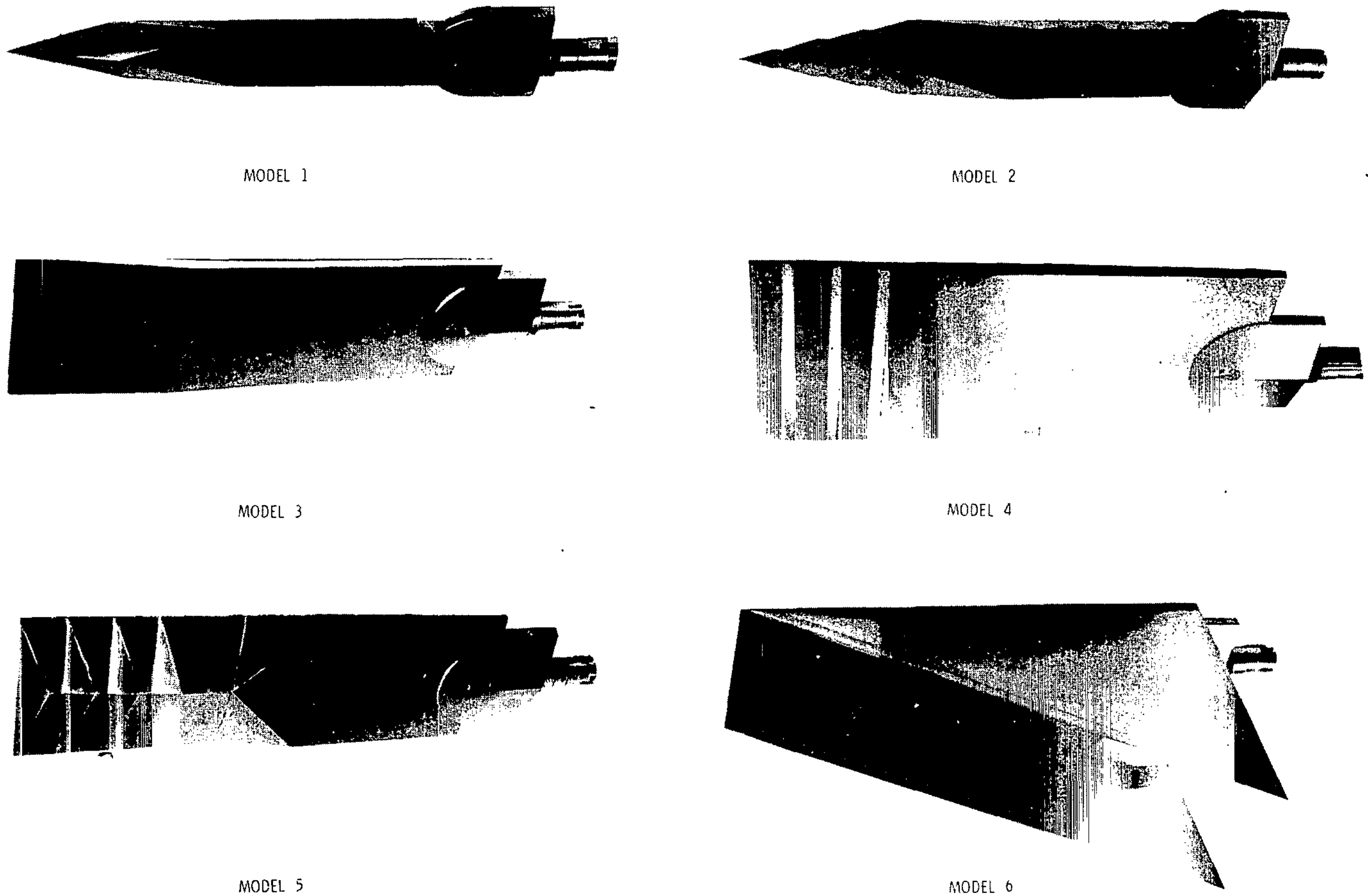

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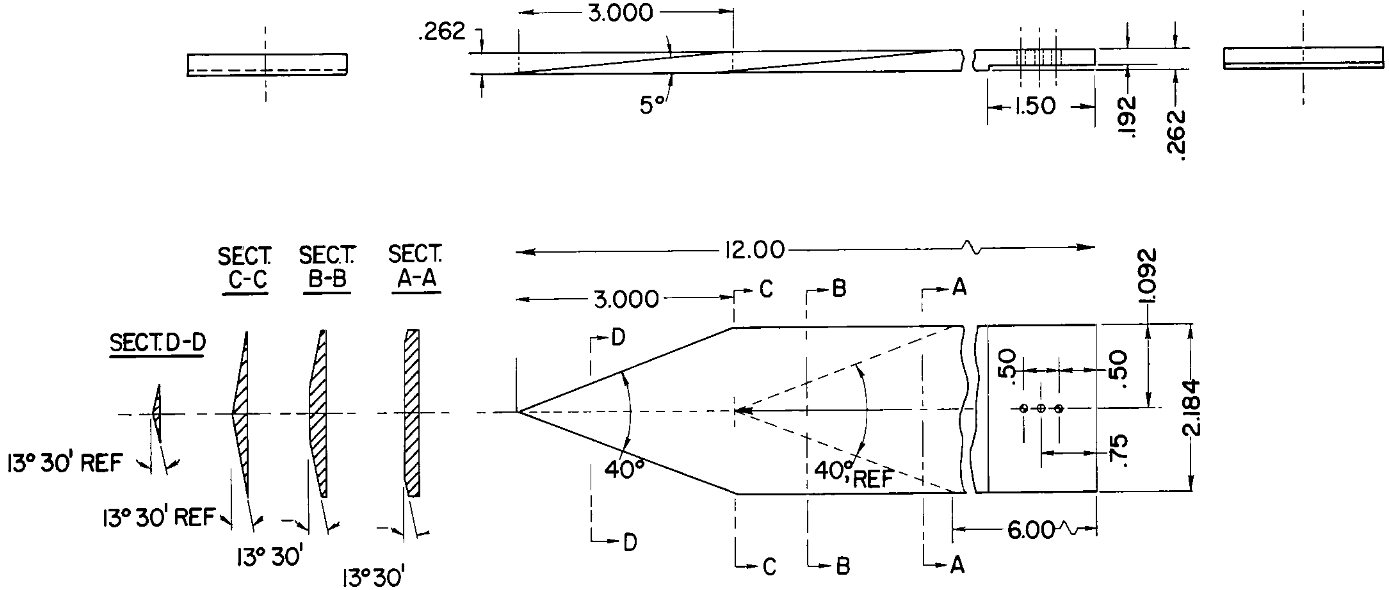
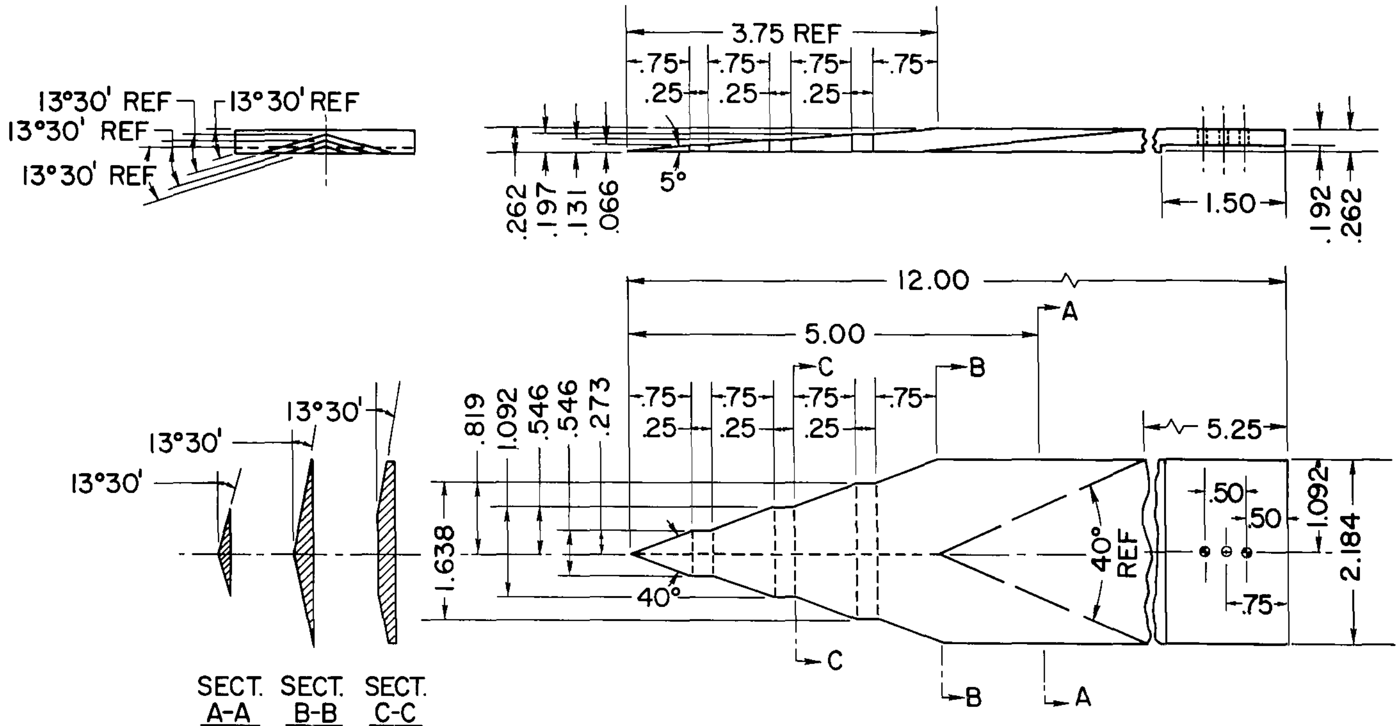
Figure 1.- Photographs of minimum-sonic-boom models with sting adapter.



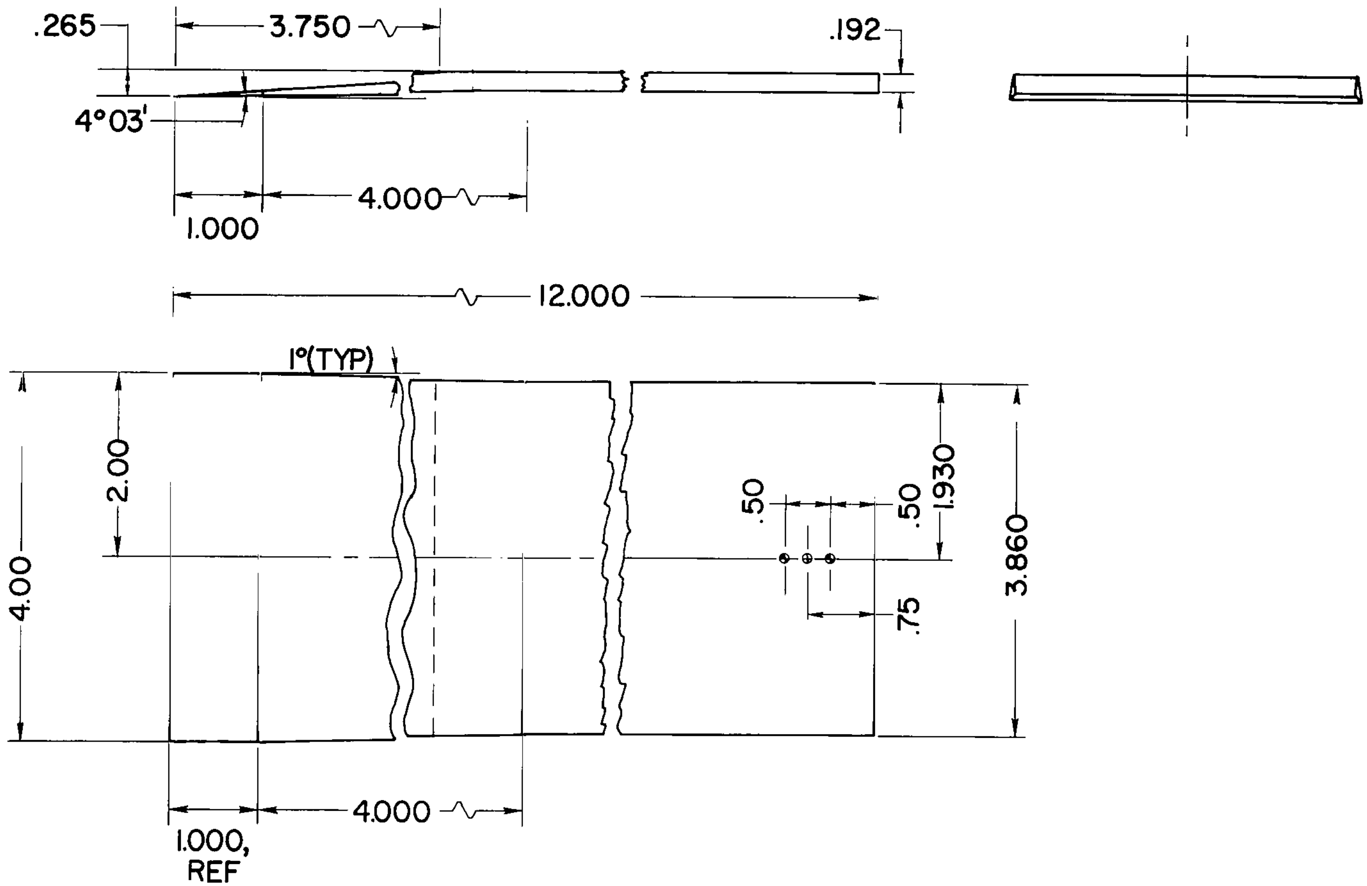
(a) Model 1.

Figure 2.- Three-view drawings showing dimensions and section characteristics of sonic-boom models used in the test. (Dimensions are given in inches. 1 inch = 2.54 cm.)



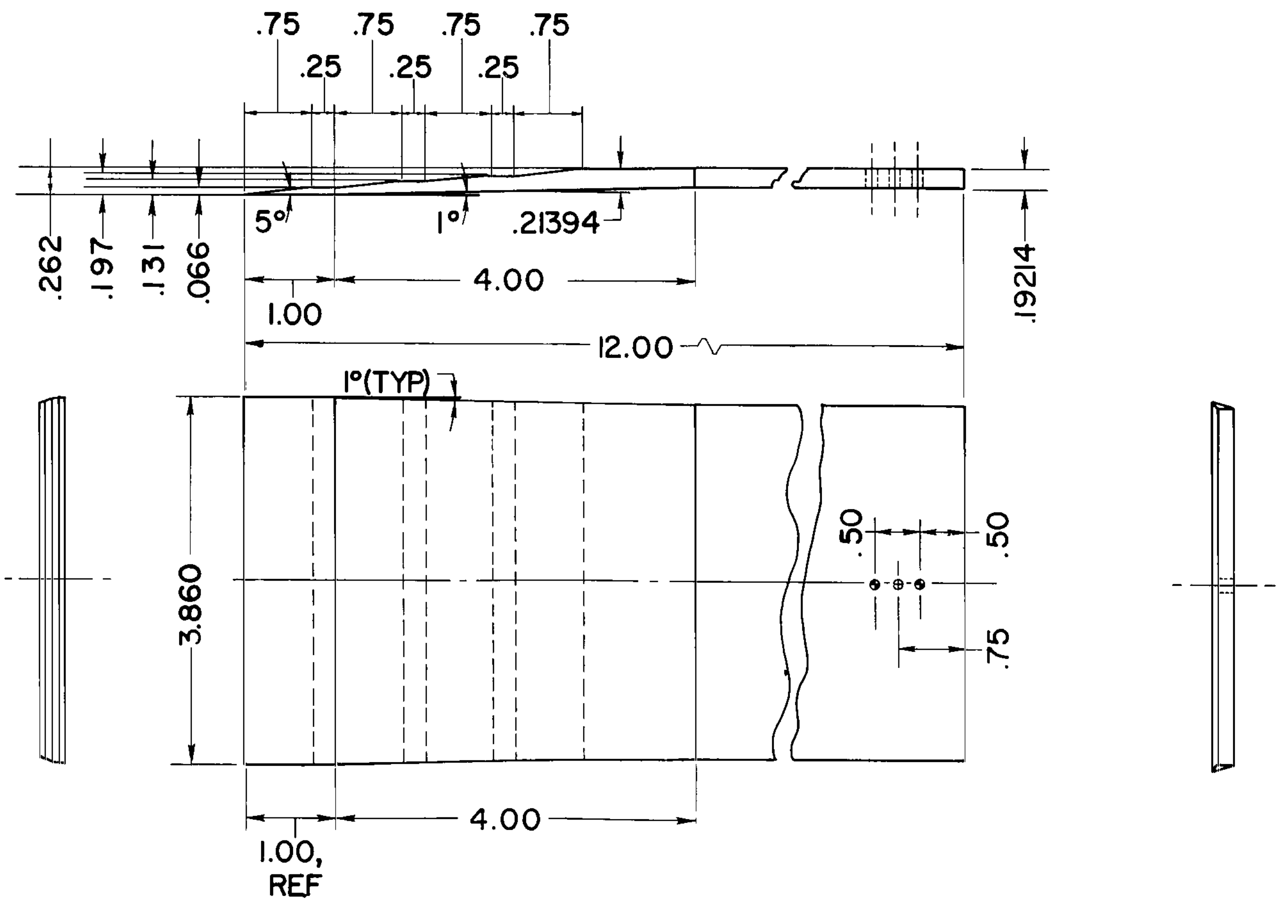
(b) Model 2.

Figure 2.- Continued.



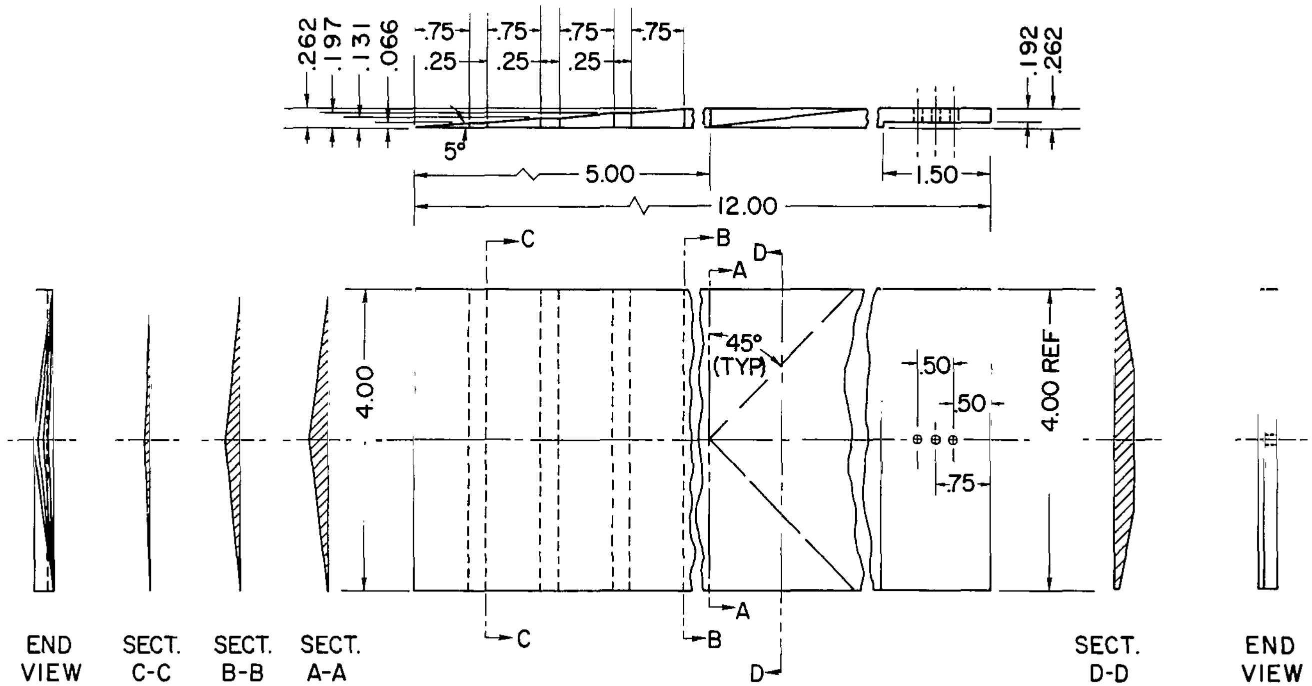
(c) Model 3.

Figure 2.- Continued.



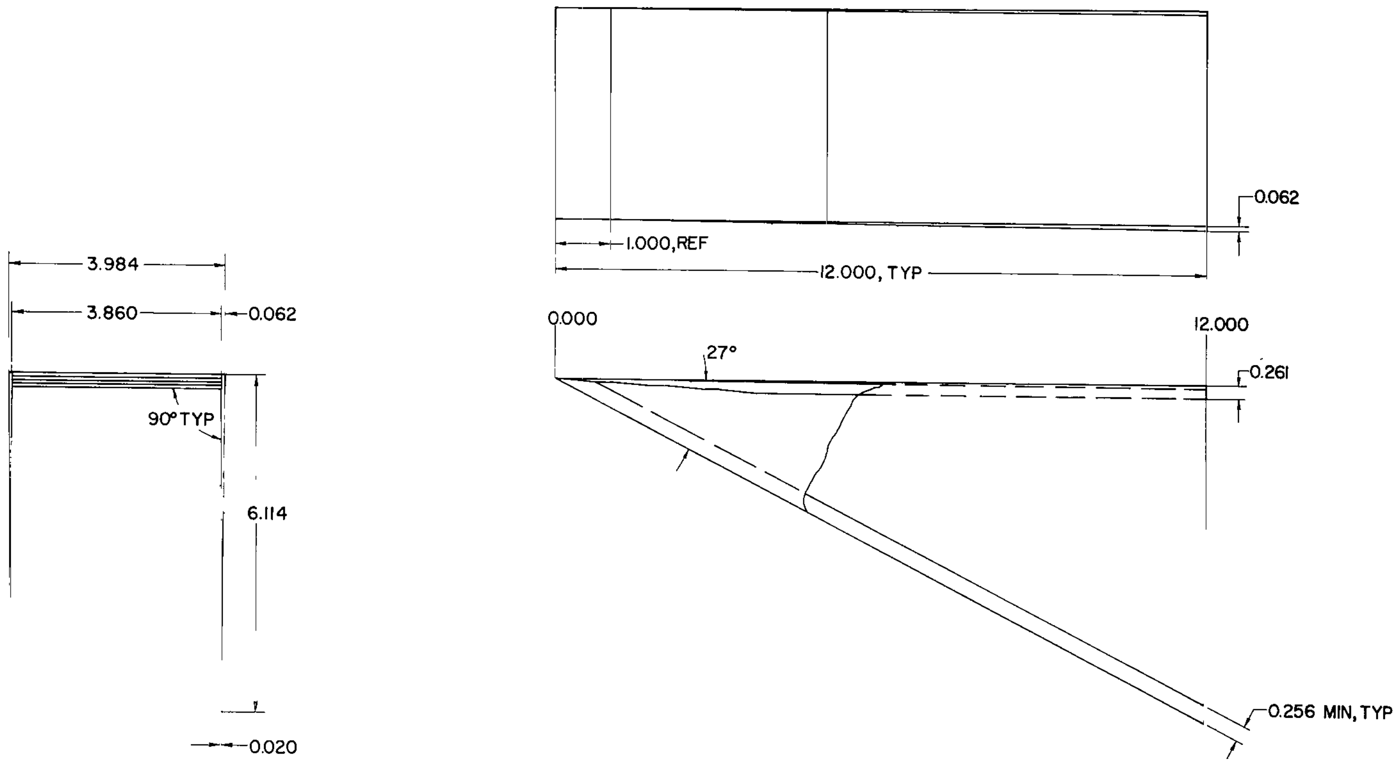
(d) Model 4.

Figure 2.- Continued.



(e) Model 5.

Figure 2.- Continued.



(f) Model 6.

Figure 2.- Concluded.

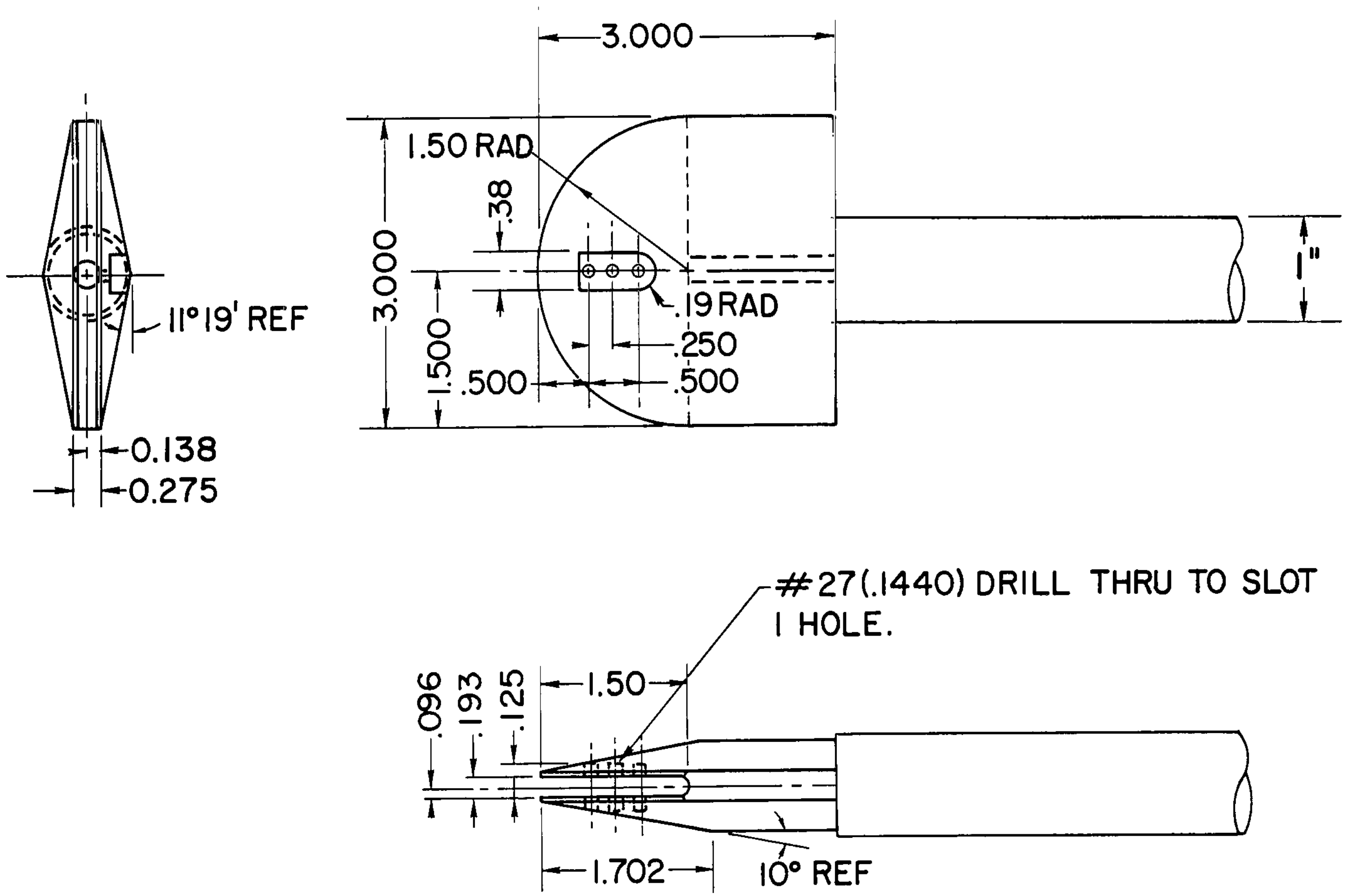


Figure 3.- Three-view drawing of model-sting adapter used in the test. (1 inch = 2.54 cm.)

tested in reference 2; the difference is that the constant-area sting-support section of the present model was lengthened from 10.2 to 20.3 cm (4 to 8 inches) (20.3 cm (8 inches) complete model length in ref. 2 compared with 30.5 cm (12 inches) complete model length herein) in an attempt to minimize the effect of the model-sting adapter on the model flow field.

Model 5.- Model 5, shown in figures 1 and 2(e), is a rectangular stepped wedge having the same number of steps (three) and the same lifting surface angles (5° and 0°) as model 4.

Model 6.- Model 6, shown in figures 1 and 2(f), is a rectangular stepped wedge with side plates. In effect, it is model 4 with side plates. The side-plate angle was established at 27° so that at $M = 2.7$, for which the Mach angle is about 22°, the bow shock and the flow behind the bow shock are contained between the side plates (to within about 15.2 cm (6 inches) radial distance from the model). In addition, these side plates were made thin and alined with the stream flow to reduce any distortion of the basic flow field from the stepped model.

Apparatus and Tests

The six sonic-boom models were tested in the Langley Unitary Plan wind tunnel (ref. 5) at a Mach number of 2.7, a stagnation pressure of 45.2 kN/m^2 (944 lb/ft^2), and a Reynolds number of 3.28×10^6 per meter (1×10^6 per foot). The wind-tunnel test section is 1.2 meters (4 feet) square by 2.1 meters (7 feet) long.

The model mounting technique and the method of measurement of the pressure field below the model are the same as those given in references 6 and 7 and are shown schematically in the sketch of figure 4. As can be seen in the figure, the model and adapter were mounted on a translating sting support from the tunnel side wall. A reference probe and static measuring probe were mounted on a support attached to the main sting. Pressure measurements of the shock field of the model were obtained by translating the model and its associated shock field across the measuring probes. These flow-field surveys were obtained at distances h below the model of 12.7, 25.4, and 50.8 cm (5, 10, and 20 inches). The 12.7-cm (5-inch) distance represents the minimum distance, and 50.8 cm (20 inches) is the maximum distance from the model that could be obtained. The distances of 12.7, 25.4, and 50.8 cm (5, 10, and 20 inches) correspond to 1.25, 2.5, and 5 body lengths below the model, respectively. In addition to obtaining pressure measurements below the models, schlieren photographs were taken of certain models for flow visualization.

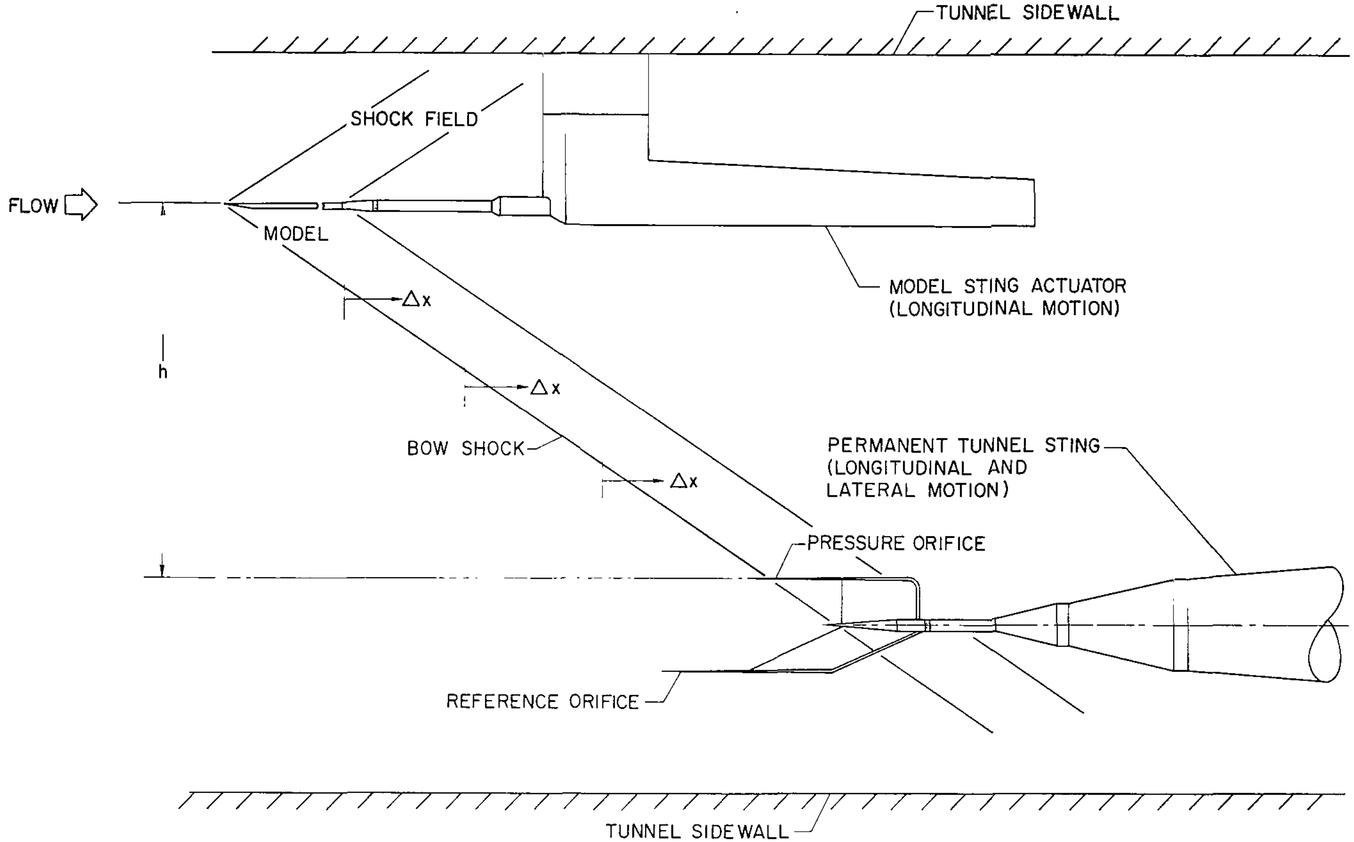
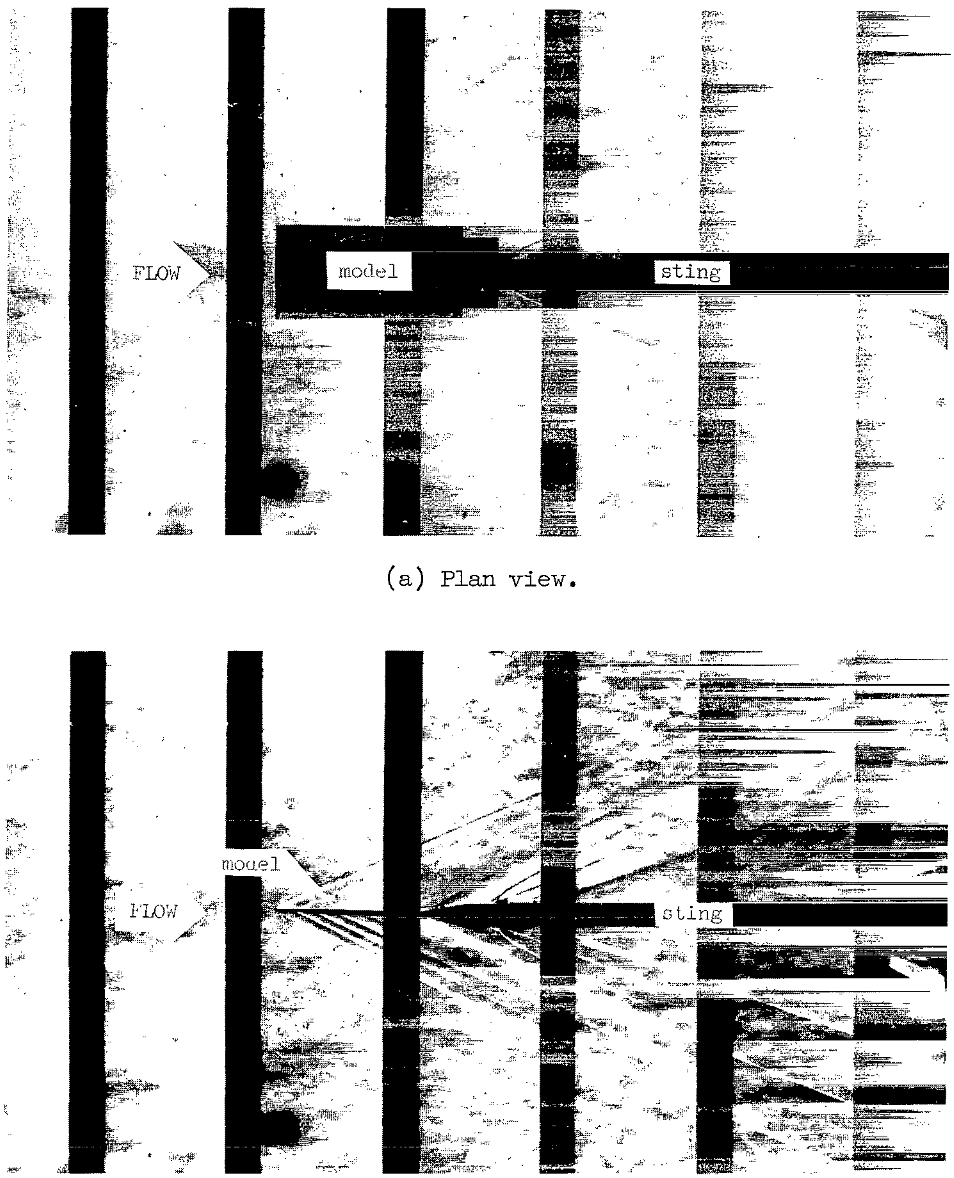


Figure 4.- Model arrangement in supersonic tunnel showing probe measurement technique.

RESULTS AND DISCUSSION

In figure 5 schlieren photographs of model 4 for $M = 2.7$ are shown. The plan view is shown at the top of the figure. It is interesting to note that no discernible shock waves are seen to originate from the corners of the leading edge. The profile view in the lower photograph shows rather clearly the shocks and expansion patterns associated



(a) Plan view.

(b) Profile view.

Figure 5.- Schlieren photographs of sonic-boom model 4 for $M = 2.7$.

with each of the steps on the model. The remaining shocks result from the model-sting adapter. The light lines indicate shock waves, and the dark areas indicate the expansion zones. The dark vertical lines are caused by the schlieren window supports, which are external to the flow.

The measured pressure distributions obtained below each of the six models at distances h of 12.7, 25.4, and 50.8 cm (5, 10, and 20 inches) for $M = 2.7$ flow, along with a sketch of each model, are presented in figure 6. The data are presented in the form of overpressure Δp divided by free-stream ambient pressure p plotted against horizontal distance Δx along the model longitudinal axis. Also shown in the figure are the calculated pressure signatures for each of the models at the three measuring distances. These pressure signatures were determined by using numerical methods (refs. 6 and 8) based on the equivalent-body principle and accounting for lift and volume contributions. Since the influence of the model-sting adapter, located between the model and the sting support, was found to be rather strong (fig. 5), these calculations were made with and without the inclusion of the adapter. Calculations based on two-dimensional flow (ref. 9) for models 4 and 6 are also included.

Examination of the experimental pressure distributions of figure 6 at the closest position ($h = 12.7$ cm (5 inches)) for each of the models indicates that the formation of an N-wave is already apparent. The step models (2, 4, 5, and 6) show only slight perturbations in the flow. As the distance from the model is increased to 50.8 cm (20 inches), the approach to an N-wave is noted to occur for all models except model 5 (fig. 6(e)), where shock perturbations are still present.

Correlation of the experimental pressure signatures with the three-dimensional theory is good for models 1, 2, and 5, which are essentially considered to be slender bodies. The correlation is also fairly good for models 3 and 4, which tend to deviate from the slender-body concept. This reasonably good agreement was not expected because it was thought that the theory did not provide valid results close to models of the type tested. In general, the agreement improves as the distance from the models increases, and although some rounding and smoothing of the experimental results are evident (due to the effects of model vibrations and probe boundary layer as discussed in ref. 6), fairly good agreement is obtained, even to the number of shocks and their locations. The strong influence of the model-sting adapter is apparent in the measured data and is predicted by the theory.

The results obtained for model 6, which had side plates to induce two-dimensional flow, are given in figure 6(f). It can be seen that the three-dimensional theory greatly underestimates the overpressure magnitude particularly at the closest measuring distance. For this position, a much better estimate of the signature is obtained by using

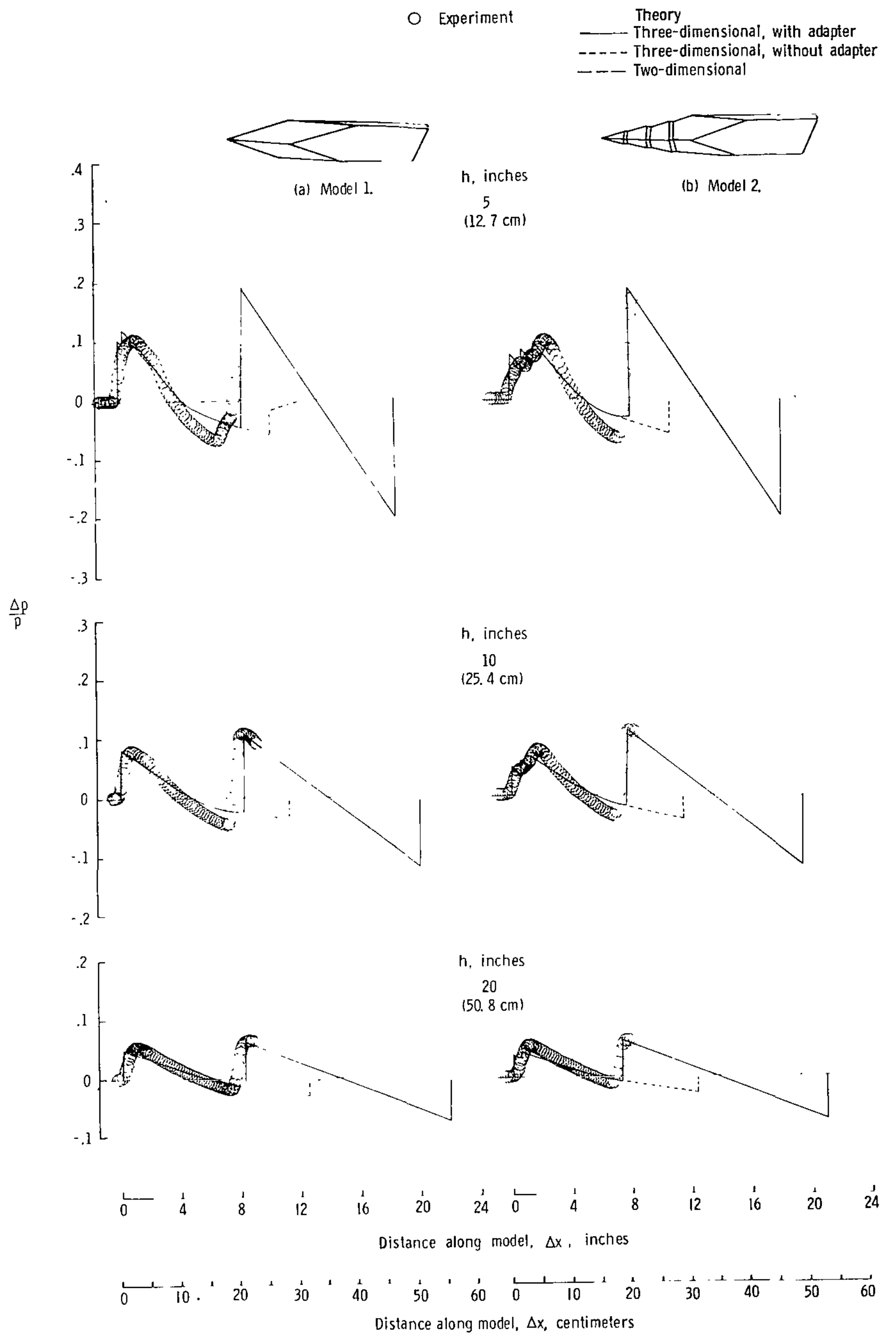


Figure 6.- Theoretical and experimental pressure distributions obtained at distances of 12.7, 25.4, and 50.8 cm (5, 10, and 20 in.) below sonic-boom models at $M = 2.7$.

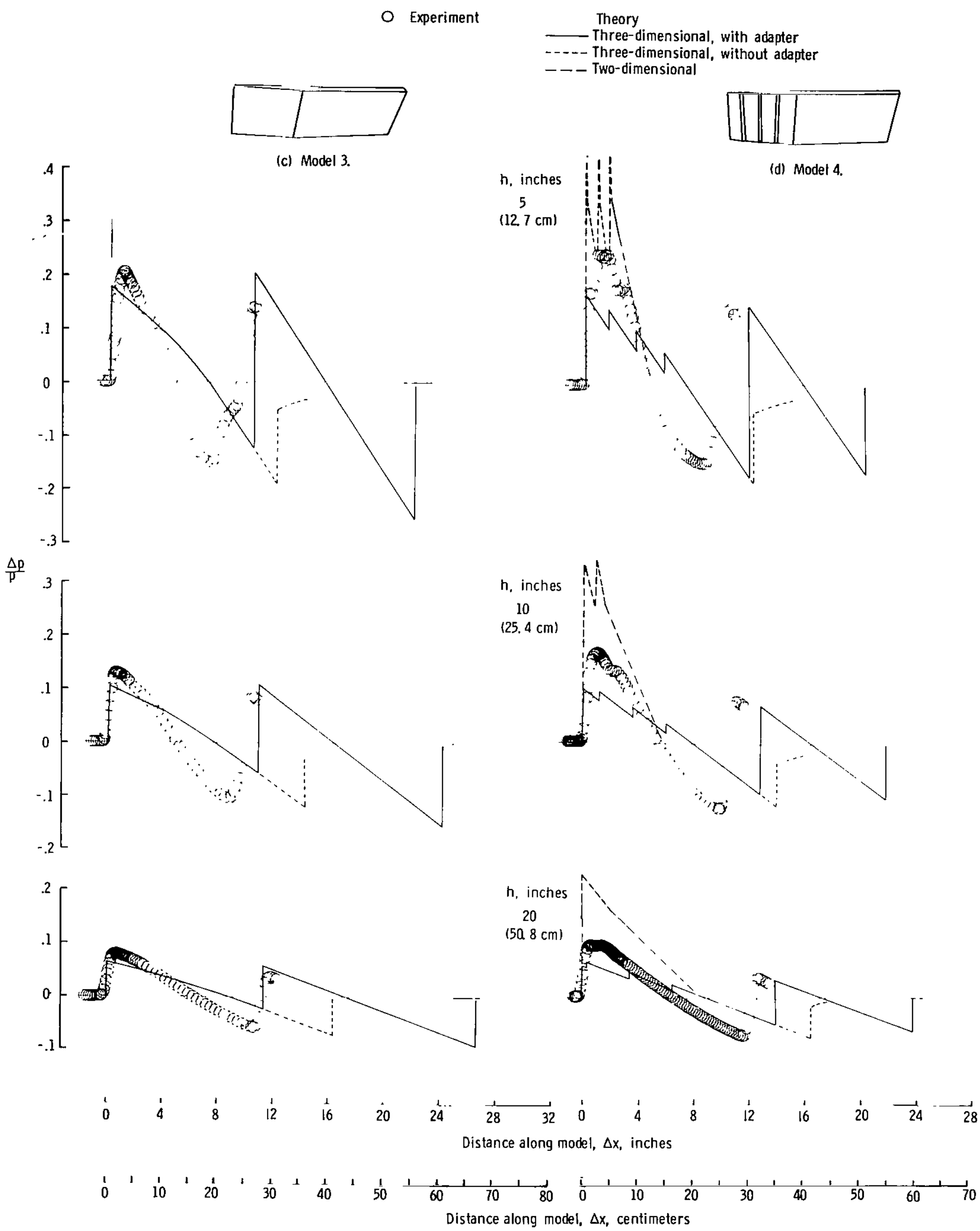


Figure 6.- Continued.

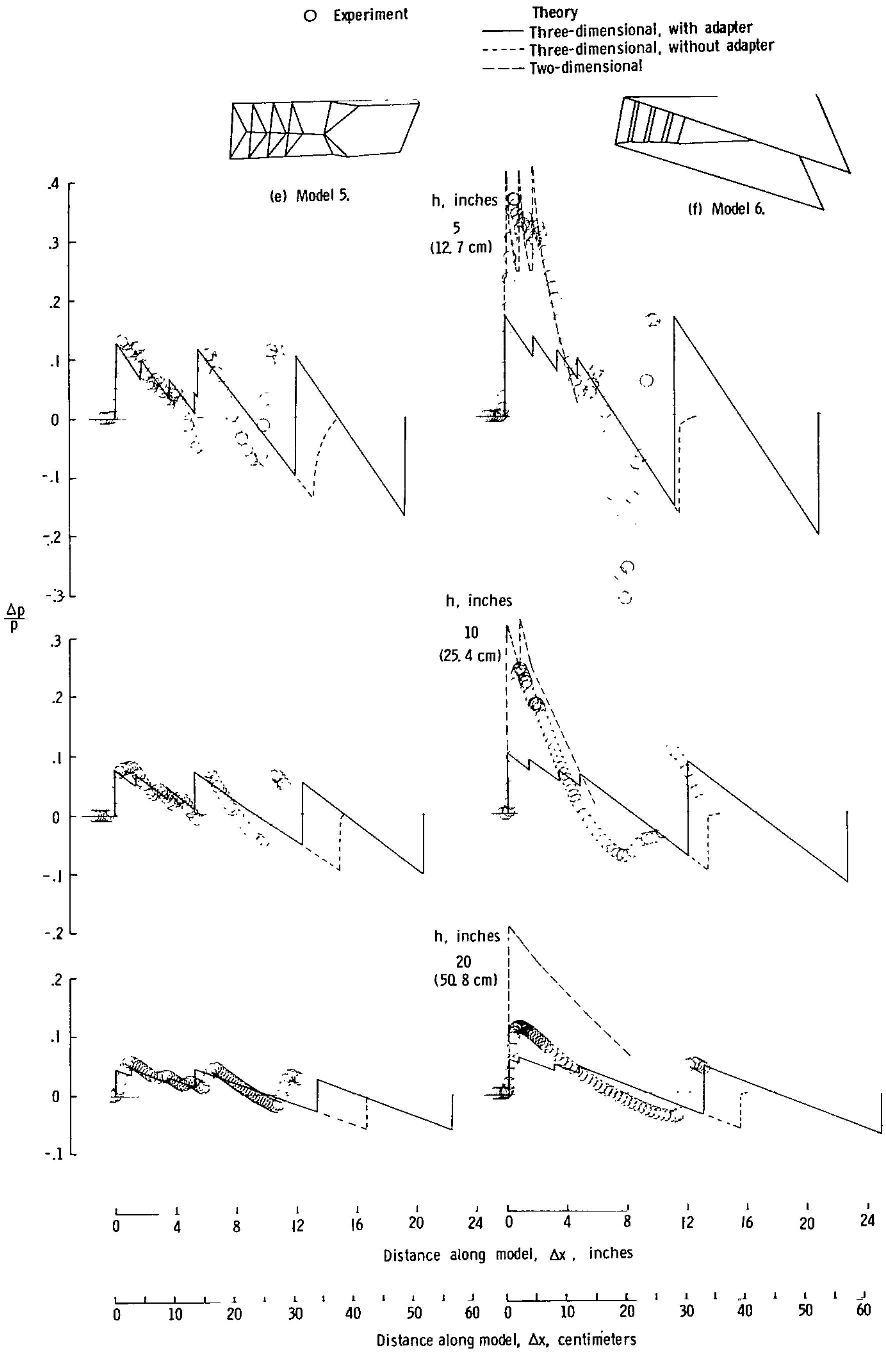


Figure 6.- Concluded.

two-dimensional theory (ref. 9). This improved result would be expected particularly at the closest distance (h = 12.7 cm (5 inches)) since the pressure survey was made between the model side plates, where two-dimensional flow was forced to exist.

CONCLUDING REMARKS

A wind-tunnel experiment has been conducted at a Mach number of 2.7 to study the growth of the pressure field as a function of distance from sonic-boom models. Six models were tested: two delta planforms and four rectangular planforms including one model with side plates. The measured sonic-boom pressure signatures are compared with calculated signatures based on theories for two- and three-dimensional flows.

The results indicated a rapid transition from two-dimensional flow characteristics, known to exist near the model lower surfaces, to the three-dimensional characteristics measured in the tests. In general, good agreement was obtained, especially at the larger distances, between the measured pressure field and the pressure field calculated by use of conventional techniques for analysis of three-dimensional flow. The notable exception occurred for a model for which two-dimensional flow was forced to exist within the confines of side plates. For that model, good agreement was obtained by use of theory for two-dimensional flow, particularly at the closest distance of about 1 body length. At the farthest measuring point, 5 body lengths, better agreement was obtained by use of three-dimensional flow theory.

These results suggest that three-dimensional flow about the models is established very rapidly, in most cases, in about 1 body length. The results also serve as a reminder that minimum or zero boom concepts based on two-dimensional reasoning can be very misleading and that the development of three-dimensional flow is predominant and must be taken into account.

Langley Research Center,
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