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THE INTERNAL AND EXTERNAL FLOW FIELD ASSOCIATED WITH PARACHUTES DURING INFLATION

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1. INTRODUCTION

The role of the parachute in supply logistics is vital to the successful accomplishment of many military objectives. In September 1968, the leading researchers in parachute technology, gathered at El Centro, California for the American Institute of Aeronautics and Astronautics, 2nd Aerodynamic Deceleration Conference, discussed the critical problems in parachute research that remain unsolved. One result of this meeting was an article titled "Technical Voids in Aerodynamic Deceleration R&D" which appeared in the December 1968 issue of "Aeronautics and Astronautics". The article delineated a number of major problem areas in parachute research such as a definition of parachute geometry during inflation, determination of parachute filling time, improvement in model scaling and knowledge of the flow field surrounding the parachute. Relative to the latter problem area, the article states, ". . . the flow field surrounding a flexible device is poorly understood, and that (field) surrounding an inflating parachute in a transient velocity field is strictly a matter of conjecture".

Up to the time of the conference the only research into parachute flow fields involved mounting a conventional survey rake at the inlet and vent openings of a parachute model. The resulting interference caused by the rake changed the flow and affected the readings. Realizing that a major breakthrough in the flow field knowledge had not been achieved to date using conventional pressure-sensitive devices, it was decided early in the flow field study to investigate other methods of flow measurement. The result of a preliminary investigation was the decision to use the hot-wire anemometer because of its low flow interference and excellent velocity sensitivity to determine the characteristic velocities of the flow surrounding a parachute. In a rough form, the hot-wire anemometer was first used over 70 years ago to measure wind velocity, but it has remained essentially a laboratory curiosity until just a few years ago when it began to be produced commercially. The problem of irrelevant readings caused by temperature sensitivity which had prevented wide spread use of the hot-wire anemometer in aerodynamic research was eliminated by conducting the flow field tests in the temperature controlled wind tunnel at Natick Laboratories. The last barrier to the application of the hot-wire had been removed and now the potential existed for a major impact on parachute flow field technology.

The procedures used in this study involved the use of the hot-wire anemometer to obtain data on the flow field associated with an inflating parachute. Seven models simulating various stages of inflation of the C-9 parachute were fabricated and tested in a specially constructed test section where the temperature could be held uniform. Using this method, it was possible to accurately measure the internal and external flow surrounding the canopy. Some possible applications of the data to full-scale parachute systems are presented.

II. THE HOT-WIRE ANEMOMETER

The hot-wire anemometer is capable of doing all the things conventional survey rakes can do with the additional advantages that it has the ability to measure extremely low velocities and has such a small cross-sectional area that the interference caused in the flow is negligible. Under good test conditions, it is possible to measure pressures of 0.02 lb/sq ft accurately with a pitot tube. This corresponds to a velocity of approximately 3 ft/sec. A hot-wire system is capable of measuring velocities of 0.1 ft/sec under the same conditions. The ability to measure such low velocities is especially useful in measuring the velocity immediately behind the model. A pitot tube survey rake would have had to be mounted at least 10 canopy diameters downstream from the model before the dynamic pressure would be high enough to be measured accurately. The hot-wire probes used in this study could be mounted either immediately behind the model or at some point downstream and not have their ability to measure the velocity affected.

III. WIND TUNNEL MODELS

A solid flat circular parachute model with 28 gores and a nominal diameter of 16 inches was chosen for the test because it is similar in design to a full size C-9 parachute. The C-9 canopy is also a solid flat circular parachute with 28 gores but with a nominal diameter of 28 feet. The use of models which are scaled-down versions of the full-size C-9 canopy made it possible to compare the wind tunnel data with the full size data and determine the validity of the results.

The models used for the study were designed to represent a 28 gore solid flat parachute at seven stages of inflation. Wire frames were covered with 1.1 oz/sq yd rip-stop nylon parachute fabric attached to the structure along the seams so the material would take the required inflated shape in the wind tunnel. To retain the inlet gore configuration required for the simulation, fine copper wire was inserted into the leading edge of each gore. Using these construction techniques, it was possible to fabricate the seven models used to simulate the various inflation stages of the C-9 parachute.

IV. WIND TUNNEL TEST FACILITY

The wind tunnel used to conduct the flow field study is located at the Climatic Research Laboratory of the US Army Natick Laboratories, Natick, Mass. The test facility is equipped with two wind tunnels, an Arctic Wind Tunnel and a Tropic Wind Tunnel, which are used to test military equipment and personnel under extreme climatic conditions. The facility was used for the study because it was possible to maintain uniform control over the temperature to $\pm$ 1°F throughout the test, thus eliminating the problem of temperature sensitivity inherent in hot-wire anemometers. The elimination of this major problem area resulted in highly accurate and uniform readings of the local velocities over a range of flow conditions.

To control the upstream and downstream velocities of the flow, a special 3 ft x 3 ft test section was constructed for the tests (Figure 1). A large flexible panel was fabricated which closed off the 8 1/2 x 15 ft test section with an opening into a 6 ft x 6 ft contraction section. The large reduction ratio created with this design increased the degree of control over the velocity of the flow prior to entering the 3 ft x 3 ft test section. This technique of controlling the flow resulted in repeatable flow conditions with velocities in excess of 110 ft/sec having low turbulence levels within the flow.

The free stream velocity, U_{oo}, was obtained from an upstream pitot tube, converted to an equivalent hot-wire current, I_{oo}, and used in the computation of the local velocity ratios, U/U_{oo}.

Since the models were mounted on the wind tunnel centerline the probes were adjusted to move radially outward from the test section centerline measuring the hot-wire current, I, at 1/2 inch intervals. With the problem of temperature compensation removed, the complicated equations for velocity found in Reference 5 can be greatly simplified. It was now possible to express the local velocity ratio, U/U_{oo}, as a function of the zero velocity current I_o, the free-stream velocity current, I_{oo}, and the local velocity current, I.

$$\frac{U}{U_\infty} = \left[\frac{I^2 - I_0^2}{I_\infty^2 - I_0^2}\right]^2 \qquad (1)$$

In this manner, it was possible to obtain the velocity ratios for the flow entering the inlet and gores of the canopy, as well as the flow exiting through the vent and fabric. By making holes in the fabric it was also possible to insert the hot-wire probes into the models and obtain the velocity ratios for the flow inside the canopies.

V. TEST RESULTS AND DISCUSSION

To make the results applicable to a number of solid flat circular canopies, the data was plotted in the form of dimensionless velocity ratios versus dimensionless radial distances from the centerline (Figures 2 and 3). Except for Models 1 and 2, each plot contains four curves. Two curves represent the velocity ratios at the skirt and vent planes and are continuous to the point where the velocity reaches free-stream or in terms of velocity ratios, unity. The other two curves represent the velocity ratios of the flow inside the canopies at Stations 1 and 2. Since these are inside the canopy, they are bounded by the radial distance to the canopy fabric at the given station. Below the plots are cross-sectional outlines of the specific stages of inflation represented by the parachute models. This method of presentation makes it possible to relate a specific data point with a physical feature on the model such as vent opening or edges of gores. As shown in Figures 2 and 3, the solid line on the outline of the model is the outer perimeter of the gore while the dashed line is the base of the gore or the seam where the suspension line is attached to the parachute.

A. Flow Into the Canopy

The flow into the canopy models has a marked transition from Model 1 to Model 7. Model 1 has a distinct core of higher velocity flow along the centerline which reduces to a low velocity region of flow in the skirt plane at the base of the gores. Models 2 and 3 show similar core flow of about the same magnitude but more uniformly distributed. They also have a lower velocity ratio at the base of the gores than the centerline value. It appears that during the early phase of inflation the low velocity region is in the form of an annulus and located at the base of the gores. Model 4 begins to show a transition in the flow into the canopy. Here, the velocity across the inlet remains uniform with a slight rise in velocity on the suspension line circle. Models 5, 6, and 7 continue with similar smooth transition curves. All the models have a rise in velocity across the inlet of the gore. In models 1 through 4 the rise is sharp and begins at the base of the gores. The last three models show a smooth change in velocity from the base of the gores and out across the gores.

B. Flow Out of the Canopy

All of the models have a high velocity flow through the canopy vent. The first four models have a high velocity flow along the centerline. In the last three models, the inlet area of the parachute is much greater than the vent area, causing the internal pressure to be more uniform, and the velocity of the flow shows a more uniform region across the vent opening.

Behind the canopy, the velocity of the flow decreases to a very low level. The average velocity ratio of the flow passing through the fabric of the seven models was found to be 0.040. All of the models experience a distinct flow separation at station 1. The higher velocity ratios shown behind the canopy for Models 1 and 2 appear to be caused by the higher velocity flow coming around the outside of the canopy due to this separation of flow. From Model 3 to Model 7 the ratio remains uniform behind the canopy with a rise in the velocity at the radial distance of Station 1 from the centerline.

C. Flow Inside the Canopy

The small internal dimensions of Models 1 and 2 made it impossible to obtain data on their internal flow. The first model in which the velocity was studied was Model 3. Here the velocity curve shows a low velocity on the centerline at Station 1 with a steady increase in velocity moving outward from the centerline. A transition is more noticeable from Model 3 to Model 5 in which the low velocity core flow at Station 1 broadens until the centerline velocity increases slightly in Model 6. Model 7 does not have a Station 1 because it would coincide with the skirt of the canopy. Therefore, the flow velocities of Station 1 in Model 6 would transition to the inlet velocity curve of Model 7.

The velocity ratios for Station 2 all seem to show similar curves. That is, they have higher velocity ratios at the centerline and lower values away from the centerline. At Station 2, the flow through the vent is beginning to form and the flow steadily increases in velocity until it exits through the vent.

D. Summary of the Data

The data presented in Figures 2 and 3 can be converted into a more useful form by taking average values of the velocity ratios and relating them to the inflating canopy shape or more exactly the parachute inlet diameter ratios. By averaging the velocity ratios for the flow into the canopy at the skirt plane it is possible to get the two curves shown in Figure 4. The lower curve represents the average velocity ratio across the circle formed by the base of the gores, while the upper curve is the average velocity ratio across a single gore. Figure 4 indicates that for a parachute with a small number of gores (12 to 28) the dominant curve affecting the early phases of inflation would be the upper one because most of the air filling the canopy would enter through the gore inlets. For parachutes with a large number of gores (64 to 160) the upper curve would only be effective in initiating the inflation process but the greatest amount of air would enter through the main inlet of the parachute.

In a similar fashion, the flow exiting the canopy at the vent plane can be simplified by plotting the average velocity ratios through vent and canopy fabric (Figure 5). The dashed portion of the lower curve represents the average value for the flow as measured behind the canopy from the test data, but since this flow was affected by separated flow coming around the side of the canopy, the average velocity ratio through the fabric is assumed to be about 0.040.

VI. APPLICATION OF RESULTS

The results of the study have many implications for future research in parachute technology. For one thing, the data from the scale-model tests can be used to predict values for full-scale systems. In discussing the applications of the model data, first to be considered is the concept of dimensionless time versus projected area during inflation, secondly, values for the filling times for two full-size parachutes are predicted.

A. Dimensionless Time Versus Projected Area

The concept of dimensionless time is that it is possible to express the times during the inflation of a parachute as a function of the instantaneous time, t, and the total filling time, t_f.

$$T = \frac{t}{t_f} \qquad (2)$$

Therefore, the value of the dimensionless time, T, ranges between zero and unity. One method for determining T as a function of the projected area of the parachute during inflation is covered in Reference 2. The assumptions used in this method require that unknown factors take on linear relationships with the various parameters. The solution to the system of equations which are developed in this fashion is by a trial and error technique. This type of iterative solution occurs because the free-stream velocity, U_{OO}, varies during inflation as a function of the drag area and mass of the parachute system.

Now that the flow field data obtained in this study is available, it is possible to determine the filling time, t_f, as a function of the change in volume and volumetric flow rate, Q, into and out of the parachute. Using the average velocity ratios from figures 4 and 5 it is possible to determine the volumetric flow rate into the parachutes, Q_{in}, through the inlet and gores of the canopy, as well as the flow out of the canopy through the fabric and vent, Q_{out}.

$$Q_{in} = U_\infty \left[\left(\frac{U}{U_\infty}\right)_{INLET} \left(\frac{\pi}{4} D_i^2\right) + \left(\frac{U}{U_\infty}\right)_{GORE} \left(\frac{\pi^2 D_i D_o}{2n} - \frac{\pi^3 D_i^2}{8n}\right) \right] \tag{3}$$

$$Q_{out} = U_\infty \left[\left(\frac{U}{U_\infty}\right)_{VENT} \left(\frac{\pi}{4} D_v^2\right) + \left(\frac{U}{U_\infty}\right)_{FABRIC} \left(\frac{\pi}{4n}\right) \left(\frac{6 D_i D_o}{4D_o + \pi D_i}\right)^2 \sqrt{4\pi^2 + n^2} \right] \tag{4}$$

Where "Do" is the nominal diameter of the parachute, "Di" is the instantaneous diameter of the parachute, "Dv" is the vent diameter and "n" is the number of gores. This results in a simplified method of determining the time between the various stages of inflation and the total inflation time.

$$\Delta t = \frac{\Delta(\text{Volume})}{Q_{in} - Q_{out}} \tag{5}$$

$$t_f = \sum \Delta t \tag{6}$$

Using this method, a full size C-9 parachute system was analyzed for two different snatch velocities (the velocity at which parachute initially begins to open).

SYSTEM CHARACTERISTICS

Parachute: 28 ft, 28 gore C-9 canopy
Suspended Weight: 200 lb
Sea Level Standard Day Conditions
Snatch Velocity: 227 ft/sec and 103 ft/sec

The system described above was chosen for the analysis because it is similar to those studied by Berndt and De Weese (Reference 3). Figure 6 shows the comparison between the computed values of projected parachute area ratios, S/S_o, versus dimensionless time obtained from this flow field study and the average curve obtained from over thirty full scale test drops made by Berndt and De Weese. The close correlation among the three curves indicates that the results of the scale model wind tunnel study can be applied to full-scale systems. This is significant because extrapolation from model parachute data has produced results very close to those obtained from the full-scale system.

B. Predicted Parachute Filling Time

Using the same technique described above an attempt was made to predict the filling time for a C-9 parachute and a G-11A parachute over a range of snatch velocities and suspended weights. The G-11A is also a solid flat circular parachute but it is 100 ft in diameter and contains 120 gores. Both canopies were analyzed over a range of snatch velocities between 150 ft/sec and 250 ft/sec. The C-9 had suspended loads from 160 lbs to 320 lbs while the G-11A loads ranged from 2200 lbs to 4400 lbs. The results of the C-9 predictions are shown in Figure 7 along with some of the data points obtained by Berndt-De Weese (Reference 3). The predicted filling times appear to be lower than the Berndt-De Weese data, but this is probably caused by the numerical model of the inflating parachute used to compute the curves. The model assumes the ideal case in which all of the gores are equally inflated. In the real case, some of the parachute gores are collapsed or folded causing the parachute to take longer to open. The predicted filling times for the larger G-11A parachute are shown in Figure 8. Although this parachute is used extensively for airdropping heavy loads, there is still a shortage of accurate information on its filling time. Estimates for this value range between 7 seconds and 10 seconds with the average being about 8 1/2 seconds for snatch velocities between 200 ft/sec and 250 ft/sec.

Another interesting result of the prediction of the filling times is that doubling the weight of the suspended load results in a 10% reduction in the filling times for the C-9 parachute and a 25% reduction in the filling times for the G-11A. These differences in filling times seem to be consistent over the complete range of snatch velocities analyzed.

C. Other Applications

Other applications of the data to full-scale systems also exist. Flow field data with so high a confidence level would be of distinct value in the determination of the parachute stability angle during inflation. This would be accomplished by looking at the relationship between the diameter of the undisturbed stream-tube of flow around the parachute and the centerline of the flow. The interaction of the flow fields of parachutes in clusters would also be used to study the problem of irregular opening of clustered parachutes. Other areas include prediction of trajectories for systems, random gore opening problems and effects of reefing on opening characteristics.

VII. CONCLUSIONS

The hot-wire anemometer study has developed the first significant data on the flow field associated with an inflating parachute. By controlling both the velocity and temperature of the flow in the test section, it was possible to identify velocities inside and immediately behind the parachute which have never been measured before. Although the objective of this study was to investigate the flow field, the results can be applied to the other problem areas in parachute technology described earlier in the study. It is now possible to relate the inflation geometry to the filling time, determine the filling time and extrapolate from scale-model data to full-scale data. Some of the other results of the study are listed below:

1. During the early stages of parachute inflation a low velocity region in the shape of an annulus forms at the base of the parachute gores.

2. As the inflation of the canopy progresses through the middle and final stages of inflation the low velocity annular region changes from the annulus shape to a region of approximately uniform velocity across the canopy inlet.

3. The velocity ratios behind the inflating canopy range between 0.03 and 0.05. The uniform distribution of the velocity ratios indicates that these values can be attributed to the flow passing through the canopy fabric.

4. The flow across the base of the hemispherical cap (Station 1) within the canopy during inflation appears to have a uniform transition from the initial to final stages of inflation.

5. The initial formation of the flow through the vent is visible in the velocity field within the canopy cap.

6. The results of the flow field study can be used to compute the filling times of various solid flat circular parachutes with a reasonable degree of agreement with full-scale data over a range of snatch velocities and suspended loads. This is significant because model simulation of full-scale systems in the field of parachutes has always been a major problem.

The state-of-art in parachute technology should be greatly advanced by the data presented in this paper, and the applications should provide better guidelines for parachute design.

VIII. REFERENCES

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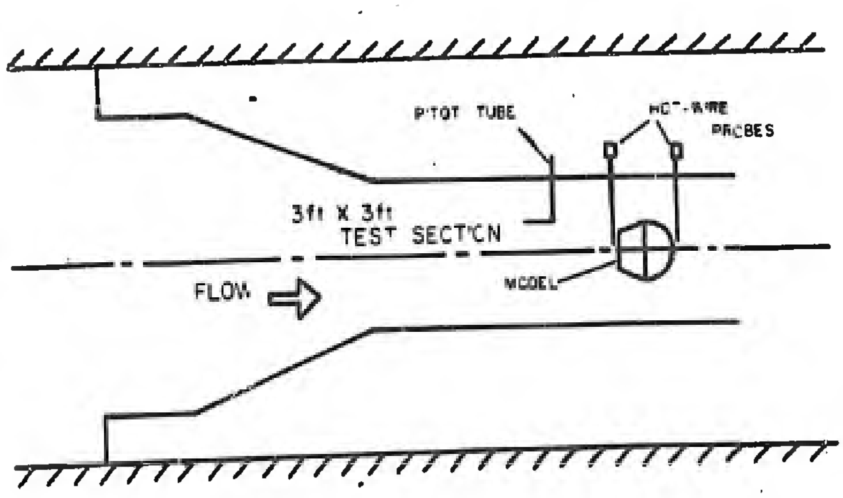

Fig. 1 Wind Tunnel Test Setup

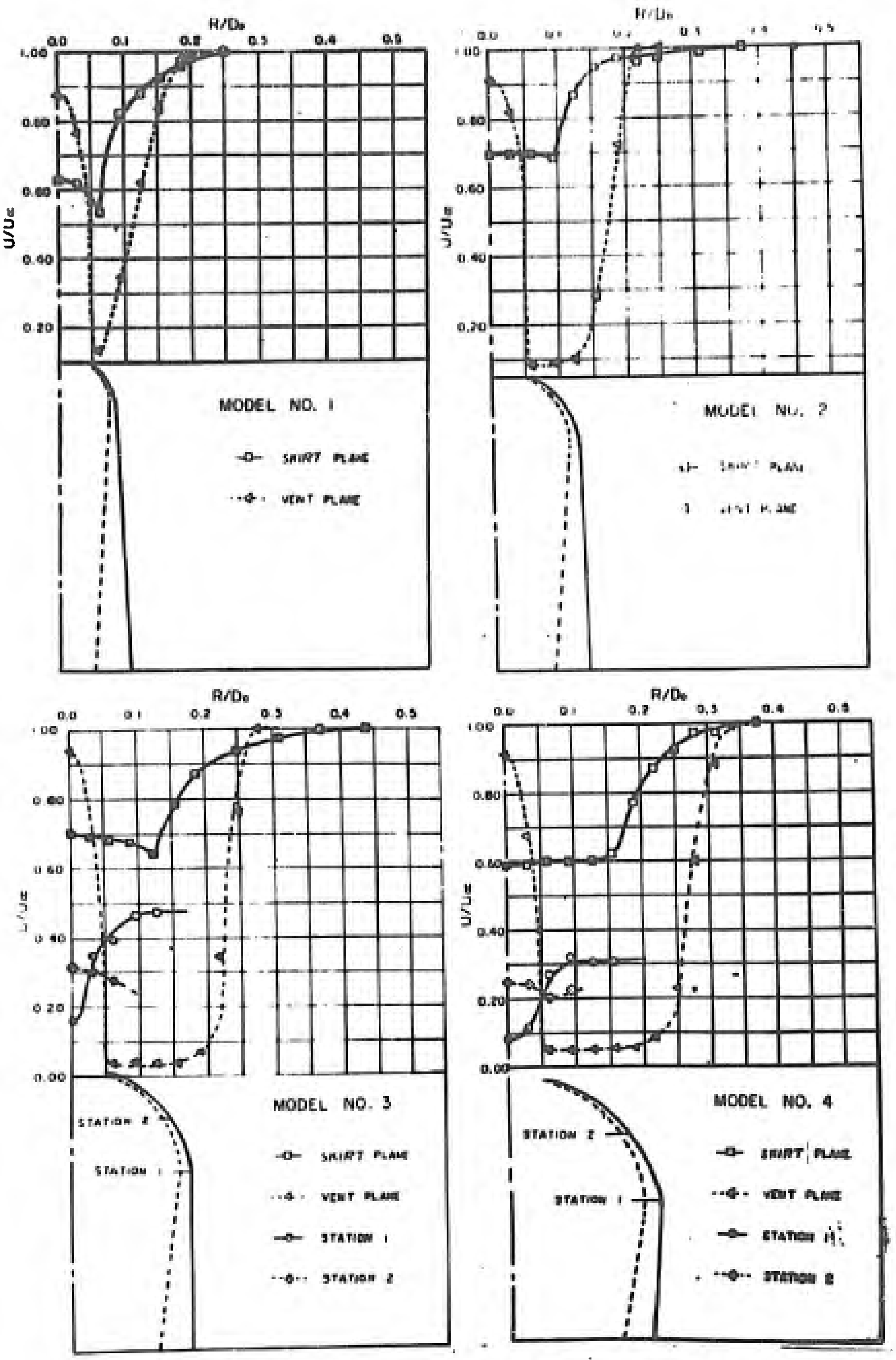

Fig. 2 Velocity Ratios vs Radial Distance From Canopy Centerline

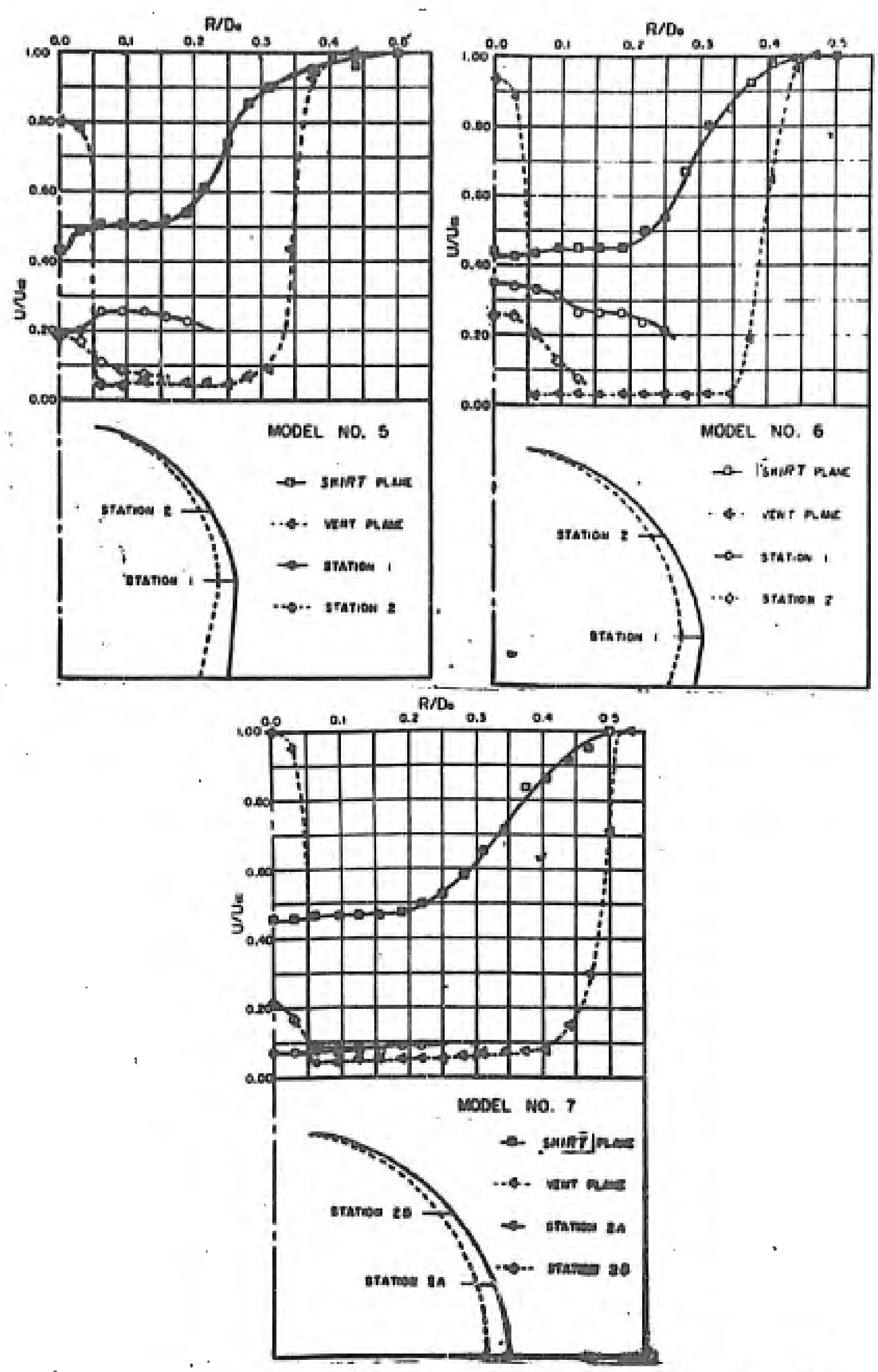

Fig. 3 Velocity Ratios vs Radial Distance From Canopy Centerline.

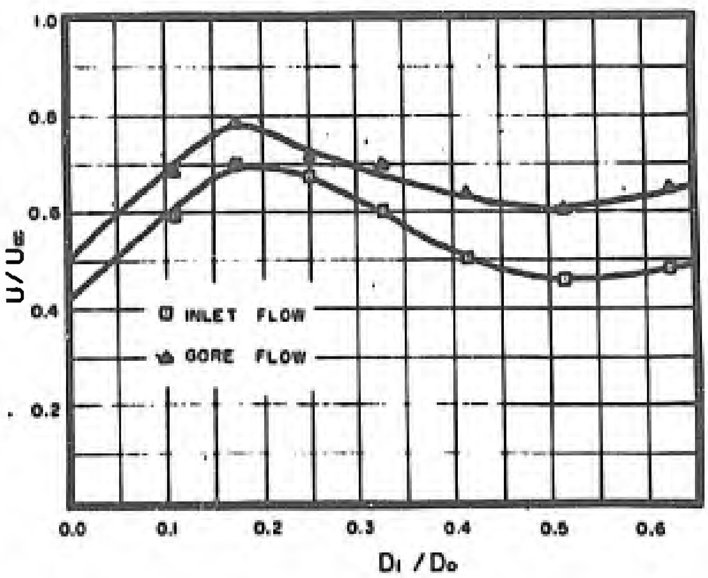

Fig. 4 Average Velocity Ratios Vs Inlet Diameter Ratio in the Skirt Plane

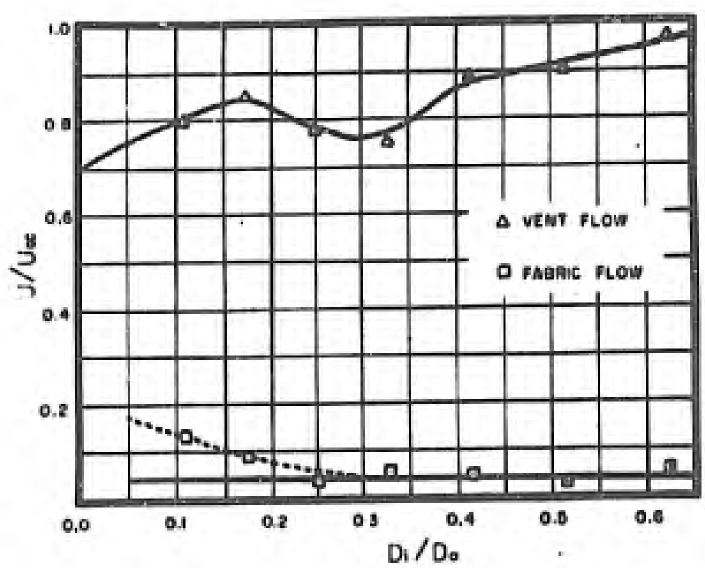

Fig. 5 Average Velocity Ratios vs Inlet Diameter Ratio in the Vent Plane

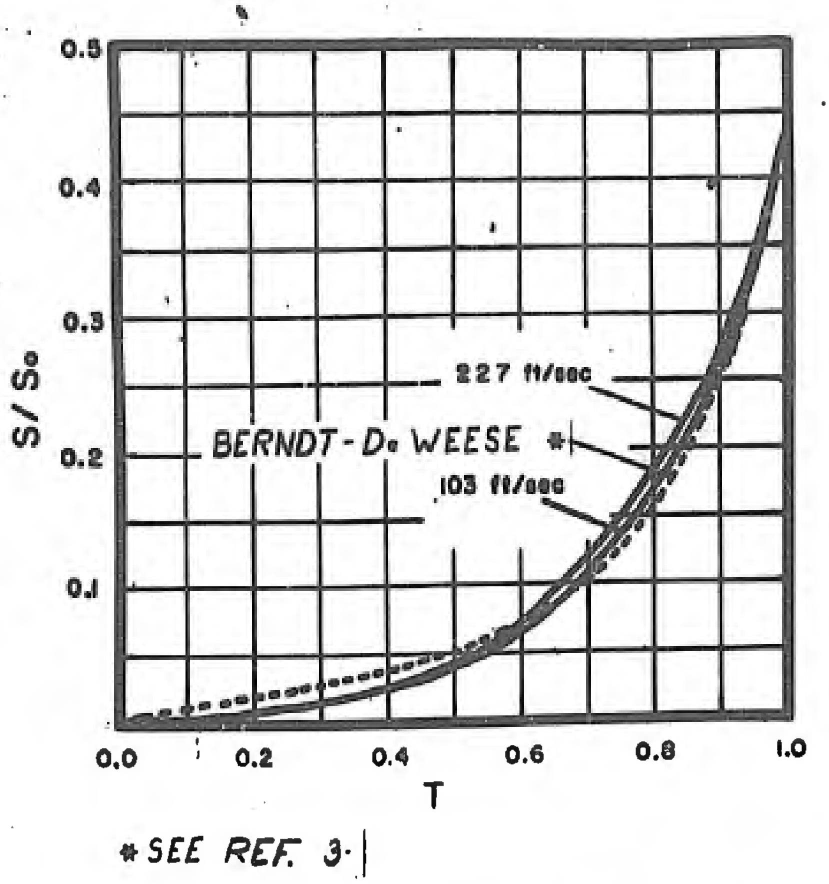

Fig. 6 Projected Area Ratio vs Dimensionless Time (Predicted Values and Full-Scale Data)

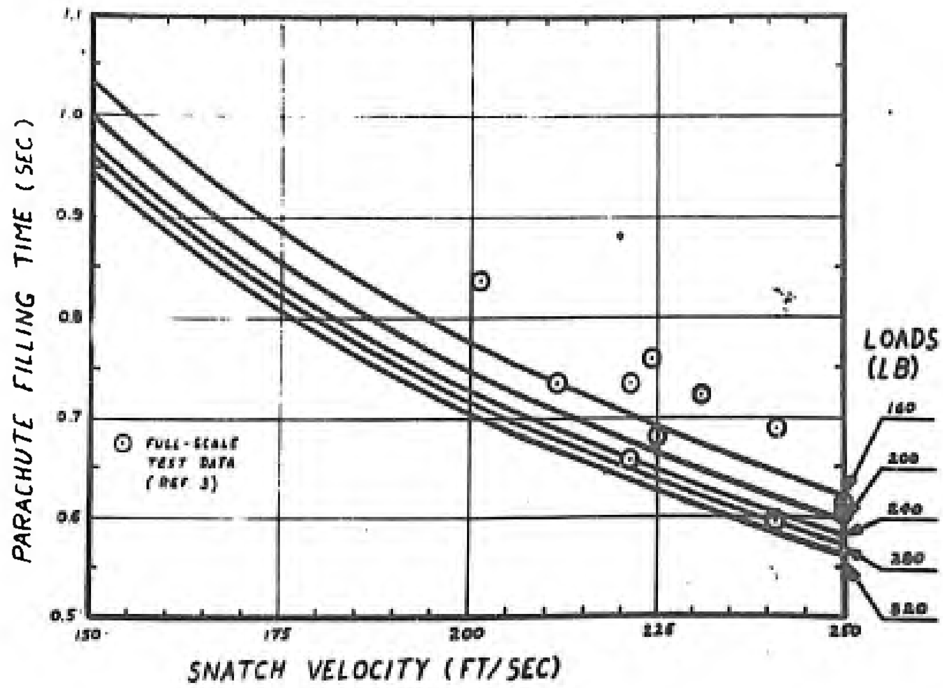

Fig. 7 C-9 Parachute - Filling Time vs Snatch Velocity (Predicted Values and Test Data)

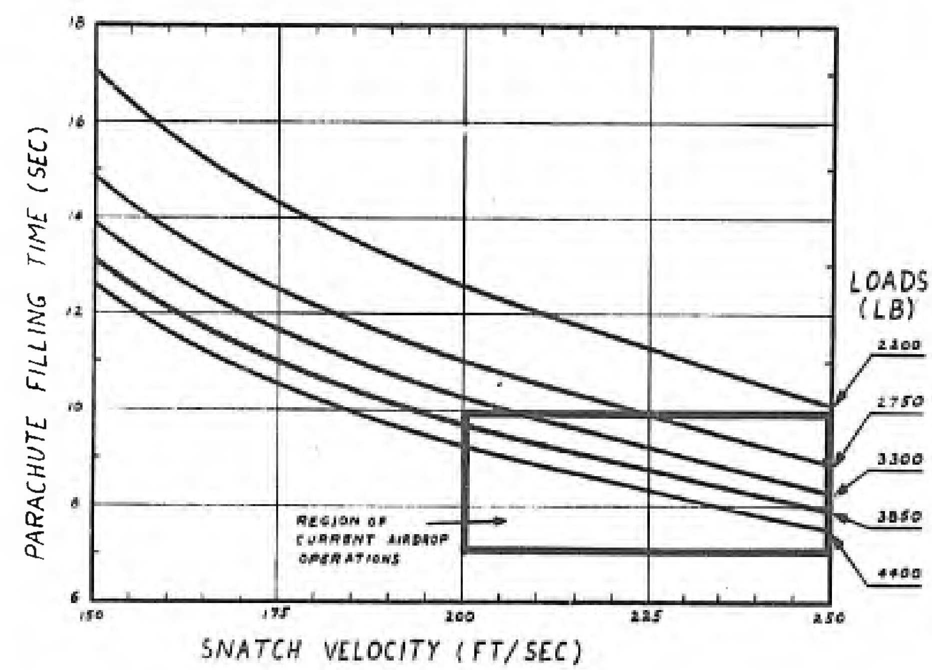

Fig. 8 G-11A Parachute-Filling Time vs Snatch Velocity (Predicted Values)