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TECHNICAL REPORT 2/75

ASSOCIATE COMMITTEE ON AIR CUSHION TECHNOLOGY

THE DEVELOPMENT OF A NON-DIMENSIONAL
LIFT AIR COEFFICIENT
FOR AIR CUSHION VEHICLES

(BASED ON A PAPER BY T.P. CUTTS
CARLETON UNIVERSITY
FACULTY OF MECHANICAL AND AERONAUTICAL ENGINEERING -
PROJECT ADVISER, DR. R.J. KIND)

OTTAWA, CANADA

APRIL 1975

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LIFT AIR COEFFICIENT
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Carleton University
Faculty of Mechanical and Aeronautical Engineering

(Project Adviser, Dr. R.J. Kind)

April 1975

ABSTRACT

The development of a non-dimensional performance parameter, describing the lift air flow required for an air cushion vehicle, was the purpose of this project. The Lift Air Coefficient had to be easily modified to account for planform geometry, the arrangement of plenum and vegetation encountered. The results of a theoretical analysis of planform effects were checked experimentally, while vegetation and clustering effects were related to Lift Air Coefficient by an empirical relation developed after tests were run.

Vehicle shape was found to have the most important planform effect, while clustering changed the coefficient by very little. The shape factor used was a ratio of the square root of the planform area to the total perimeter. Vegetation of uniform density was accounted for by a modification of the coefficient by a ratio of vegetation height to the height above ground of the same material under a heavy weight. Due to a leakage problem, the accuracy of the Lift Air Coefficient values was poor in the lowest hoverheight region.

The coefficient proved to be easily modified to allow for many variables, but it was noted that many restrictions imposed were unrealistic.

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INTRODUCTION

There is no universal method used in the design of an air cushion vehicle at present, given the required size, shape, hovering height and expected terrain. The design is usually based on a comparison of the proposed craft with one already in existence. The comparison is only valid though, if the vehicle being designed is identical in planform and skirt geometry. For instance, one value which must be predicted is the volume air flow rate required. If a non-dimensional performance parameter was developed which linked air flow required with planform and terrain characteristics then the design process could become more standardized.

The development of such a parameter was the aim of this project. The parameter had to take into consideration the size, shape and plenum arrangement of the vehicle and had to be easily modified by factors which accounted for vegetation encountered over solid ground. It was hoped that factors could be developed which were easily made non-dimensional by relating the respective geometry of the situation. A non-dimensional flow coefficient developed by Trillo (Reference 1) was known to be dependent on size, shape, skirt type and terrain encountered. Since it was already published and accepted, it was decided to use it as a part of the proposed parameter. The parameter was named "Lift Air Coefficient" and was developed with the aid of tests on different models.

Models which were very different in size, shape and clustering of the plenum were required. The three decided upon were as follows; one consisting of three circular plenums; one with four square plenums; and a more conventional single rectangular plenum with two to one aspect ratio. All had identical skirts of stiff steel sheet to help decrease the number of variables to only size, shape and clustering over smooth ground. Each model had different surface areas. (Figures 5, 6, 7) but all models had the same total perimeter length of the plenums.

These models and a flow meter were designed and built at the National Research Council Engine Laboratory. Testing and modification was carried out from June 1974 to March 1975.

EXPERIMENTAL METHODS

It was noted that the motor driving the blower was of the induction type and as such could not be controlled to vary the flow rate Q . After examining the possibility of bleeding air using vents upstream of the orifice, it was decided to leave the flow rate as it was at maximum speed. Instead, the vehicle weight W was varied to obtain different hoverheight values. Barometric pressure and temperature at the blower inlet were recorded as well as hoverheight for each setting. The upstream orifice pressure and the differential across the orifice were registered on a water manometer so that flow rate could be calculated.

Size and Shape Effect

After the empty weight of the model was recorded, the blower was switched on and allowed to stabilize in speed. The cushion pressure of the model was then recorded in terms of inches of water and the other readings as noted above were taken. Hoverheight was measured using an adjustable set square with the handle flush against the plywood ground and the rule perpendicular. A metal projection on each plenum, or on each corner in the case of the rectangular model, indicated the hoverheight with respect to a zero reading. By averaging the readings a reasonable mean hoverheight was found. An increment of weight was added next and readings were taken again; this procedure was continued until the hoverheight became too small. The multi-plenum (circular, square) models were very stable but instability of the rectangular model necessitated careful balancing using the load increments.

Clustering Effect

The effect of clustering the plenum was examined by taking the worst case (the four square plenum model) and traversing the gaps between the plenums with a static probe to compare the pressure there with ambient pressure. The value of cushion pressure multiplied by total plenum area was calculated to see how well it agreed with the all up weight of the craft for all models.

$$P_c \times S_c = W$$

Thus, an examination of the results would indicate whether any support of the vehicle was occurring between the separate plenum.

Vegetation Effect

After an examination of approaches used in soil analysis, it was decided there was not enough time to become involved in such a factor as soil porosity due to its complexity as compared to the apparatus

used here. (Reference 2, 3) The effect of vegetation over nonporous ground was examined. Two carpets of different fibre construction and density were used. One circular plenum was used and to eliminate the difficulties inherent with the measuring of hoverheight on such a surface, the hoverheight was controlled by supporting the model on aluminum shims and the plenum was weighed down with 60 lb. of weight. (Figure 9) The height of the model above the squashed height of the carpet could then be calculated by noting the number of 1/32 inch shims used. The height of the squashed carpet would have to be added to the height of the shims to obtain hoverheight above the carpet backing. Other readings taken include cushion pressure, orifice pressures and air property readings.

ANALYSIS

The Lift Air Coefficient is based on Trillo's non-dimensional air flow coefficient, C_{Qc} which is dependent on craft shape.

where $C_{Qc} = \frac{Q}{Sc \times V_d}$ (1)

Since Trillo's coefficient has already been accepted it was decided to use it as a basis and modify it by multiplying factors which accounted for vehicle size and shape, vegetation encountered and clustering of the plenum.

The definition of Lift Air Coefficient then becomes:-

L.A.C. = I x J x K x C_{Qc} (2)

where I accounts for clustering, J takes into consideration the shape dependence, and K accounts for vegetation effect.

Size Parameter and Shape Factor

The following simple analysis suggests a definition of a size parameter applicable to any cushion planform, and of a non-dimensional shape parameter which can be used to characterise the shape of any cushion planform.

For an air-cushion plenum (see Fig. 2), the volume flow rate Q of air escaping from the cushion is given by:-

$Q = C_D h L V_d$ (3)

- where C_D is a discharge coefficient
- h is the hover height
- L is the perimeter of the skirt
- V_d is the velocity of the escaping air

Substitution of equation (3) into equation (1) gives:-

$C_{Qc} = \frac{C_D hL}{Sc}$
 or $C_{Qc} = C_D \frac{(h)(L)}{(r)(r)}$ (4)

where by definition, $r = \sqrt{Sc}$ (5)

For a given cushion planform shape the cushion area Sc is proportional to the square of the vehicle size or length. Thus, r as defined by equation (5) would be a suitable size parameter, or measure of cushion size. Then the parameter (h/r) in equation (4) could be interpreted as a non-dimensional hoverheight, while the parameter (L/r) would be interpreted as a shape parameter. This shape parameter (L/r) has a different value for different cushion planform shapes (e.g. $L/r = 2\pi$ for a circle, $L/r = 4$ for a square, etc.) and its value is independent of the cushion size. Thus, the shape parameter J of equation (2) can be taken as (r/L) .

Furthermore, equation (4) indicates that for given values of the shape, clustering, and vegetation parameters,

$$LAC = I \times (r/L) \times K \times C_{Qc} = C_D (h/r) \dots\dots\dots (6)$$

If leakage is considered, the experimental data (Figure 10) agree well with this solution, showing that size and shape are well accounted for in equation (6). The discharge coefficient C_D will of course be dependent on the geometry of the skirt/ground interface. (Reference 5).

Clustering Effect

Given close enough plenums and high enough velocity from the skirt-to-ground clearance, a pressure greater than ambient would be expected between the cluster and under the air distribution plenum. A lift force besides that in the plenum must then be accounted for by some empirical relation equal to I if the effect was found to be significant. In actual fact it was found to be insignificant.

Vegetation Effect

Using different carpets, the effect of uniform density vegetation of known height on the Lift Air Coefficient was studied. (shape factor was known, as well as hoverheight). The modification factor K was found as follows. (Figures 4, 9).

It was felt that the blockage of air was the important effect of vegetation for a static plenum. Since the carpets were reasonably uniform in density, the parameters chosen were 'a' the full height of the carpet above its backing, and 's' the compressed height of the carpet under a 20 psi. load. (The load was calculated by the vehicle weight on the supporting shims). The value 'a' would probably be an

r.m.s. value to allow for irregular carpets. Since one requirement was that the K factor had to be 1 for flat non-porous ground, the ratio of a/s was used.

RESULTS

Shape Factor J

The experimental results are plotted on a graph of Lift Air Coefficient vs. Non-Dimensional Hoverheight in Figure 10. The theoretical line was plotted using the relation $L.A.C. = C_D \times h/r$ from the Analysis section; equation 6. The discharge coefficient used was .611 for 90° stiff skirts.

The use of r/L to account for shape of the plenum works well. Regardless of shape, the Lift Air Coefficient varies with non-dimensional hoverheight along a curve shown as a dotted line on the graph. The scatter is very small considering the crude models used.

The results lie very close to the theoretical line but pass through the Lift Air Coefficient axis at about $L.A.C. = .00055$. This indicated a leakage in the system of both model and the air supply system. To investigate this further a single circular plenum was loaded until hoverheight was zero over a smooth flat non-porous surface. Readings were taken as explained in 'Experimental Methods, Size and Shape Effect', and gave a result of L.A.C. equal to .00055 also. Then, the effect of small leaks in the air connecting tube was examined by purposely puncturing it to simulate leakage through small holes. These small holes drastically reduced cushion pressure. Since all the equipment was sealed as best as possible it had to be accepted as part of the system. The problem is that this leakage could not be simply subtracted from all other L.A.C. values, and thus shift the line to pass through the origin (as it should) due to the fact the pressure here is the back pressure. The best way to view the results then, is to be wary of the values of L.A.C. below $h/r = .002$ in this experiment, since in the range of 0 to .002 not many values were obtained due to the difficulty in measuring accurately such a small hoverheight. As well, the cushion pressure is higher in this region and consequently leakage is more significant within these limits.

This poses an interesting problem. An experiment could be run to find a factor which would account for various flexible skirt types, and which would relate it to the stiff skirt data. However, the factor would assume a perfectly new skirt; not one which had been dragged, poked and possibly ripped. This is yet another leakage which did not have to be accounted for in the steel skirt factor but which would seriously restrict the lift performance of a vehicle. It would also be virtually impossible to account for in the L.A.C. equation, other than using that L.A.C. to compare the worn skirt's performance as compared to a new skirt.

Clustering Factor I

An examination of the static pressures found between the cluster of square plenum showed very insignificant pressure rise relative to ambient. The clustering effect then, was small. To provide another check, the actual weight of the vehicle was compared to that calculated from cushion pressure and planform area. The results were used to find an average per centage error for each model. (Figure 11) The error ranged from 1.8 to 3.7 per cent average.

It must be kept in mind that this error is not all due to clustering. An idea of the error introduced by reading manometer heights was found by assuming a reading error of .01 inches of water. This gave a 1 per cent change in the calculated weight of the square model, so this shows the clustering effect to be small also. This is due mainly to the small ratio of exit flow area to cross section area between the plenums. Consequently the value of I was assumed to be 1.

Vegetation Factor K

The results of this experiment are summarized on the graph of Lift Air Coefficient vs. Non-Dimensional Hoverheight. (Figure 12) Readings for the single circular plenum are plotted to show that it obeys the shape relation developed earlier for a plenum over plywood. Then, the results for the two carpets were plotted without correcting them with the K factor. The significance of the vegetation can be easily seen. With the correction included, the results lie close to the theoretical line, showing the suitability of the relation $K = a/s$. For the thick carpet the value of K was calculated to be 3.29 since $a = 11.5/32$ in. and $s = 3.5/32$ in. The values of a and s were found to be $5/32$ in. and $2.5/32$ in. respectively, for the thin carpet. This resulted in $K = 2.00$. It was noticed that the backing on the carpets was not impermeable to air, by the nature of its construction, but this was assumed to be of little importance since there was a plywood sheet underneath.

The factor is a simplification of the actual situation since vegetation is not usually of uniform density. Also, soil porosity would cause some of the air to penetrate into the ground, thus demanding more air flow for the same hoverheight. In general, erosion of the soil would also affect the flow due to a build up of ridges at discharge, resulting in a different discharge coefficient.

Also neglected, was the fact that the vehicle will be moving in real life and interaction with terrain then becomes significant as well as difficult to model.

The use of shims to 'measure' hoverheight was found to be very convenient. It should be used instead of measuring the hoverheight of a hovering vehicle due to the elimination of any instability.

CONCLUSIONS

Size was found to have no effect on the Lift Air Coefficient, while the shape factor developed reduced data to a curve very close to the theoretical. (Especially at the higher h/r range) The parameter $J \times C_{qc}$ was found to be a good basis and could be modified to account for different situations such as vegetation effects. Other modification possibilities include soil porosity encountered, erosion effects in static hover, and skirt type used. The possibilities seem endless for the inclusion of parameters in the Lift Air Coefficient, but this is not the important fact. The Lift Air Coefficient is more useful as a gauge to compare the effect of varying one variable with the others fixed. As an example, it could be used as a basis for skirt performance comparison on various plenum shapes. This could be done for different skirts, or one skirt in different states of wear.

Clustering of the plenums showed no significant effect. Elimination of the leakage problem by using more sophisticated equipment would check the relation of L.A.C. and h/r at the lower range of h/r to see if it lies along the theoretical line.

It must be realized that the effect of moving the models over various terrain was not examined, and would lead to a better understanding of Lift Air Coefficient instead of a purely static analysis.

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Dr. E.P. Cockshutt) Engine Laboratory, Mechanical
Mr. H.S. Fowler) Engineering Division, National
Research Council of Canada

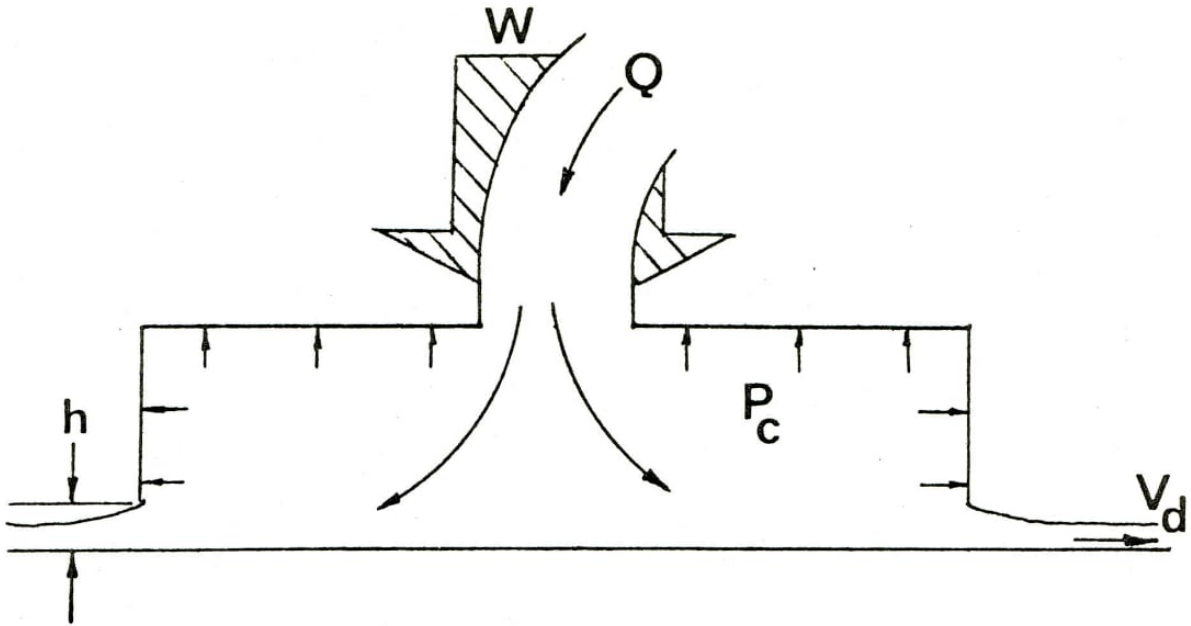
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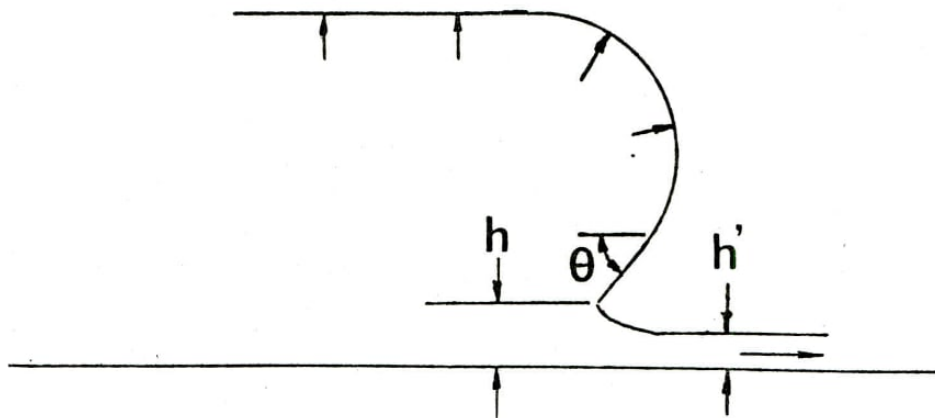
NOMENCLATURE

- ρ - air density (lbm/ft^3)
- a - height of carpet fibre from backing (inches)
- C_{Qc} - Trillo's flow coefficient
- D_c - discharge coefficient
- g_c - constant $32.2 \frac{\text{lbm ft}}{\text{lbf sec}^2}$
- h' - actual discharge height of air flow (ft.)
- h - measured hoverheight (ft.)
- I - clustering factor
- J - shape factor
- K - vegetation effect factor
- L - total planform perimeter (ft.)
- P_c - air cushion pressure (p.s.f.)
- Q - volume flow rate of air ($\text{ft}^3/\text{sec.}$)
- r - shape parameter (ft.)
- S_c - planform area (ft^2)
- V_d - discharge velocity between skirt and ground (ft./sec.)
- W - all up weight of the vehicle (lbf.)

Fig. 1

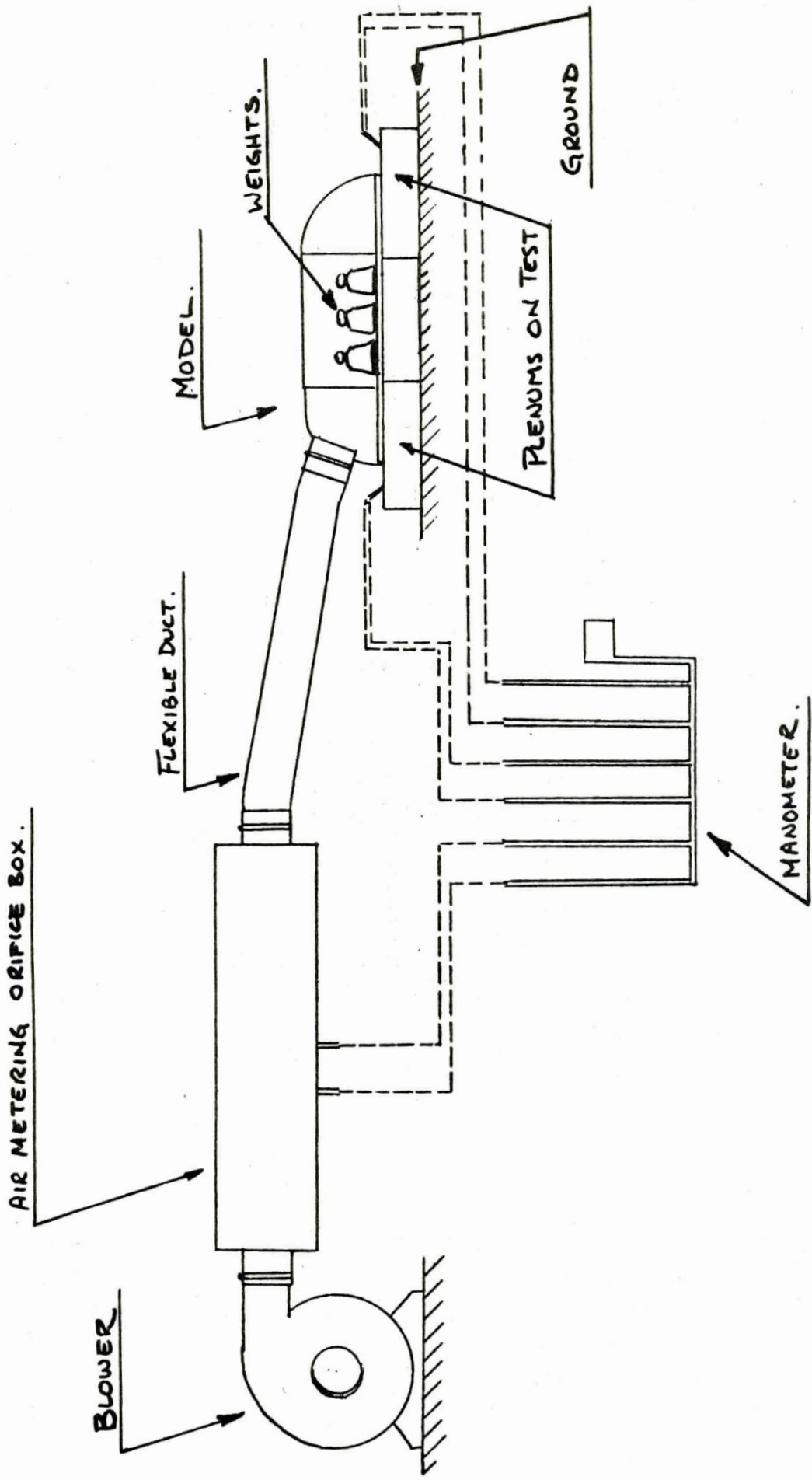


flow coefficient parameters



discharge effect

Fig.2. System Parameters



AIR METERING ORIFICE BOX.

BLOWER

FLEXIBLE DUCT.

MODEL.

WEIGHTS.

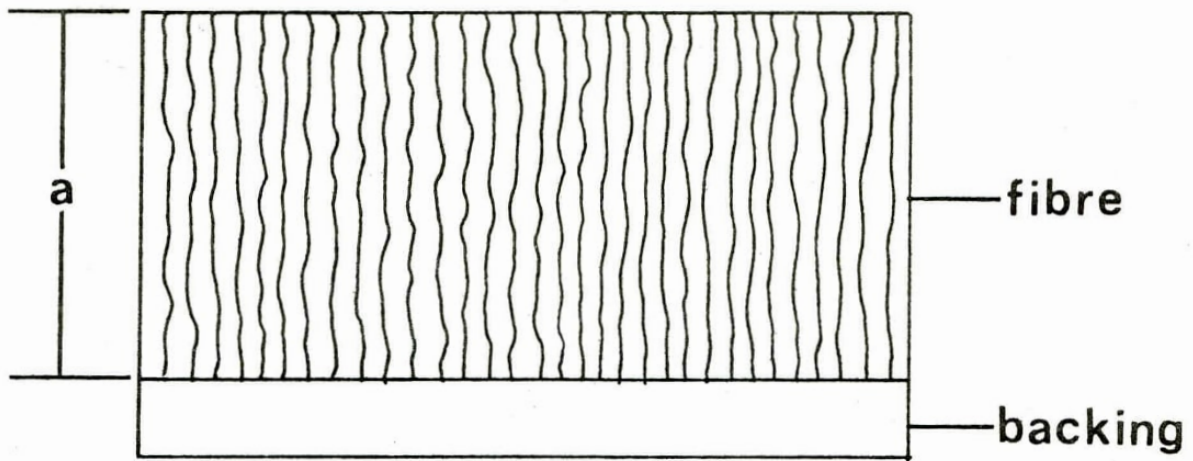
PENUMS ON TEST

GROUND

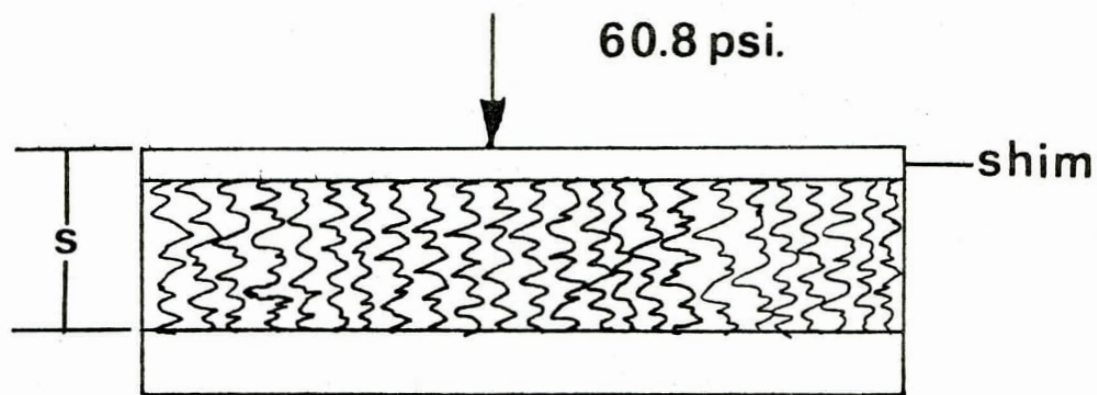
MANOMETER.

EXPERIMENTAL SET-UP.

FIG. 3.



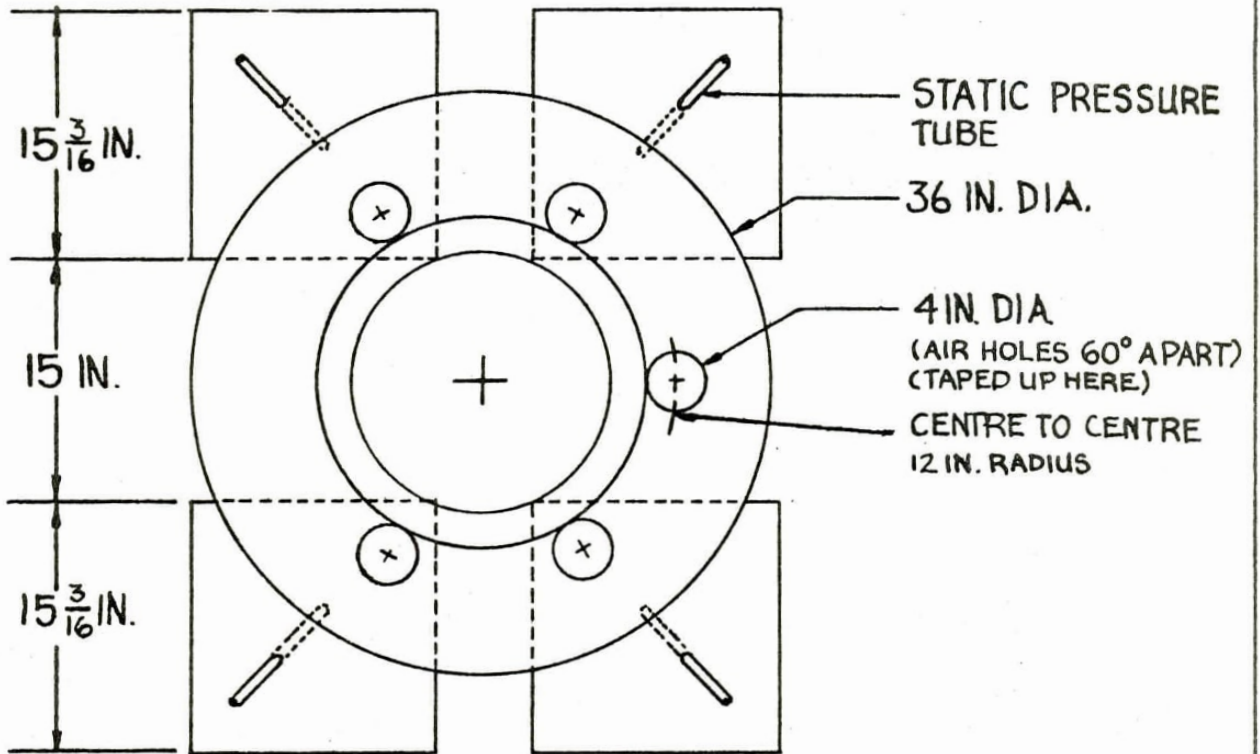
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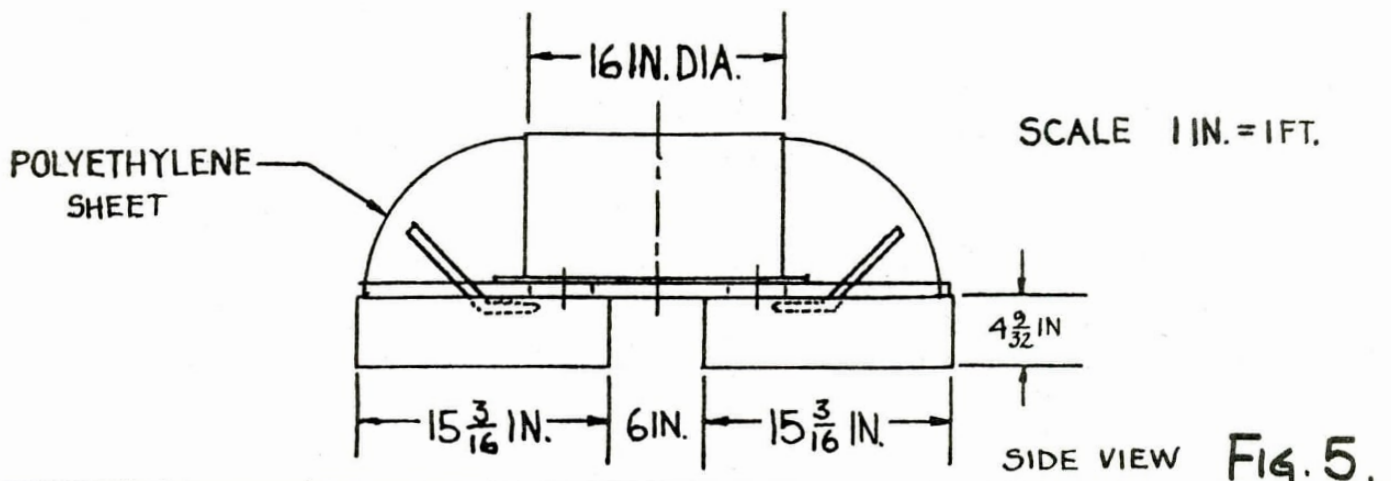
loaded section

Fig.4 Carpet Model Cross Section

ASSEMBLED SQUARE PLENUM MODEL

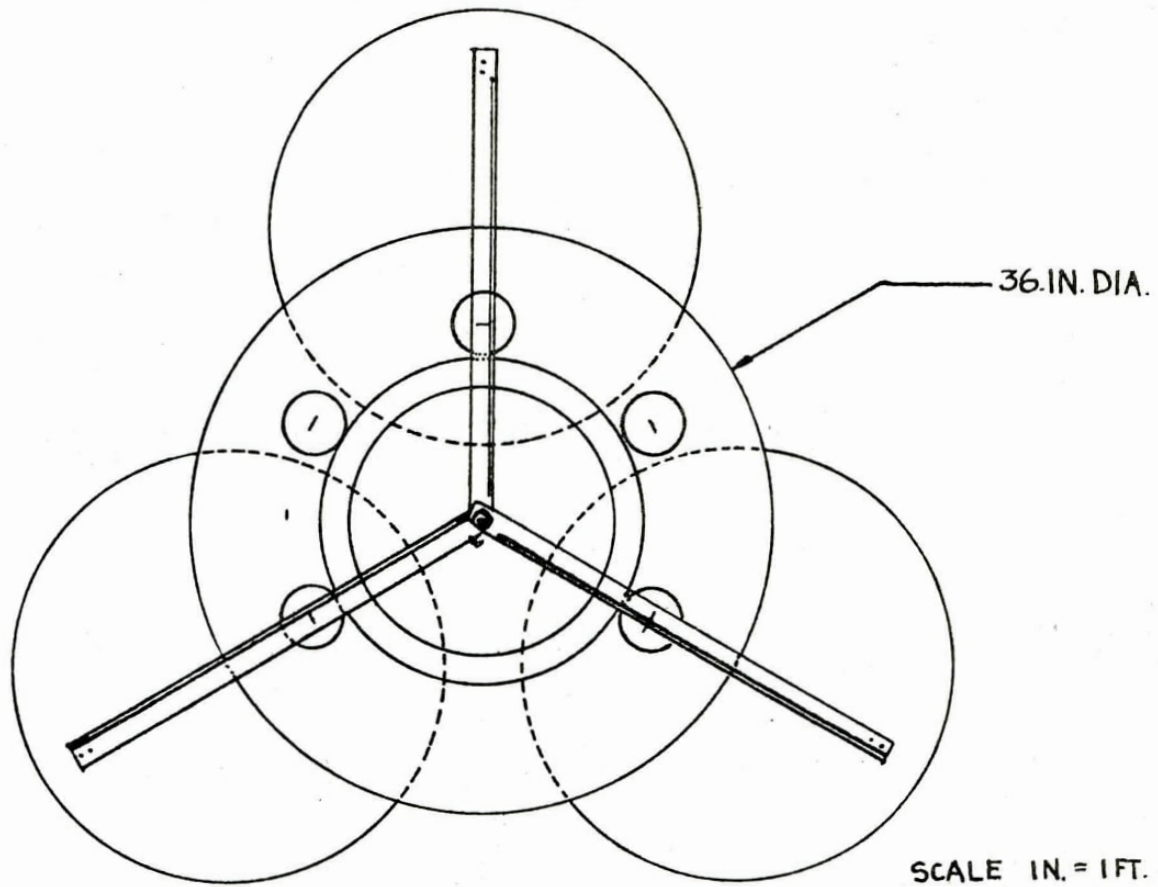


TOP VIEW



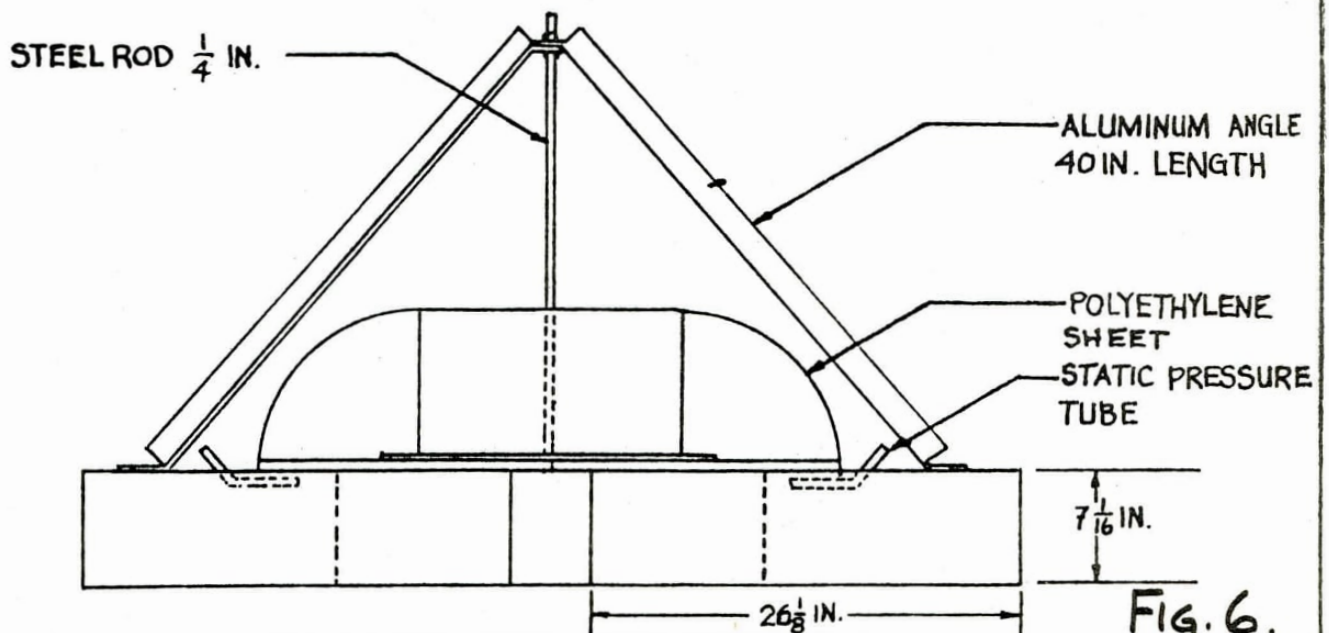
SIDE VIEW FIG. 5.

ASSEMBLED CIRCULAR PLENUM MODEL

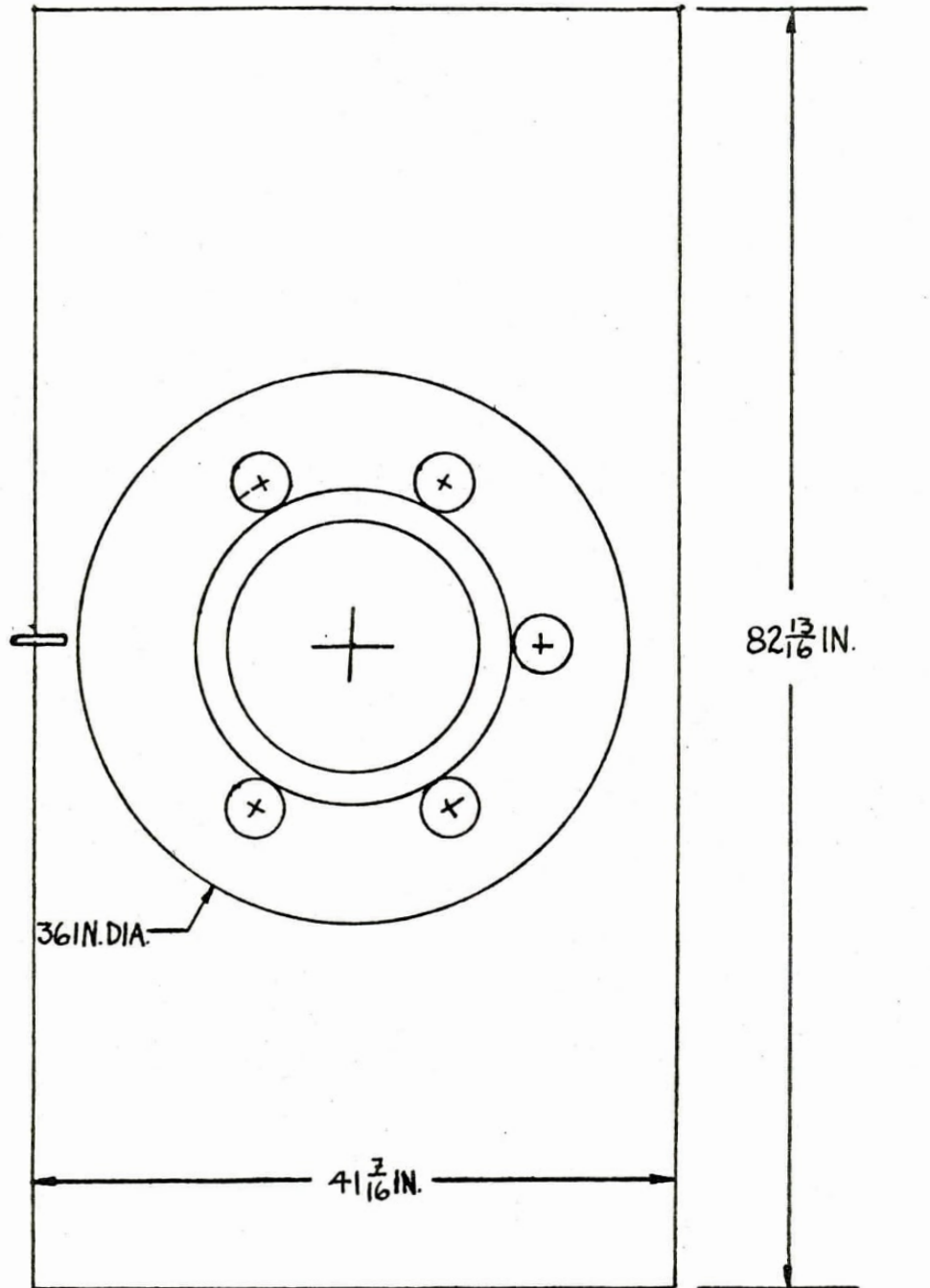


TOP VIEW

SIDE VIEW



ASSEMBLED RECTANGULAR PLENUM MODEL



TOP VIEW

SIDE VIEW

STATIC PRESSURE TUBE

SCALE : 1 IN. = 1 FT.

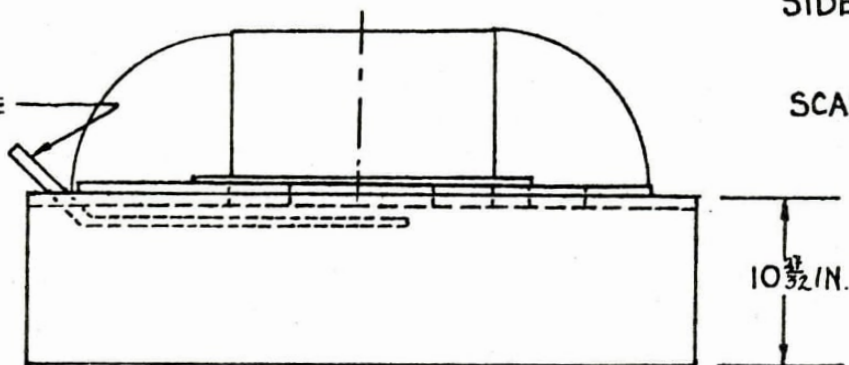
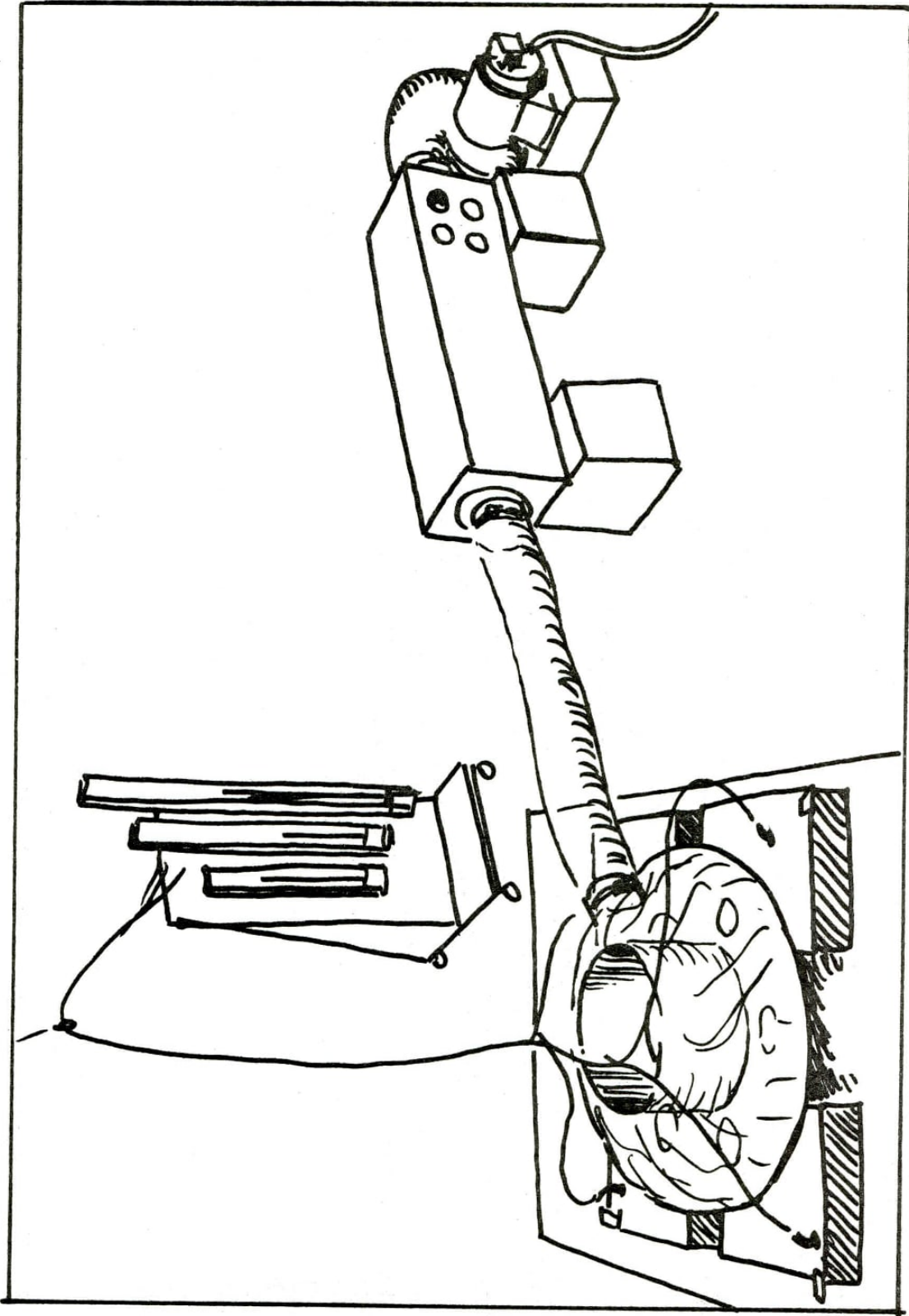
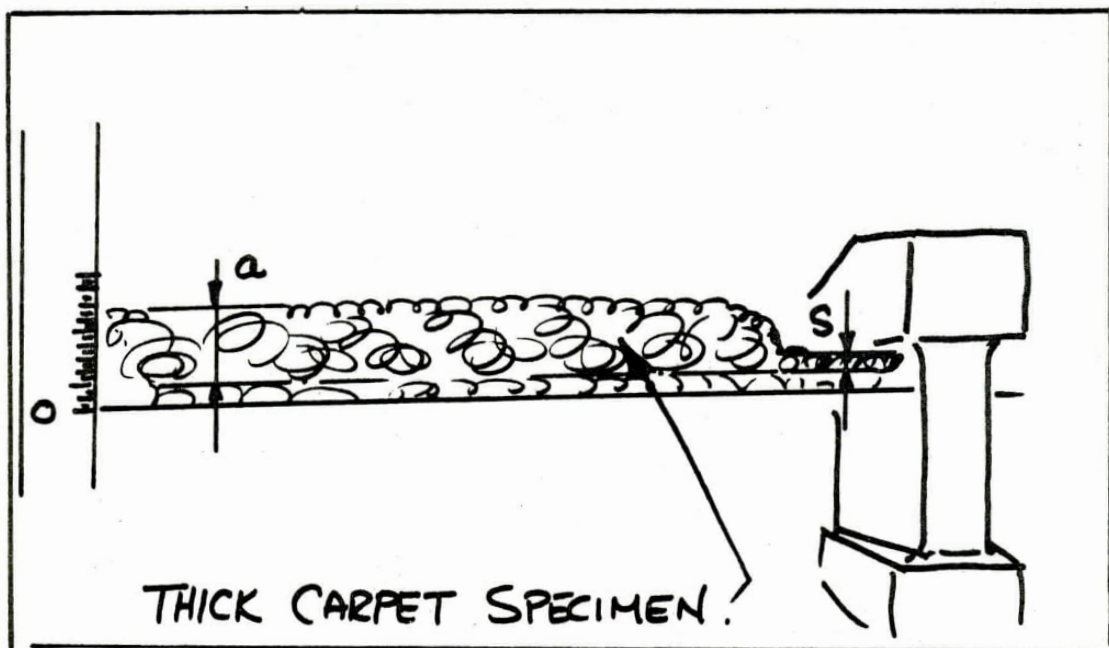
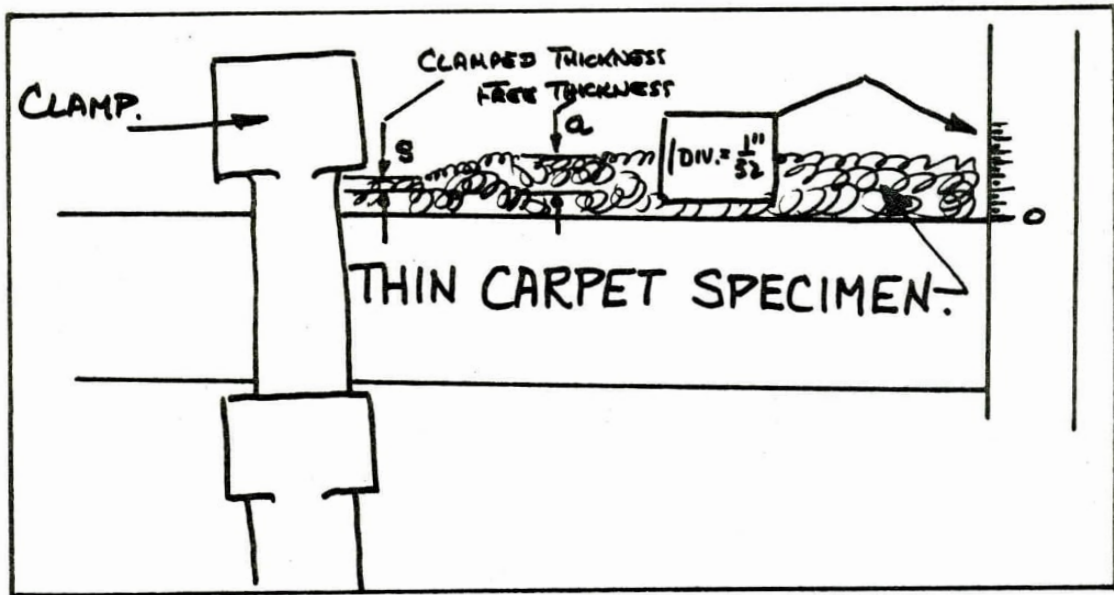


FIG. 7.

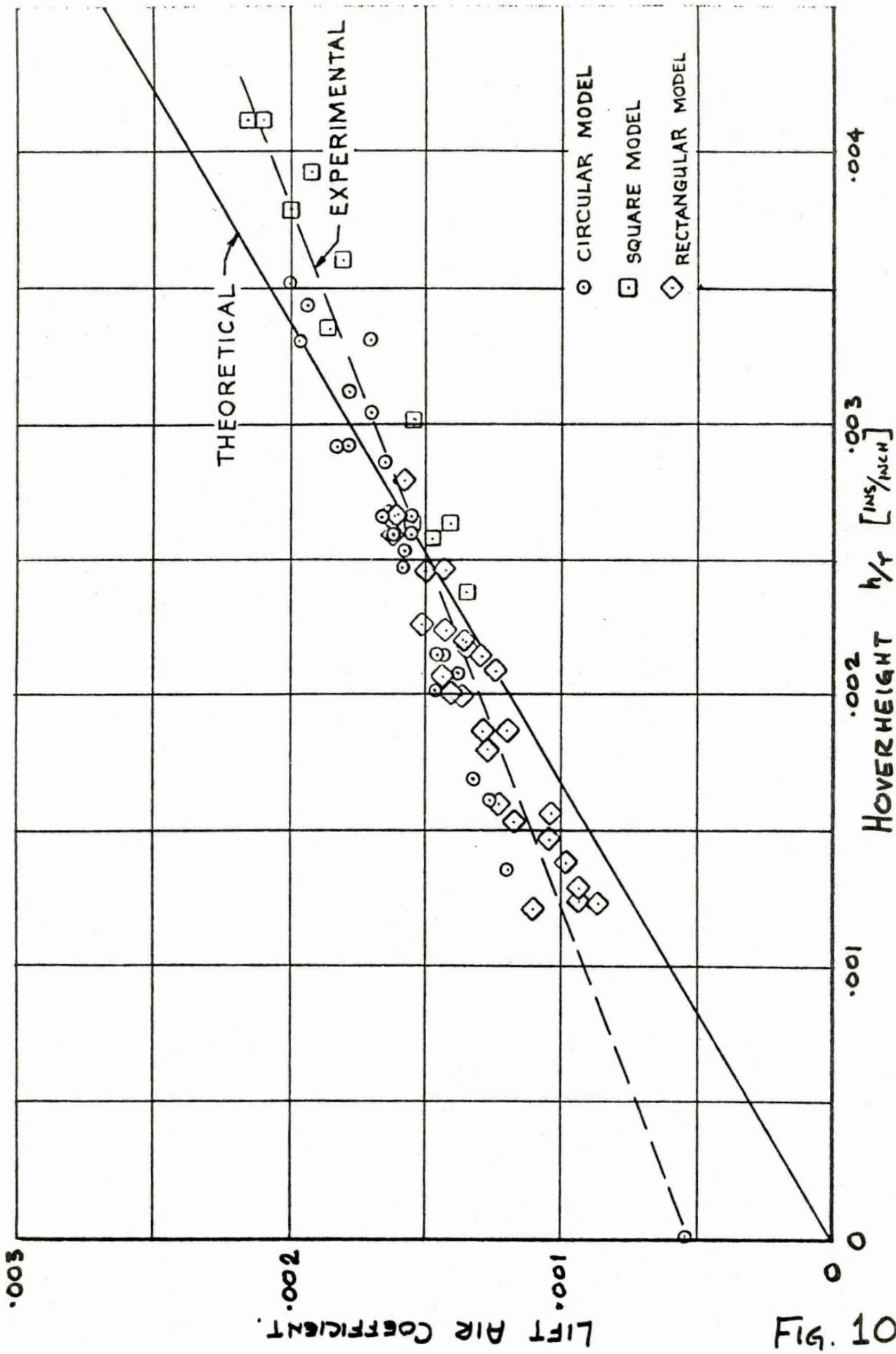


EXPERIMENTAL SET-UP; SQUARE MODEL SHAPE FACTOR TEST.



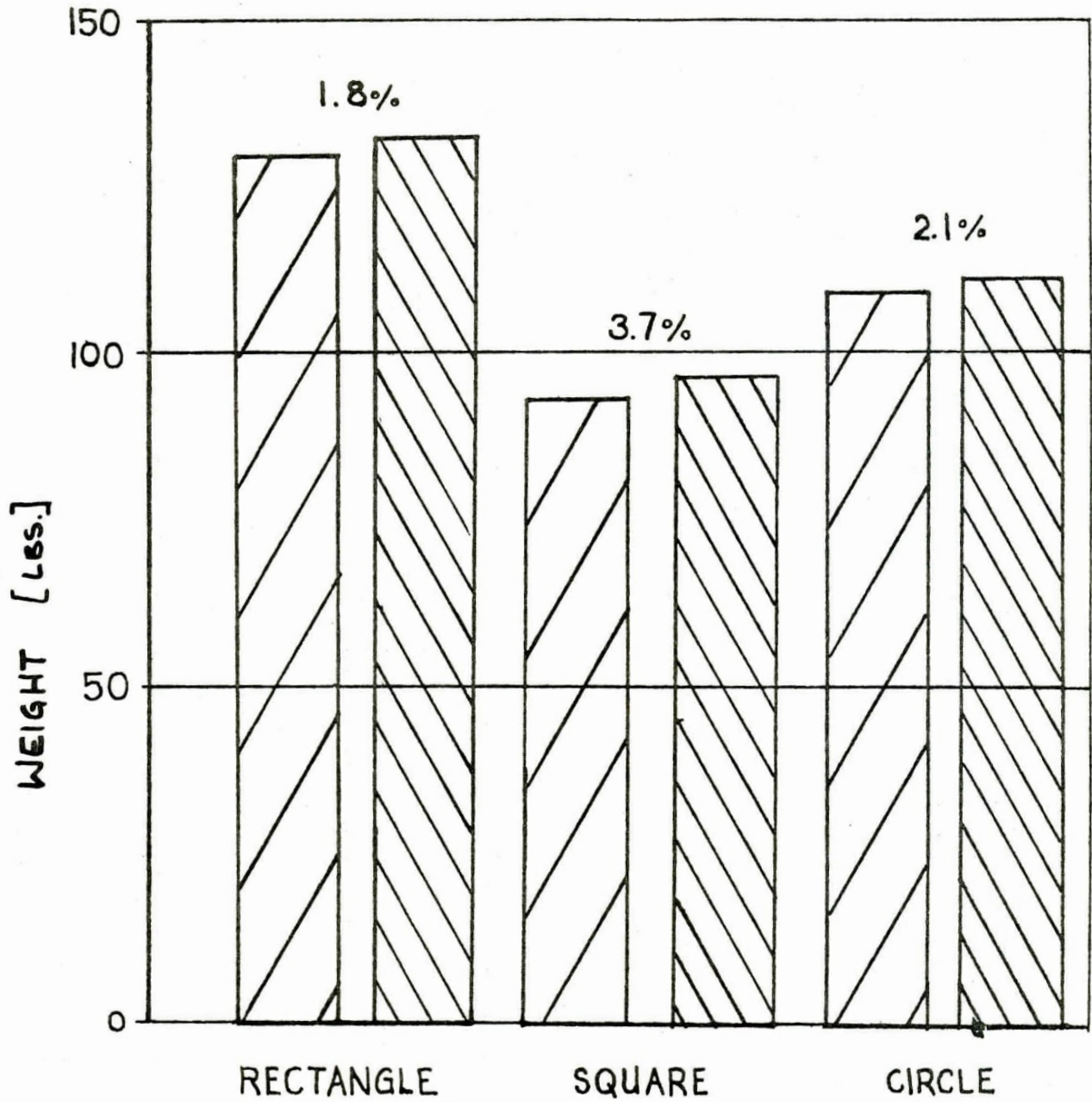
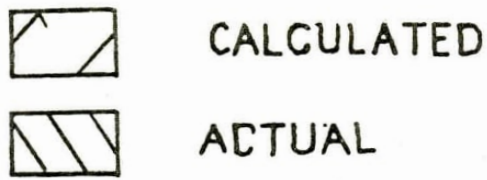
VEGETATION MEASUREMENT SIMULATION,
SHOWING DIMENSIONS 'S' AND 'a'

FIG. 9.



L.A.C. vs. h/r for Three Models on Plywood

Fig. 10.



COMPARISON OF ACTUAL vs. CALCULATED VEHICLE WEIGHT.

Fig. 11.

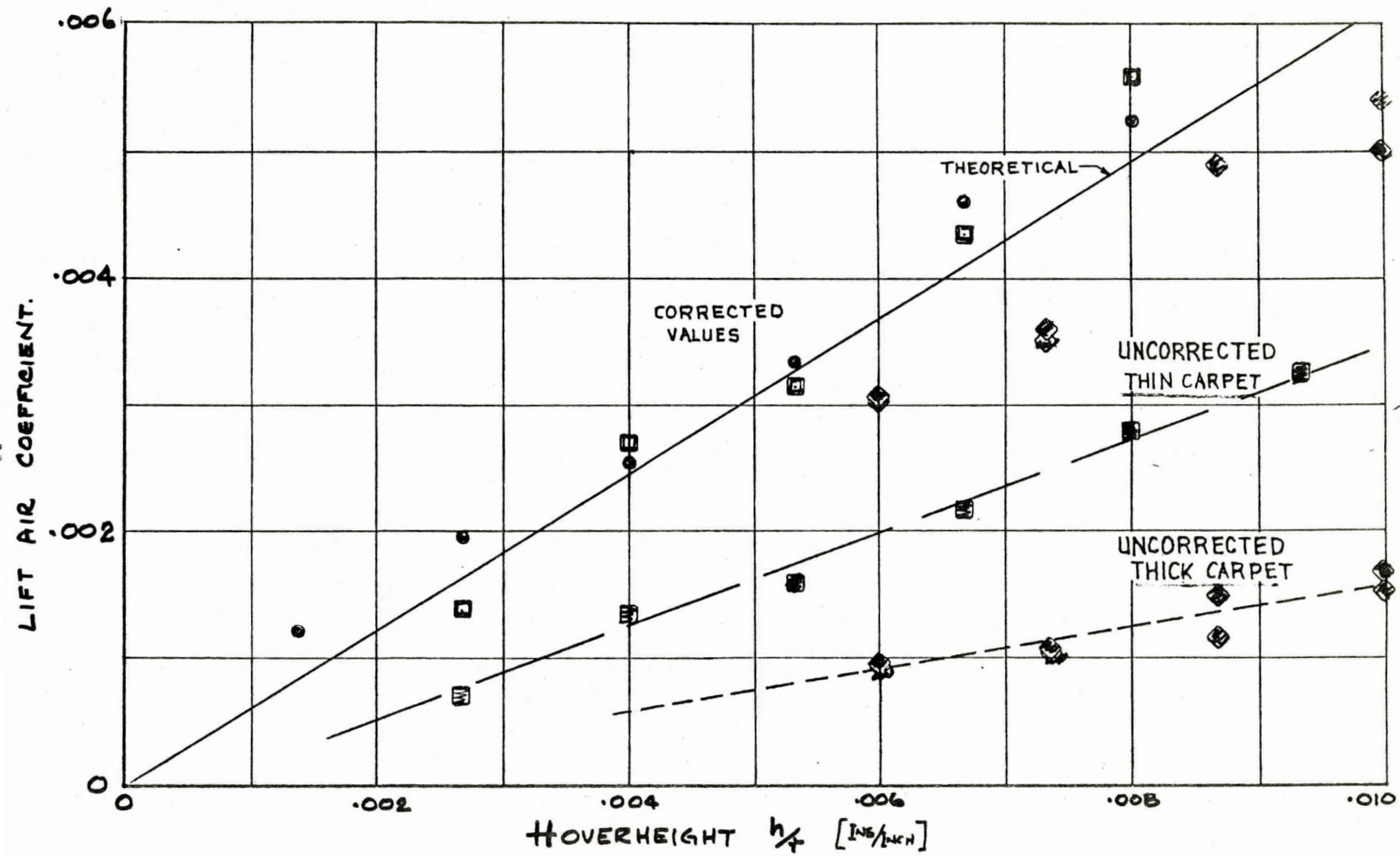


Fig.12.L.A.C. vs. h/r for a Circular Plenum on Plywood and Two Carpets