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by

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CABIN CONDITIONING TESTS ON A SIMULATED M 2.2 TRANSPORT AIRCRAFT CABIN

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SUMMARY

This paper describes tests made to investigate a cabin insulation scheme and to determine cooling air distribution requirements for a supersonic (M 2.2) passenger transport aircraft. Thermal conditions of flight were simulated in a ground rig with a section of aircraft fuselage equipped as a cabin.

Several methods of introducing air into the cabin were tested. That employing the principle of jet entrainment was found to be the most economical in cooling air mass flow, to provide overall passenger thermal comfort.

The insulation and cooling scheme for the cabin wall was evaluated and the amount of heat leakage in the test specimen established.

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*Replaces R.A.E. Technical Report 66118 - A.R.C. 29102

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1 INTRODUCTION

In supersonic transport aircraft it is more difficult to achieve a comfortable environment for crew and passengers than in subsonic aircraft, because of the high temperature of the aircraft skin induced by aerodynamic heating[1].

In order to provide a comfortable environment in the passenger cabin it is necessary to minimise the heat entering the cabin from the hot skin (e.g. by means of thermal insulation) and to distribute cooling air to remove the incoming heat and the internally generated heat, the major part of which is the passenger metabolic heat output[2].

The cooling air requirements and the amount of insulation necessary to maintain a given cabin environment are interrelated, i.e. a decrease in insulation would have to be balanced by a greater supply of cooling air. The best combination is that which gives a minimum combined weight penalty for the insulation and air cooling and distribution system, taking account of the power to drive the system. An important saving of space and weight may be achieved by a system of wall cooling[3] which intercepts some of the heat entering the aircraft before it reaches the cabin. Cabin cooling air requirements may thus be reduced, with consequent reduction in air velocities and temperature gradients; furthermore cabin wall temperatures are reduced. At aircraft speeds of about M 2 it is convenient to use cabin discharge air for wall cooling.

The British Aircraft Corporation (Filton Division) designed a supersonic (M 2.2) aircraft passenger cabin in connection with their studies of the Bristol 198 project. A representative section of the passenger cabin, 20 ft long and 12 ft in diameter, was constructed for testing in the R.A.E. Cooling Systems Laboratory. The specimen was designed to have insulated walls incorporating cooling air ducts.

The basic aim of the investigation was to develop a suitable cooling air distribution scheme to give overall passenger comfort throughout the cabin with maximum economy of cooling air. Air flow requirements and total heat loads were to be investigated, and the installed transmittance of the primary insulation determined. The effect of aircraft structure and structural attachments (i.e. heat leakage) on the effectiveness of the insulation was to be assessed. In the event the tests provided valuable information to assist in the design of the Concord.

2 THE TEST FACILITY

The tests were made in the Mechanical Engineering Department Cooling System Laboratory[4]. Essentially, a radiant heating array was used to heat the specimen skin up to the required temperature, and cold air supplies with mass flow and temperature control were provided. A number of the tests were made in the large altitude chamber.

3 THE CABIN SPECIMEN

3.1 General

The specimen was built up from two sections of fuselage structure of a Britania aircraft and was 20 ft long by 12 ft diameter. The section was terminated with wooden bulkheads which were enclosed by domed ends in steel (Figs.1 and 2). The skin structure was modified slightly by the inclusion of sub frames, as crack stoppers, between the main frames (these were required to make the structure thermally representative - since at that time this type of construction was considered likely on the Concord). The walls of the specimen were lined with a composite insulation (Para. 3.2). The specimen had no windows.

The cabin was fitted with representative furnishings, including hat racks, carpeting, and twelve pairs of aircraft seats. Further details are given in Appendix A.

Passengers in most of the later tests were simulated by 24 two dimensional heated dummies each of 110W output (see Para. 9.1 and Fig.6).

3.2 Wall insulation

As cruising speed and consequently aircraft skin temperature increases, the thickness of insulation required to produce reasonable cabin wall temperatures become impracticable both from weight and space considerations. One method of achieving satisfactory wall temperatures is to use a wall cooling system, in which a fluid is passed through a space in the insulation and removes much of the heat which has entered the aircraft from the skin[3]. This type of wall cooling, using cabin discharge air as the cooling fluid, was employed in the test specimen.

The insulation used in the test specimen was developed with the aid of tests made in a guard box conductivity rig[5]. Details of the insulation are given in Fig.8

For convenience, the insulation between the cabin skin and the wall cooling duct, comprising a (still) air space, reflective insulation, glass fibre blanket and foamed polyvinyl chloride, is called the primary insulation, while that between the wall cooling duct and the cabin proper, consisting of thin glass fibre board, either uninsulated or only lightly insulated, is called the secondary insulation.

4 RANGE OF INVESTIGATION

4.1 General

The basic aim of the investigation was to develop a suitable air distribution scheme for an insulated supersonic (M 2.2) aircraft cabin, capable of giving overall passenger comfort throughout the cabin with maximum economy of conditioning air. The investigation may be broadly divided under a number of headings.

4.2 Air distribution system

Six different methods of introducing the air into the cabin were tested. These are described in Section 5.

4.3 Air flow requirements

With the exception of the earliest scheme, the air flow inlet temperature combinations to give comfort to a seated passenger were determined. In the early schemes the conditions to give comfort to seated passengers were frequently incompatible with comfortable conditions in the aisle.

4.4 Heat loads

In addition to the known internal heat load, a considerable quantity of heat enters the cabin from the hot outside skin. Heat enters through the thin secondary insulation and influences cabin conditions, but the major part coming through the primary insulation increases the temperature of the wall cooling air. In some applications the wall cooling air may be partly recirculated to the cabin, while in other applications it may be required to do further cooling elsewhere (e.g. equipment) before being discharged from the aircraft. In either case it is necessary to know the temperature of the exhaust air.

4.5 Heat leakage

The insulation scheme used in the construction of the test specimen was based on theoretical considerations supported by experimental work with small heat transfer specimens[5]. Experience has shown, that in practical applications there usually exist discontinuities in the insulation (structural attachment points, insulation junctions, etc.) which may considerably degrade the overall effectiveness of the insulation[6]. The additional heat flow contributed by these discontinuities is called heat leakage and it cannot readily be calculated.

For design purposes it is desirable to know the installed overall transmittance of the aircraft insulation, and if possible, to determine the manner in which the heat leakage occurs. Later tests of the series were arranged to provide this information.

5 THE AIR DISTRIBUTION SCHEMES

5.1 Scheme A (Figs.3 and 4(a))

The cooling air was introduced into the cabin through grilles located in the cabin wall just below the hat rack at about head level of a seated passenger. Air was fed to the grilles, via discrete ducts enclosed in the wall cooling duct, from two main inlet ducts below the passenger compartment floor.

Air was exhausted from the cabin via discharge grilles in the roof and at the foot of the walls (called "floor discharge" hereafter). The air discharged through the roof exit was passed down the wall gap to a collection area at the bottom of the specimen from whence it was ducted from the specimen. Floor discharge air was discharged via stub pipes, again enclosed in the wall cooling gap, to collector pipes in the baggage compartment.

5.2 Scheme B (Fig.4(b))

The first major modification was the provision of a hollow hat rack which was fed with air from what had previously been the cabin air inlet grilles, in the manner shown in Fig.4(b). The air was fed into the cabin through perforations in the under surface of the hat rack (3/16 inch diameter holes at 3/4 inch pitch).

5.3 Scheme C (Fig.5(a))

This scheme was similar to Scheme B except that the air was supplied to each hat rack from a longitudinal duct located above the racks in the manner shown in Fig.5(a). Connections between these ducts and the main inlet ducts in the baggage compartment was by means of vertical pipes (risers) in one of the domed ends of the specimen. The discrete ducts which had previously been used to feed air to the grilles, and later to the hat rack, were disconnected at both ends and allowed to pass wall cooling air (it was not possible to remove them at this stage).

5.4 Scheme D (Figs.5(b) and 6)

This major modification was introduced when a major overhaul of the specimen became necessary because of deterioration of the insulation. This scheme was introduced following a suggestion that cabin racks might be dispensed with to save space and weight. The perforated racks were removed and replaced by the arrangement shown in Figs.5(b) and 6 in which air was fed into the cabin through perforated ducts on each side of the cabin.

5.5 Scheme E (Fig.7(a))

This scheme was a modification of the previous scheme to determine whether it was feasible to distribute cabin air by means of high velocity air jets, relying on the entrainment of cabin air to provide good mixing.

The perforations in the side ducts were sealed and the ducts used as manifolds supplying air to the nozzles, located immediately below the hat racks which had been refitted as shown in Fig.7(a). This method of introducing air seemed promising and led to the development of Scheme F.

5.6 Scheme F (Fig.7(b))

Scheme F was a refined version of Scheme E. The perforated ducts were removed exposing the inner feed ducts which were sealed and insulated and used to feed nozzles located just below the hat rack.

6 INSTRUMENTATION (See also Appendix A)

6.1 Externally recorded instrumentation

Over 100 thermocouples were welded to the outer skin of the specimen and connected to an automatic data recorder in the Cooling Systems Laboratory control room. Selected thermocouples were monitored to give a continuous check on the specimen skin temperature, control of the radiant heat intensity being either manual or automatic (controlled by a thermocouple output). Specimen inlet and outlet air temperatures were measured by thermocouple grids also connected to the Control Room data recorder.

Flow measurement was by means of a calibrated orifice plate in the specimen outlet duct. The associated pressure gauges were located in the Control Room.

6.2 Internal instrumentation

Over 200 thermocouples had been installed through the depth of the insulation during the manufacture of the specimen. These were confined to a small portion of the specimen about mid length. (The locations and identification of the thermocouples are given in Fig.8.) The thermocouples were connected through appropriate switching to three strip chart recorders in the cabin.

Initially wall duct air temperatures were recorded by means of mercury in glass thermometers inserted through the secondary insulation at various points in the measuring sections (i.e. two frame pitches). Later a much more extensive survey of wall duct air temperatures was made on the port side using thermocouples (Appendix C, Fig.C2).

6.3 Cabin air temperatures

Cabin air temperatures were measured extensively using a "sling thermometer" or by fixed mercury in glass thermometers. Typical locations are given in Fig.9. Apart from general temperature surveys, temperature was sensed at a "control point" using a nickel wire resistance thermometer; the associated indicator was located in the Control Room.

Globe temperatures[7] were recorded at about the centre of the cabin and at chest (seated) level above one of the aisle seats.

Humidity was measured by wet and dry bulb equipment, and cabin air velocities by means of a Hastings portable air velocity meter.

7 PROCEDURE

7.1 General

The test procedure was broadly similar for the whole test series. Most tests were made outside the altitude chamber under ground level conditions, and in all these tests observers were present in the cabin (usually two or three).

After entry of the observers the required number of dummy passengers were switched on and the wooden inner door and the specimen outer door were secured. Radiant heat was applied to the outside skin of the specimen, which was heated to the equilibrium temperature, corresponding to the aircraft cruise condition, as quickly as possible (5 min) if stable conditions were the test requirement. Thereafter this skin temperature was maintained by automatic control. From the start of the test the cabin was supplied with the desired air mass flow, the inlet temperature being adjusted to a pre-selected value, or more usually to maintain a nominated control temperature.

After a suitable "settling" time the observers commenced recording conditions in the specimen, a comprehensive survey of cabin temperatures being made every 15 minutes for the remainder of the test run. At the same intervals the chart recorders were switched on to print a complete cycle of thermocouple readings (insulation and wall duct air temperatures). Simultaneously Control Room readings were recorded, adjustment of air flow and temperature being made if there was any deviation from the required test condition.

Thermal stability, which was a requirement of the majority of test runs, was judged from the recordings. For stable inlet air conditions the best criterion of stability was a constant specimen outlet temperature. In general it was found that a test run of less than 3 hours duration was unlikely to reach stable conditions over a half hour period (i.e. three successive recordings).

7.2 Subjective comment

Certain test runs, particularly in the early phases of testing, were very largely subjective, i.e. the main purpose of the test was to determine the degree of comfort afforded by a particular air distribution scheme under certain nominated conditions. Comfort observations ideally required seated non-working passengers and additional observers were usually carried for this purpose.

On a limited number of occasions the opinions of the observers were checked against those of a full compliment of passengers who were tested under identical conditions.

7.3 Flight plan tests

The procedure in these tests was virtually the same as that for the stable runs except that the skin temperature and cooling air supplies were varied to a preset programme. Recordings were made from commencement of the test.

7.4 Altitude tests

A number of tests were made to determine whether the heat balance would be affected by altitude. For this purpose the cabin specimen was installed in the laboratory's large altitude chamber. No observers took part in these tests and operation of the chart recorders was by remote control. A less extensive survey of air temperatures than previously was made by means of thermocouples.

8 RESULTS

8.1 Presentation

The tests of the early air distribution schemes (Phases 1 to 3) were to a large extent subjective, leading to the development of Scheme D, and have been recorded in detail in Test Notes[8, 9, 10]. However, pertinent derived data from these early tests have been summarised in graphical form in Appendix B. The remaining phases of testing, which were more extensive, are described in Appendices as follows:-

Appendix C - Phase 4 tests. Scheme D. Heat transfer data obtained from steady state tests under ground level conditions. Heat leakage included.

Appendix D - Phase 5. Tests of Scheme D under altitude conditions. Results compared with those of Phase 4.

Appendix E - Phase 6. Schemes E and F (nozzles) tested. Flight plans simulated including part system failure.

Appendix F - Complete system failure represented.

8.2 Derivation of heat transfer coefficients

In the simplest case of a specimen without wall cooling, the heat entering the outside skin of the specimen would equal the heat entering the cabin interior and, in keeping with common practice, it would be convenient to express the heat flow as a heat flow per unit area, per degree of temperature difference from the outside skin to the cabin interior (i.e. as a heat transfer coefficient).

With a wall cooling arrangement such as that used in the test specimen, only a small portion of the total heat intake into the specimen actually penetrates into the cabin, the greater part being removed by the wall cooling air. However both the total heat entering the specimen and the fraction of the heat entering the cabin are of importance, the former because it contributes to the total heat load to be dealt with by the aircraft cooling system, and the latter because it reflects the efficiency of the complete insulation scheme including the wall cooling. Again, it is convenient to express these heat quantities in the form of heat transfer coefficients (called respectively the specimen overall heat transfer coefficient and the cabin overall heat transfer coefficient) as defined below.

The heat flow into the specimen is dependent on the effectiveness of the primary insulation scheme and it is pertinent to evaluate the primary insulation in isolation. This is best done by examining the transmittance of the insulation in the usual way, where the heat flow per unit area is expressed per degree of temperature difference across the insulation (in this case from the outside skin to the wall cooling gap). Two main values are used in the present context, a value corresponding to the installed primary insulation transmittance which includes leakage heat and a basic value which does not include leakage heat.

8.2.1 Specimen overall heat transfer coefficient

The specimen overall heat transfer coefficient (H_O) relates the total heat flow into the specimen from the outside skin to the temperature difference between the specimen skin and the cabin as follows:-

$$H_O = Q/A_S\,(T_S - T_{CM}) \quad \text{CHU/hr ft}^2\ {}^\circ\text{C} \qquad (1)$$

where Q = heat taken in through specimen walls = $Q_T - Q_{int}$,

Q_T = the heat gain of the air in passing through the specimen*,

Q_{int} = the total specimen internal load,

A_S = surface area of specimen excluding the domed ends,

T_S = specimen mean skin temperature,

T_{CM} = cabin mean air temperature.

Cabin mean temperature is taken as the arithmetic mean of the cabin inlet and outlet temperatures with proportionate adjustment if both floor and roof discharge are used, i.e. if a fraction of x of the total cabin cooling air leaves as floor discharge, then the effective mean temperature was taken as

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* Note - the specimen is defined as the cylindrical portion between the end (wooden) bulkheads. An allowance has been made for heat pick up in the domed end.

$$T_{CM} = (T_3 + (1 - x)\, T_4 + x\, T_{4A})/2 \qquad (2)$$

where T_3 = cabin inlet temperature,

T_4 = roof discharge temperature,

T_{4A} = floor discharge temperature (as shown in Fig.2).

8.2.2 Cabin overall heat transfer coefficient

The cabin overall heat transfer coefficient (H_C) relates the heat which enters the cabin interior to the temperature difference between the specimen outer skin and the cabin interior in the following manner,

$$H_C = Q_C/A_S\,(T_S - T_{CM}), \qquad (3)$$

Q_C = heat flow into cabin through walls and floor,

= $Q_{TC} - Q_{int(C)}$

Q_{TC} = total cabin heat pick up,

$Q_{int(C)}$ = cabin internal heat load.

[A_S and $(T_S - T_{CM})$ are defined above.]

8.2.3 Installed primary insulation transmittance (i.e. including leakage heat)

The installed primary insulation transmittance (U''_p) relates the total heat flow into the specimen through the insulation and structure, to the temperature difference between the specimen skin and the centre of the wall cooling gap, in the following manner,

$$U''_p = Q/A_S\,(T_S - T_G)_M \qquad (4)$$

Q and A_S are defined above, while $(T_S - T_G)_M$ = the mean temperature difference between the specimen skin and the centre of the air gap over the whole specimen.

More precisely,

$$U''_p = \Delta Q/\Delta A_S\,(T_S - T_G)_M \qquad (4a)$$

where $(T_S - T_G)_M$ is the mean temperature difference over the area ΔA_S.

Strictly, logarithmic mean temperature differences should be used. However, in the detailed analysis of Phase 4 results (Appendix C) in which the specimen was divided into sections in the analysis, arithmetic rather than logarithmic mean temperature differences were used in expression (4a). The error so introduced was negligible (less than 1%).

The value of primary insulation transmittance calculated in this way does not include the external (aerodynamic) heat transfer coefficient to the skin, which was not represented in the tests. Inclusion of this coefficient would modify the transmittance value by approximately 1% only in the aircraft cruise case.

8.2.4 Primary insulation transmittance (corrected for leakage heat)

The installed primary insulation transmittance U''_p as defined above may differ substantially from the ideal value because of "short circuiting" of the insulation by structural attachment points which pass through the insulation, the main source of heat leakage being the floor beam attachments in the case of the specimen tested.

Part of the floor beam heat leakage passes into the wall cooling duct and appears as an air temperature rise as the air crosses the floor beam attachments (see Appendix C). The value of primary insulation transmittance corrected for this leakage has been called U'_p, where

$$U'_p = (Q - Q_{LD})/A_S\,(T_S - T_G)_M \tag{5}$$

Q_{LD} = floor beam heat leakage into the cooling air duct, and the other quantities are as defined above.

The value of primary insulation transmittance still differs from that obtained from tests of a 3 ft square panel in a guard box conductivity apparatus[5], reproduced in Fig.13. This is due to additional heat leakage, via the floor beams, directly into the cabin. This heat quantity was not determined in the 20 ft specimen tests. The value of insulation transmittance from the panel tests[5] has therefore been accepted as the basic value (U_p). Applied to the specimen,

$$U_p = (Q - Q_{LD} - Q_{LC})/A_S\,(T_S - T_G)_M \tag{6}$$

where Q_{LC} = floor beam heat leakage directly into the cabin.

Remaining symbols are defined above.

9 DISCUSSION

9.1 Dummy passengers

The sensible heat output of a seated resting subject[2] in an effective ambient temperature of 24°C is approximately 80 watts. In practice a substantial time may be required before the metabolic heat output is reduced to this value, the time depending on the degree of activity beforehand. In addition the metabolic heat production increases during and after a meal. It is therefore likely that the sensible heat output from an average aircraft passenger over a flight period will be greater than 80 watts.

In the very early tests of the series, 100 watt electric light bulbs were used at each seat position to represent the passenger sensible heat output. Due to the high filament temperature, radiation effects on observers were pronounced. Another limitation was that the effect of passenger bulk on the air distribution was not represented. The bulbs were therefore replaced by two dimensional dummies of representative dimensions in side elevation (but not volume), each containing an electric element of 110 watts output. The surface temperature of the dummies was 45°C. Radiation effects were considerably reduced but, as a precaution, observers commenting on cabin conditions were careful to avoid sitting adjacent to hot dummies.

From a heat balance aspect it was important to know the total internal heat load, and the possible error in estimating its value became greater with a greater number of observers. However in most heat balance tests the number of observers was small.

9.2 Comfort

The indications were that at the prevailing level of humidity (15%-25% R.H.) and provided that the air velocity over the passengers was moderately low (less than 30 ft/min), the majority of subjects appeared to be comfortable at a globe temperature of 24°/25°C.

A given globe temperature at any point may be achieved in theory by a wide range of inlet air mass flow and temperature combinations. In practice there are well defined limits. The upper limit is that flow above which passengers are made uncomfortable due to the high air velocities (i.e. the passengers complain of "draughts"). There are in fact good reasons for reducing the air flow as much as possible (e.g. duct pressure losses are reduced). However, reduction in air flow, with corresponding reduction in inlet air temperature, can result in large temperature gradients and possibly locally excessive cooling of the passenger, emphasised by the temperature gradient. Also there may be a lack of air penetration resulting in inadequate ventilation of some parts of the cabin. The tests illustrated how the minimum air flow at which such undesirable effects occurred, varied with different air distribution schemes.

Examples of cabin temperature distribution, compatible with overall comfort, are shown in Figs.10(a) and (b). These particular combinations of temperature were recorded during transient tests of Schemes E and F. It is not implied that identical conditions are necessary for comfort.

It is important to note that throughout all the tests the relative humidity of the air was low. Should the air be artificially humidified in the case of an aircraft then somewhat lower ambient temperatures would be required to produce the same passenger effective temperature. (Effective temperature is a scale of subjective comfort determined experimentally[2].)

9.3 Comparison of air distribution schemes

In Scheme A (Figs.3 and 4(a)) the inlet grilles were such that at moderate air flows, necessary for good penetration into the aisle, passengers adjacent to the grilles were made uncomfortable due to the high air velocities. Reduction in air flow resulted in lack of ventilation at the aisle seats. In addition the momentum of the incoming air was so reduced that the cool inlet air tended to "fall" down the cabin wall resulting in differential cooling of the wall seat passengers. The scheme showed little promise and tests were therefore limited.

Scheme B (Fig.4(b)) was designed to provide a more even air distribution over the passengers. However due to the cold air inlet feeds enclosed in the wall duct there were local areas of cool cabin trim which caused discomfort to adjacent passengers. (At the lower air flows the cabin wall temperatures varied by up to 10°C over a frame pitch.) Partly for this reason it was found that the lower limit of air flow was approximately 55 lb/min. This effect was eliminated in Scheme C (Fig.5(a)) and it was found possible to produce comfortable conditions for seated passangers at reduced air flows; however conditions in the aisle, even with ventilation from the end of the hat racks, were such that the lower limit of air flow necessary to give overall comfort in the cabin were little better than previously.

Scheme D (Fig.5(b)) was introduced following the reinsulation of the specimen (Appendix C) and represented a method of introducing air into the cabin in the absence of hat racks. The configuration of ventilation holes was such that the aisle was better ventilated and, in general, the holes were more distant from the passengers. Overall comfort was achieved with flows reduced to 40 lb/min - again the limit was imposed by conditions in the aisle.

The most effective method of ventilation was that used in Schemes E and F (Figs.7(a) and (b)) in which the cabin cooling and ventilating air was introduced through nozzles at a relatively high velocity. Jet entrainment was relied on to "pre-heat" the cold incoming air which rapidly achieved a temperature little different from that of cabin ambient (see Fig.3, Appendix E). Unlike Scheme A, air circulation near the walls was upwards due to the entrainment action, rather than a cold downward draught. Also, because of the initially high jet velocity, penetration into the aisle was improved, and better overall conditioning resulted. For these reasons it was found possible to maintain comfortable overall conditions with air flows as low as 25 lb/min.

Examples of conditions during tests of Schemes E and F are given in Figs.10(a) and (b).

9.4 Heat transfer

9.4.1 Specimen overall heat transfer coefficient

The specimen overall heat transfer coefficient gives an indication of the heat which the cooling system has to remove to produce a given condition in the cabin. The coefficient depends to a great extent on the effectiveness of the primary insulation and to a lesser extent on the secondary insulation and the cabin internal heat transfer processes.

The values of overall heat transfer coefficient for Phases 2 and 3 agree fairly closely, both differing from the Phase 4 values (Fig.11). Since the primary insulation was extensively repaired after the Phase 3 tests, it seems likely that the difference is largely due to direct heat leakage which occurred due to partial exposure of some of the main frames due to shrinkage of the foamed plastic insulation (see Appendix C). Also because of the close agreement between the Phase 2 and 3 values it seems likely that this form of heat leakage occurred early in the test series.

9.4.2 Cabin overall heat transfer coefficient

The cabin overall heat transfer coefficient is of interest because it indicates the effectiveness of the complete insulation scheme including the wall cooling scheme. Due to the method of calculation (i.e. a small heat flow is determined by difference between relatively large heat quantities) there is substantial scatter in the results (Fig.C17, Appendix C). The mean value over the range of mass flows for Phase 4 (Scheme D) was approximately 0.05 CHU/h °C per square foot of specimen curved surface area.

9.4.3 Primary insulation transmittances

The difference in performance of the primary insulation before and after repair is emphasised by comparing the installed primary insulation transmittance for Phases 3 and 4 (Fig.12). The partial repair of the primary insulation resulted in approximately 20% reduction in heat flow into the specimen over the range of mass flows tested.

9.5 Heat leakage

Heat leakage due to deterioration of the insulation or its imperfect installation may be considerable, as discussed in the previous paragraphs and illustrated in Fig.12. However with this source of leakage largely eliminated, there still remains a substantial difference between the practical value of primary insulation transmittance (U_p'') and that of the bulk primary insulation itself. Some of this difference is attributable to the fact that the skin structural members (frames and crack stoppers) partly penetrate the insulation, thus reducing its effectiveness. Values of primary insulation transmittance (U_p), including the effect of skin structural members were obtained from the results of tests on 3 ft square panels made in a guard box thermal conductivity apparatus[5] and from electrical analogue investigations[11]. These results have been extrapolated (Fig.13) to cover the range of air flows used in the 20 ft specimen tests, and these extrapolated values are included in Fig.12. It can be seen that the frames and crack stoppers increase the theoretical bulk primary insulation heat flow by 20 to 30% for specimen air flows of 30 to 60 lb/min.

An assessment of heat leakage through the floor beam attachments into the cooling duct is made in Appendix C. In addition tests on representative floor beam attachment in the guard box thermal conductivity rig showed that there was floor beam heat leakage directly into the cabin. It has been assumed that this additional leakage accounts for the difference between U'_p and U_p, the ideal transmittance obtained in the guard box conductivity rig.

In the following table, information from Fig.12 is expressed in the form of heat leakage factors (F). These relate the actual heat flow through the primary insulation, taking into account "heat leakage", to the theoretical heat flow through the bulk insulation, at various heat flows. The data is expressed in the form of transmittance values.

Table

	Specimen total air flow - lb/min							
	30		40		50		60	
	U*	F	U	F	U	F	U	F
1 Bulk insulation theory	0.095	-	0.096	-	0.0965	-	0.0975	-
2 Bulk insulation plus frames (panel tests[5])	0.115	1.21	0.120	1.25	0.124	1.28	0.127	1.30
3 As 2 but all heat leakage (mainly via four beams) included	0.177	1.96	0.198	2.06	0.215	2.23	0.230	2.36
4 As 3 but including additional heat leakage due to insulation deterioration	0.22	2.32	0.252	2.62	0.277	2.87	0.295	3.03

* U = transmittance in CHU/hr ft^2 °C.

The above heat leakage factors (F) apply strictly to the specimen tested. The overall heat leakage factor in an aircraft may be substantially greater due to additional heat leakage sources as discussed below.

9.6 Other heat leakage sources

9.6.1 Door frame heat leakage

Installed in the wall of the specimen in later tests was a 3 ft length of structure, thermally representative of a door surround. Analysis of the test results (Appendix C) showed that leakage through this structure was small compared with the total primary insulation heat flow (less than 2%) and therefore it has not been applied as a correction in Fig.12. However, a complete door frame (of 16 ft perimeter) in proportion, would contribute from 10 to 20 CHU/min (air flow per 20 ft from 30 to 60 lb/min). Due to the temperature rise in the air duct over the door it is thought that a substantial proportion of this heat will enter the cabin itself unless the secondary insulation is increased to prevent it.

9.6.2 Window heat leakage

Windows were not included in the test specimen, but any discussion of cabin heat loads would be incomplete without an attempt at evaluating their contribution to the total cabin heat load.

Tests were made to determine cabin window heat loads using guard box conductance test equipment[13]. The results of the tests are summarised in Fig.14. For a 100°C difference between the aircraft outer surface and mean wall duct temperature, the heat flow per window would be 108 CHU/hr at 30 lb/min (specimen) air flow and 128 CHU/hr at 60 lb/min. Apart from the heat which enters the cabin through the inner (perspex) transparency, a substantial proportion of the total window heat flow may pass into the cabin through the secondary insulation below the window, due to the air gap temperature rise, unless precautions are taken to avoid it.

9.7 The effect of cabin altitude

The results of a limited number of tests to determine whether tests made under ground level conditions are representative of the flight case, are discussed in Appendix D.

An incidental but important conclusion was that there is a need for a properly designed means of cabin pressure relief across the primary insulation to cope with cabin altitude change. Reliance on pressure relief by leakage at insulation joints is incompatible with good insulation practice, particularly if the joints are above frames, as was the case in the test specimen.

Because of failure of the primary insulation due to the development of pressure differential across the insulation with change in cabin altitude, many of the later test results were invalid, the heat pick up being considerably increased.

The limited number of valid tests indicated that the specimen heat balance was not affected by a cabin altitude change from ground level to 6000 ft, a conclusion supported by evidence from other tests[14]. No evidence was available on the effect on comfort. However, since cabin air velocities are deliberately kept low, some of the heat transfer from the passengers will certainly be by a natural convection process, which will be affected by altitude change. At 6000 ft cabin altitude natural convection coefficients will be less than those at sea level, which may have a minor effect on passenger comfort (possibly equivalent to a 1° to 2°C rise in cabin ambient temperature).

9.8 Transient tests

9.8.1 Flight plans

Tests were made in which flight plans were represented from take-off to the start of descent (Appendix E). Equivalent specimen air flows considered appropriate to the Concord (20 to 30 lb/min) were used and it was assumed that the aircraft would be conditioned pre-flight to the desired control temperature (24°C) before entry of the passengers. Under these conditions it was found possible to programme the cabin air inlet temperature to maintain a constant globe temperature until the end of cruise. Longitudinal temperature scatter was less than approximately 1.5°C over the 20 ft length for most of the "flight", and vertical scatter considerably less. Apart from the greater range of inlet temperature required it is considered that cabin temperature control (to allow for variations in passenger metabolic heat output and variations in solar radiation intensity during flight) would be no more difficult than that of subsonic aircraft.

It was found that at the critical end of cruise/beginning of descent period when the inlet air temperature momentarily increases due to the throttling back of the engines (10°C temperature rise assumed), ambient temperatures rose momentarily, but due to the thermal inertia of the cabin furnishings, passenger clothing, etc, little passenger discomfort was evident.

9.8.2 Part system failure

At the time of testing the cooling air refrigeration system of the Concord was to be a quadrupled system. Tests representing failure of one of the four systems showed that under these circumstances cabin ambient temperature will stabilise at about 5°C higher than its value before failure after about one hour. The temperature level of 29°C to 30°C does not appear to be excessive for an emergency case.

9.8.3 Complete system failure

A test representing complete system failure had been conducted earlier (Appendix F) and further evidence was available from an inadvertent failure of air supplies during a later test (Appendix E). In both cases full passenger load was represented and the specimen skin temperature was maintained at cruise value after failure. The tests showed that complete system failure would not be catastrophic from a thermal aspect, and indicated that adequate time would be available for corrective action (after 16 minutes the air temperature at a seat position had risen to 35°C from an initial value of 23°C). If foamed plastic material similar to that of the specimen was used in the aircraft primary insulation such a failure of air supplies might result in permanent deterioration of the insulation.

9.8.4 Effective cabin thermal capacity

In the tests, cabin temperature control was exercised manually, whereas in an aircraft the control would be automatic. In order to be able to design an effective cabin temperature control system, and to predict cabin temperatures under transient conditions, it is essential to know the effective thermal capacity of the cabin.

A special test was arranged in which the temperature history of the cabin air was determined after simulated failure of the air supplies during cruise. The temperature history was then simulated with an electrical analogue, from which a value of effective thermal capacity was determined as 0.22 CHU/hr °C per cubic foot of passenger compartment volume. The significance of this "effective thermal capacity" and its possible application to other cabins is described fully elsewhere[12].

9.9 Application of results to Concord

9.9.1 General

The bulk insulation of the Concord is expected to be basically similar to that used in the 20 ft test specimen except that instead of glass fibre blanket and foamed plastic, glass fibre blanket alone is used in the primary insulation scheme. Crack stoppers, in the form of sub frames, are dispensed with.

Primary insulation transmittance values applicable to the Concord are estimated below for a wall duct air flow of 25 lb/min for a 20 ft length of cabin.

9.9.2 Bulk primary insulation transmittance

Assumed equal for the 20 ft specimen and the Concord = 0.095 CHU/hr ft^2 °C.

9.9.3 Transmittance including frames

Reference to Fig.12 shows that at 25 lb/min air flow the transmittance of the primary insulation, including frames and crack stoppers was 0.112 CHU/hr ft^2 °C composed of 0.095 bulk insulation contribution plus 0.017 due to structure.

Electrical analogue tests[11] show that the crack stoppers contribute 35% of the combined structural heat flow. If the crack stoppers are dispensed with the structural heat flow is reduced from 0.017 CHU/hr ft^2 °C to 0.011 CHU/hr ft^2 °C.

Expected primary insulation transmittance (including frames)

$$= 0.095 + 0.011$$

$$= 0.106 \text{ CHU/hr ft}^2 \ {}^\circ\text{C}.$$

9.9.4 Overall primary insulation transmittance (including floor beam)

An overall value of primary insulation transmittance including floor beam heat leakage may be estimated if the aircraft floor beam attachments are assumed similar to those of the specimen used in the tests.

The Concord cabin diameter is approximately 10 ft, compared with 12 ft for the 20 ft specimen, the curved surface areas therefore being in the ratio of 1 : 1.2. The contribution of floor beam heat leakage per square ft of surface is therefore greater in the Concord.

Total contribution of floor beam heat leakage to the apparent primary insulation transmittance in the 20 ft specimen tests was 0.055 CHU/hr ft^2 °C (Fig.12). The contribution is likely to be proportionately greater (1.2 : 1) in the Concord being 0.066 CHU/hr ft^2 °C. The total transmittance will therefore be 0.172 CHU/hr ft^2 °C for a wall duct air flow of 25 lb/min per 20 ft length of cabin. This value does not allow for door frame and window heat flows (Para.9.6 refers).

9.10 Conditions within the Concord cabin

It is considered that the reduction in area of cross section of the Concord will result in a marginal increase in the general level of air velocity.

However the velocity in the later tests was very low and it is thought that this slight change would have a negligible effect on cabin conditions when the test results are related to the Concord cabin.

10 CONCLUSIONS

The tests showed that with cabin wall temperatures maintained only a little (5 to 6 °C) above cabin air temperatures (by means of wall cooling), and with relative humidity between 15% and 25%, a globe temperature of 24°/25°C in the vicinity of the passenger appeared comfortable to the majority of observers provided that the air velocity over the passengers was low (i.e. less than 30 ft/min was achieved in the majority of tests). Passengers were quite sensitive to differential radiation from "hot spots" on the cabin wall, a window inner surface temperature of 8°C above the general level of cabin wall temperature being uncomfortable to adjacent passengers.

The effect of cabin altitude (6000 ft) may be to reduce the coefficient of heat transfer from the passenger; in addition, ambient humidity may be artificially increased in the case of an aircraft cabin. It may therefore be appropriate to aim for a slightly lower globe temperature (say 22°/23°C).

Of the cabin air distribution schemes tested, that in which air was injected into the cabin through nozzles just below the hat rack (Fig.7(b)) was found to be the most economical in air supplies, good overall conditioning being achieved with an air flow of 1.25 lb/min per foot run of cabin. Typical cabin temperatures achieved with this ventilation scheme are shown in Fig.10. (The case shown is for 1.5 lb/min per foot of cabin.) Provided the proportion of wall duct cooling air is not allowed to become too small, discharging some of the air through grilles at the foot of the cabin walls does not appear to greatly affect cabin conditions.

With the final ventilation system (nozzles) and an initial total air flow of 1.25 lb/min per foot run of cabin, failure of one out of a possible 4 systems delivering the air would cause no great discomfort and the flight plan could be maintained, the globe temperature stabilising at 29°C (from an initial 23.5°C) after 1 hour. In the event of complete failure of air supply to the cabin the rate of temperature rise is such that 15 minutes may be considered a reasonable time to complete corrective action such as modification of the flight plan to reduce the aircraft skin temperature.

Tests showed that little or no passenger discomfort will result from the momentary cabin air temperature rise at the end of cruise.

Heat flow analysis showed that the overall heat transfer coefficient of the specimen (including all heat leakage) was 0.15 CHU/hr ft^2°C at an air flow of 30 lb/min (i.e. 1.5 lb/min per foot length). The corresponding overall primary insulation transmittance (from skin to the centre of the air gap) was 0.177 CHU/hr ft^2°C. The cabin overall heat transfer coefficient was of the order of 0.05 CHU/hr °C per square foot of specimen surface area.

The importance of heat leakage and its dependence on air flow was illustrated (Fig.12). After reinsulation of the specimen, with an air flow of 30 lb/min, the heat entering the specimen from the skin was approximately twice that which would be expected from theoretical considerations of the bulk primary insulation (i.e. a heat leakage factor of 2) 25% of the additional heat flow was due to partial penetration of the insulation by the frames and sub frames, the remainder being attributable mainly to heat leakage at the floor beam, some of which enters the wall duct, the remainder passing directly into the cabin via the floor beams.

A further source of heat leakage was experienced in the early tests, causing the overall heat leakage factor (based on the theoretical value of bulk insulation transmittance) to increase from 1.96 to 2.3 at 30 lb/min cabin air flow. This increased heat leakage stemmed directly from the inadequacy of the foamed plastic material used for the inner layers of the primary insulation. High temperatures at the joints in the material (at the frames) is believed to have caused initial local shrinkage with rapid accumulative damage. It is important that any insulating materials be thoroughly checked to avoid this type of damage which can give rise to extensive and unpredictable heat leakage.

Limited tests made in an altitude chamber (Appendix D) showed that, from a heat balance aspect, the ground level tests were representative of conditions in a cabin maintained at 6000 ft altitude. An incidental but important conclusion from the tests was that means of pressure relief between the static air gap (between the aircraft skin and the primary insulation) and the wall cooling air gap should be provided to prevent damage to the insulation from (inadvertent) rapid cabin altitude change.

If the specimen results are related to the Concord, it is estimated that for a wall air flow of 1.25 lb/min per foot run of cabin, a total primary insulation transmittance (from aircraft skin to the centre of the wall duct) of 0.172 CHU/hr ft^2 °C might be expected. Additional heat leakage through door frames (Appendix C, Fig.C14) and windows (Fig.14) are estimated to be respectively, 9 CHU/min for a door of 16 ft perimeter, and approximately 1.8 CHU/min for a window.

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Appendix A

DESCRIPTION OF SPECIMEN AND TEST RIG

A.1 Specimen

The specimen which was designed and built by B.A.C. Ltd consisted of a 20 ft length of Britannia fuselage. This was 12 ft in diameter with a 16 swg light alloy skin with frames 3.0 inches deep at 20.5 inches pitch and stringers 1.0 inch deep at 4.0 to 7.0 pitch. To make construction similar to that for the then proposed supersonic transport aircraft, crack stoppers of 2 inch depth were fitted midway between frames. No windows were fitted and no door structure was incorporated.

At each end of the specimen insulated domed ends were fitted, one incorporating an access door and the other an emergency escape hatch. The domed ends were separated from the 20 ft parallel test section by means of wooden bulkheads containing access doors. The floor of the specimen was of $\frac{1}{2}$ inch plywood except for approximately 9 inches adjacent to the wall and outboard of the seat rails which was of $\frac{1}{2}$ inch durestos. The floor was covered with representative aircraft carpeting. Access was provided to the cabin underfloor area by means of an 18 inch trapdoor in the cabin floor . The cabin underfloor area was itself floored with $\frac{1}{2}$ inch plywood to represent a baggage compartment.

The interior of the cabin was finished with trim cloth. A diagrammatic illustration of the insulation scheme is shown in Fig.8 of the main report.

The specimen as delivered was fitted with a representative luggage rack to which were attached 12 × 15 watt lamps to simulate reading lights. Six striplights of 80 watt power each were mounted centrally in the cabin roof. Ex B.O.A.C. passenger seats were fitted by the R.A.E., these were D.C.7 aircraft seats and were not fixed to the seat rails but bolted to metal strip to enable easier movement. The final cabin layout was as shown in Figs.A1 and A2. Originally it had been intended to test a number of air distribution schemes and for this reason alternative supply ducts were incorporated within the specimen walls during manufacture. The scheme in the specimen as supplied was to supply the ventilating air to the cabin through grilles at hat rack level by means of risers incorporated in the 1.0 inch gap in the insulation. These risers were supplied from common mains on either side of the luggage bay. The two main supply ducts joined in one domed end and entered the specimen at a common connection. Each supply duct incorporated a 5 point thermocouple grid just downstream of the junction, each duct was insulated with a nominal $\frac{1}{2}$ inch thickness of glass fibre.

The majority of the cabin ventilating air was collected in a central roof duct, passed round the cabin wall through the air gap in the insulation and collected in a manifold in the luggage bay. A common line discharged all the air from the collector box through the specimen domed end and it incorporated a 7 point thermocouple grid. The remainder of the cabin ventilating air was discharged from the cabin at foot level being collected in ducts in the luggage bay which connected to the wall cooling air manifold. The foot discharge air ducts were arranged to give sufficient straight length to incorporate orifice plates to B.S.S.1042 and 5 point thermocouple grids on each side. During the initial tests difficulty was experienced in getting the required flow through these foot discharge ducts under ground level conditions so 24 volt aircraft fans were fitted to the ducts before they entered the collector box. To reduce the restriction the orifice plates were replaced by pitot static heads for flow measurement. The electric fans were later removed as they were noisy and inefficient, and the ducting modified to discharge the foot airflow directly overboard.

An industrial TV camera was fitted to the interior of the specimen to enable control room staff to observe the occupants of the specimen. A duplicated three way communication system between the specimen, test rig area and control room was also fitted.

A.2 Description of test rig

The specimen was mounted within an oven of radiant heaters on its own bogies. The radiant heater framework was 13 ft in diameter and 20 ft long. It consisted of 18 inch pitch stainless steel frames 4 inches deep with 2 inch wide stringers also at 18 inch pitch. The reflector plates which were of 18 swg commercial light alloy were bolted to the stringers from the outside. The radiant heaters were mounted on $1\frac{3}{4}$ inch porcelain insulators bolted through the reflector plates at $4\frac{1}{2}$ inch pitch. Each reflector plate therefore carried 4 radiant heaters which were at right angles to the longitudinal axis of the specimen. The exception to this arrangement was the position of the reflector where the specimen support rails were fitted. At this point the plates were 18 inches by approximately 13 inches to allow for the rail and because of the interference from the specimen wheels only 2 radiant heaters were fitted per plate, mounted parallel to the longitudinal axis. The heater structure was constructed in this manner in order to be able to remove reflector plates relatively easily, from the exterior of the rig to replace any radiant heaters that failed. In practice during the whole series of tests there were only 3 failures in the assembly of 1400 heaters. There were a total of 27 rows of reflectors, 24 of which were connected to the 800 kilowatt infra-red regulator, while the 2 rows of reflectors opposite the specimen wheels and the bottom central row of heaters were connected to the 400 kilowatt regulator. The inclusion of the bottom central row in the 400 kilowatt supply was in order to obtain balanced loads on the regulators without too much wiring complication. The heaters connected to the 800 kilowatt supply were wired with 2 heaters per plate in series, these were connected to the miniature circuit breakers in the control room so that there were four circuit breakers per reflector row. The heaters could therefore be selected in the front or rear half of the row, or every other heater could be selected which in effect doubled the pitch. The wiring arrangement was intended to give as much flexibility as possible within the limitations of two sources of variable voltage supply. The maximum amount of power required by the rig was of the order of 450 kilowatts. Early in the tests it was found that with uniform heating and operating the rig outside the altitude chamber, the temperature scatter as measured by the thermocouples attached to the inside of the skin in the instrumented centre section was of the order of 30°C. By halving the intensity of the heaters by means of the circuit breakers over the top part of the specimen the scatter over the measuring section was reduced to about 10°C in steady conditions. The temperatures as recorded on the 108 evenly distributed external skin thermocouples were lower at the ends presumably due to the fin effect of the domed end support flanges, this led to a scatter along the length of the specimen of about ±10°C with the lower values towards the ends and underneath the specimen. There were larger variations around areas such as support wheels. With the revised selection of heaters this maximum power demand was reduced to 320 kilowatts - a mean intensity of just under 0.5 kilowatts/ft^2. This power supply enabled the specimen skin to be heated to approximately 120°C from ambient in about 4 minutes. To maintain the skin temperature constant the power supplied then had to be reduced to about 120 kilowatts, or an intensity of 1/6 kilowatts/ft^2.

A.3 Air supply

Cold air was supplied to the specimen from the high altitude test plant by means of an 8 inch duct connected to the supply line connection in the large altitude chamber bulkhead. The duct incorporated trimmer heaters which consisted of radiant heaters mounted inside the duct. There were 2 heaters of total power 10 kilowatts, and one of 9 kilowatts. The 10 kilowatt heater was arranged so that 6 kilowatts was controlled by means of off/on switches and the remaining 4 kilowatts by means of a Variac. The 9 kilowatt heater was purely switched on/off. The main air discharge ducts passed immediately underneath the reflector assembly to give sufficient straight length to incorporate orifice plates to B.S.S.1042 and to bring the discharge air clear of the specimen skin.

Appendix B

PHASE 1 TO PHASE 3 - SUMMARISED RESULTS OF TESTS OF SCHEMES A TO C

Relevant results of early tests[8, 9, 10] are given.

Specimen overall heat transfer coefficients for cooling air distribution Scheme B and Scheme C are given in Figs.B1 and B2 respectively, while the primary insulation transmittance for Scheme C is shown in Fig.B3(a). These heat transfer quantities have been recalculated on the same basis as later results. A comparison of Figs.B3(a) and (b) shows, as an example, the difference in values of primary insulation transmittance when calculated on the new and old bases.

A common inlet air temperature/mass flow characteristic for Schemes B and C to give a constant control temperature of 25°C is shown in Fig.B4.

Appendix C

PHASE 4 - HEAT TRANSFER AND THERMAL COMFORT TESTS OF SCHEME D

C.1 Preliminary inspection of specimen

Following Phase 3 tests the cabin secondary insulation was removed to permit inspection of the primary insulation. The condition of the primary insulation was such that any further testing without first undertaking extensive repairs would be of doubtful value for heat balance purposes. The damage to the insulation was due to shrinkage and general distortion of the foamed PVC insulation layer (see Fig.C1).

The secondary effects were as follows:-

(a) Possibly direct air leakage from the first (static) air gap to the wall cooling gap,

(b) variation in the width of the wall cooling air gap making the air flow non uniform within inter-frame gaps and between different gaps,

(c) distortion of the insulation caused leakage between the inlet air duct (i.e. the feed to the hat rack) and the wall gap in the measuring sections, where thermocouple leads were brought through into the cabin from the specimen structure.

It was evident that extensive repairs to the insulation were necessary.

C.2 Repair of specimen

The method of repair of the specimen was largely governed by the need to continue testing at the earliest date, and the non-availability of improved materials.

The Scheme D air distribution system required that the luggage racks be removed, thus leaving the cabin secondary insulation exposed and readily removable. In the baggage compartment the removal of the secondary insulation was not possible without first stripping out the flooring and the extensive inlet and outlet air ducting with their associated feeder ducts and instrumentation. Repairs were therefore confined to the cabin area.

Basically the method of repair was to fill the gaps, which had opened over the frames, with a mastic sealing compound and, then, to positively joint the lap joints and cover strips with a cold setting epoxy resin adhesive. (This was not intended to be a practical solution for the aircraft since inspection of the skin was not thereafter possible.)

A small area of insulation in the roof (directly above the roof discharge grille) was replaced, using a variant of the foamed PVC and a somewhat different method of attachment.

The original secondary insulation was reused.

C.3 Specimen modifications

C.3.1 Scheme D air distribution system

At this time, the abolition of luggage racks was being seriously considered as a means of saving both space and weight. Scheme D therefore dispensed with the racks and thus required a substantial change in the method of introducing air into the cabin.

The Scheme D air distribution system is shown in Fig.C2. Air was introduced into the cabin through perforated bulges in the cabin wall just above head (seated) level. The air was fed into the region from two perforated oval sectioned ducts, enclosed by the perforated trim. The relative total area of the perforations in the inner duct and those in the "trim" were such that the main pressure loss occured over the former.

Also enclosed in the "bulges", which were of thin translucent material, were the strip lights which had been located previously near the roof discharge grille.

Air was supplied to the oval feed ducts from the main inlet air ducts in the baggage compartment by two "riser" ducts in one of the domed ends of the specimen.

C.3.2 Additional modification

Since the primary insulation was exposed for repair the opportunity was taken to incorporate, in one inter-frame section, structure thermally representing a 36 inch length of door frame to investigate heat leakage through this type of structure (Fig.C3).

C.4 Object

The object of the test series here described was:-

(1) To investigate the cabin air distribution following the removal of the luggage racks which had been used previously to distribute the conditioning air,

(2) to investigate, in greater detail, the heat transfer into the specimen,

(3) to assess heat leakage generally,

(4) to assess heat leakage through typical door frame section.

C.5 Instrumentation

Initially instrumentation was similar to that for previous phases of testing except that the cabin inlet air temperature was measured at the surface of the perforated trim cloth, first by mercury in glass thermometers wired to the surface, and later by thermocouples which could be better located in the actual plane of the inlet perforation.

Control temperature (T_C) was measured near the roof outlet. This and other temperature measuring points are indicated in Fig.C2.

Later in the series emphasis was placed on more general measurement of wall cooling air temperatures. In order to make as detailed a survey as possible the wall duct instrumentation was concentrated in the port side on the assumption that the measurements would be equally representative of the starboard side (i.e. that flow would be equally divided between the port and starboard wall gaps).

Due to the frame "cover strips" the wall gap was divided into discrete ducts on each side. However, because of distortion of the primary insulation no single duct could be considered typical, and therefore wall gap instrumentation, which might well have been concentrated in a limited number of ducts, was necessarily dispersed to make as wide a temperature survey as possible. Apart from a few locations where more detailed surveys were made, single thermocouples were located at the centre of the ducts, being distributed as shown in Fig.C2.

C.6 Results

Except for a few exploratory tests early in the series, the emphasis was on stable conditions for heat balance purposes.

Summarised data, recorded during the stable period of heat balance runs are recorded in Tables 1 to 5. The tables include some derived data, e.g. primary insulation transmittance. Further experimental data is presented graphically in Figs.C5 to C9.

Phases 4A and 4B refer respectively to tests made before and after instrumentation of the wall gap.

C.7 Discussion of results

C.7.1 Comfort

Initially some time was devoted to modifying the arrangement of ventilating holes in the perforated trim cloth to minimise the slight sensation of draught which occurred under certain conditions, i.e. at the low and high limits of air flow. The initial and final arrangement of the perforations are shown in Fig.C4.

With the final arrangement of inlet perforations it was found that the minimum air supply to maintain comfortable conditions could be reduced to less than 40 lb/min. As with the previous arrangement (Phase 3 tests[10]) the onset of discomfort at low air flows was first felt in the aisle. A cabin control temperature of 24°C was considered to be comfortable. Temperature distribution within the cabin is summarised in Tables 3 and 4.

C.7.2 Graphical presentation

Due to the thermal inertia of the cabin and associated equipment the exact setting up of specified conditions could be very protracted, and in practice, if conditions appeared to be approaching stability near those nominated, no further adjustment of air flow or temperature was attempted. This gives rise to some scatter in control temperature, and hence in the dependent quantities. For this reason temperatures have been plotted in some cases as temperature differences or even percentage temperature rise (e.g. Fig.C7).

The idealised wall air temperatures given in Fig.C8 are derived from the information of Fig.C7, assuming a "level" temperature of 27°C which inspection showed corresponded to a roof exit temperature of 25.5°C. The derivation of the overall heat transfer coefficients and primary insulation transmittance is indicated in the main text.

C.7.3 Assessment of heat leakage and primary insulation transmittance values

Wall air temperature measurements (Figs.C7 and C8) indicated that between levels 4 and 6 (i.e. above and below the floor beam attachments) there was a sudden discontinuity in temperature rise, indicating that in this locality there was a substantial increase in heat flow into the air gap. Since the primary insulated structure was uniform except at the floor beams it was assumed that elsewhere the rate of increase in wall duct air temperature would be influenced mainly by the particular arrangement of secondary insulation, and except where a change in the latter occurred, the wall duct temperature rise has been assumed to be approximately linear for the purpose of heat flow analysis. The unbroken lines of Fig.C8 were therefore drawn using the idealised data of Fig.C7.

Due to part obstruction of alternate ducts by the floor discharge pipes, and due to "heat leakage" at the floor beam (also indicated by tests of 3 ft square panels in a guard box conductivity rig[5]), flow and temperature measurements at level 5 were not considered usable in the heat flow analysis.

However, the effective temperature of the wall cooling air just below the floor beam could be determined by again assuming a linear wall cooling air temperature rise from the underside of the floor beam to the bottom of the wall duct (i.e. in effect, to specimen discharge).

The temperature rise over the floor beam attachment area was substantially greater than one would expect from the primary insulation in this area. The excess temperature rise (ΔT_{FB}) was due to heat leakage through the floor beam attachments into the air duct (Q_{LD}),

$$\text{i.e.} \quad Q_{LD} = M\, C_p\, \Delta T_{FB} \quad . \qquad (1)$$

The method in which this heat leakage quantity was used in calculating a partly corrected value of insulation transmittance U_p' is shown in the main text in Para.8.2.4.

C.7.4 Further discussion of heat leakage

In the foregoing paragraph it has been assumed that all heat leakage occurred at the floor beam attachments, (i.e. other than the homogenous "leakage" due to frame and crack stoppers). In earlier tests there had been some heat leakage near the (roof) entry to the wall duct but this had been eliminated to a large extent by a minor modification.

There still existed a substantial discrepancy between the values of primary insulation transmissivity, corrected for floor beam heat leakage into the wall cooling duct (U'_p) and the values obtained from panel tests in a thermal conductivity test rig[5]. This appears to be due to floor beam heat leakage directly through into the cabin (Q_{LC}). This conclusion is borne out by tests on a 3 ft square panel which included a floor beam, which showed that at an equivalent specimen flow of 50 lb/min there was an additional flow into the cabin equal to about half the leakage into the air duct.

C.7.5 Door frame heat leakage

The "door frame" section is shown in Fig.C3. Pairs of thermocouples were welded onto the structure, but in general heat leakage estimates were based on wall duct air temperature measurements.

Air velocity measurements made in the wall duct containing the "door frame" showed that the air velocity down the gap was somewhat reduced (to approximately 85% of that for the remaining part of the cabin). Due to possible distortion of the air gap cross section the mass flow reduction was estimated in the following manner.

Assuming that the mass flow alteration is not great enough to affect heat transfer through the primary and secondary insulations above the representative door frame, then the temperature rise between levels 2 and 3 (Fig.C2) in the door frame section relative to that for the remainder of the specimen indicates the change in mass flow (i.e. $M\ C_p\ \Delta T_{2-3}$ should be the same in the door frame section as for the remainder of the cabin). Door frame duct temperatures were recorded and using a similar technique to that used previously, (to produce Figs.C7 and C8) idealised duct air temperatures were derived.

In Figs.C13(a) and (b) the temperature rises down the wall gap in the door frame section are compared with those for the remainder of the specimen. The increased temperature rise between levels 2 and 3 in the former case confirms that the air flow is reduced to 85% of that for other inter-frame sections.

In Fig.C13(b) the wall duct air temperature rise over the "door frame" itself is compared with the rise over the same distance for the remainder of the specimen, the former points being adjusted to correct for the reduction in air flow. The additional temperature rise due to the "door frame" is readily extracted and used to calculate the net heat gain of the duct air expressed per foot of door frame in Fig.C14. Also shown is a heat flow value calculated for the metal structure of the door frame and based on measured temperature differentials.

Below the door frame the air duct temperature is high, which must result in a slight reduction in the heat intake through the primary insulation but a substantial increase in heat flow through the secondary insulation. The result is a decrease in the net heat gain between levels 4 and 6, i.e. a smaller temperature change between these levels, particularly at low flows (see Fig.C13(a)).

Cabin trim temperatures in the region of the representative door frames indicated that over most of the region heat flow into the cabin through the secondary insulation was small, though, near the bottom of the frame, trim temperatures were locally 10°C higher, indicating that over a greater depth of door frame, secondary insulation heat flow might become important, and that to overcome this it may be necessary to increase the secondary insulation thickness locally.

C.7.6 Duct pressure losses

During one test the opportunity was taken to record pressure losses through the system. The results are recorded in Fig.C15.

C.7.7 Cabin air velocities

Cabin air velocities during a number of runs are recorded in Table 5. The velocities were recorded at the top of the seat backs in a downward direction (this corresponded approximately to the maximum velocity at this position). It was considered that air movement in this location (i.e. in the region of the head) would have a maximum effect on subject comfort. The variation in mean cabin velocity measured in the above locations is shown in Fig.C16.

C.7.8 Cabin overall heat transfer coefficient

The cabin overall heat transfer coefficient (defined in Para. 8.2.2 of main text) is of interest because it is a measure of effectiveness of the complete insulation scheme. Values for individual tests are shown in Fig.C17. There is substantial scatter because of the method of obtaining the secondary insulation heat flow required in the calculation of the coefficient (i.e. by subtraction of two relatively large heat quantities).

The mean value over the range of mass flow is approximately 0.05 CHU/hr ft^2 °C.

Table 1

Summary of heat transfer data - Phase 4A

	Run No.	1	2	3	4	5	6	7	8	9	10	11
1	Control temperature °C	25.6	25.0	25.6	24.7	23.9	24.15	25.1	24.4	24.9	–	-
2	Air flow lb/min	55.0	55.0	44.9	NR	48.6	41.6	34.8	48.6	48.7	44.3	35.2
3	Mean inlet temperature to specimen °C	11.15	10.7	6.4		8.7	3.5	-1.3	8.7	12.5	6.5	-1.5
4	Mean outlet temperature from specimen °C	37.5	36.1	38.0		37.7	38.1	39.6	38.6	39.4	31.0	40.1
5	Specimen mean skin temperature °C	109.5	109.5	111.4		111.0	114.1	115.6	118.8	117.2	115.0	118.2
6	Total heat pick up CHU/min	348.0	335.0	340.0		339.0	346.0	338.0	349.0	308.0	336.0	353.0
7	Total specimen internal Ht CHU/min	119.8	120.0	123.3		127.8	124.1	127.1	127.1	74.1	134.3	129.5
8	Total heat through walls CHU/min	228.2	215.0	216.7		211.2	221.9	210.9	222.8	233.9	201.7	223.5
9	Cabin inlet temp (in riser) °C	12.0	11.9	7.8		10.5	6.15	1.0	10.3	13.9	9.0	1.2
10	Cabin outlet temperature °C	25.4	24.7	25.1		24.0	24.2	23.3	24.6	25.0	–	25.4
11	Total cabin temperature rise °C	13.4	12.8	17.3		13.5	18.05	22.3	14.3	11.1	–	24.2
12	Cabin heat pick up CHU/min	117.0	168.0	186.0		158.0	180.5	186.0	167.0	130.0	–	204.0
13	Cabin internal load CHU/min	115.0	115.2	118.5		123.0	119.3	122.3	122.3	69.3	129.5	124.7
14	Heat in through cabin trim and floor CHU/min	62.0	52.8	67.5		35.0	61.2	63.7	50.0	60.7	–	69.3
15	Effective cabin inlet temperature (at perforated trim) °C	18.1	17.4	15.1		16.1	13.9	11.5	16.2	18.7	–	10.7
16	Effective cabin mean temperature °C (10) + (15) /2	21.8	21.1	20.1		20.1	18.9	17.4	20.3	21.9	–	18.1
17	Overall wall ΔT °C (5) - (16)	87.7	88.4	91.3		90.9	95.2	98.2	97.5	95.3	–	100.1
18	Specimen overall coefficient H CHU/hr ft^2 °C	208.0	0.193	0.188		0.184	0.186	0.171	0.185	0.195	–	0.178
19	Approximate mean temperature in wall duct (10) + (4) /2	31.5	30.4	31.6		30.9	31.2	31.5	31.6	32.2	–	32.8
20	ΔT from skin to wall gap air °C	78.0	79.1	80.2		80.1	82.9	84.1	87.2	85.0	–	84.4
21	1st approx to primary insulation transmittance (skin to wall gap air) CHU/hr ft^2 °C U'_p	0.233	0.216	0.215		0.210	0.213	0.200	0.207	0.219	–	0.210
22	Cabin overall heat transfer coefficient CHU/hr °C per foot of specimen curved surface.	0.056	0.048	0.058		0.030	0.054	0.053	0.041	0.050	–	0.061

Note Values not corrected for duct heat pick up in the domed end.

Table 2

Summary of heat transfer data - Phase 4B

	Run No.	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Control temperature °C	25.6	23.3	24.7	24.4	23.3	26.2	26.1	23.9	24.1	23.9	22.2	22.8	23.9
2	Total air flow lb/min	52.8	35.6	42.0	36.7	51.9	62.4	30.0	48.6	57.3	56.6	47.1	46.8	49.6
3	Mean inlet temperature to specimen °C	11.3	4.25	3.9	0	8.2	14.1	-3.75	5.3	10.7	8.6	4.3	6.0	8.7
4	Mean outlet temperature from specimen °C	38.3	37.3	38.4	38.6	37.6	40.6	40.3	38.7	39.3	38.1	36.7	36.1	37.3
5	Specimen mean skin temperature °C	116.3	115.1	115.2	114.1	117.0	118.7	116.5	117.7	116.5	114.5	115.6	114.1	117.9
6	Total heat pick up CHU/min	242.0	283.0	350.0	340.0	368.0	398.0	319.0	391.0	392.0	399.0	366.0	338.0	340.0
7	Total specimen internal Ht CHU/min	132.1	132.1	131.1	144.9	132.1	131.1	131.1	132.1	131.1	131.1	126.1	132.8	128.1
8	Total heat thro' walls CHU/min	209.9	150.9	218.9	195.1	235.9	366.9	187.9	258.9	250.9	267.9	239.9	205.2	211.9
9	Cabin inlet temperature (in riser) °C	13.3	7.4	7.7	3.7	11.0	16.25	0.5	8.2	12.5	11.0	7.6	8.5	11.1
10	Cabin outlet temperature °C	26.6	26.2	26.9	26.8	26.8	29.7	27.5	25.2	25.2	25.0	23.4	23.8	24.7
11	Total cabin temperature rise °C	13.3	18.8	19.2	23.1	15.8	13.45	27.0	17.0	12.7	14.0	15.8	15.3	13.6
12	Cabin heat pick up CHU/min	168.0	160.5	193.5	203.0	198.0	202.0	195.0	198.0	175.0	190.0	178.5	171.5	162.0
13	Cabin internal ht load CHU/min	127.4	127.4	126.4	140.2	127.4	126.4	126.4	127.4	126.4	126.4	126.1.	128.1	123.4
14	Heat input thro' cabin trim and flow CHU/min	40.6	33.1	67.1	62.8	70.6	75.6	68.6	70.6	48.6	63.6	52.4	43.4	27.6
15	Effective cabin inlet temperature (at perforated trim) °C	18.7	13.4	14.0	11.4	16.75	21.0	12.7	16.0	17.4	16.4	15.1	14.75	17.5
16	Effective cabin mean temperature °C (10) + (15) /2	22.7	19.8	20.5	19.1	21.8	25.4	20.2	20.6	21.3	20.7	19.3	19.3	21.1
17	Overall wall ΔT (5) - (16) °C	93.6	95.3	94.7	95.0	95.2	93.3	96.3	97.1	95.2	93.8	96.3	94.8	96.8
18	Specimen overall coefficient H CHU/hr ft^2 °C	0.178	0.126	0.175	0.163	0.197	0.228	0.155	0.212	0.210	0.227	0.196	0.172	0.174
19	Approx mean temperature in wall duct (10) + (4) /2 °C	32.45	31.8	32.7	32.7	32.2	35.2	33.9	32.0	32.3	31.6	30.1	30.0	31.0
20	ΔT skin to wall gap °C	83.8	83.3	82.5	81.4	84.8	83.5	82.6	85.7	84.2	82.9	85.5	84.1	86.9
21	1st approx to primary insulation transmittance (skin - wall gap) CHU/hr ft^2 °C U'_p	0.199	0.144	0.211	0.191	0.221	0.254	0.181	0.241	0.237	0.257	0.223	0.194	0.194
22	Cabin overall heat transfer coefficient CHU/hr °C per sq ft of specimen curved surface.	0.035	0.028	0.056	0.053	0.059	0.065	0.057	0.058	0.041	0.054	0.044	0.036	0.023

Note Values not corrected for duct heat pick up in the domed end.

Table 3

Phase 4A - Cabin temperatures

Run No.	1	2	3	4	5	6	7	8	9	10	11
Air flow lb/min	55.0	55.0	41.6	24.7	48.6	41.6	34.8	48.6	40.7	45.0	45.0
Control temperature °C	25.6	25.0	25.6	-	23.9	24.5	25.1	25.0	24.9	25.0	25.0
Inlet temperature - P °C F/C/R		N/R									
Inlet temperature - S °C F/C/R	18.7/19.9/19.0	16.4/17.3/17.2	14.8/15.7/15.8	N/R	14.7/16.5/16.2	12.2/14.5/13.9	9.0/12.8/11.7	14.4/16.5/16.2	17.5/18.5/18.5	N/R	9.0/10/12.0
Outlet temperature F/C/R	25.0/26.0/25.8	24.5/24.3/25.0	24.9/25.3/25.8	N/R	24.0/23.9/24.0	24.0/24.1/24.6	25.5/ - /25.0	24.4/ - /25.0	23.8/ - /25.3	N/R	24.9/ - /25.8
Aisle globe temperature °C	24.8	24.3	24.75	N/R	25.0	23.9	24.4	24.5	24.0	N/R	24.3
Cabin air temperatures:-											
Front Feet level	N/R*	23.3	23.0	N/R	22.1	21.7	22.2	22.5	22.8	N/R	21.1
Seat level	N/R	22.8	22.9	N/R	22.2	21.7	22.2	22.2	23.3	N/R	21.4
Seated head level	N/R	22.8	23.0	N/R	22.2	21.8	22.5	22.2	23.3	N/R	22.5
Standing head level	N/R	22.8	23.5	N/R	22.3	22.3	23.3	23.0	23.6	N/R	22.5
Centre Feet level	N/R	24.4	23.9	N/R	22.5	22.5	23.6	23.9	23.0	N/R	22.5
Seat level	N/R	24.0	23.9	N/R	22.3	22.8	23.3	24.7	22.8	N/R	22.5
Seated head level	N/R	23.9	24.3	N/R	23.0	22.9	23.6	25.0	23.0	N/R	22.5
Standing head level	N/R	23.9	24.7	N/R	23.5	23.0	23.9	24.4	23.3	N/R	22.5
Rear Feet level	N/R	25.1	25.8	N/R	24.2	24.4	23.9	24.7	24.2	N/R	23.3
Seat level	N/R	24.7	25.7	N/R	24.7	24.4	24.1	25.0	24.4	N/R	23.5
Seated head level	N/R	24.7	25.3	N/R	24.2	24.5	24.6	25.3	25.0	N/R	23.8
Standing head level	N/R	24.7	25.6	N/R	24.4	24.6	25.0	25.5	25.6	N/R	22.3

* N/R = not recorded.

Table 4

Phase 4B - cabin temperatures

Run No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Air flow - 16/min	52.8	35.6	42	36.7	51.9	62.4	30	48.6	57.3	56.6	47.1	47.5	49.6
Control temp. °C	25.6	23.3	24.4	24.4	23.3	26.7	26.1	23.9	24.3	23.9	22.2	22.8	23.9
Inlet temp-P °C F/C/R	18.8/18.5/18.7	12.9/13.2/13.6	13.3/13.8/14.6	11.0/11.1/12.6	15.1/15.6/16.3	20.1/20.2/22.6	9.4/10.4/19.3	13.9/13.7/20.6	16.6/16.6/17.5	13.9/13.7/20.6	14.4/14.9/15.9	14.8/13.7/16.0	17.5/17.4/17.6
Inlet temp-S °C F/C/R	18.1/18.5/19.4	13.6/12.8/14.3	14.0/13.3/14.9	11.0/10.5/12.0	15.0/16.2/16.0	20.0/21.7/21.5	11.0/ 9.5/17.5	16.0/13.8/17.8	17.1/17.1/20.0	16.0/13.8/17.8	15.0/13.4/16.8	15.8/13.0/15.3	18.4/16.0/18.2
Outlet temp. F/C/R	27.0/25.3/27.5	27.5/23.6/27.5	27.5/24.3/28.8	27.5/24.1/28.9	30.5/22.8/27.0	33 /26.4/29.7	27.2/26.8/28.5	25.4/23.5/26.8	25.3/23.8/26.7	25.4/23.5/26.5	23.7/21.8/24.6	24.3/22.8/24.5	25.2/23.7/25.3
Seat globe temp. °C	25.5	22.8	24.6	25.3	23.8	27.4	25.4	24.5	24.7	24.5	-	22.5	-
Aisle globe temp. °C	25.5	23.0	24.5	23.5	23.6	27.3	25.2	24.1	24.4	24.1	22.1	22.5	-
Cabin air temps:-													
Front Feet level	24.7	22.8	23.9	23.0	23.0	26.7	24.2	23.0	23.9	23.9	N/R*	N/R	N/R
Seat level	24.7	22.8	23.9	23.0	23.0	26.4	24.2	23.0	23.6	23.6	"	"	"
Seated head level	24.7	23.0	24.4	23.6	23.0	26.4	24.2	23.3	24.1	23.9	"	"	"
Standing head level	24.7	23.6	25.6	25.0	23.0	26.4	24.7	23.3	24.1	23.9	"	"	"
Centre Feet level	25.3	22.8	23.9	22.8	23.3	27.0	24.4	23.6	24.4	24.1	"	"	"
Seat level	25.6	22.8	23.6	22.8	23.0	27.0	24.4	23.6	24.4	23.9	"	"	"
Seated head level	-	22.8	23.6	22.8	23.0	27.0	24.4	23.3	24.1	23.9	"	"	"
Standing head level	25.3	22.8	23.9	23.0	23.0	27.0	24.4	23.6	24.1	23.9	"	"	"
Rear Feet level	25.9	23.3	24.4	23.9	23.9	27.8	25.3	24.7	24.4	24.4	"	"	"
Seat level	26.1	23.3	24.7	24.4	23.9	28.0	25.6	24.7	25.0	24.6	"	"	"
Seated head level	-	23.6	25.0	24.4	24.4	28.3	25.8	25.3	25.6	25.3	"	"	"
Standing head level	26.7	23.6	24.7	24.1	24.7	28.6	26.7	25.6	26.1	25.6	"	"	"
Underfloor temp.	30.6	30.5	N/R	N/R	N/R	N/R	35	34.5	33.5	N/R	N/R	N/R	N/R

*N/R = Not recorded

Table 5

Cabin air velocities - Phase 4B

Vertical (downward) velocities measured at top of seat backs - ft/min

Test No.		1	2	3	5	6	7	8	10
Air flow	lb/min	52.8	35.6	42.0	51.9	62.5	30.0	48.6	56.6
Seat No.	P2A	15	15	20-25	22	25	18	20	10
	P2W	25.0	0.5	5	15	17	16	8	7
	P3A	15-20	5-15	10	30	30	10	15	6
	P3W	25-30	5	10	30	35	10	10	11
	P4A	50	50	50	90	95	35	65	90
	P4W	40	5	10	40	15	7	10	5
	P5A	40	5-10	10	35	50	10	22	35
	P5W	20	5-10	5-10	35	20	15	20	22
	S1A	25	15	5	30	38	15	30	17
	S1W	20	20	20	25	35	20	22	7
	S2A	20	50	5	40	30	35	25-60	20
	S2W	25	5-10	50	30	30	18	40	20
	S3A	30	25	25	35	35	20	50	20
	S3W	20	5	10	25	22	12	25	50
	S4A	25	10	10	20	15	15	25	15
	S4W	15	5	5	15	20	12	18	10
	S5A	NR	5-10	5	15	20	20	20	5
	S5W	NR	10	10	35	25	12	40	35

Appendix D

PHASE 5 - ALTITUDE TESTS OF SCHEME D

D.1 Introduction

The previously reported tests (Appendices B and C) were made under ground level conditions, whereas in the cruise condition the supersonic aircraft cabin would be maintained at a pressure corresponding to an altitude of 6000 ft. Tests were arranged to determine whether internal heat transfer would be affected by the change in altitude. No subjective tests were possible under altitude conditions.

D.2 Test rig arrangement

For the altitude tests use was made of the larger altitude chamber of the Mechanical Engineering Department Cooling Systems Laboratory (Fig.1 main report, Ref.4). This necessitated some modification of the ducts external to the specimen and, since no observers were to be in the cabin in the actual tests*, the switching on of the internal recording instruments, dummy men, etc, was converted from local (internal) control to remote (external) control.

D.3 Preliminary tests

Initially tests were made under ground level conditions in the altitude chamber to check the operation of the equipment. Some redistribution of the skin temperature resulted from the specimen being in the chamber. This was corrected to a great extent by adjustment of the radiant heater array but some difference remained (e.g. the bottom of the specimen was somewhat hotter relative to the specimen mean skin temperature than previously).

It was also found that due to the thermal inertia of the chamber and chamber air, the external skin temperature and/or the power requirements took a greater time to stabilise.

D.4 Range of investigation

Tests were made at various mass flows between 40 and 60 lb/min under conditions representing a cabin altitude of 6000 ft. The inlet temperature was adjusted to maintain a control temperature of 25°C (nominal) as in the earlier ground level tests.

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* Note No observers were permitted to take part in the tests because of the difficulty, in this case, of providing adequate emergency escape facilities.

D.5 Results and discussion

D.5.1 General

One immediately evident difference in results was that in the chamber, the specimen air inlet temperature had to be reduced below that required to produce the same cabin conditions when the test was made outside the chamber. This appeared to be due to the additional heat pick up in the inlet risers in the forward domed end. The air temperature in the domed ends was substantially higher with the specimen in the chamber than it had been previously.

For the above reason, and because the "scatter" of the results was found to be greater than had been experienced previously, tests under ground level conditions were interspersed in the altitude test series to act as control tests. At one stage in the test series the specimen overall heat pick up radically increased, accompanied by a change in wall duct air temperature distribution. The indications were that a failure of the primary insulation had occurred somewhere near the exit end of the specimen. Inspection showed that a foamed plastic insulation panel (and attached glass fibre blanket) had become distorted and detached from its frame fixings. This breakdown provided direct and substantial leakage between the wall duct and the aircraft skin, which affected the air gap temperature distribution over most of the specimen. It was also possible that the effective leakage area varied between tests and that some leakage occurred early in the series. A repair was made in the relatively accessible area of damage but the heat pick up and temperature distribution were restored only temporarily, indicating that further primary insulation damage may have occurred in some more inaccessible area (as extensive an inspection as possible had been made but in some areas this required stripping out all underfloor pipework, instrumentation and secondary insulation; this was not considered practical).

For the above reasons, only the earlier tests of the series were considered acceptable for any assessment of altitude effects.

D.5.2 Presentation of results

In Fig.D1(a), cabin inlet air temperatures, measured in the riser duct and at the "nozzles" in the perforated trim are plotted against air flow and compared with the values for Phase 4 tests made outside the altitude chamber. Agreement between the Phase 4 and Phase 5 tests is close, the difference in inlet temperatures at the perforated trim being attributable to the change in cabin heat load (24 dummy passengers only in the altitude tests, while in the ground tests there were additional live observers) and possibly due to the change in thermometry brought about by the need for automatic recordings in the Phase 5 tests. A comparison of specimen inlet air temperatures (Fig.D1(b)) indicates the additional heat pick up in the riser ducts, in tests made in the chamber, due to the higher temperature of the domed ends (see Para. 5.1).

Wall duct temperatures (corrected to 27°C at level 1) are shown in Fig.D2 and compared with the idealised values for Phase 4. Good correlation was obtained between Runs 1 to 5 and the Phase 4 results, while Runs 6 to 9 showed a departure from the earlier values. Repair of the specimen at this stage (see Para 5.1) restored the correlation (Runs 10 to 12) but thereafter it was apparent that further primary insulation breakdown had occurred (Runs 13 and 14). Later tests, not recorded, showed that still further deterioration had occurred.

It is apparent that only Runs 1 to 5 and 10 to 12 may be used with confidence. The variation of primary wall insulation transmittance with air flow is shown for these runs in Fig.D3(a). The departure from the Phase 4 results is attributable to the additional temperature rise in the riser ducts in the domed ends. Correction for this additional heat pick up produces the points shown in Fig.D3(b), which agree well with the Phase 4 results.

D.5.3 The effects of altitude

Control tests made under ground level conditions have been identified in Figs.D1 to D3. It can be seen that within the limits of experimental scatter there is no detectable difference between the internal heat transfer processes at ground level and at a cabin altitude of 6000 ft.

An attempt made to measure the low cabin air velocities by remote instrumentation was not successful but it is evident that the velocities at any particular air mass flow must be increased at the reduced ambient pressure corresponding to a cabin altitude of 6000 ft. No evidence was available on the subjective effect of this combined velocity and density change, however it is thought that to some extent the effects will tend to be self cancelling.

D.5.4 Further comments

The primary insulation breakdown experienced in the tests was directly caused by the need for pressure relief across the primary insulation when the cabin altitude was changed. Evidently, direct air leakage between the outer (static) air gap in the insulation, and the inner wall gap, which was expected in the baggage compartment where the primary insulation had not been repaired, was insufficient.

The extent of the primary insulation damage was accentuated by the embrittled state of the foamed PVC insulation.

Bearing in mind that in the 20 ft length of the test specimen the total volume of the outer air gap was of the order of 80 cubic ft, it would appear essential that if an air gap is included in the primary insulation then a suitable method of pressure relief should be incorporated in the design.

Conclusions

The tests showed that no difference in overall heat transfer in the specimen was detectable between the ground level, and the 6000 ft altitude tests.

No observers took part in the tests but it is considered that in view of the low cabin air velocities heat transfer from the passengers may be mainly by natural convection processes, in which case the change in ambient pressure may affect these processes and hence influence comfort. (See Para.9.7 of the main text.)

The tests showed the need to provide some means of pressure relief across the primary insulation if a static air gap is incorporated in the primary insulation scheme.

Appendix E

PHASE 6 - THE USE OF JETS FOR INTRODUCING CABIN COOLING AIR TRANSIENT CASES - SCHEMES E AND F

E.1 Introduction

Though it was evident that further tests on the cabin specimen would be of limited value for heat transfer investigations, because of the deterioration of the primary insulation, the opportunity was taken to investigate a final air distribution scheme in which air was introduced into the cabin through nozzles, jet entrainment being an important part of the cabin conditioning process.

E.2 Specimen and test rig

Scheme E

For these tests a hat rack was refitted to the specimen, approximately 30 inches wide and 5 ft above the cabin floor level. All perforations in the perforated trim of the previous air distribution scheme were blanked off and the duct used as a manifold for supplying air to the nozzles, just below the hat rack, in the manner shown in Fig.E1(a). The starboard side of the cabin was provided with **discrete** nozzles, $\frac{1}{4}$ inch diameter and at 2 inch pitch with centres 3/16 inch below the hat rack. Initially the port side of the specimen was provided with a continuous slot which could be varied from 1/16 inch to 3/16 inch width. Later this slot was dispensed with and the same arrangement used as was on the starboard side.

On both sides "half round" moulded wooden section strips were fitted to the underside of hat racks, as shown in Figs.E1(a) and (b), to induce some turbulence and possibly induce better mixing of cabin and nozzle air.

Scheme F

This scheme was an improved version of Scheme E. The perforated trim was removed and all holes in the inner longitudinal ducts sealed off. Connection to the nozzle manifold was by 1 inch diameter pipes sufficient in number to ensure choking at the nozzles. These short connecting pipes and the longitudinal ducts were then insulated with approximately an inch thickness of glass fibre mat.

The strip lights, previously located under the translucent perforated trim cloth were removed to their earlier position (Schemes A to C) near the air exit in the roof.

During the series, the $\frac{1}{4}$ inch nozzles were opened out first to 9/32 inch and finally to 5/16 inch diameter.

Finally, the roof discharge grille was covered with a thickness of woven nylon cloth to reduce radiation from that source. In most of the tests air was expelled from the cabin from both the roof and floor discharge grilles.

Three simulated windows, consisting of perspex panels fitted with electrical heaters (variable) were installed to determine the effect of window surface radiation on passenger comfort.

E.3 Instrumentation

The instrumentation was similar to that used in Phase 4 tests. The control thermometer was restored to its early position near the centre of the cabin.

E.4 Procedure

Scheme E

The required air flow was set up with the nominated ratio of roof to foot discharge and the cabin control temperature raised to the required value. This usually required supplying air to the cabin at about 35°C for a half hour. The observers then entered the specimen and the dummy men were switched on to give full passenger load. The control temperature was then maintained at its preselected value (by adjusting the inlet air temperature) for one half hour, with the specimen skin at ambient temperature, representing the take off and climb. At the end of the period the radiant heaters were put on to automatic control and the skin temperature raised to approximately 115°C in about 10 minutes, representing the acceleration phase of the flight. Skin temperature was then held constant for 2 hours 20 minutes to represent the cruise while the cabin inlet temperature was reduced to keep a steady control temperature. At the end of the cruise period the radiant heat was switched off and readings continued for a further 20 minutes to cover the descent period.

Scheme F

In these later tests the short term rise in air supply temperature, which occurs when the engines are throttled back at the beginning of descent was represented. This was arranged to occur simultaneously with switching off the radiant heat.

At the time of testing it was intended that in normal flight, air should be obtained from four cooling systems operating in parallel. Should one system fail the remaining three systems would continue to supply cooling air but somewhat reduced in quantity. In a number of the tests, a one in four system failure, after one hours cruising, was represented.

E.5 Results

The tests are summarised in Table 1. Results for a selection of tests are given in graphical form in Figs.E2 to E12.

E.6 Discussion of results

E.6.1 The use of nozzles

The merits of using this method of introducing ventilating air into the cabin were substantiated by the tests. The quantity of ambient air entrained by the jet may be quite large compared to the quantity of "primary" air, and as near as 6 inches from the nozzle entrainment factors may be as high as 8 : 1 (Ref.2) for conditions such as existed in the tests. Thus the temperature of the mixed air approaches that of the ambient (entrained) air, while its velocity decays rapidly. Some jet temperature and velocity profiles are given in Figs.E2 and E3 respectively and in Fig.E6. The velocities are maxima (i.e. on the jet axis), the average velocity being about one third of the maximum.

The mechanism of entrainment induces a circulation of low velocity air over the passengers while the direct jet passes above head level.

Another advantage of this method of introducing cabin air is that the final mixing of the air is done in the cabin. Thus a relatively small flow of cold air is ducted to the cabin rather than a larger flow of mixed air with its higher duct losses.

E.6.2 General comments

The test runs showed that reasonably good cabin temperature control was achieved, using manual control based on previous experience. The indications are that, because of the thermal capacity of the cabin, a pre-programmed inlet air temperature would probably be an effective means of providing a reasonably constant cabin temperature for any given flight plan. The programme selected would vary with the number of passengers and the initial conditions before take off (ideally the latter should be obtained by ground conditioning). Some normal subsonic type automatic control might be superimposed to allow for general variations in passenger metabolic heat output, e.g. at night the passenger metabolic rate might be expected to decrease while at meal times one might expect a substantial increase in metabolic rate.

E.6.3 Comments on Scheme E tests

The first series of tests showed a marked improvement in general cabin conditions when compared with earlier tests (Appendices B and C).

With previous schemes the minimum air supply capable of maintaining satisfactory conditions overall, including the aisle, was 40 lb/min (Scheme D). With the nozzle system, conditions throughout the cabin became more uniform and discomfort in the aisle at low mass flows was alleviated. It was found that with a total air mass flow as low as 29 lb/min (at a control temperature of 22°C measured in the aisle) cabin conditions were comfortable throughout (Figs.E4 and E5). There was no marked cooling of the ankles in spite of the fact that up to 17 lb/min of the air was discharged at the bottom of the walls.

With a total air flow of 23 lb/min, with 8 lb/min discharged through the roof (control temperature 24°C) observers in the cabin were conscious of a feeling of "stuffiness", more particularly in the aisle (Figs.E7 and E8). This was thought to be due to a combination of reduced air movement at head level in the aisle combined with greater direct radiation from the roof grille and the roof primary insulation visible through the grille. It was considered that this condition was only marginally comfortable over a complete flight but was more than adequate as an emergency condition.

With 3 lb/min of air discharged through the roof and 17 lb/min discharged through "foot discharge" grilles, the undesirable features of the previous condition were emphasised and though conditions were adequate for a part system failure case, they were not sufficiently comfortable for normal operation over a long period.

E.6.4 Limitations of Scheme E tests

Cabin conditions may have been influenced by the fact that direct radiation could be felt from the roof primary insulation through the roof discharge grille, though this may have been offset by the cold surface of the uninsulated duct (i.e. "perforated trim") above the luggage rack. In addition, there was certainly some (unknown) leakage from the latter duct which diffused into the cabin at the expense of the nozzle flow.

E.6.5 Comments on Scheme F tests

These tests, on a more representative installation, were made to confirm and extend the previous investigation with Scheme E installed in the cabin.

There was a noticeable improvement in conditions in the aisle and in the seats adjacent to the aisle from the provision of a nylon cloth radiation barrier over the roof discharge grill, particularly at low air flows.

In general, conditions were found to be most comfortable at a control temperature of 24°C. Total air flow could be reduced to 25 lb/min, with 10 lb/min through the roof exit, with no thermal discomfort. Under these conditions some observers complained of slight draughts in the aisle seats apparently due to residual velocity from the jets on the opposite wall (see comments of Table 2 which apply to a 29 lb/min case).

Observers seated adjacent to a simulated window were quite conscious of the thermal radiation from its surface which was maintained at about 8°C above general cabin wall temperature. Evidently a smaller differential must be achieved in an actual aircraft.

E.6.6 One in four system failure

Practical difficulty was experienced in maintaining the same specimen and cabin air inlet temperatures when simulating a quarter system failure (see Figs.E9 and E10) due to the thermal inertia of the ducting etc, and interaction of wall and floor discharge. However, in general, cabin temperatures rose approximately $2\frac{1}{2}$°C in the first fifteen minutes after failure and then increased at a slower rate until after about 1 hour the temperature stabilised at approximately 5°C above the original (full air flow) condition. It was considered that these conditions were not unacceptable in an emergency.

E.6.7 End of cruise conditions

The temporary increase in system delivery temperature at the beginning of "descent" (about 10°C) caused the general level of cabin temperatures to rise almost linearly to a maximum of 5°C above the end of cruise level and then fall at the same rate in the case of Run 9 (Fig.E12). The maximum temperature was reached in 12 minutes. In tests where skin heat was cut simultaneously the momentary temperature rise was not as great and was of shorter duration.

In most cases the observers were hardly aware of the temperature rise before it commenced to drop, perhaps due to the thermal inertia of their clothing. Certainly any discomfort was momentary.

E.6.8 Complete system failure

During Test 4 there occurred an inadvertant failure of the air supplies and the opportunity was taken to record the cabin temperatures after failure (Fig.E8). Skin heat was kept on, simulating the worst possible condition. It was evident that an appreciable time was available for corrective action. A failure case is discussed in more detail elsewhere (Appendix F).

E.6.9 Limitations of Scheme F tests

Progressive deterioration of the specimen took place as the test programme proceeded. The main deterioration was in the condition of the primary (foamed PVC) insulation above the roof discharge grille, which was exposed on stripping down the specimen on completion of the tests. It was believed that the deterioration was accelerated by prolonged tests with low air flow through the roof discharge grille.

Insulation break down in the roof resulted in substantial heat leakage into the wall gap. This gave higher wall duct air temperatures and consequently somewhat higher cabin wall temperatures. The effect is illustrated by comparing data for two similar tests as in Table 3. It is thought however that even the later tests gave a good indication of cabin conditions and, the limiting air flow of 25 lb/min probably still applies though, without leakage, it could possibly have been introduced into the cabin at a somewhat higher temperature.

E.7 Conclusions

The use of nozzles mounted beneath the hat rack seemed to be a very effective way of introducing conditioning air into the cabin. Air penetration and circulation was improved generally over previous schemes. It was found possible to effectively air condition the 20 ft × 12 ft diameter cabin with air flows as low as 25 lb/min, the cabin control temperature being 24°C and 10 lb/min of the air being discharged through the roof.

The quantity of air discharged through the roof did not appear to be particularly critical as long as it was kept above 10 lb/min.

Tests representing complete flight plans indicated that the severe conditions at the beginning of descent caused little or no discomfort to the passengers.

Failure of one in four of the aircraft cabin air systems supplying an initial 25 lb/min of air caused the general level of cabin temperature to rise approximately 5°C but the conditions were considered to be quite reasonable in an emergency.

It appears quite feasible to programme inlet air temperature to suit any flight plan, allowing for the initial cabin conditions and the passenger load, though a temperature control system would still be required, to cater for variations in passenger metabolic heat and in solar radiation through the transparencies.

An 8°C differential between transparency surface temperature and general cabin wall temperature is not compatible with passenger comfort and efforts should be made to reduce this differential.

Table 1

Summary of Scheme E and F tests

Test No.	Object	Air flow lb/min		Control temp	Remarks
		Roof	Floor	°C	
	Scheme E tests				
1	Flight simulation from ground to start of descent in all cases, with varying air flows.	19	16	24°	All runs were primarily subjective, major temperatures recorded in each case.
2		12	17	22°	Run 2 results given in Figs.E4 and E5.
3		12	17	22°	
4		8	15	23-24°	Inadvertent cooling air failure. Skin temperature maintained for 10 minutes and records taken. Results given in Figs.E7 and E8.
5		3	17	27°	
	Scheme F tests				
6	As above with 1 in 4 system failure, during flight — Before failure After failure	11.5 3	18 17	24°	
7	Ditto — from to	11.0 5.5	18.5 16.5	24°	Results given in Figs.E9 and E10.
8	from to	29 20		22°	
9	Test includes momentary inlet temperature rise at commencement of descent.	29		25°	Results given in Figs.E11 and E12.
10		12.5	12.6	24-25°	
11	from to	14 6	10.5 10	25°	
12	from to	23 11	6	25°	

Table 2

Subject comments - Test No.7

Seat numbering

P = Port
S = Starboard
Numbered from front
W = Wall seat
A = Aisle seat

S1A

Before failure

Quite cool. Left side slight draught on arm. Otherwise quite comfortable Just sufficient air movement. In aisle, draughty to head.

S2A

11.15 Noticeable noise from air inlet holes.
Generally comfortable. Wearing jacket etc - no pullover.
No draught at head level.
No feeling of stuffiness.

12.40 Feel slightly warm and stuffy.
Reduced noise from distribution system.
No draught.

S5A

11.15 Temperature comfortable but slight draught on face adjacent to aisle.
Nozzle noise noticeable. Slight draught on knees.

S5W

11.15 Mean air temperature is good.
Wall seems to be hot.
Window seems to be too hot.
Light draught at feet and knee level.
Nozzle noise is quite "sensible".

S6A Ambient temperature good. A little cold at feet level
Slight draught on face from time to time.
Distribution of noise identical to aerodynamic noise at front end of Caravelle.

Table 2 (Contd)

P3A (Experience showed that this subject favoured somewhat warmer conditions than average.)

11.10 Jacket off, sleeves rolled up.

Body temperature comfortable. Sensation of cold air movement on right side of head and right arm.

If seated for long would require jacket to obviate discomfort to right arm and shoulder. No sensation of air movement whatsoever on left side of head.

12.40 Very slight sensation of air movement on right side of head and right arm.

Completely comfortable with jacket off and sleeves rolled up.

No air movement on left hand side.

Slight suggestion on left of radiant heat from tin men.

Body temperature warm but not uncomfortable.

P5A Distinct draught from the aisle.

General temperature level quite comfortable. (A general sensation of air movement is desirable but this is probably a shade excessive for most people.)

Foot temperature a shade too low. Left hand side of face always seems warmer than right hand side even when leaning forward away from the tin men.

After failure

Greatly reduced draught from aisle - just enough to be comfortable. General atmosphere not too stuffy. Temperature level quite comfortable provided one is seated. Foot temperature satisfactory.

P6A

11.10 Shirt sleeve order.

Good smoke dispersion.

Plenty of air movement but I like this.

Slight coolness of right arm.

Quite comfortable.

Slight coolness of ankles.

Small reduction in velocity may be beneficial.

Table 3

Comparison of cabin conditions during similar tests before and after development of heat leakage in roof

Measurements made approximately 1½ hours after start of acceleration

Test run	Air flow lb/min		Air inlet temp °C		Cabin air temp °C			Wall surface temp °C	Wall duct mean temp		No. of passengers	
	Roof	Floor	Specimen	Cabin	Control	Aisle globe	Aisle air		Level 3	Level 4	Live	Dummy
2	12	17	-8	9	23.5	22.5	21	30	32	38	7	24
7	11	18.5	-7	6.5	24.5	23.5	22	37	41	42	7	24

Note

1 The difference in cabin air inlet temperature in the two tests is due to improved ducting insulation incorporated for the later tests.

2 The wall temperatures were recorded over two frame pitches adjacent to Starboard Seat 3 at about shoulder (seated) level and could be influenced by the exact position of adjacent dummy men. The wall duct air temperatures give a better indication of the leakage in the roof primary insulation.

3 Level 3 is 4 ft from floor level.
Level 4 is 1 ft from floor level.

Appendix F

CABIN TEMPERATURES FOLLOWING COMPLETE SYSTEM FAILURE - SCHEME D

F.1 Introduction

Some disquiet was felt about the effect of complete failure of air supplies on thermal conditions in the cabin of a supersonic aircraft when cruising at M 2.2. The test described was devised to determine the rate of deterioration of cabin conditions in such a case.

F.2 Specimen and test rig

The specimen and test rig were as described in Appendix A. Ventilation Scheme D was installed at the time of the test, but the type of ventilation scheme should have a negligible effect on conditions after failure of air supplies.

F.3 Procedure

With a fuselage outside skin temperature of 105°C and full internal heat load, cooling air mass flow and inlet temperature were set to values known from previous tests to give comfortable conditions (at a control temperature of 24°C). Temperatures and cabin heat pick up were monitored until it was established that conditions within the cabin were stable.

Complete failure of the cabin cooling system was then simulated by closing the valve in the cabin supply duct. Mean outside skin temperature was meanwhile kept at its original value. From the time of system failure, temperatures within the specimen were recorded at 1 minute intervals for 16 minutes by four observers. Wall temperatures were recorded automatically.

F.4 Results

Conditions before simulated failure were as follows:-

Mean outside skin temperature 105.6°C
Total cabin air mass flow 57 lb/min
Proportion of air discharged through floor discharge grilles 18%
Cooling air inlet temperature 10.2°C
Cabin control temperature (at roof) 24°C. Humidity approx. 15% RH.

Remaining temperatures before system failure are included in the attached tables.

The internal heat loads were as follows:-

Roof lights 6 off 80 watts = 480 watts
Reading lights 12 off 15 watts = 180 watts
Recorders, etc = 180 watts
Under floor lighting = 60 watts
Dummy passengers - 24 off at 110 watts (nominal) = 2640 watts (measured)
4 observers each assumed to dissipate 110 watts = 440 watts
Total heat load = 3980 watts.

Cabin air temperature histories from just before failure to 16 minutes after failure are recorded in Table 1. Cabin wall surface temperatures are given in Table 2.

The more important results are presented graphically in Figs.F1 and F2. Due to thermal inertia the globe temperature values probably lag behind the remaining temperatures and, therefore, they have not been plotted.

F.5 Discussion of results

The rate of increase of cabin temperature after system failure with the aircraft skin kept at a nominal 110°C is shown in Fig.F1. The initial humidity was 15% RH, but measurements were not made after failure since the number of human passengers (4) was unrepresentative.

At 5 to 10 minutes after failure of the system, the observers found it desirable to remove their jackets, but thereafter, conditions did not deteriorate so rapidly and even after 16 minutes, conditions, though hot (34°C at a seat position), were far from unbearable. Initially, the temperature rise at a seat position was about 1°C per minute, but later it decreased to about 0.5°C per minute. At the end of the test the inside wall trim temperature was 38°C at head level decreasing to 34°C at foot level and the radiation effect to a seated subject was not very noticeable.

The results show that complete failure of the cooling system would not be catastrophic from a thermal aspect, and indicate the order of the time permissible for corrective action. The problem of maintaining pressurisation after cooling system failure requires separate study.

Table 1

Cabin air temperatures after system failure

Time after system failure - min	Temperature °C						
	Roof	64" above floor	44" above floor	5" above floor	Globe 47" above floor	Aisle seat Stbd	Aisle seat Port
-4	23.6	23.0	22.5	21.5	23.5	22.0	23.0
0	System failure						
1	24.4	24.4	23.6	21.6	23.5	26.0	25.6
2	26.1	25.7	24.7	22.5	23.8	26.0	27.0
3	27.8	27.2	26.0	23.0	24.2	26.0	28.3
4	28.3	28.5	27.3	23.5	24.7	27.0	29.4
5	29.2	29.5	28.4	24.0	25.5	28.0	30.6
6	30.0	30.4	29.2	24.5	26.1	28.0	30.85
7	30.6	31.0	29.8	24.7	26.8	29.0	31.1
8	31.1	31.7	30.5	25.0	27.5	29.0	31.1
9	31.9	32.4	31.2	25.2	28.2	29.5	32.0
10	33.1	33.0	31.8	25.4	28.9	30.0	32.5
11	33.6	33.8	32.5	25.7	29.7	30.5	33.3
12	33.6	34.4	33.1	25.8	30.3	31.0	33.6
13	34.7	35.0	33.5	26.2	31.0	31.5	34.1
14	35.3	35.5	34.0	26.5	31.5	32.0	34.4
15	36.1	35.9	34.5	26.5	32.0	32.5	35.1
16	36.4	36.4	35.0	26.9	32.6	33.0	35.6

Table 2

Trim temperatures* after system failure

Time after system failure min	Temperature °C								
	Trim cloth temperatures							Air outlet to recirc. - in roof	Under floor air
	4A9	4B9	4C9	4D9	2C9	3C9	1C10		
-1.30	28.0	28.5	28.5	30.0	27.0	27.0	26.0	24.5	26.0
-0.30	28.0	28.5	28.5	30.0	27.0	27.5	26.0	25.0	26.0
0.20	28.0	29.0	28.5	30.0	27.0	27.0	26.0	25.0	25.5
1.20	29.0	29.0	29.0	30.0	27.0	27.5	26.0	28.5	26.0
2.10	30.0	30.0	29.0	29.0	28.5	28.0	27.0	30.0	26.0
3.10	32.0	32.0	29.0	30.0	28.0	28.0	27.0	32.0	26.0
4.00	33.0	32.0	29.0	30.0	28.0	28.5	27.0	33.0	26.0
5.00	34.0	33.0	30.0	30.0	28.5	28.5	27.0	34.0	26.5
5.50	34.5	33.5	30.0	30.5	28.5	29.0	28.0	34.5	28.0
6.40	35.0	34.0	30.0	31.0	29.0	29.0	28.0	35.5	28.0
7.40	36.0	34.5	31.0	31.0	29.0	29.0	29.0	36.0	29.0
8.30	36.5	35.0	32.0	32.0	30.0	30.0	29.0	36.5	28.5
9.20	37.0	36.0	32.0	32.0	30.0	30.5	29.5	37.0	29.0
10.20	38.0	36.5	32.0	32.0	30.5	30.5	30.0	38.0	29.0
11.10	38.0	37.0	32.0	32.0	31.5	31.5	30.0	38.0	29.0
12.10	38.5	37.5	32.5	32.5	32.0	32.0	30.5	38.5	29.0
13.10	39.0	38.0	33.0	33.0	32.0	32.0	31.0	39.0	29.0
14.10	39.0	38.5	33.0	33.0	32.5	32.5	31.5	39.0	29.5
15.00	39.5	38.5	33.5	34.0	32.5	32.5	31.0	39.5	29.0
16.00	40.0	39.0	33.5	34.0	33.0	33.0	32.0	40.0	29.0
16.50	40.0	40.0	34.0	34.0	33.5	33.5	32.0	40.0	29.0

*Note: Two air temperatures recorded on the same chart are also included in the Table.

SYMBOLS

Q_T = total heat pick up in the specimen
= $M\ C_p\ (T_5 - T_1)$ corrected for heat pick up between X and Y (see Fig.2)

Q_{int} = total internal heat load (i.e. instrument heat, dummy passenger heat, lighting and observers metabolic heat.)

Q = total heat intake through the specimen walls
= $Q_T - Q_{int}$

Q_{TC} = total cabin heat pick up
= $(1 - x)\ M\ C_p(T_4 - T_2) + x\ M\ C_p\ (T_{4a} - T_2)$ (see Fig.2)

$Q_{int(C)}$ = cabin internal heat load

Q_C = heat through the secondary insulation and floor and by leakage directly into the cabin
= $Q_{TC} - Q_{int(C)}$

Q_{LD} = floor beam heat leakage into the wall cooling duct

Q_{LC} = floor beam heat leakage directly into the interior of the cabin

A_S = specimen curved surface area through which all heat is assumed to pass

T_S = specimen mean curved surface temperature

T_{CM} = mean cabin air temperature

T_G = general expression for wall gap air temperature

T_1 to T_6 = temperatures at various locations in ducts (see Fig.2)

T_{L1} to T_{L6} = mean temperatures at various levels in wall cooling ducts (see Fig.C2, Appendix C)

$(T_S - T_G)_M$ = effective mean temperature difference from specimen skin to the centre of the wall cooling duct

ΔT_{FB} = wall cooling air temperature rise due to floor beam heat leakage into duct

M = total specimen air mass flow

x = fraction of total mass flow discharged through floor discharge

C_p = specific heat of air at constant pressure
= 0.24 CHU/lb °C

SYMBOLS (Contd)

H_o = specimen overall heat transfer coefficient

= $Q/A_S(T_S - T_{CM})$

H_C = cabin overall heat transfer coefficient

= $Q_C/A_S(T_S - T_{CM})$

U''_p = installed primary insulation transmittance

= $Q/A_S\,(T_S - T_G)_M$

U'_p = primary insulation transmittance corrected for floor beam heat leakage into the air duct

= $(Q - Q_{LD})/A_S\,(T_S - T_G)_M$

U_p = primary insulation transmittance fully corrected for heat leakage. The value obtained from panel tests[5] was used, and Q_{LC} could be determined from

U_p = $(Q - Q_{LD} - Q_{LC})/A_S\,(T_S - T_G)_M$

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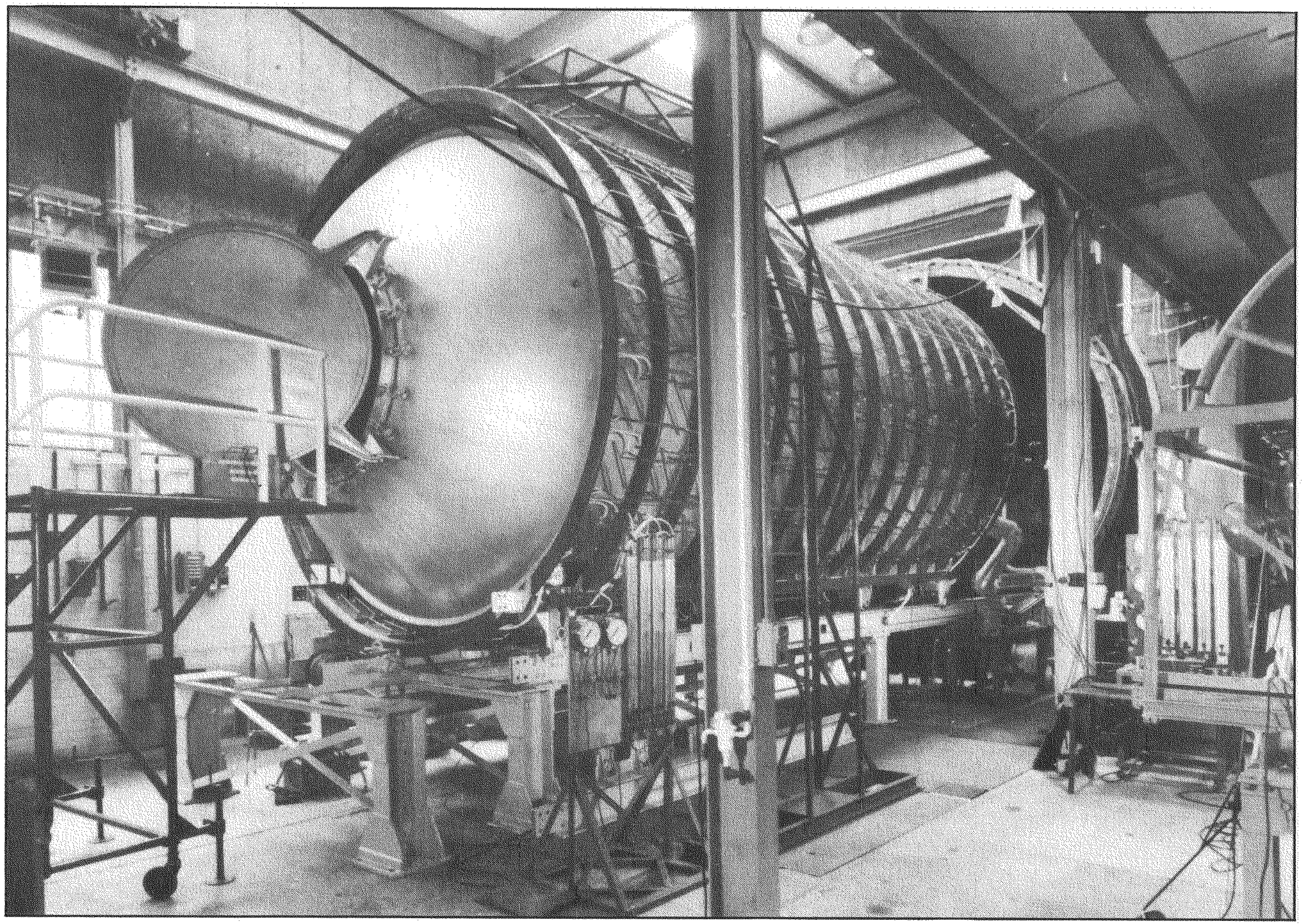


Fig.1. General view of test rig

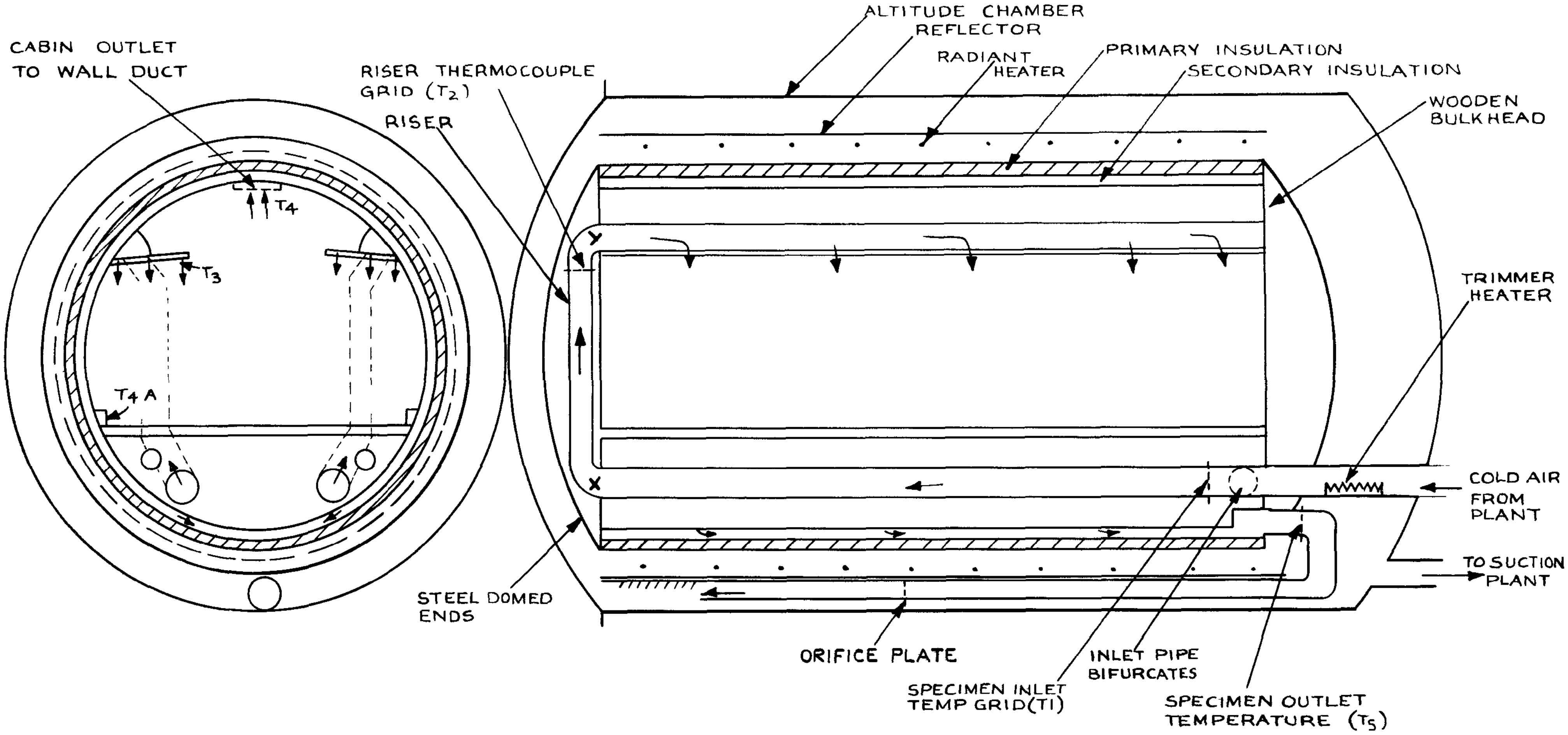


FIG 2 ARRANGEMENT OF SPECIMEN IN ALTITUDE CHAMBER (SCHEME D SHOWN)

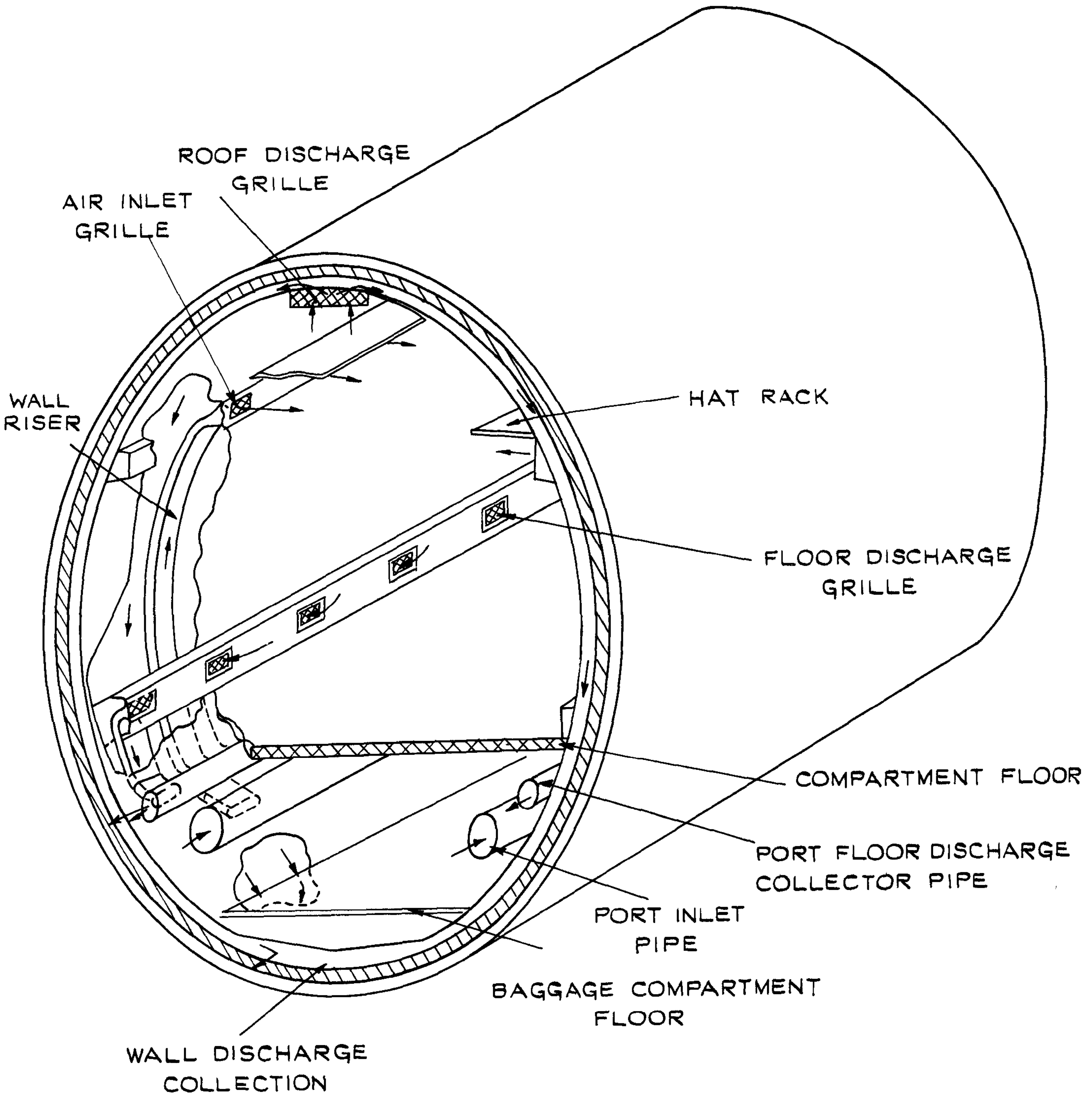


FIG 3 SECTION THROUGH CABIN SPECIMEN-(SCHEME A)

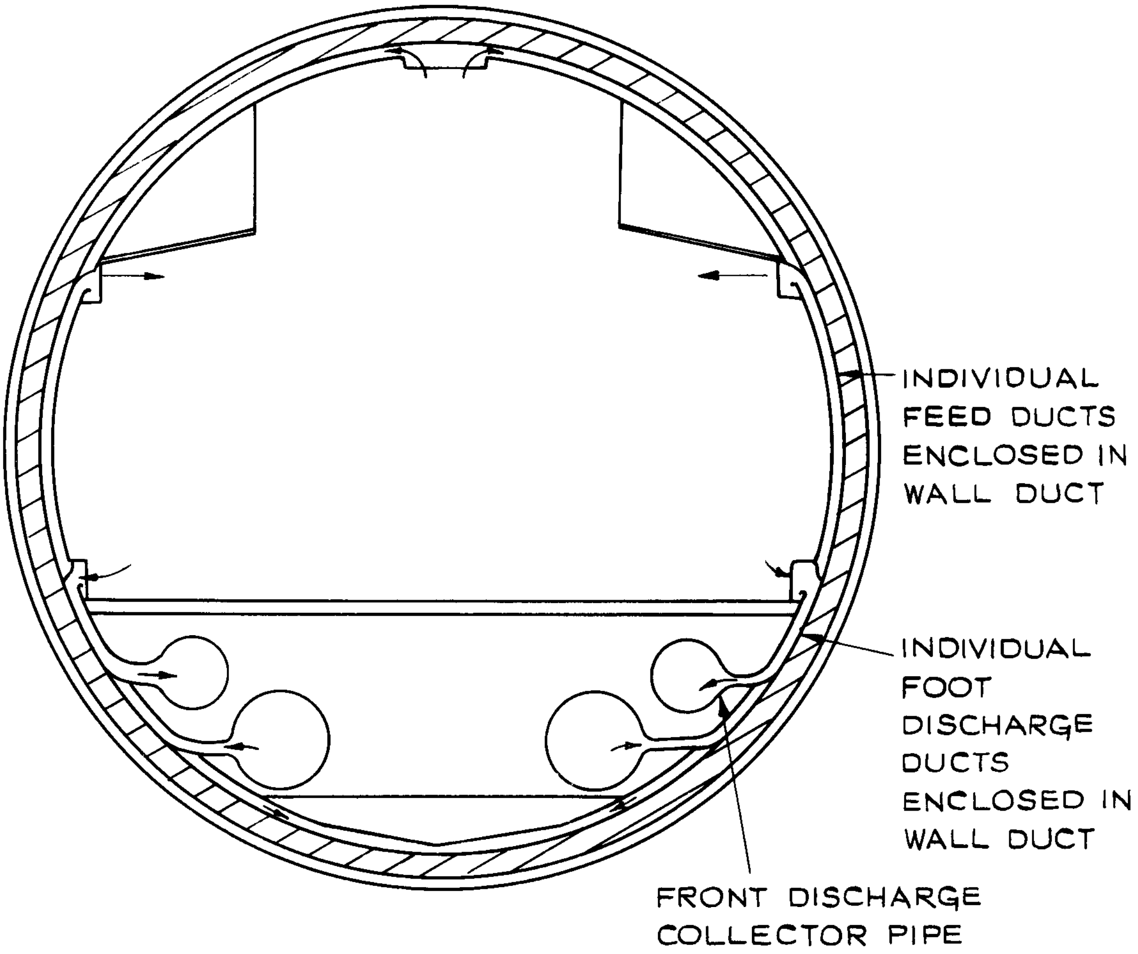


FIG 4 (a) VENTILATION SCHEME A

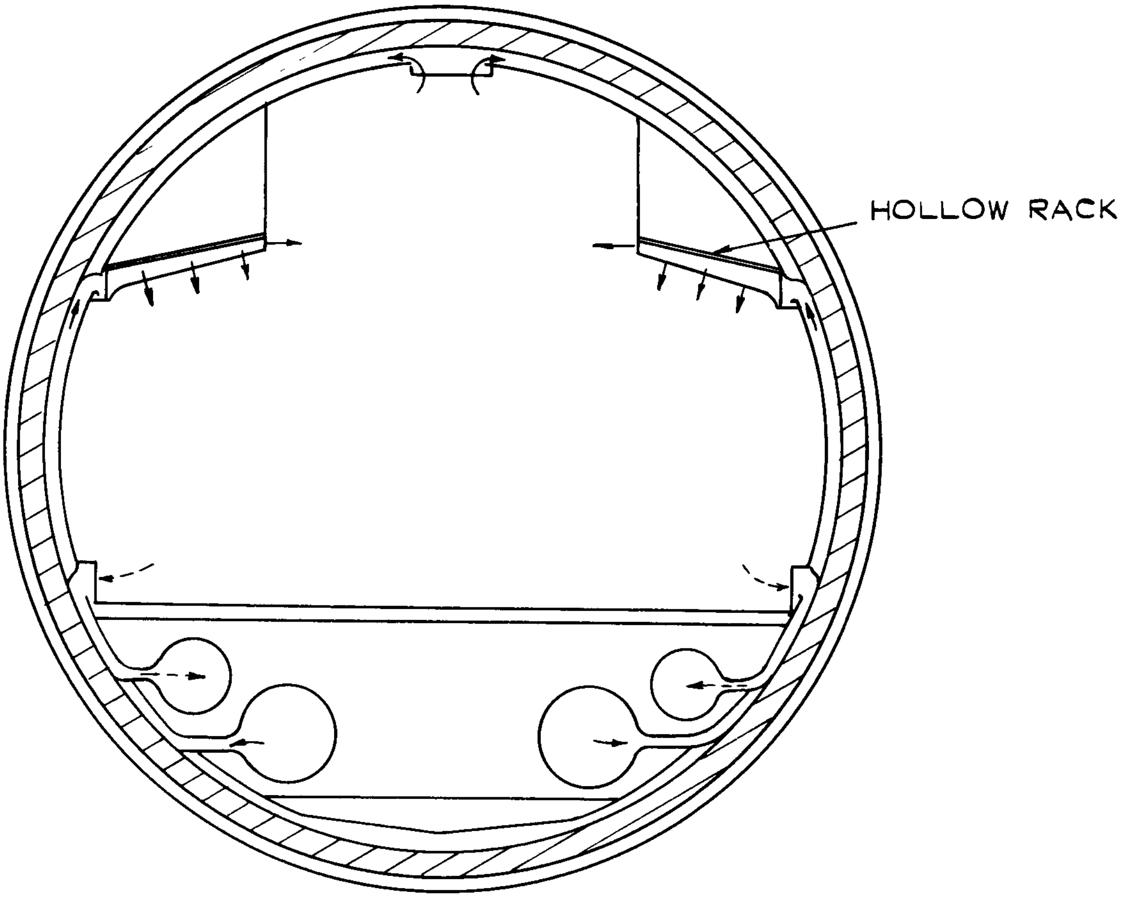


FIG.4(b) VENTILATION SCHEME B

FIG 4 CABIN AIR DISTRIBUTION SCHEMES A & B

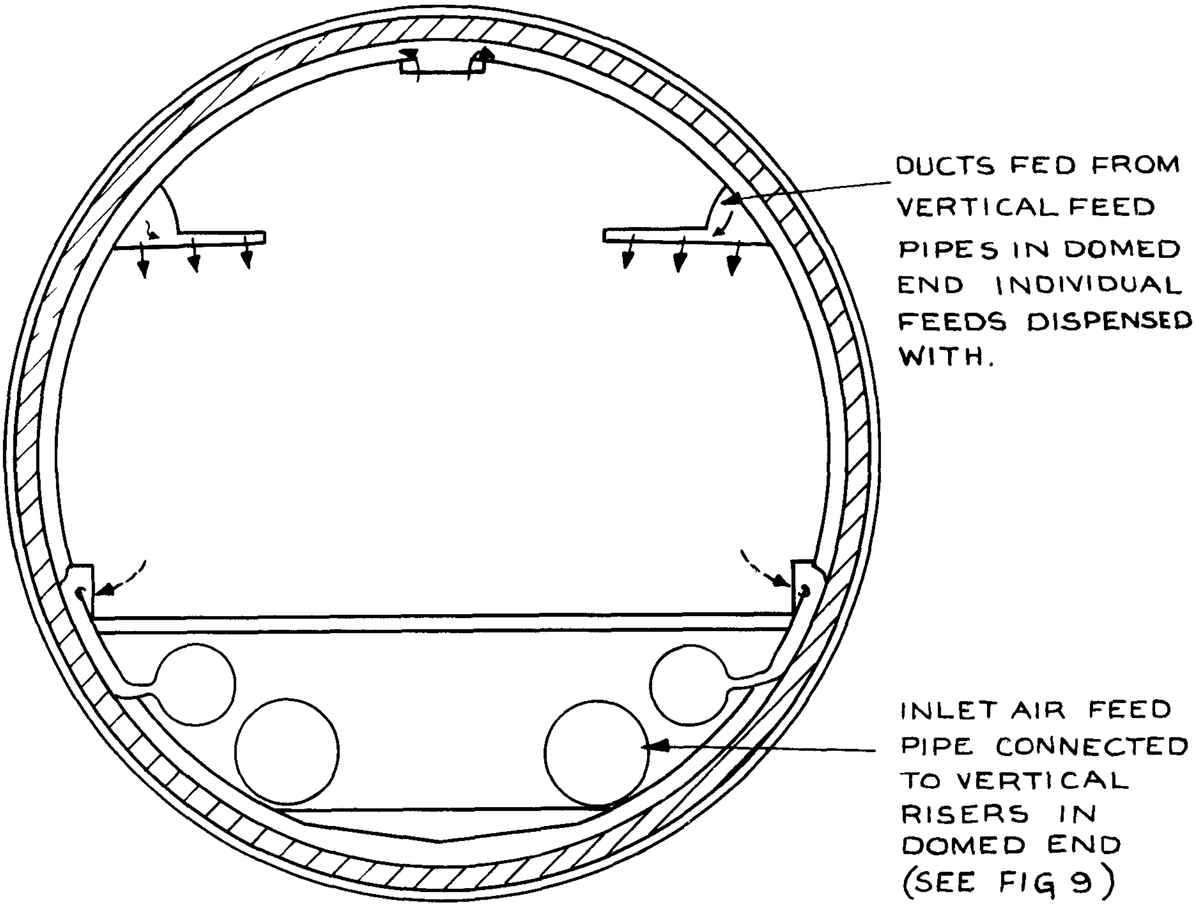


FIG. 5 (a) VENTILATION SCHEME C

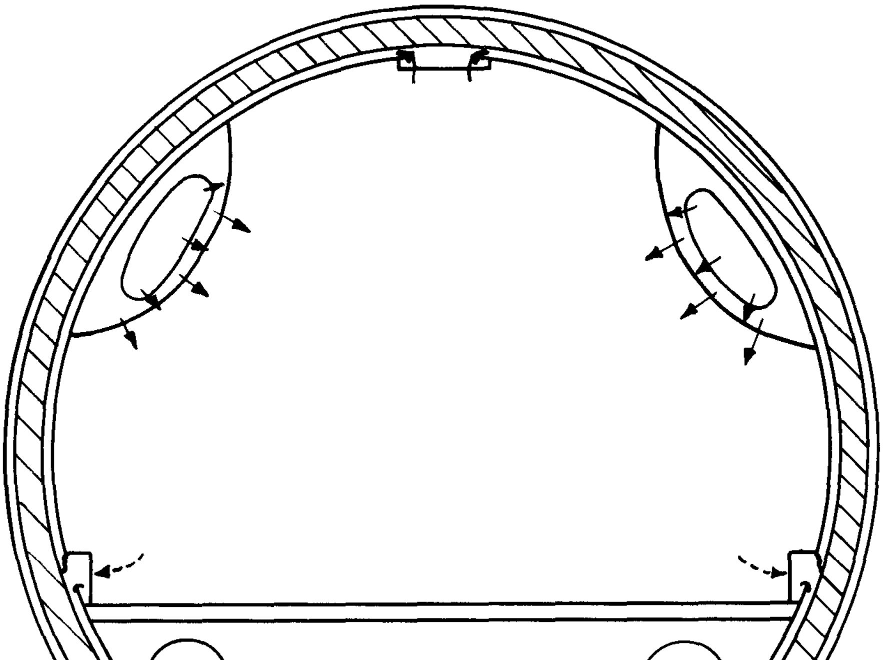


FIG. 5 (b) VENTILATION SCHEME D

FIG. 5. CABIN AIR DISTRIBUTION SCHEMES 'C & D'

Fig.6. Cabin interior, air distribution scheme D

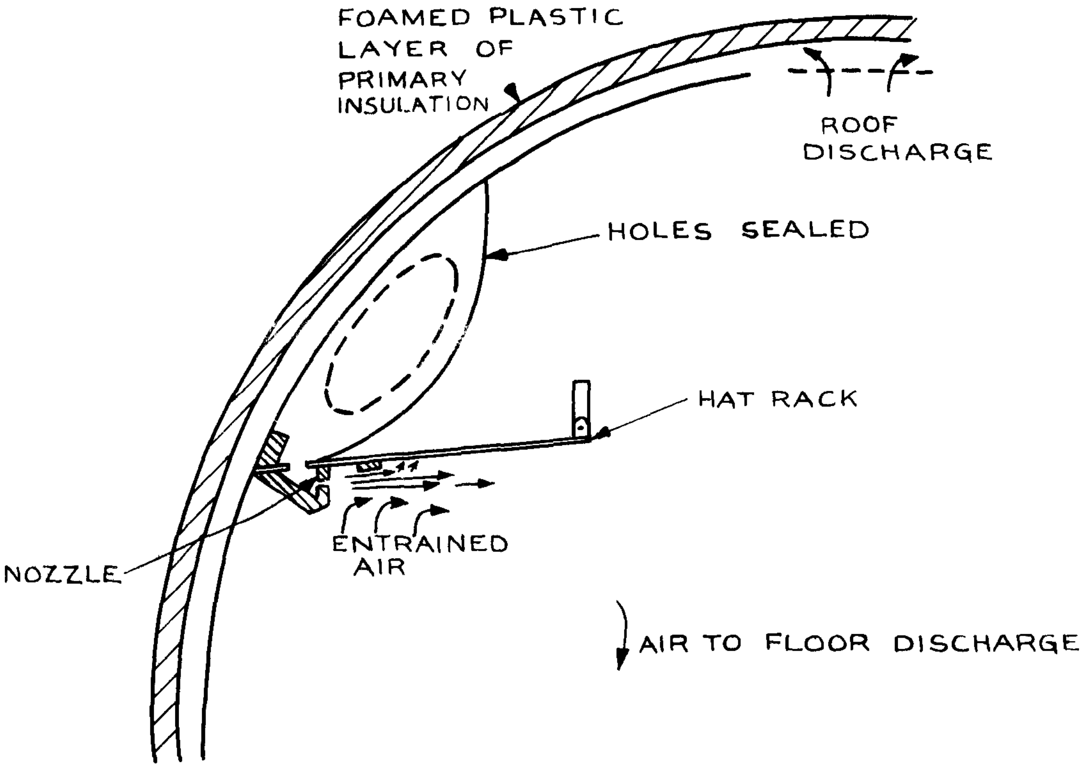


FIG. 7 (a) SCHEME 'E'

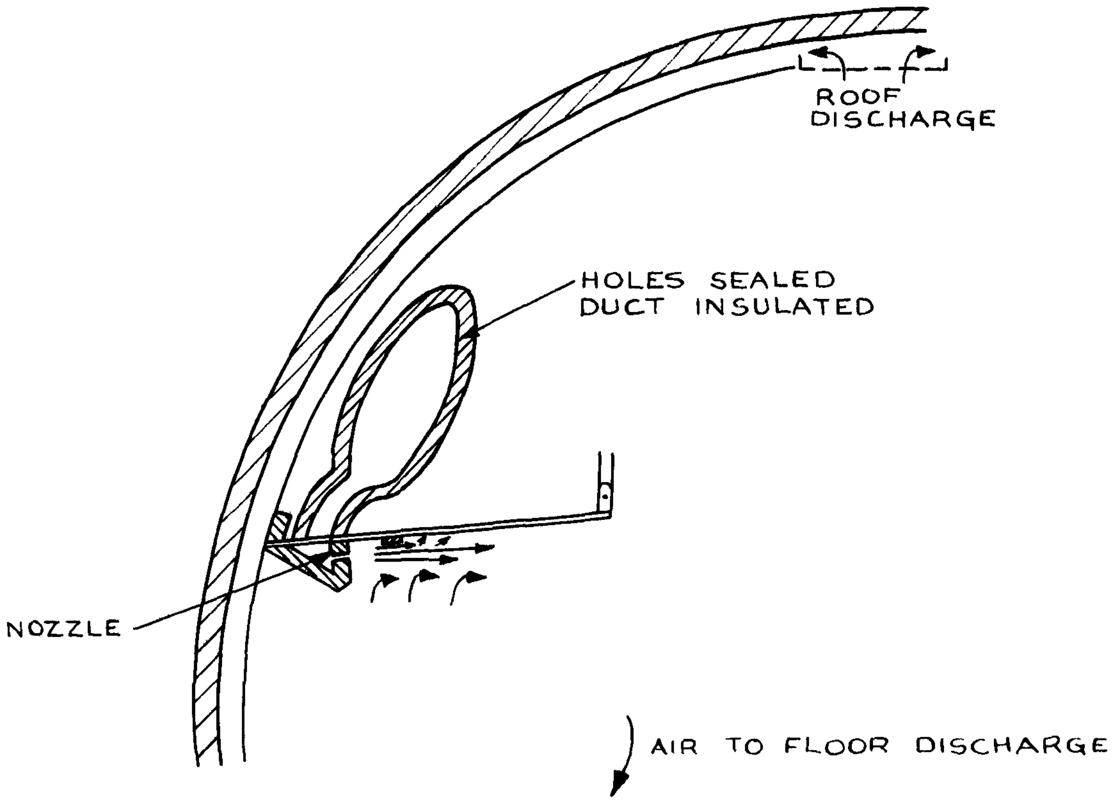
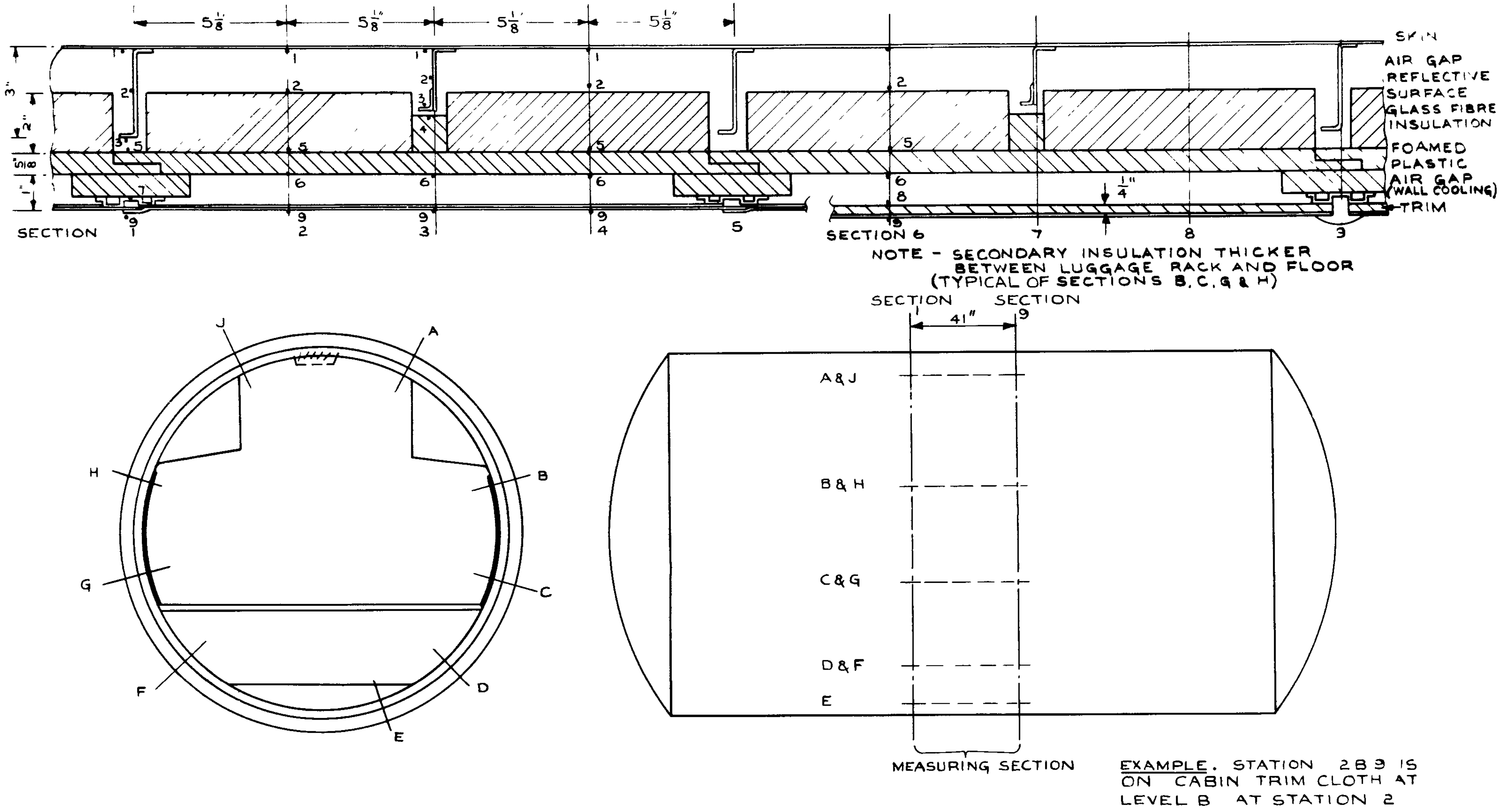


FIG. 7 (b) SCHEME 'F'

FIG. 7. CABIN AIR DISTRIBUTION SCHEMES 'E & F'



NOTE - SECONDARY INSULATION THICKER BETWEEN LUGGAGE RACK AND FLOOR (TYPICAL OF SECTIONS B, C, G & H)

<u>EXAMPLE</u>. STATION 2B9 IS ON CABIN TRIM CLOTH AT LEVEL B AT STATION 2

FIG. 8. INSULATION INSTRUMENTATION

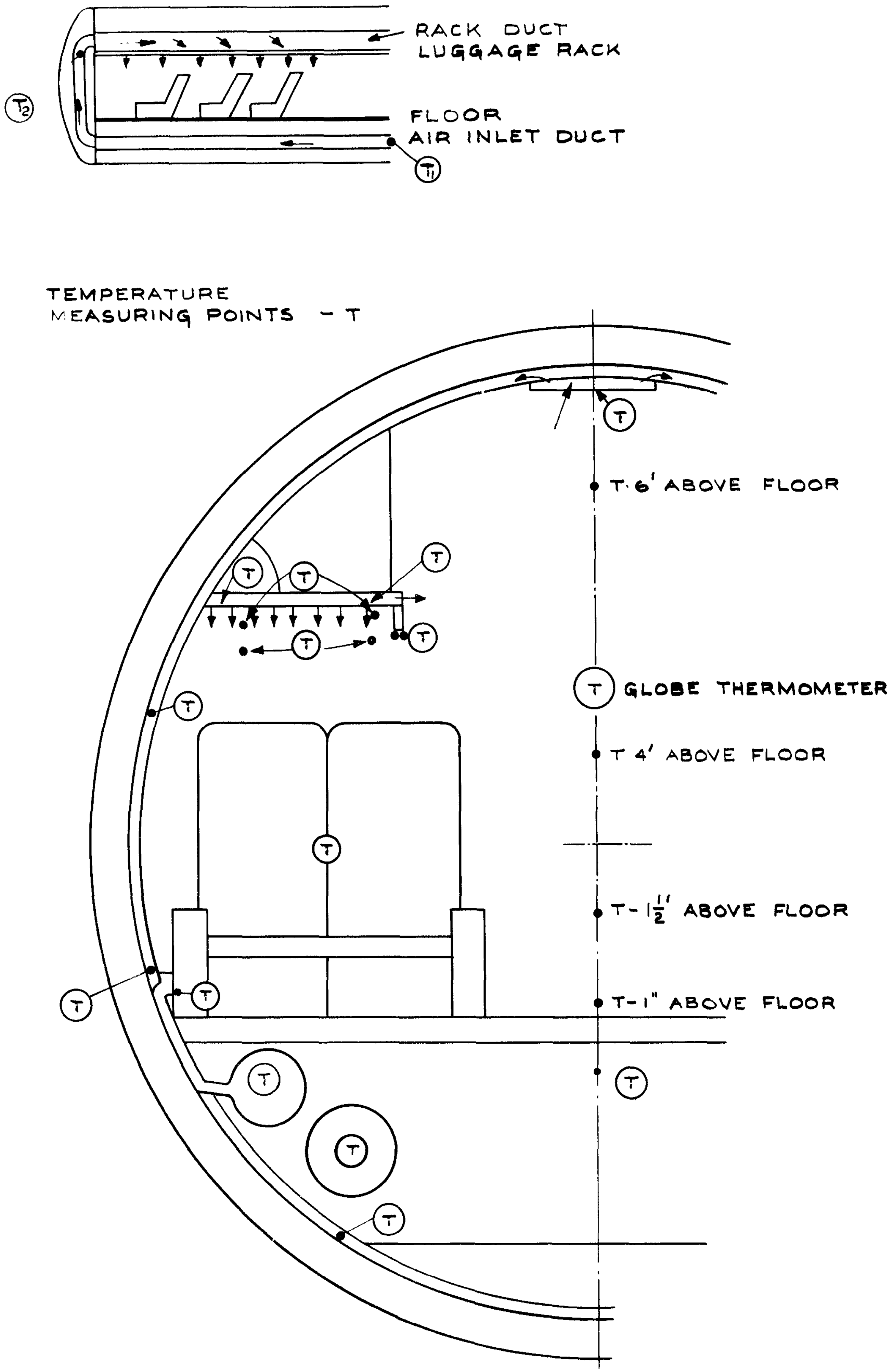


FIG 9 TEMPERATURE-RECORDING POINTS WITHIN SPECIMEN SCHEME C

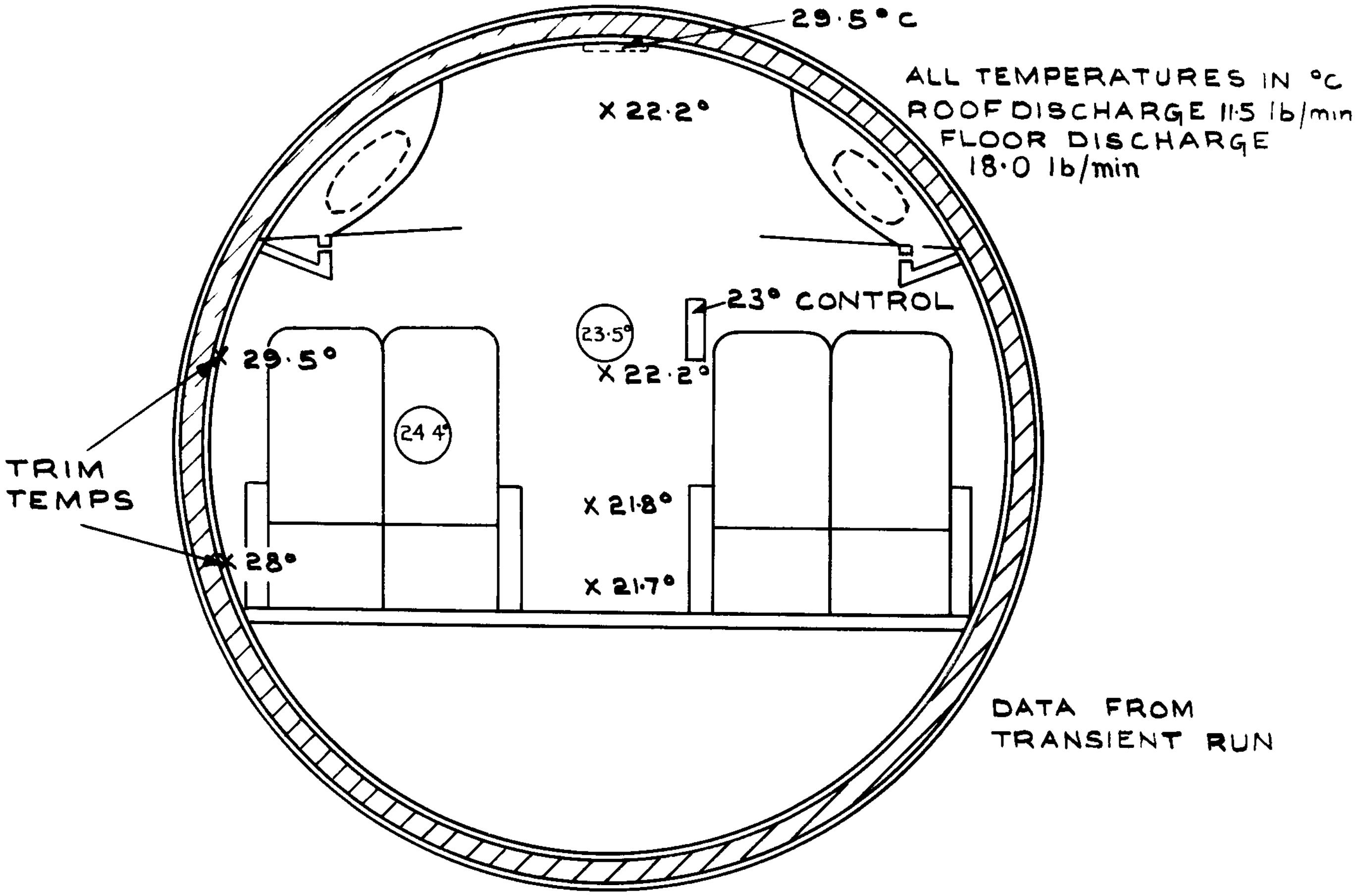


FIG 10 (a.) SCHEME E-29·5 lb/min AIR FLOW

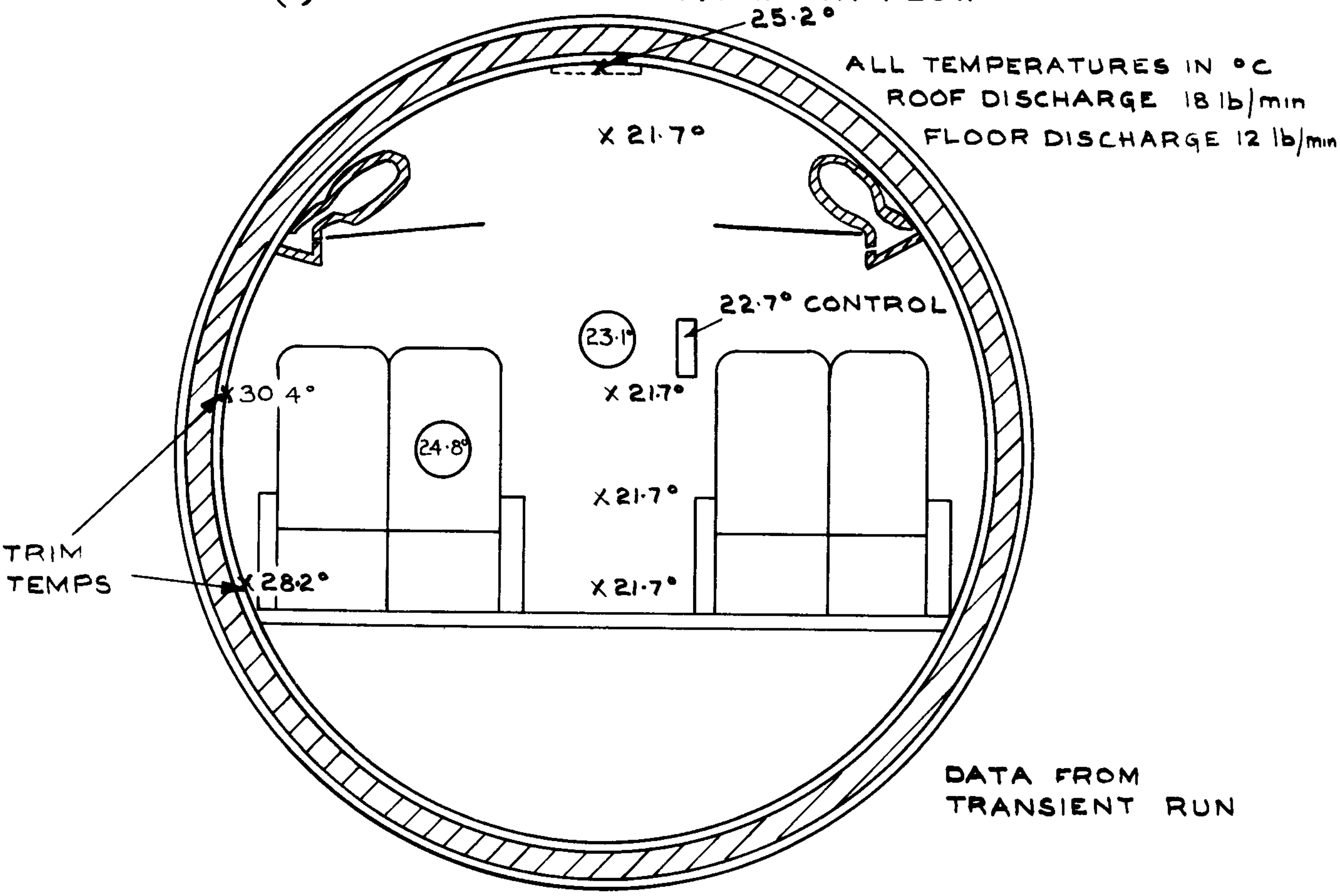


FIG. 10 (b.) SCHEME F 30 lb/min AIR FLOW

FIG. 10. CABIN CONDITIONS COMPATIBLE WITH PASSENGER COMFORT

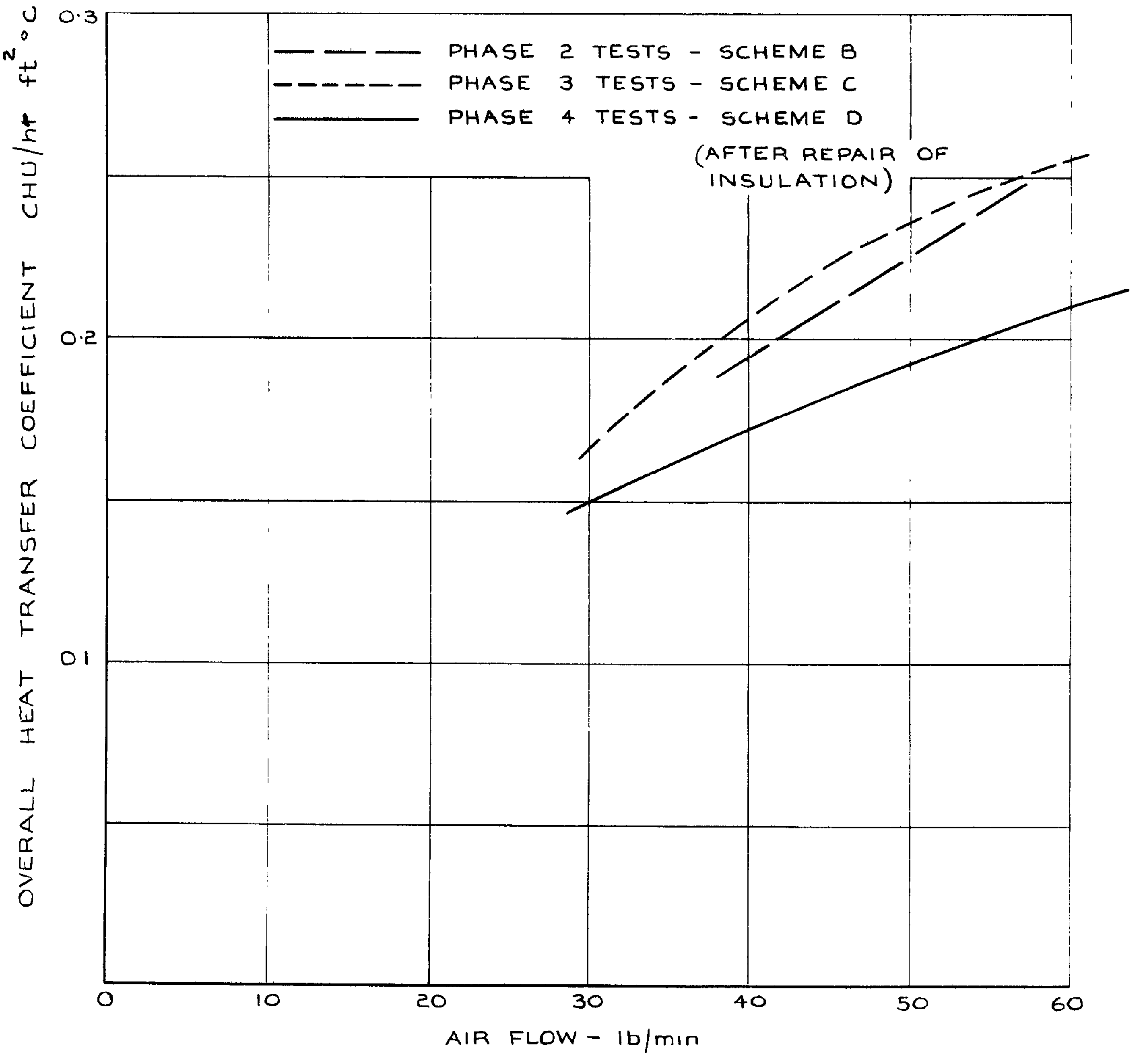


FIG. 11. EFFECT OF INSULATION REPAIR ON SPECIMEN OVERALL HEAT TRANSFER COEFFICIENT

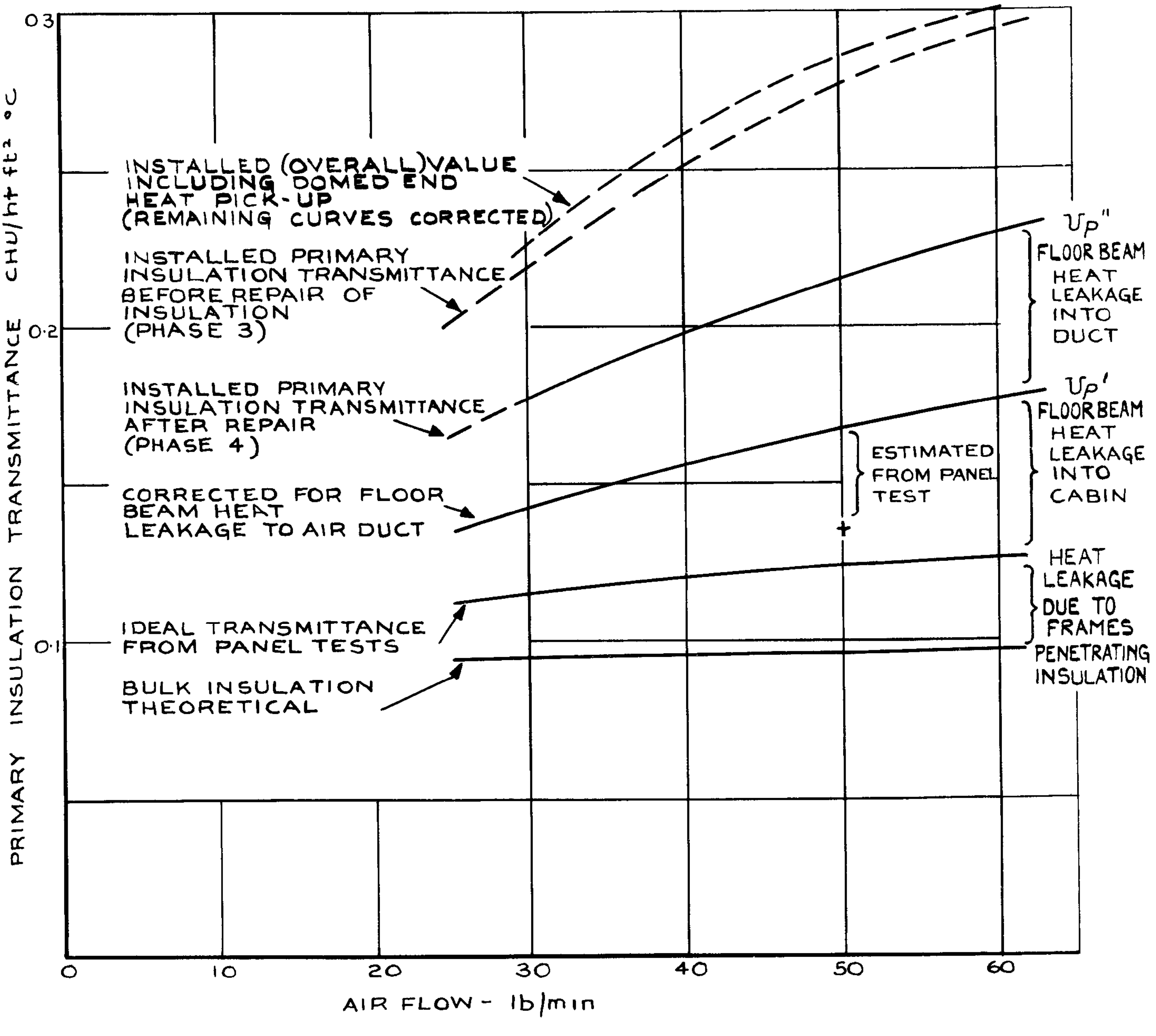


FIG.12 PRIMARY INSULATION TRANSMITTANCE V AIRFLOW

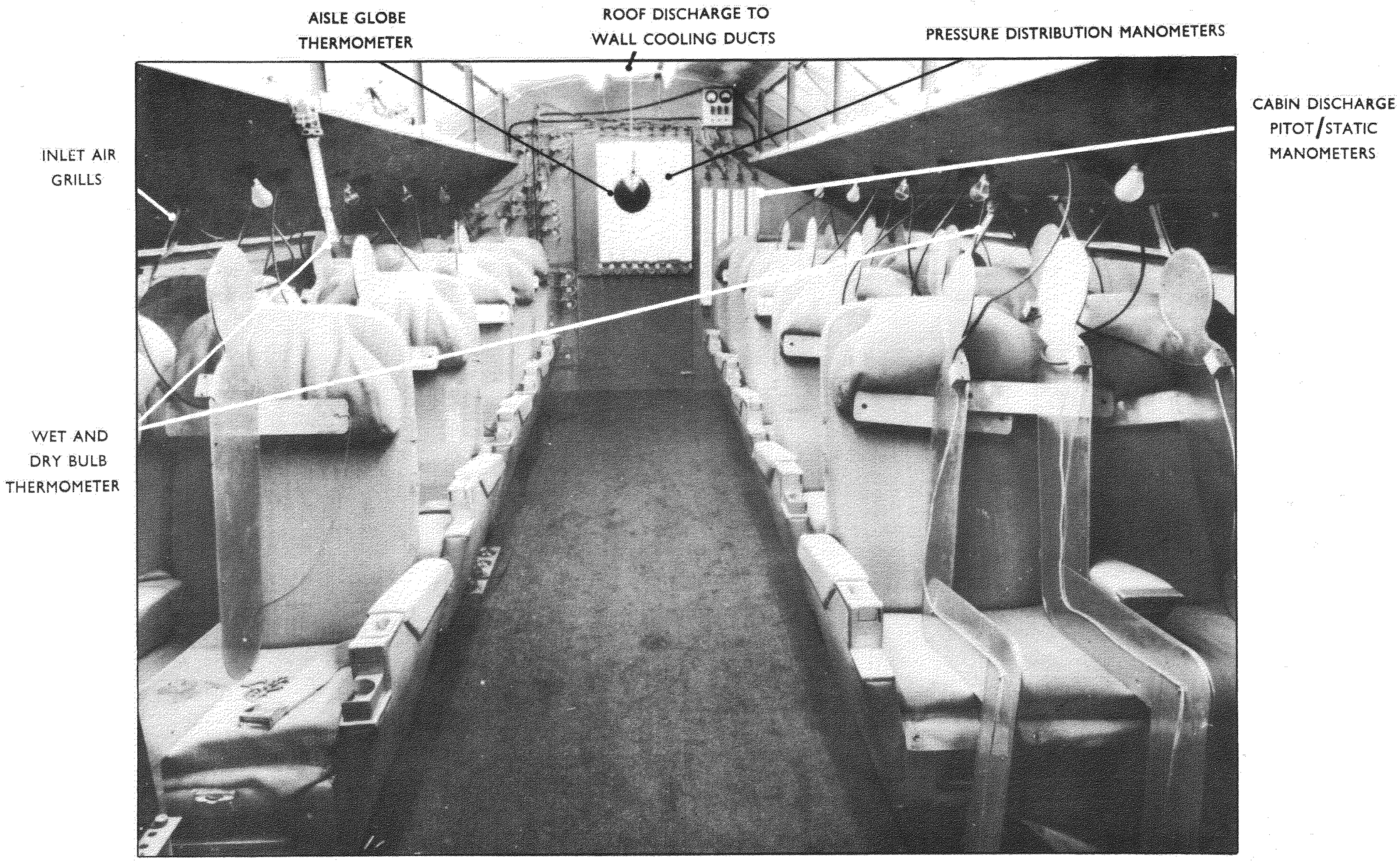
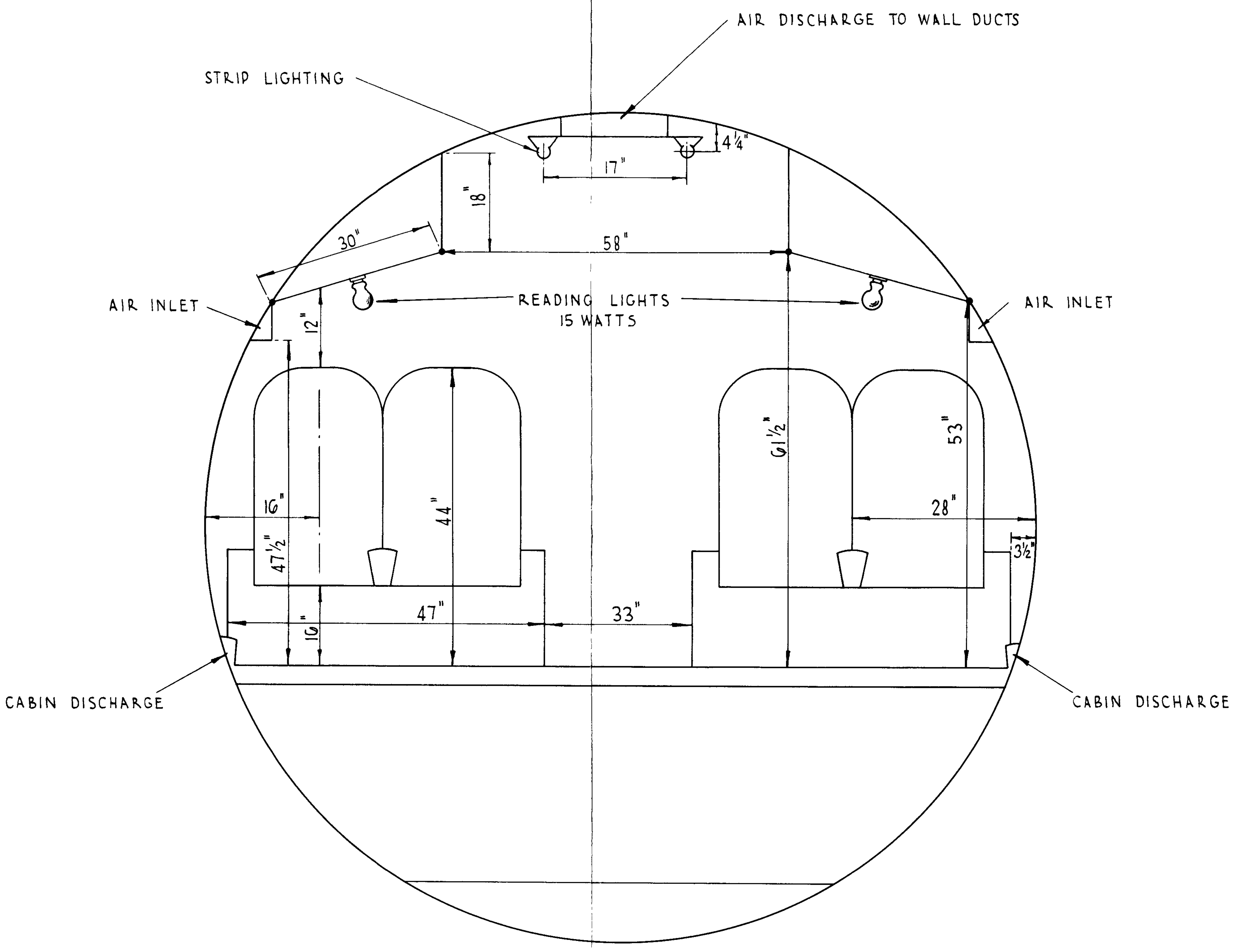


Fig.1. A. Specimen cabin looking aft (scheme A)



5 ROWS OF SEATS PER SIDE, PITCH 34"

FIG. A2 ARRANGEMENT OF CABIN (SCHEME 'A' SHOWN)

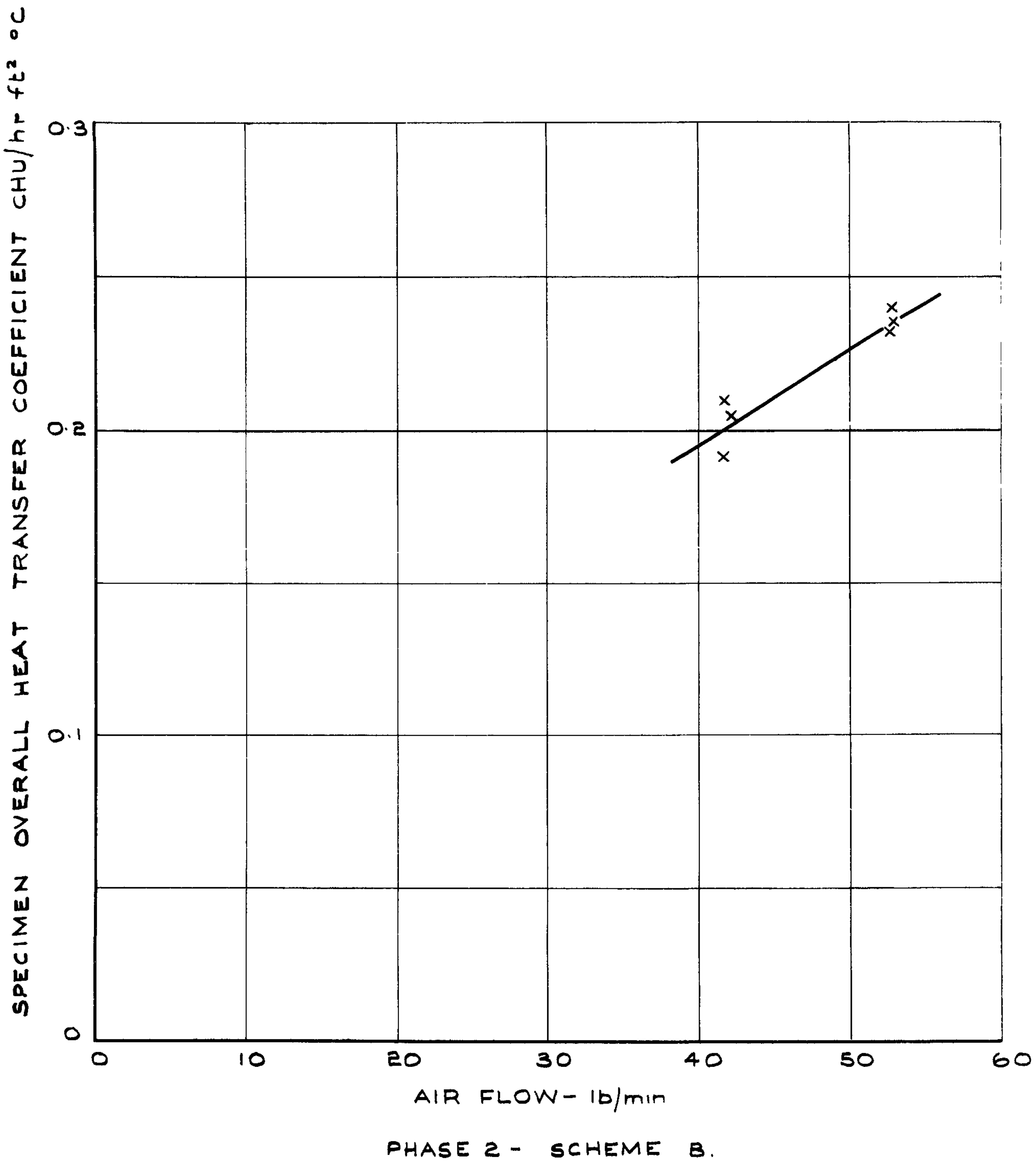
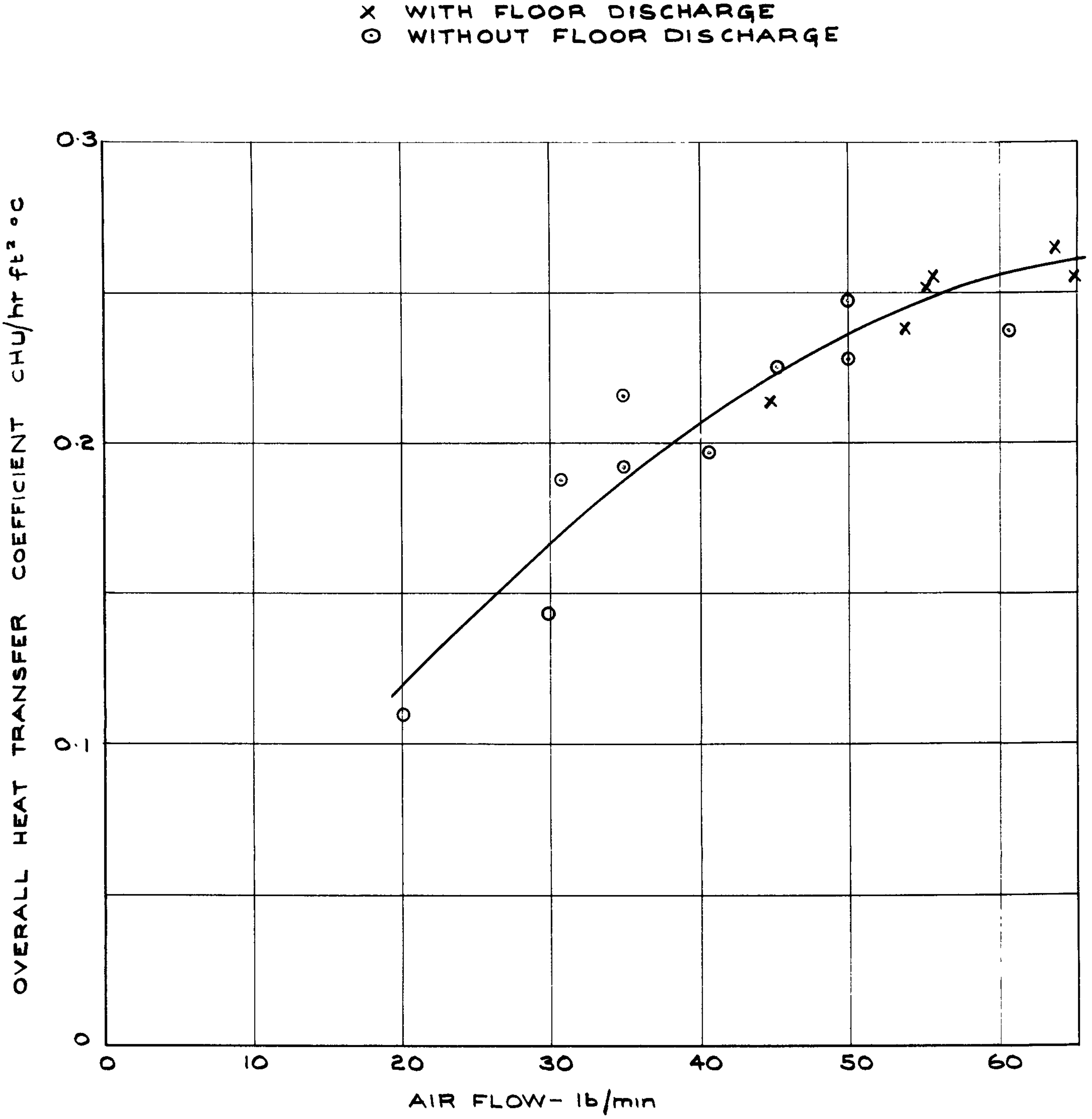


FIG.B.1 SPECIMEN OVERALL HEAT TRANSFER COEFFICIENT v AIRFLOW



BASED ON OVERALL MEAN SKIN TEMPERATURE

PHASE 3 – SCHEME C.

FIG. B.2. SPECIMEN OVERALL HEAT TRANSFER COEFFICIENT v AIRFLOW

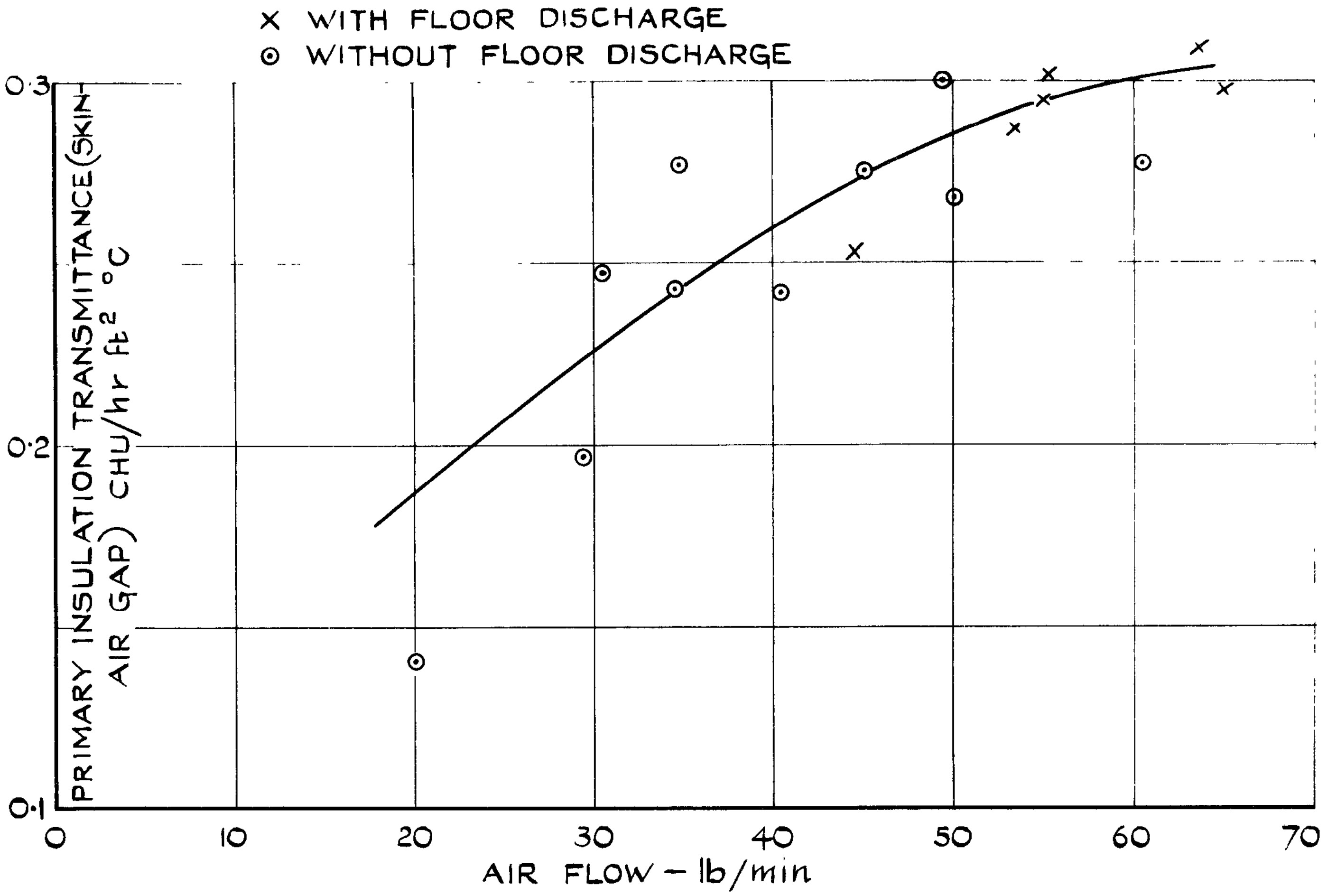


FIG B3(a) BASED ON OVERALL MEAN SKIN TEMPERATURE

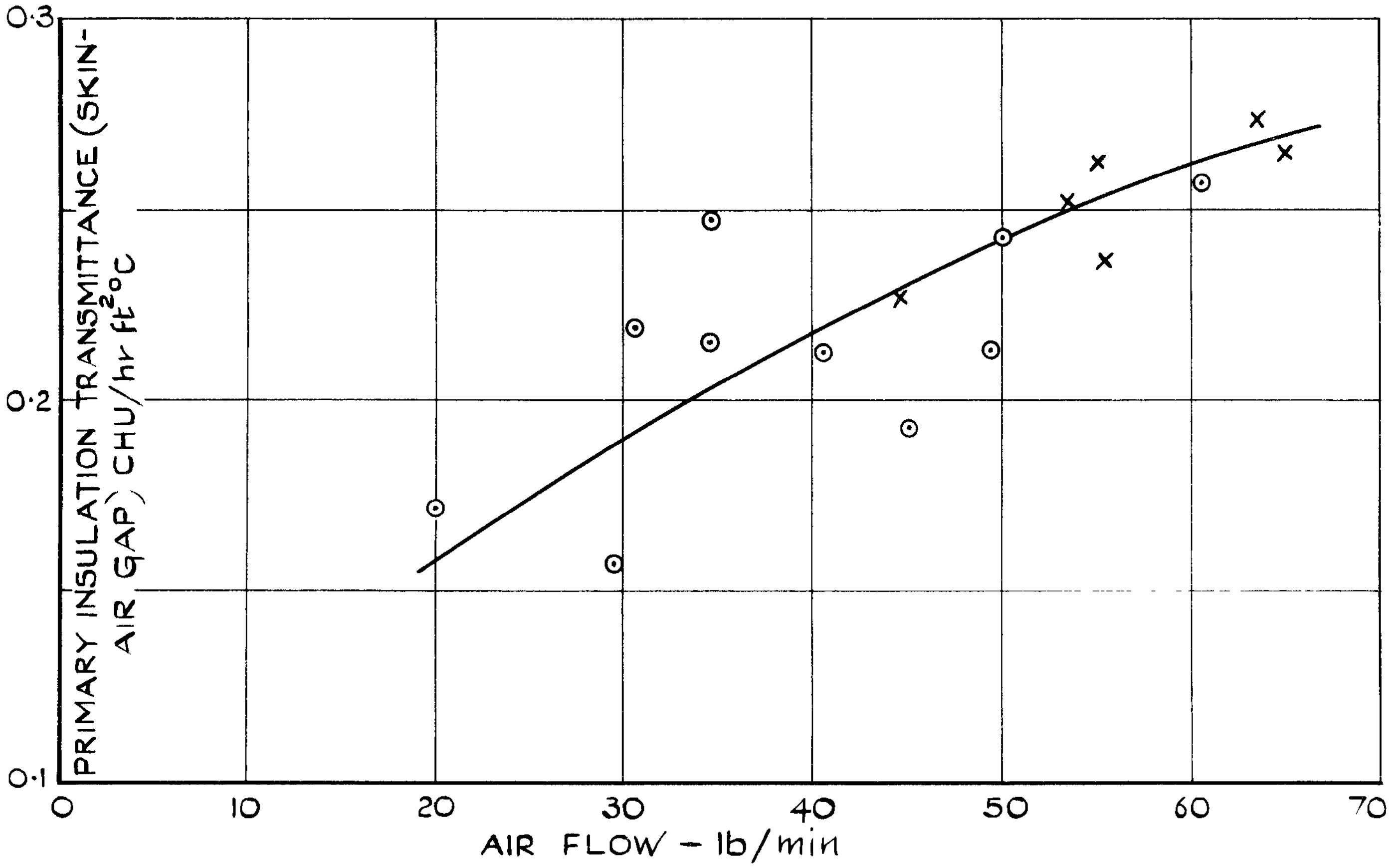


FIG B3(b) BASED ON LOCAL MEAN TEMPERATURE

FIG. B 3 PHASE 3 SCHEME C PRIMARY INSULATION TRANSMITTANCE v AIR FLOW

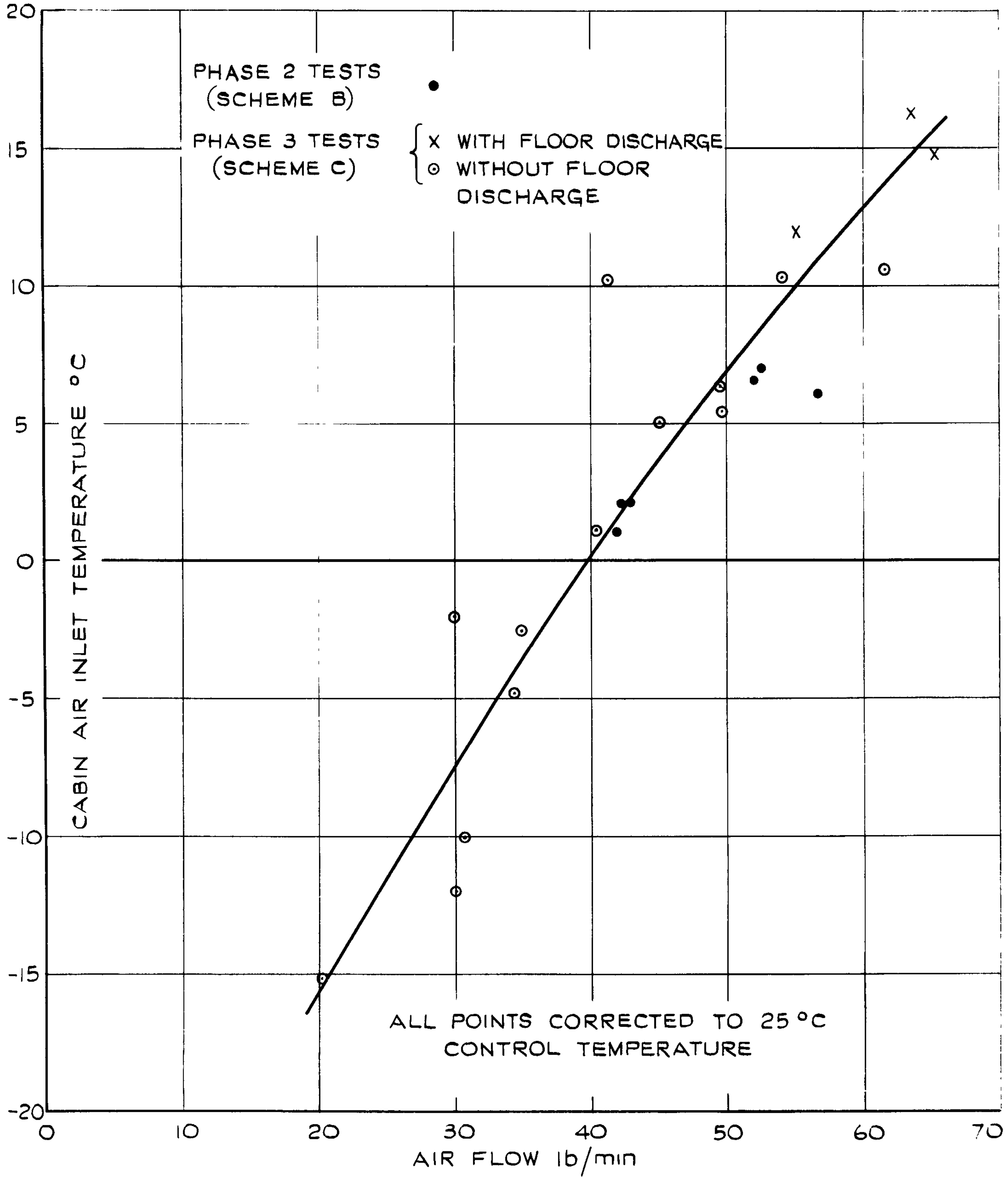


FIG.B.4 SCHEMES B AND C CABIN AIR INLET TEMPERATURE v. AIR FLOW

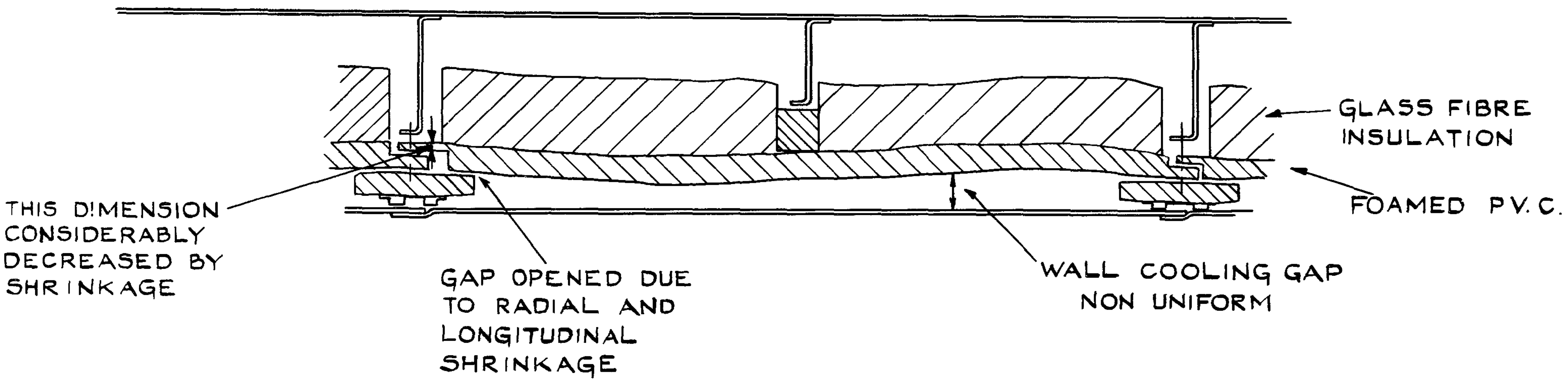
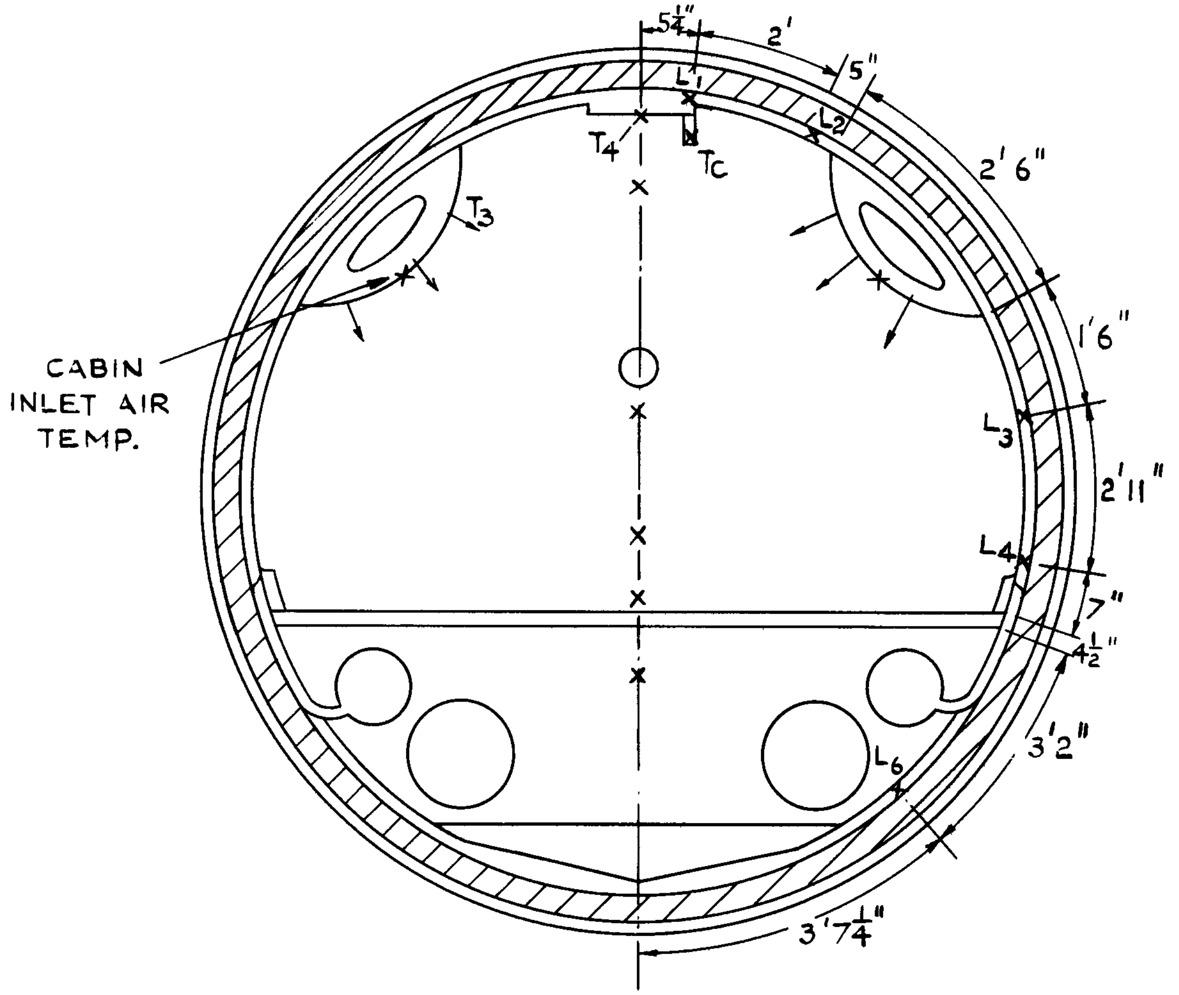


FIG. C 1 PRIMARY INSULATION DISTORTION (PRIOR TO REPAIR)



TEMPERATURE MEASUREMENTS AT LEVELS L1 TO L6
EACH A MEAN OF 9 THERMOCOUPLES

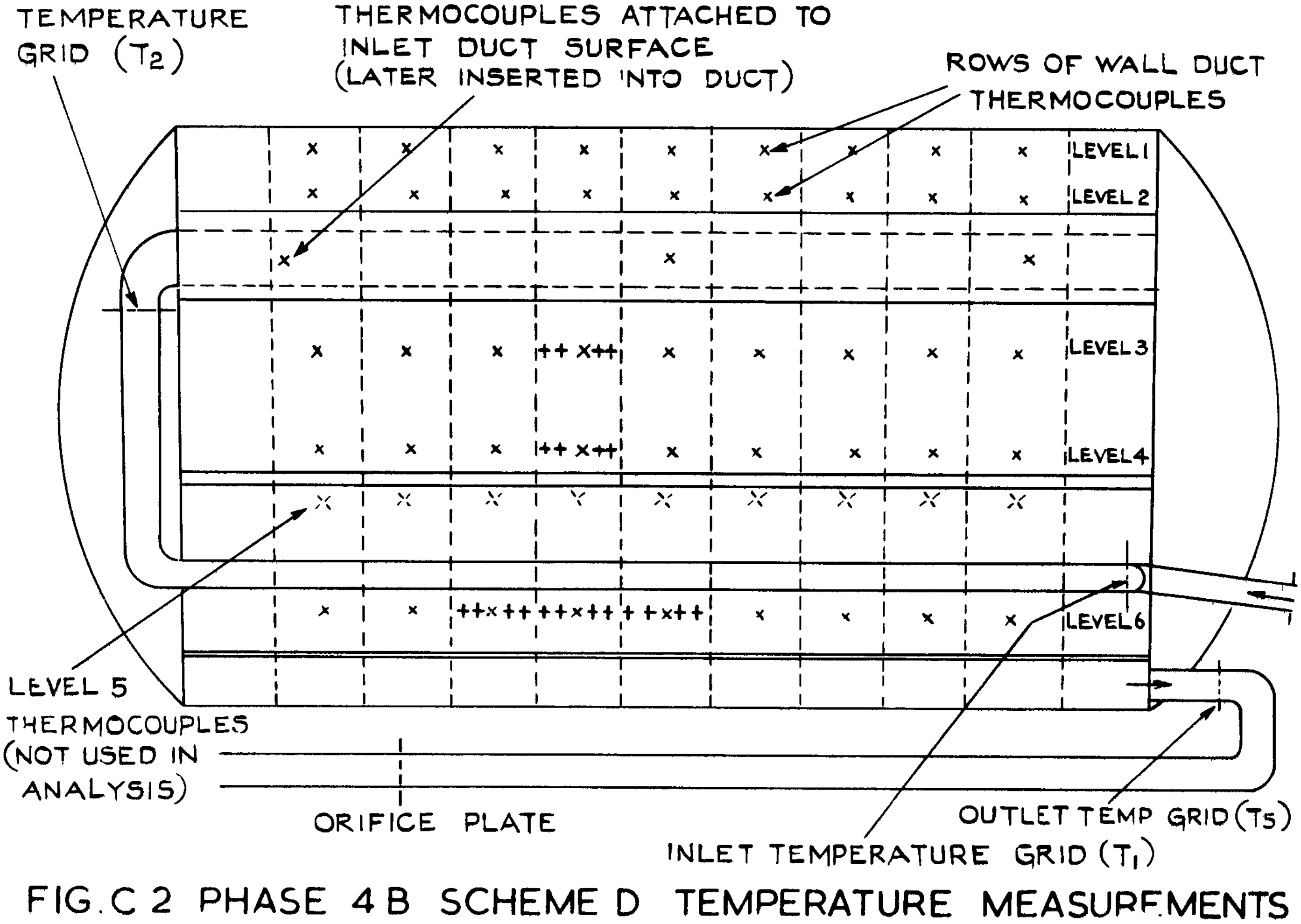
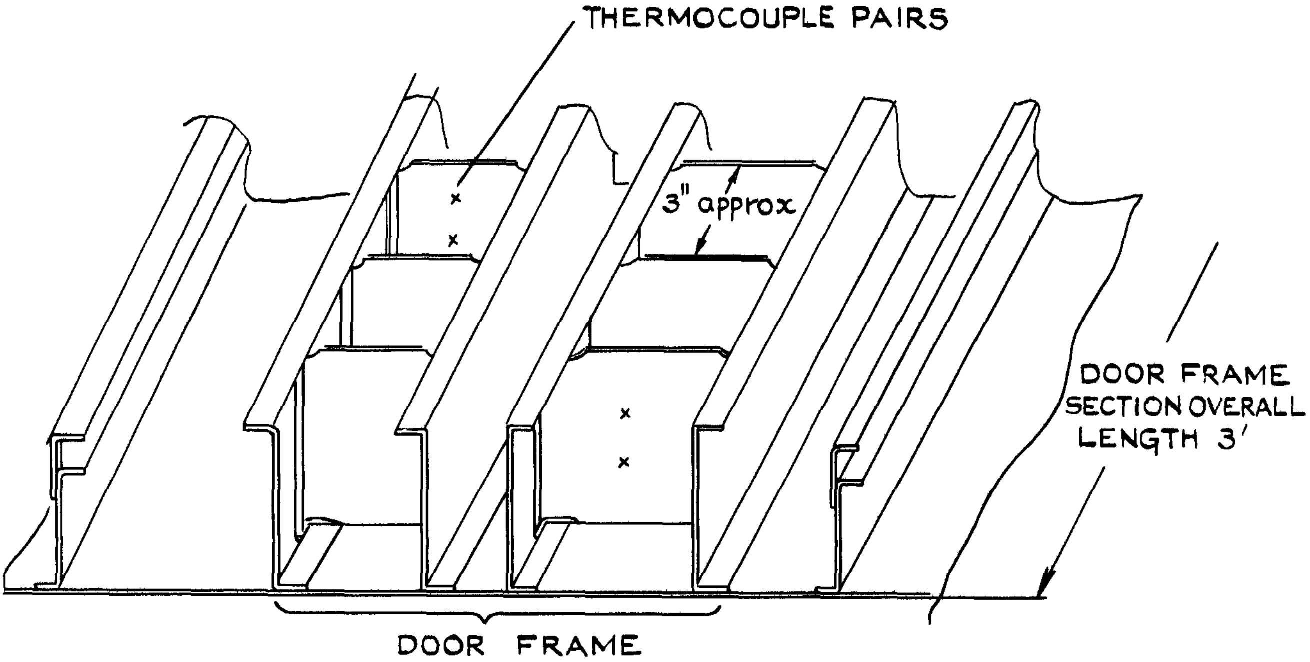


FIG. C 2 PHASE 4 B SCHEME D TEMPERATURE MEASUREMENTS



VIEW SHOWING STRUCTURE – INSULATION REMOVED

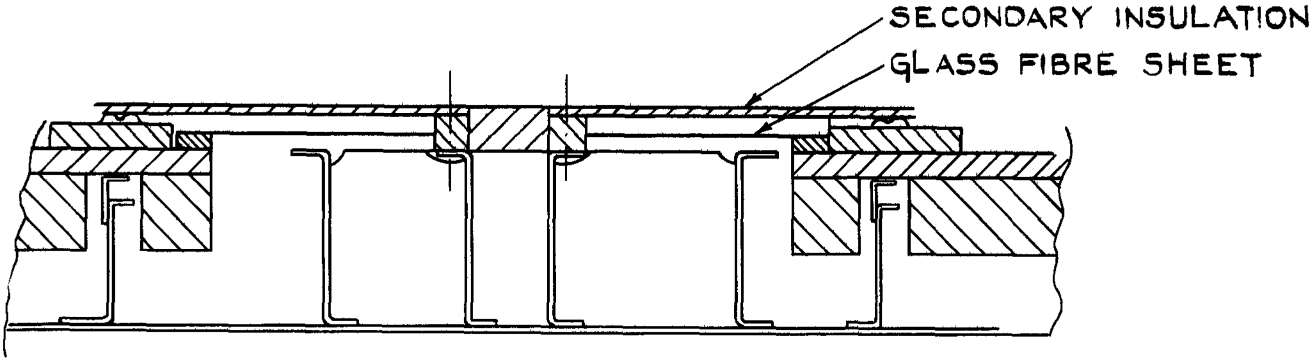
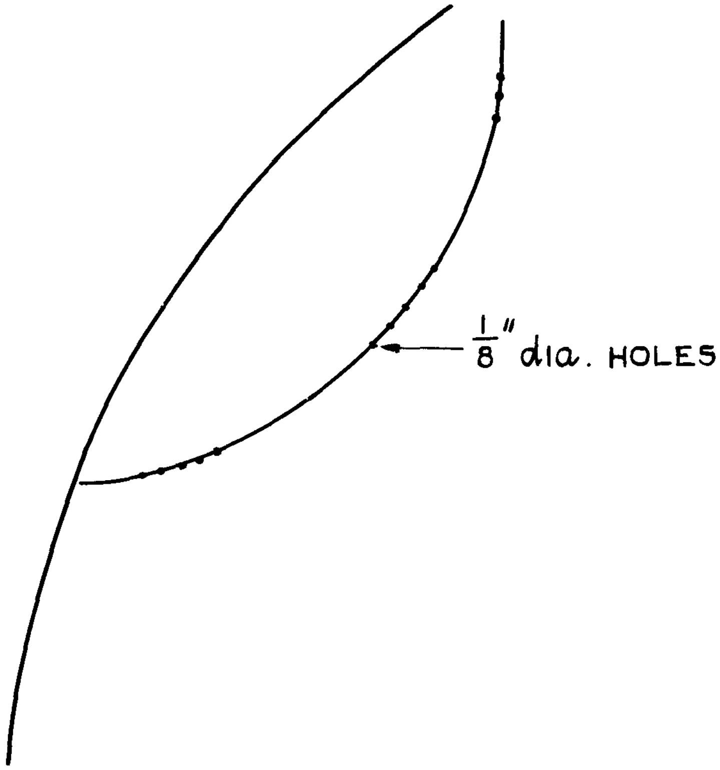
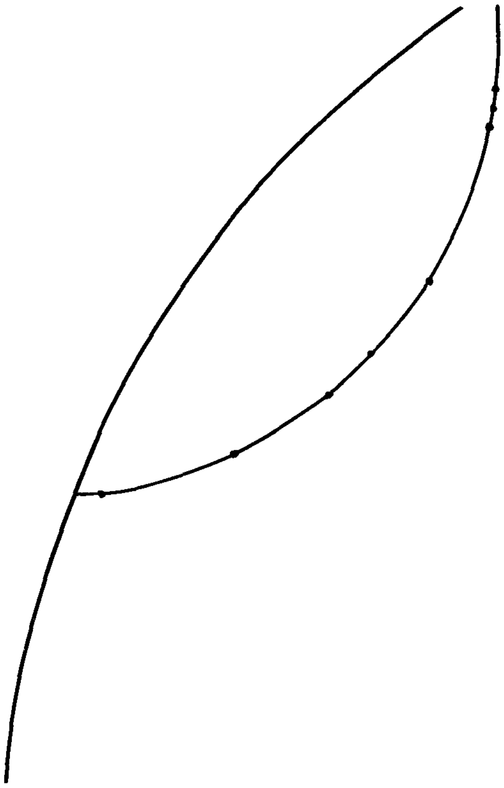


FIG. C 3 "DOOR FRAME" SECTION



ORIGINAL ARRANGEMENT OF VENTILATION HOLES



MODIFIED ARRANGEMENT OF VENTILATION HOLES

FIG. C 4 MODIFICATION TO VENTILATION DURING RUN 6

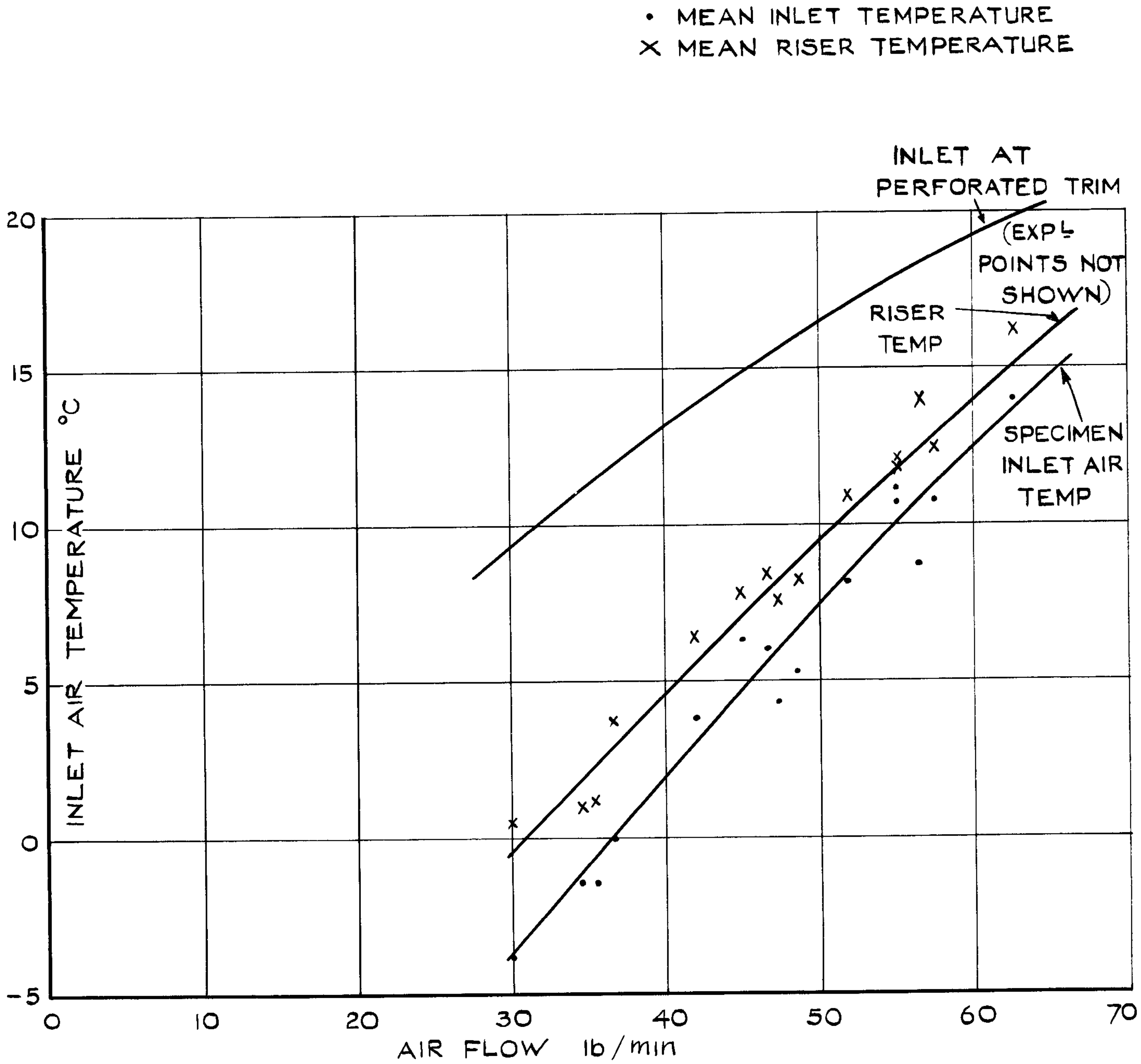
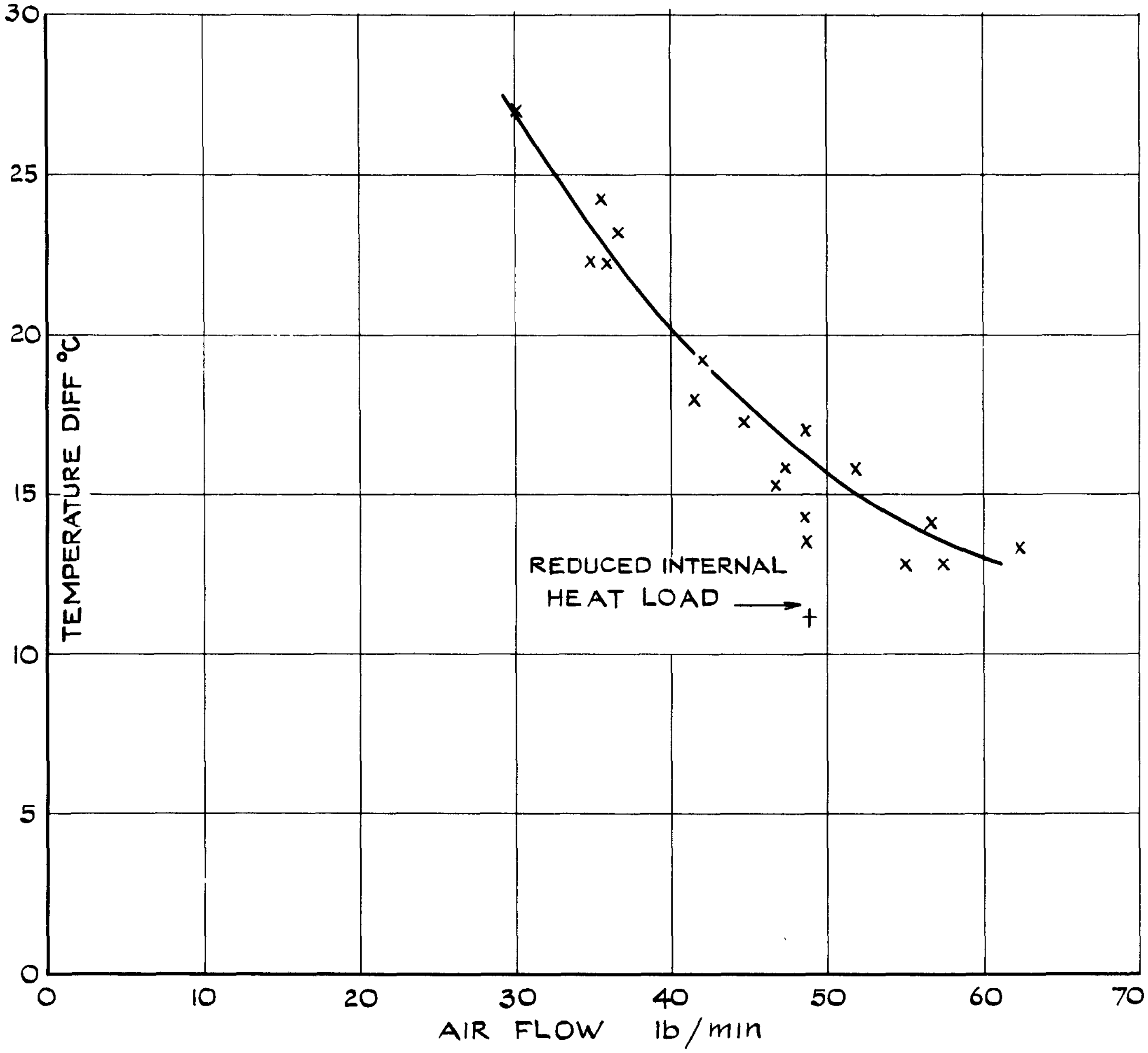


FIG. C 5 PHASE 4 SCHEME D INLET AIR TEMPERATURE VARIATION WITH MASS FLOW



RISER TO CABIN OUTLET TEMPERATURE RISE
PHASE 4 – SCHEME D

FIG. C 6 CABIN AIR TEMPERATURE RISE AGAINST AIR FLOW

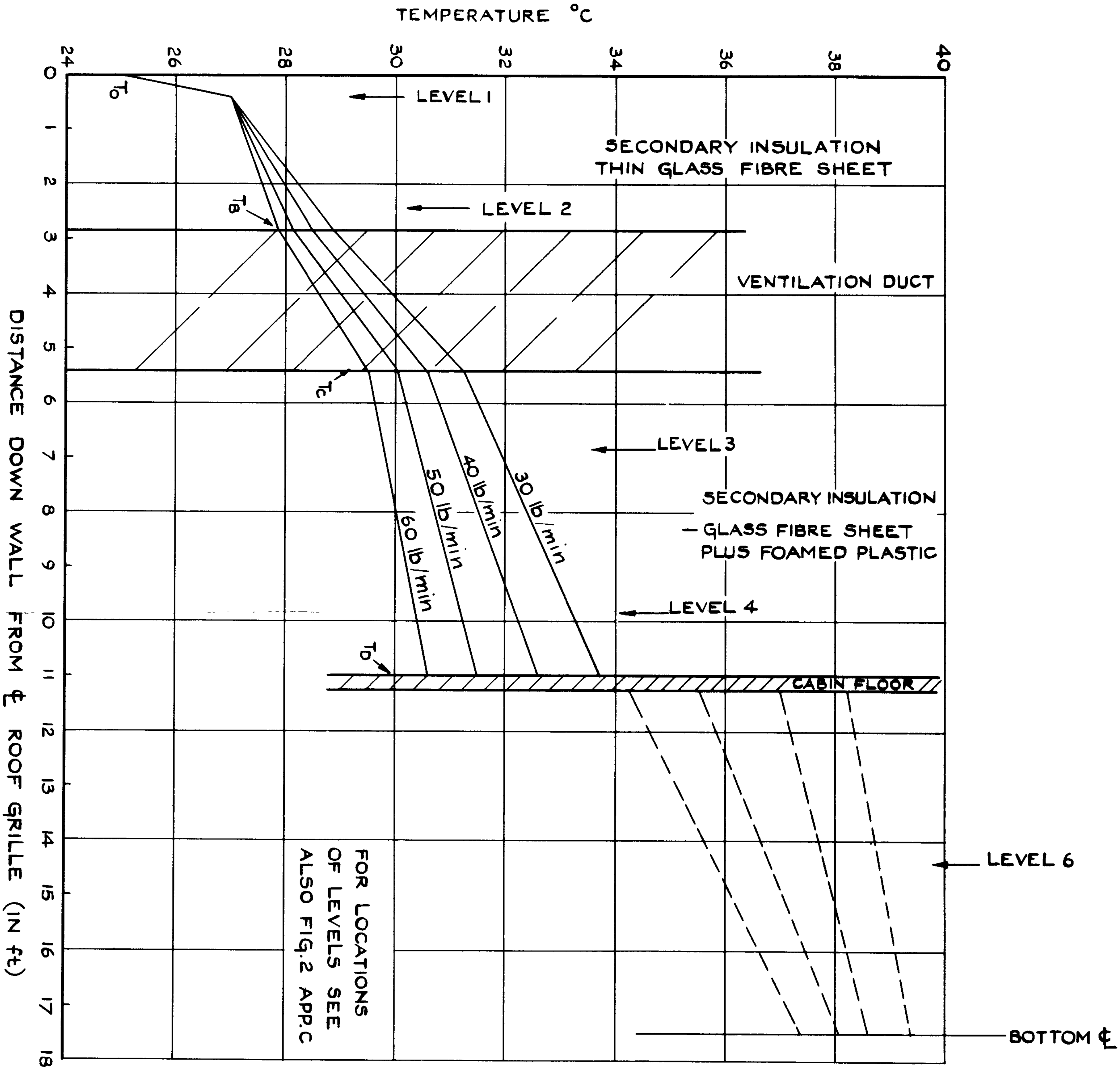
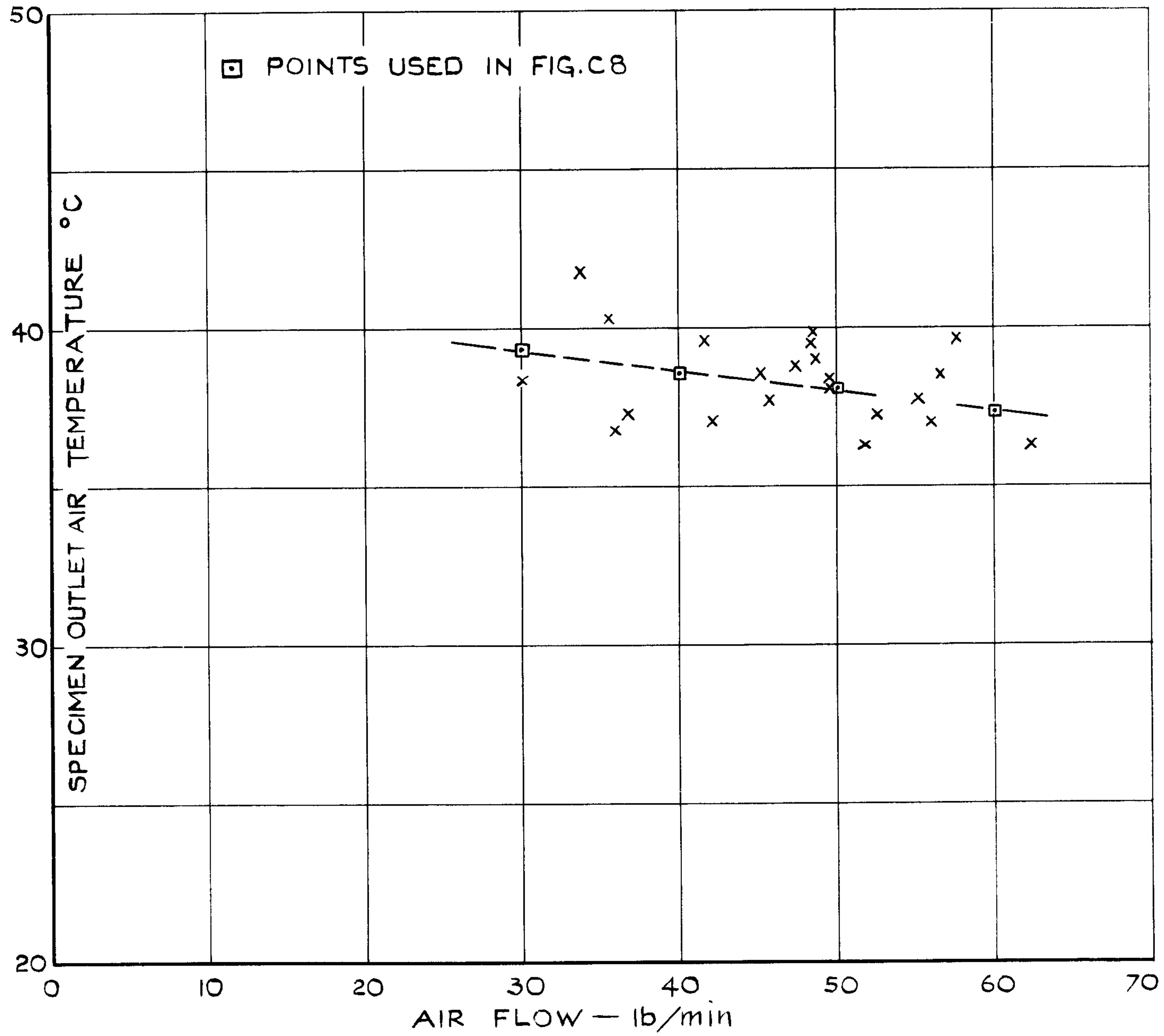


FIG. C 8 WALL DUCT AIR TEMPERATURES



TEMPERATURES RELATIVE TO 25·5°C CABIN OUTLET

FIG.C9 SPECIMEN OUTLET AIR TEMPERATURE v AIR FLOW

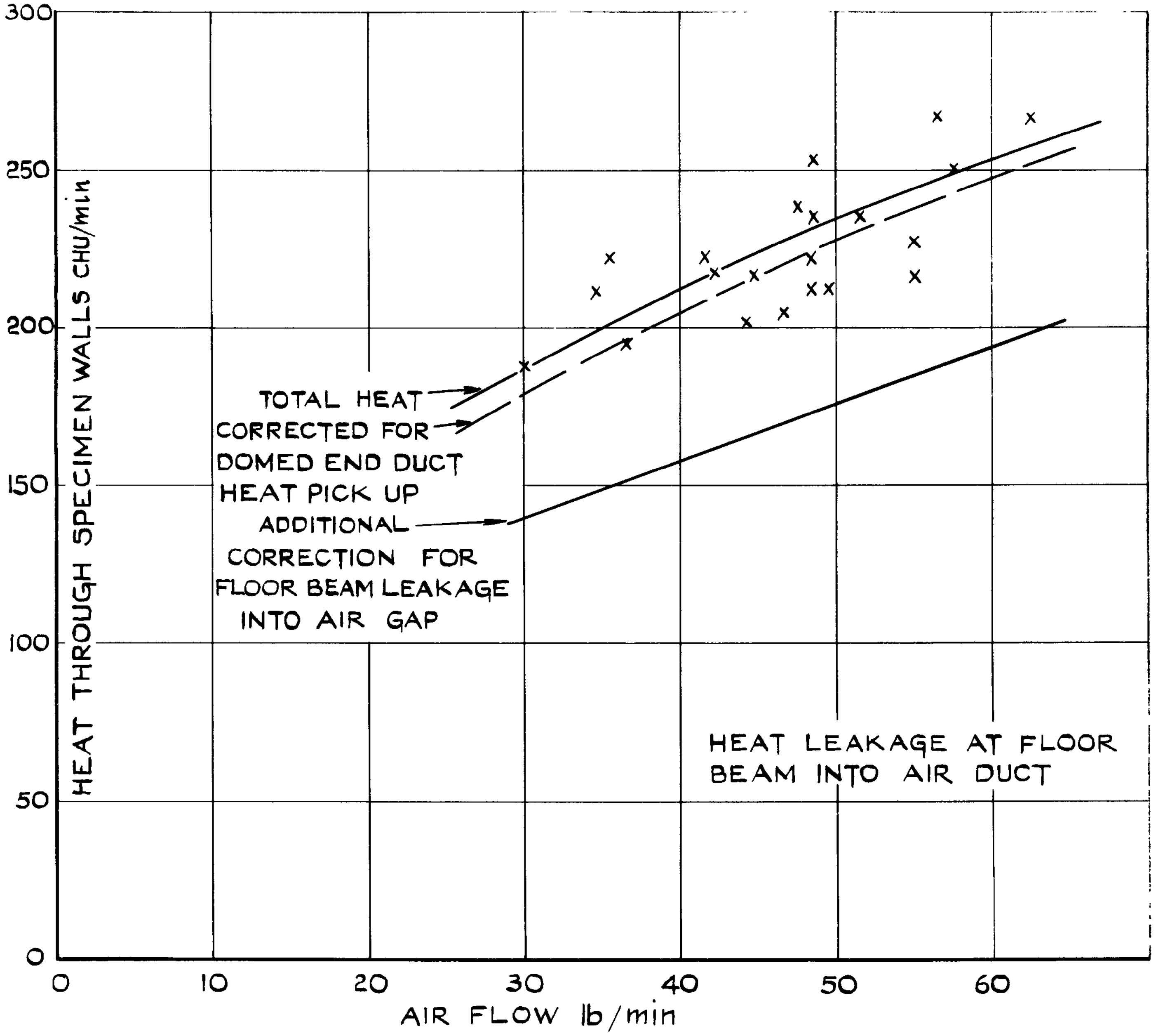


FIG. C 10 VARIATION OF "AERODYNAMIC" HEAT INTAKE WITH AIR FLOW

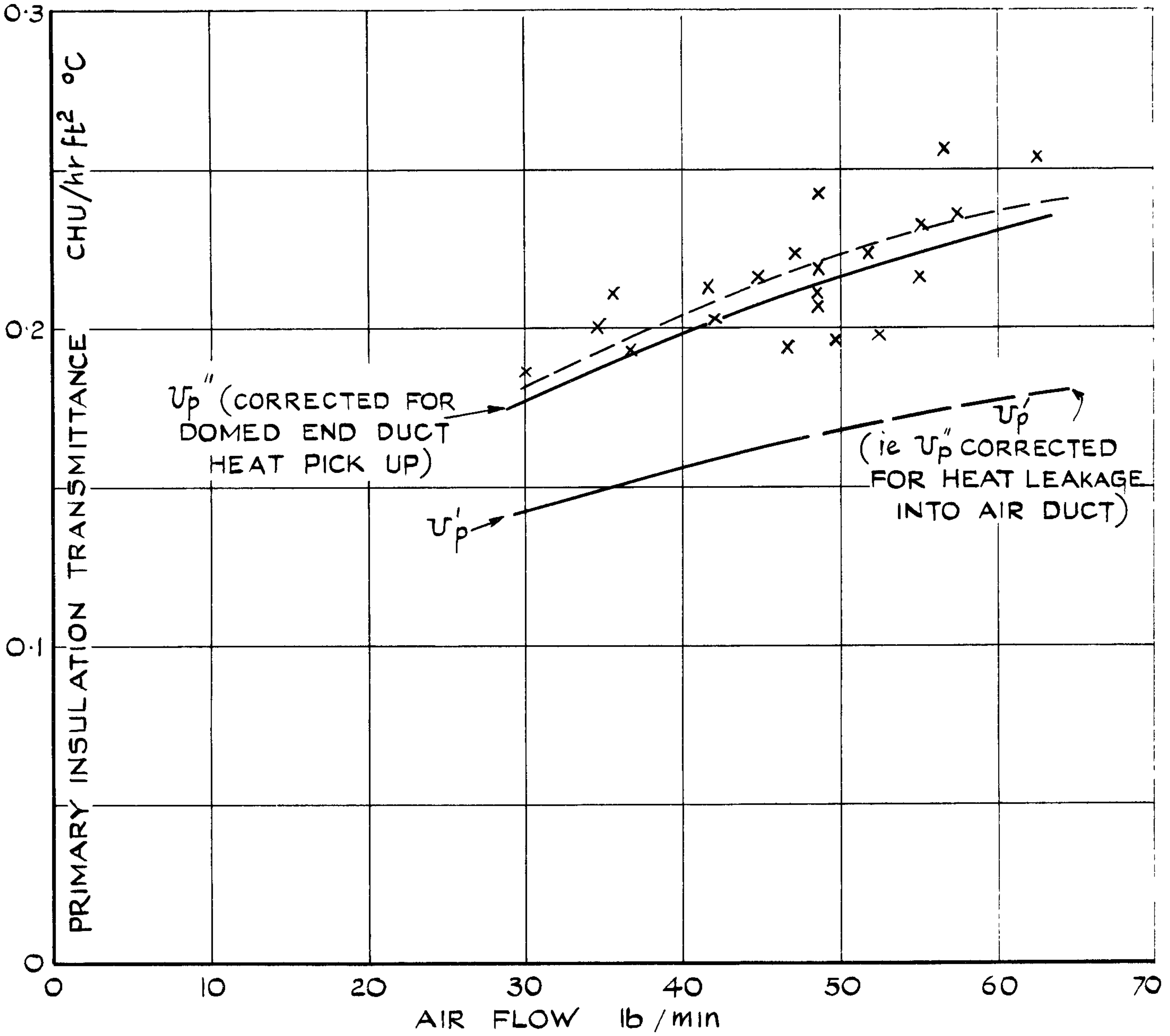


FIG. C II PRIMARY INSULATION TRANSMITTANCE VARIATION WITH WALL AIR FLOW

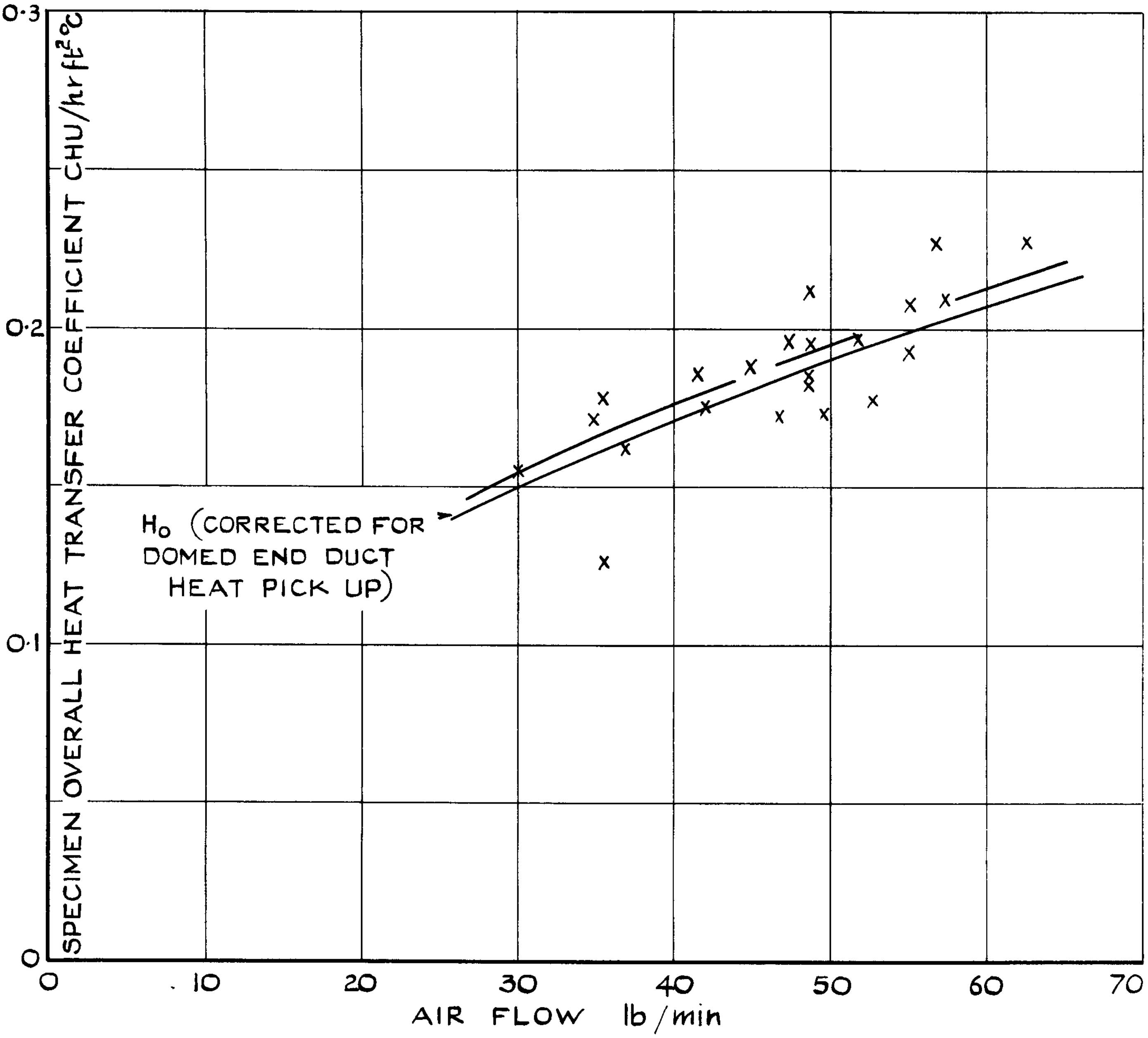


FIG.C 12 SPECIMEN OVERALL HEAT TRANSFER COEFFICIENT V AIR FLOW

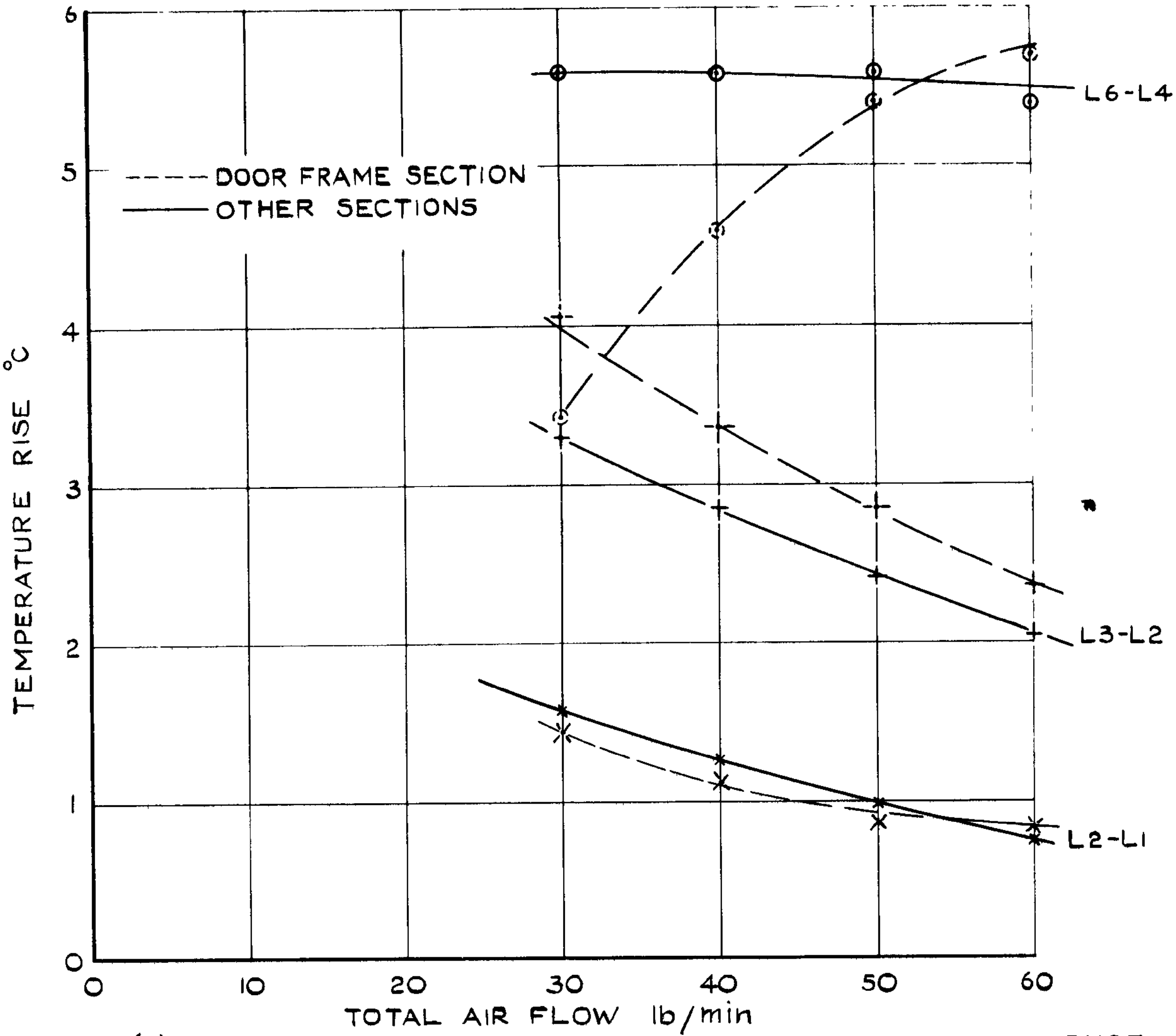


FIG.C13(a) TEMP RISE BETWEEN ADJACENT LEVELS IN WALL DUCT

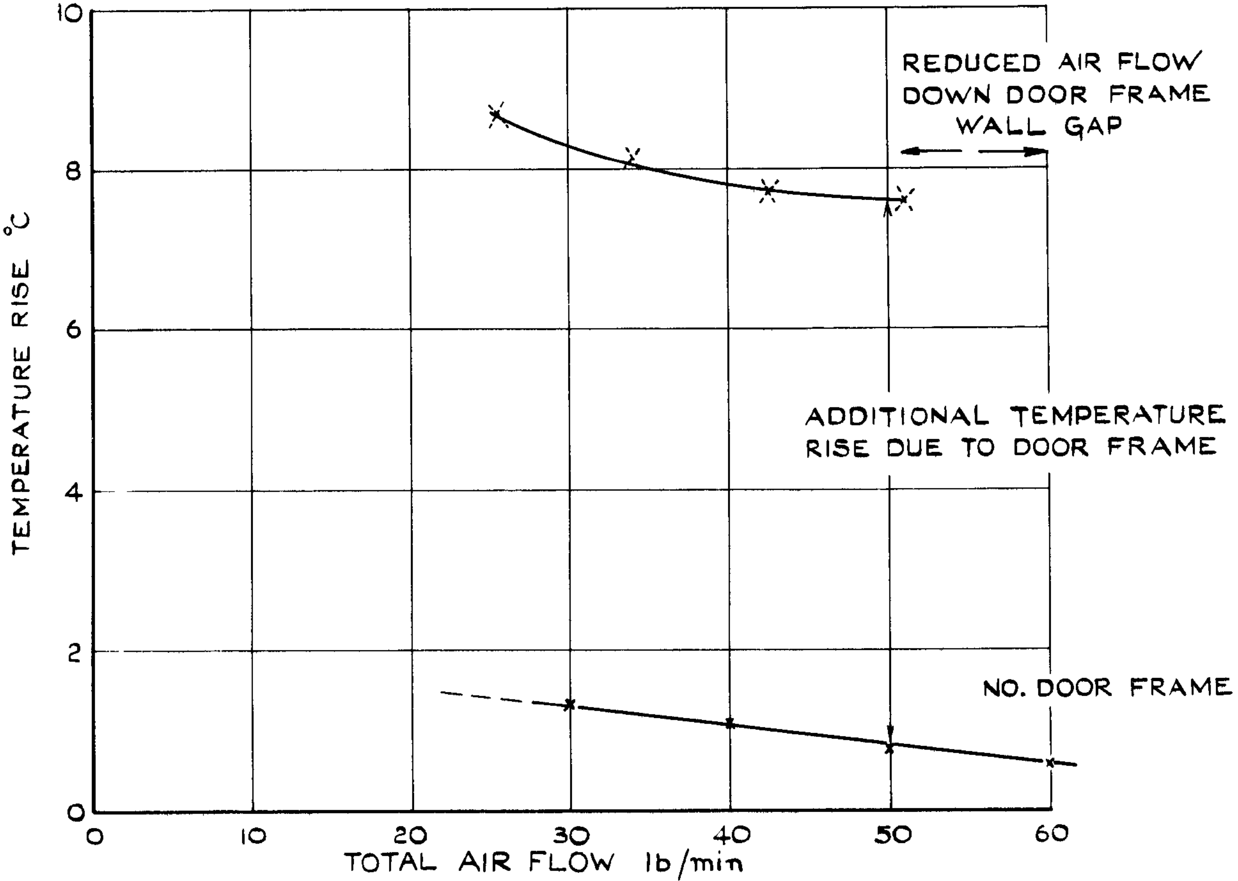


FIG. C13 (b) WALL DUCT TEMPERATURE RISE LEVEL 3-4

FIG.C13 TEMPERATURE RISE OVER DOOR FRAME

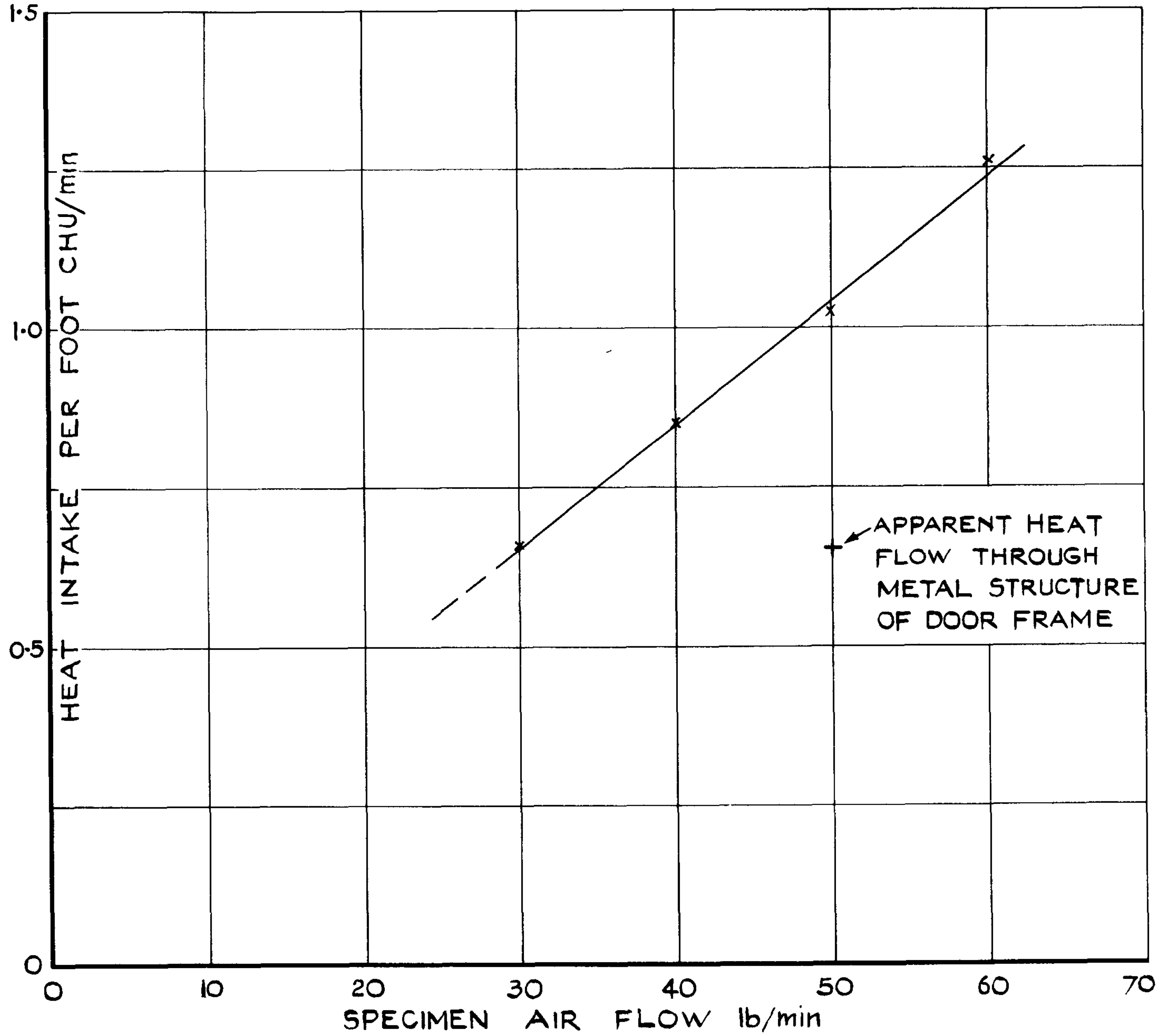
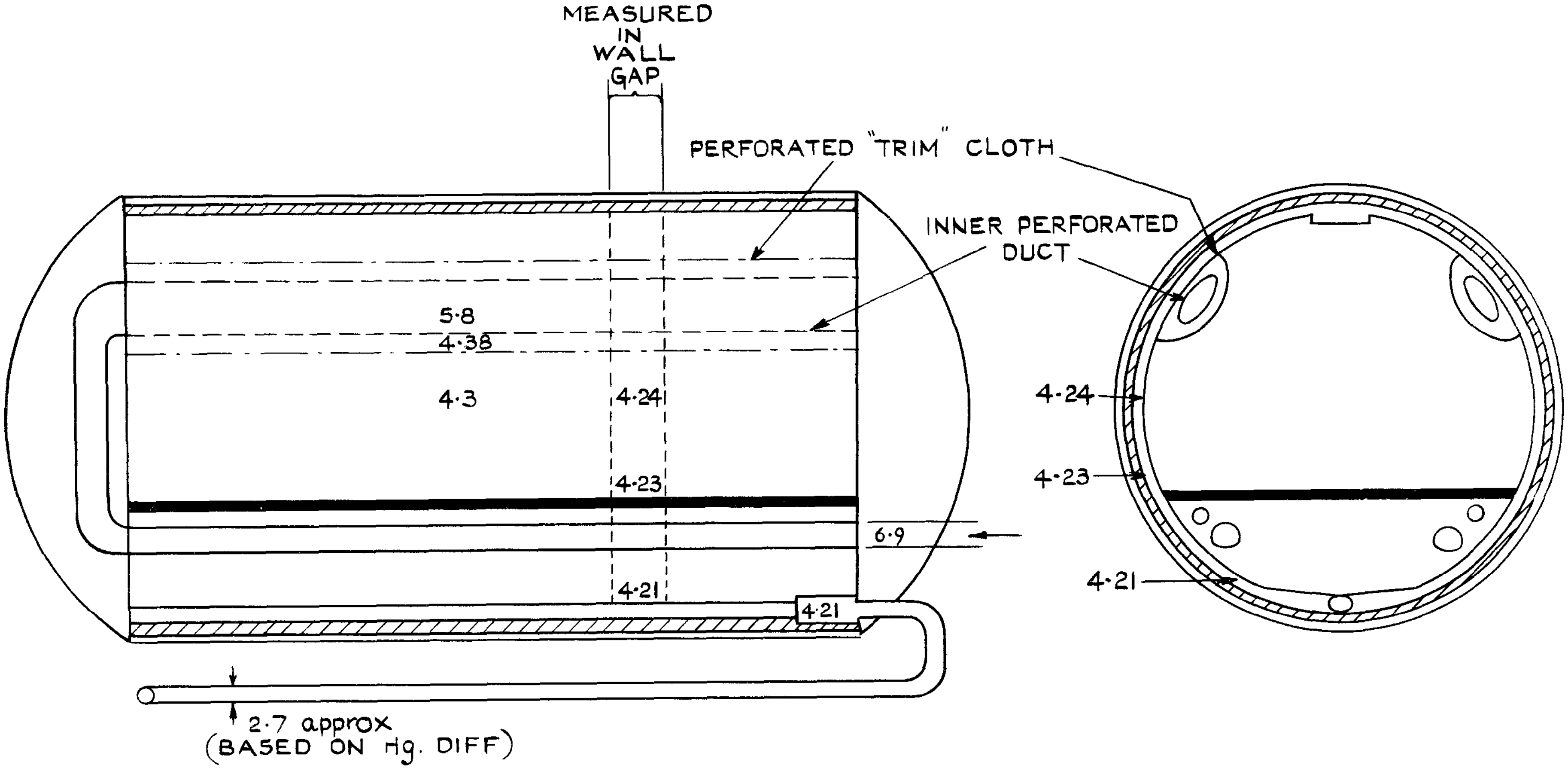


FIG. C14 HEAT INTAKE PER FOOT OF DOOR FRAME
v AIR FLOW



FIGURES GIVE PRESSURES IN INCHES OF WATER RELATIVE TO LABORATORY

FIG. C 15 PRESSURE LOSSES IN THE SYSTEM — AIR FLOW 48·6 lb/min

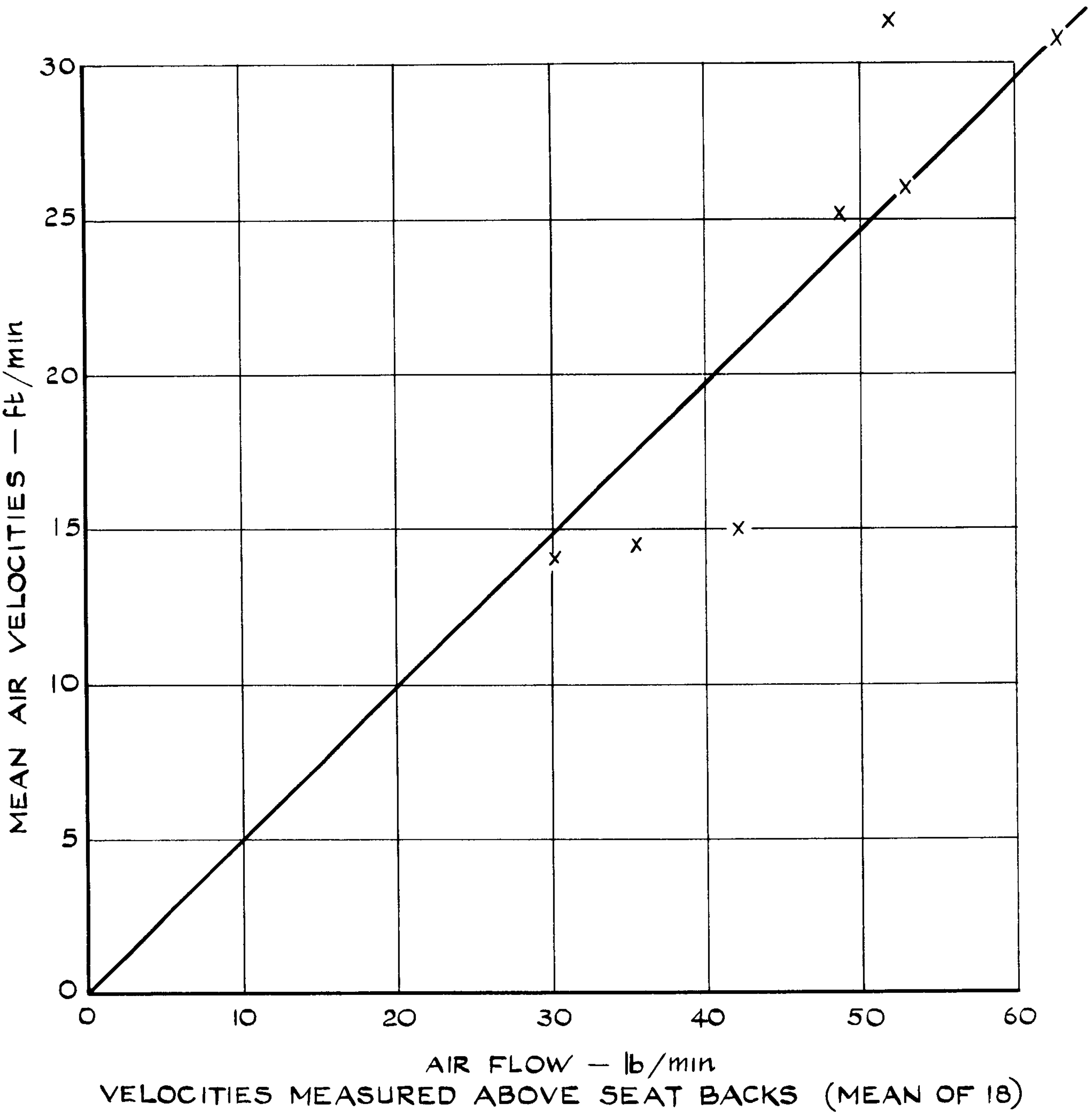


FIG. C16 MEAN CABIN AIR VELOCITIES — PHASE 4B

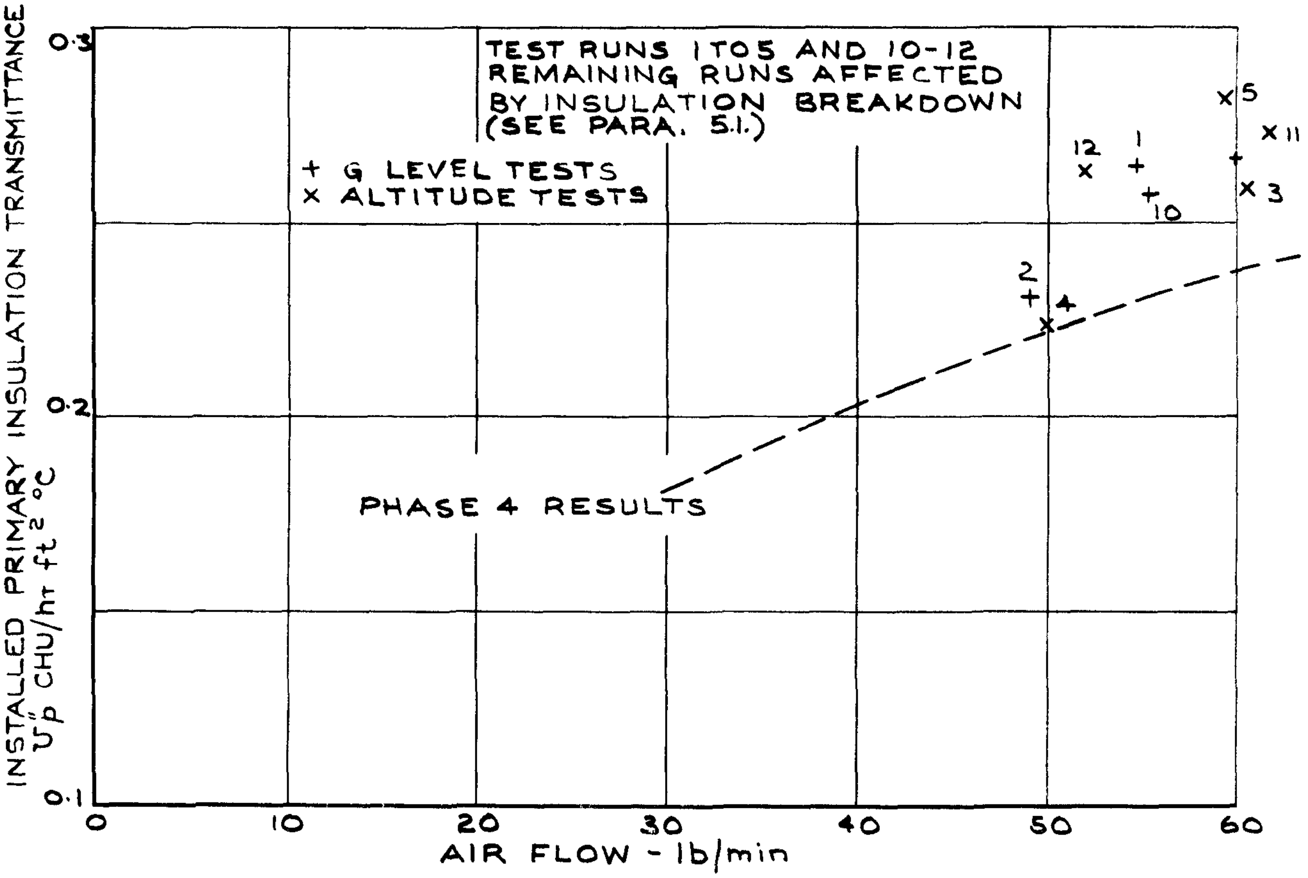


FIG. D3 (a) PRIMARY INSULATION TRANSMITTANCE - NOT CORRECTED FOR DOMED END DUCT HEAT PICK UP

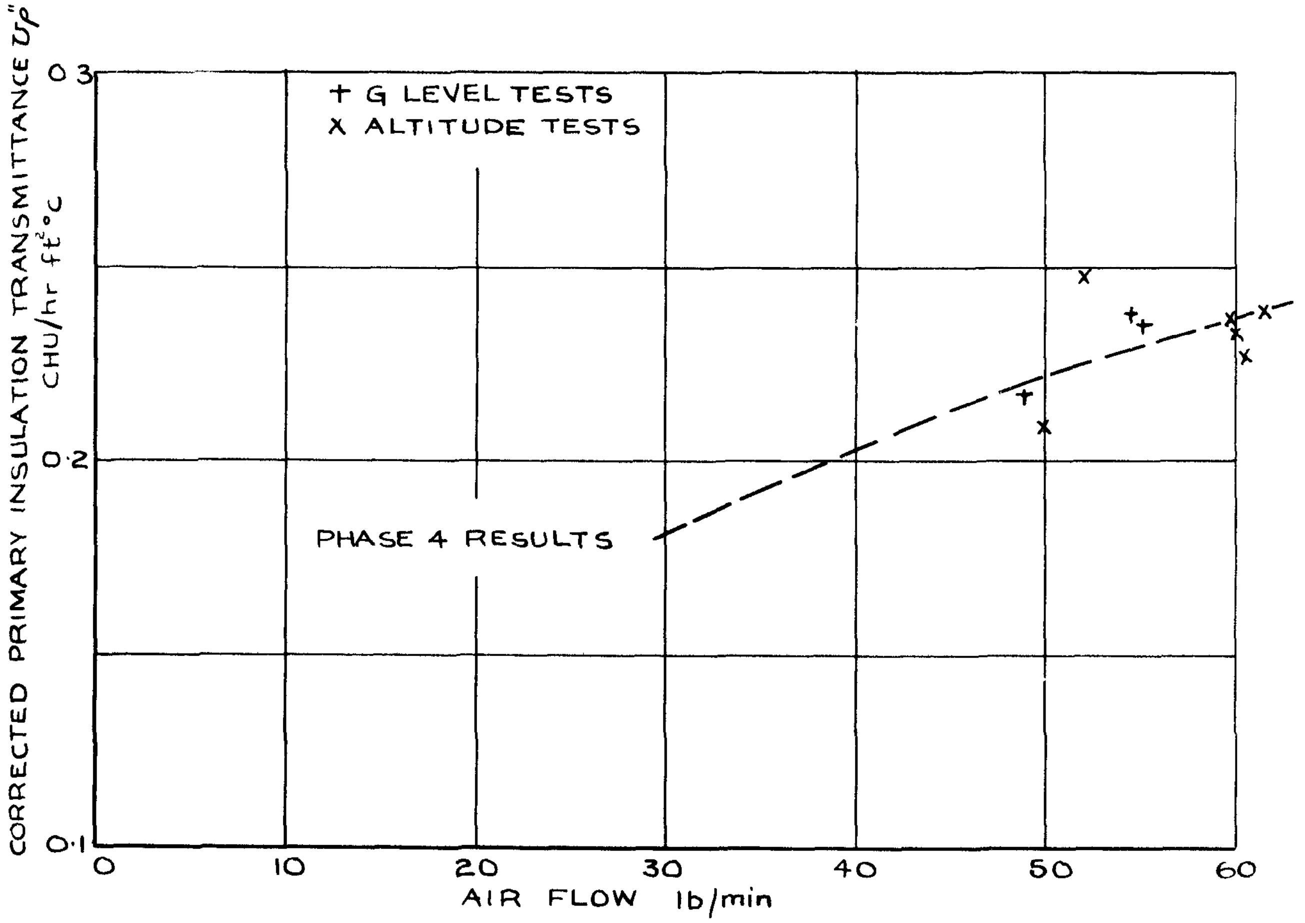


FIG. D3 (b) PRIMARY INSULATION TRANSMITTANCE - CORRECTED FOR ADDITIONAL DOMED END DUCT HEAT PICK UP DUE TO ALTITUDE CHANGE

FIG. D3 PHASE 5 INSTALLED PRIMARY INSULATION TRANSMITTANCE v AIRFLOW

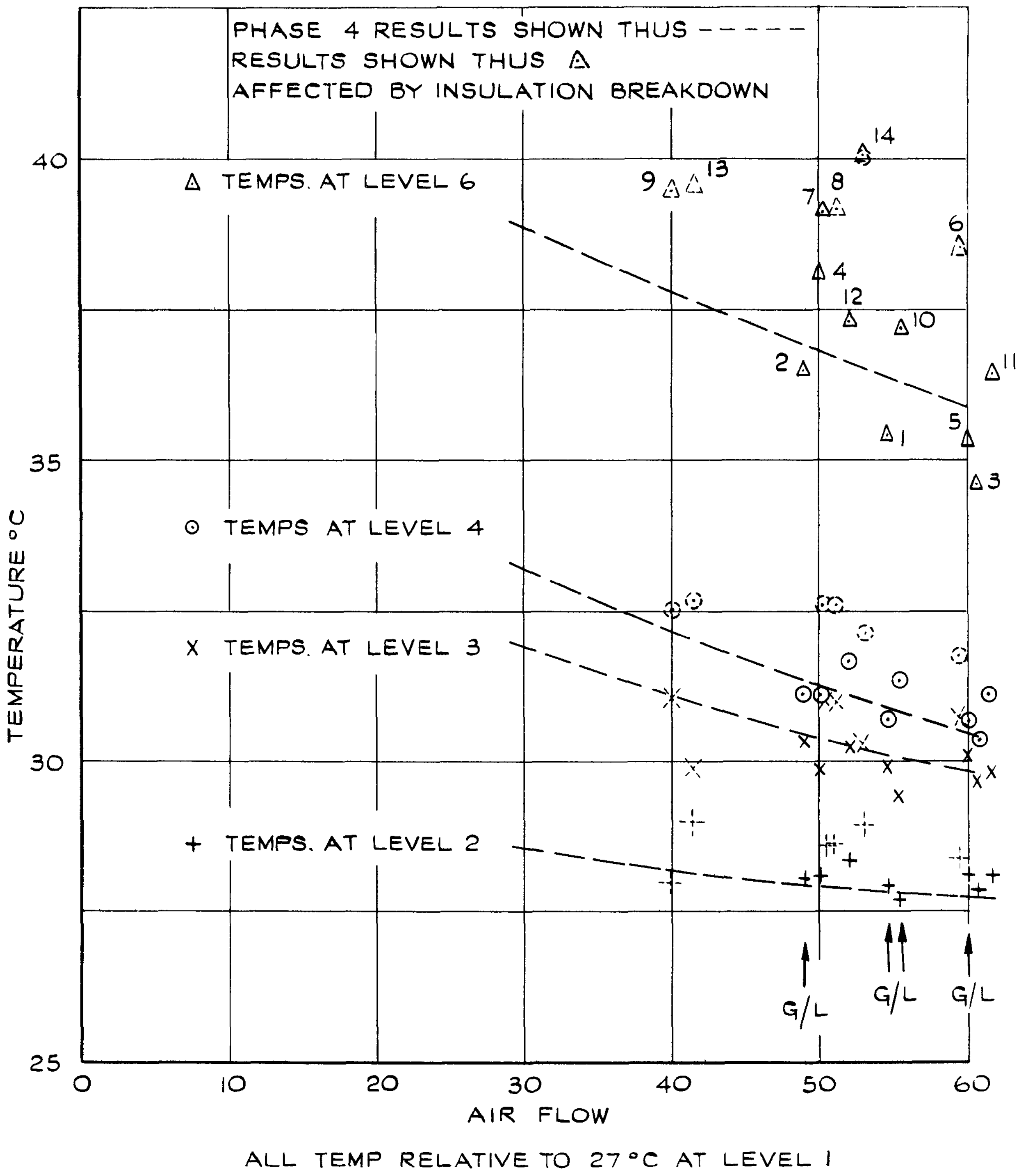
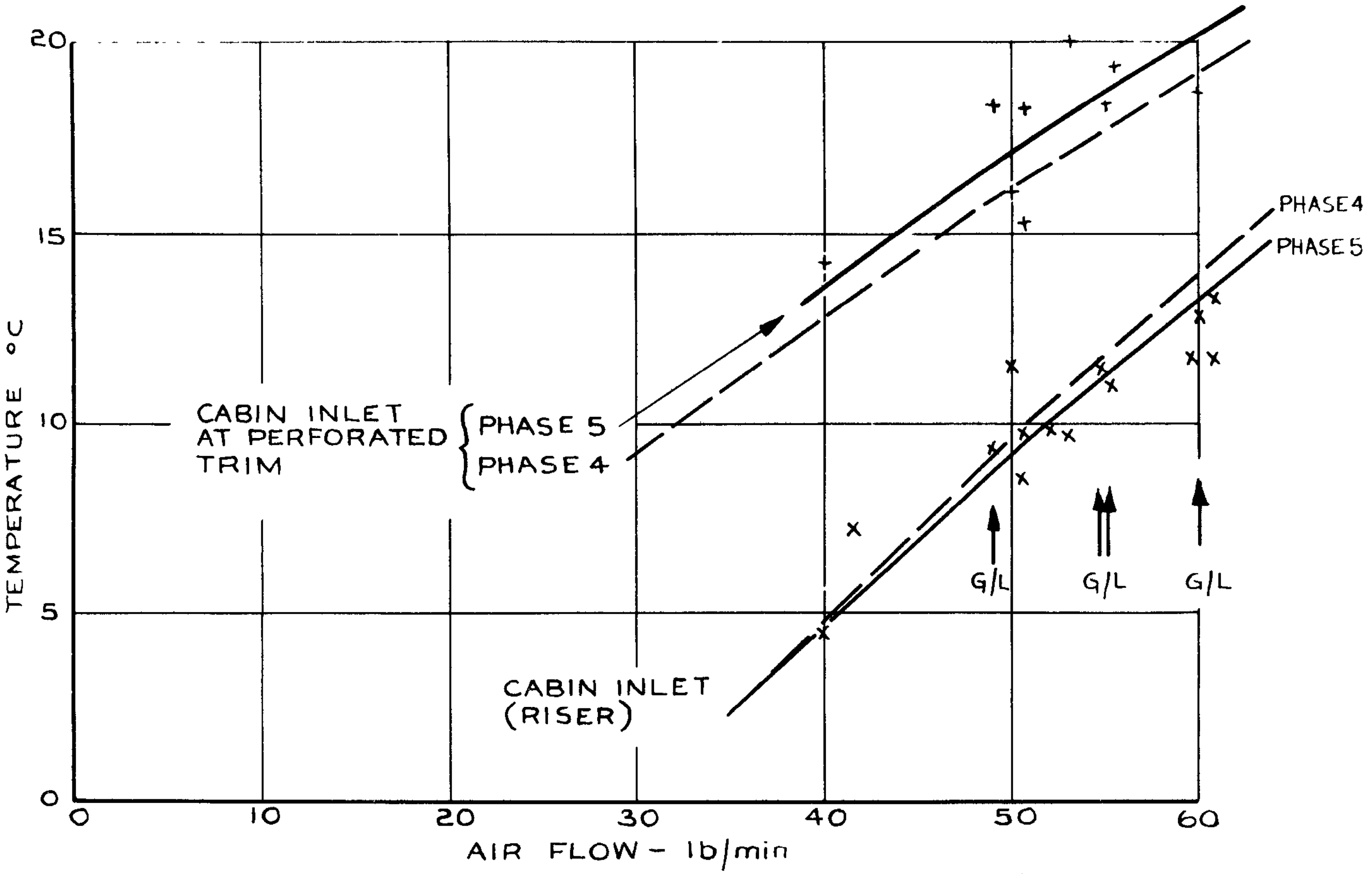
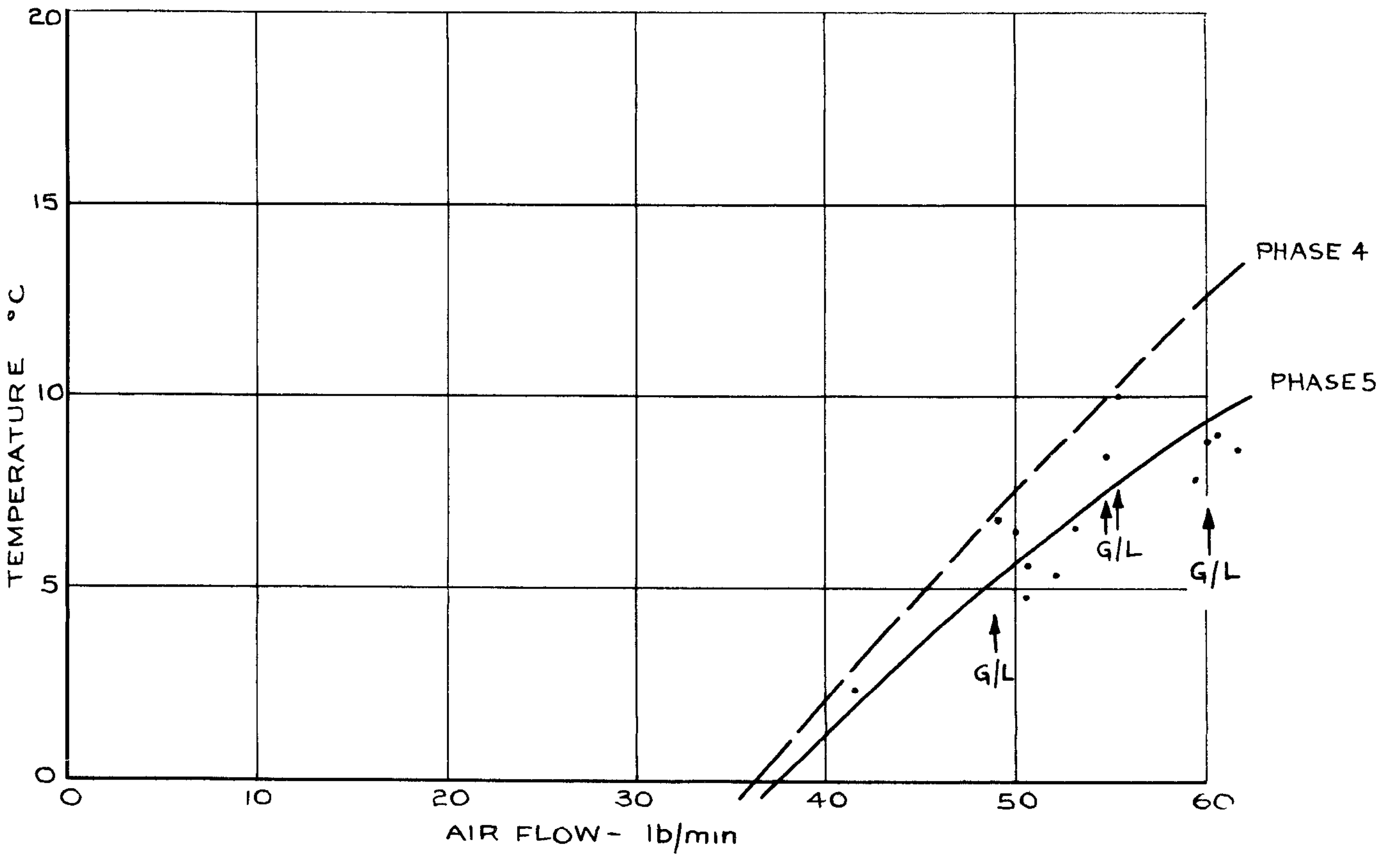


FIG. D2 COMPARISON OF PHASE 5 WALL DUCT TEMPS WITH THOSE OF PHASE 4



TEMPS RELATIVE TO A 25°C CABIN CONTROL TEMP

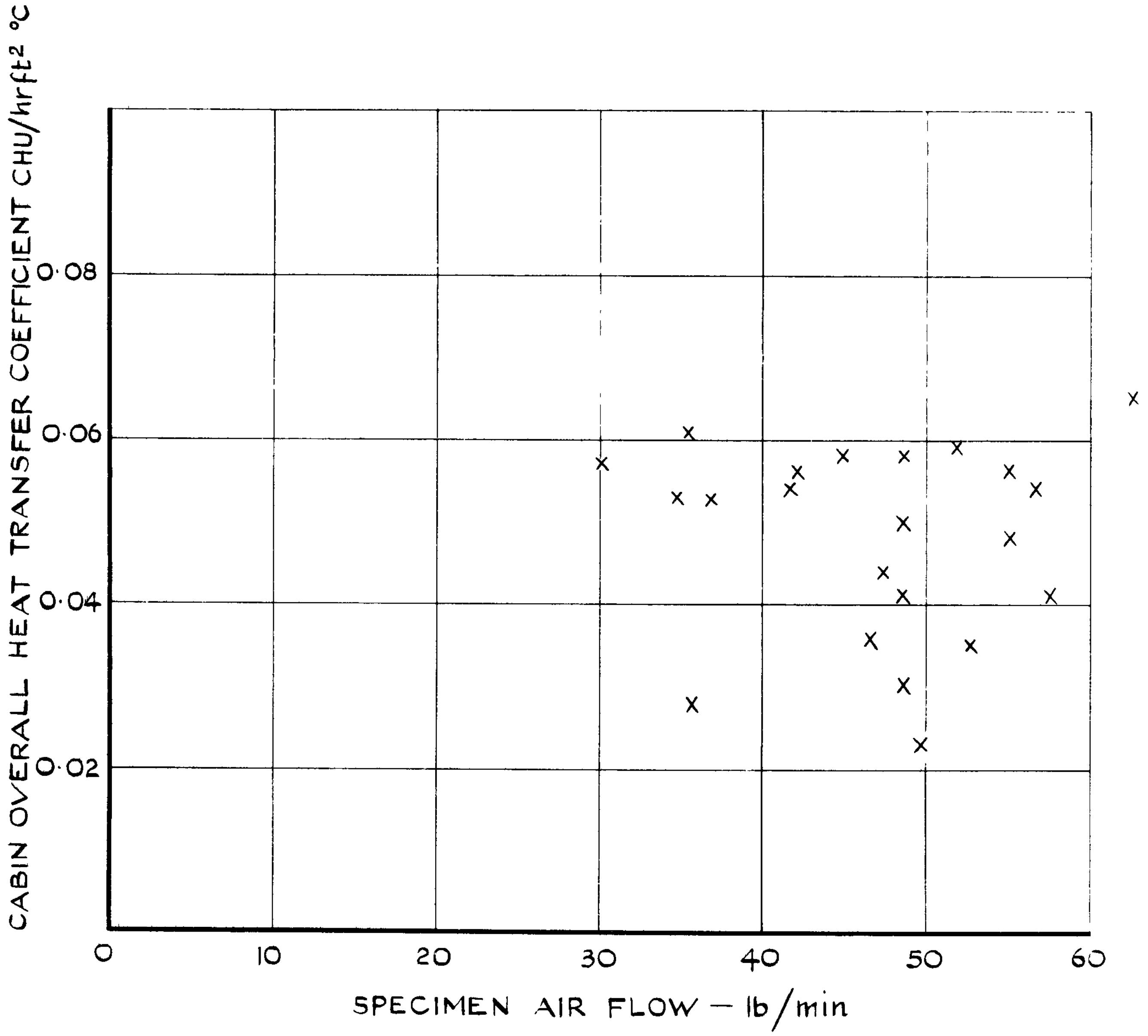
FIG. D1(a) PHASE 5 RISER & CABIN INLET TEMPS v AIRFLOW



TEMPS RELATIVE TO 25 °C CABIN CONTROL TEMP.

FIG. D1(b) PHASE 5 SPECIMEN INLET TEMP v AIR FLOW

FIG. D1 SPECIMEN AIR TEMPERATURES



H_c BASED ON SPECIMEN CURVED SURFACE AREA

FIG. C 17 CABIN OVERALL HEAT TRANSFER COEFFICIENT v AIR FLOW

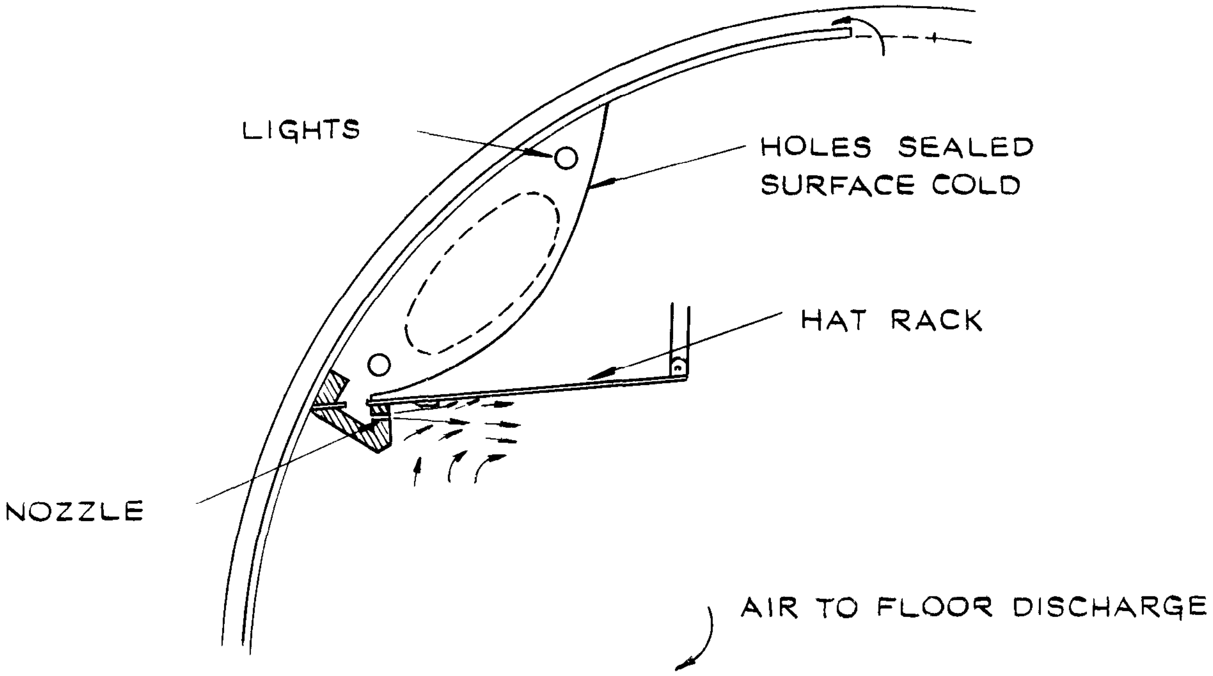


FIG. E I (a) NOZZLE-SCHEME E

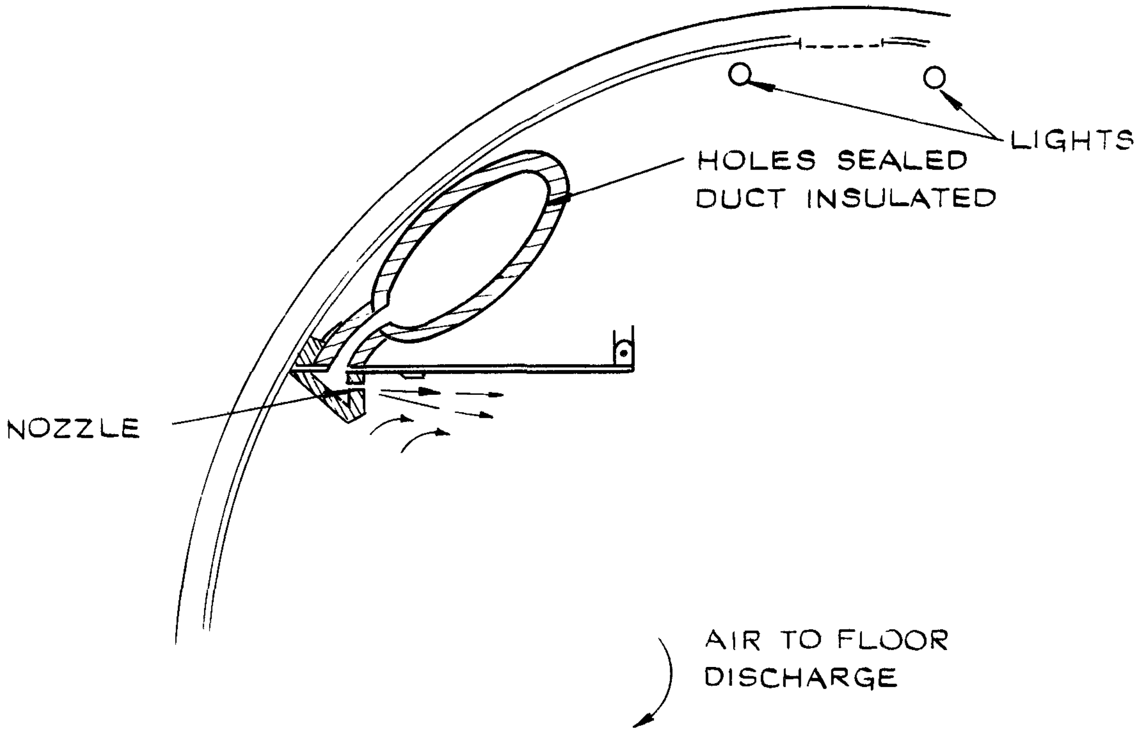


FIG E I (b) NOZZLE-SCHEME F

FIG. E I NOZZLE SCHEMES E & F

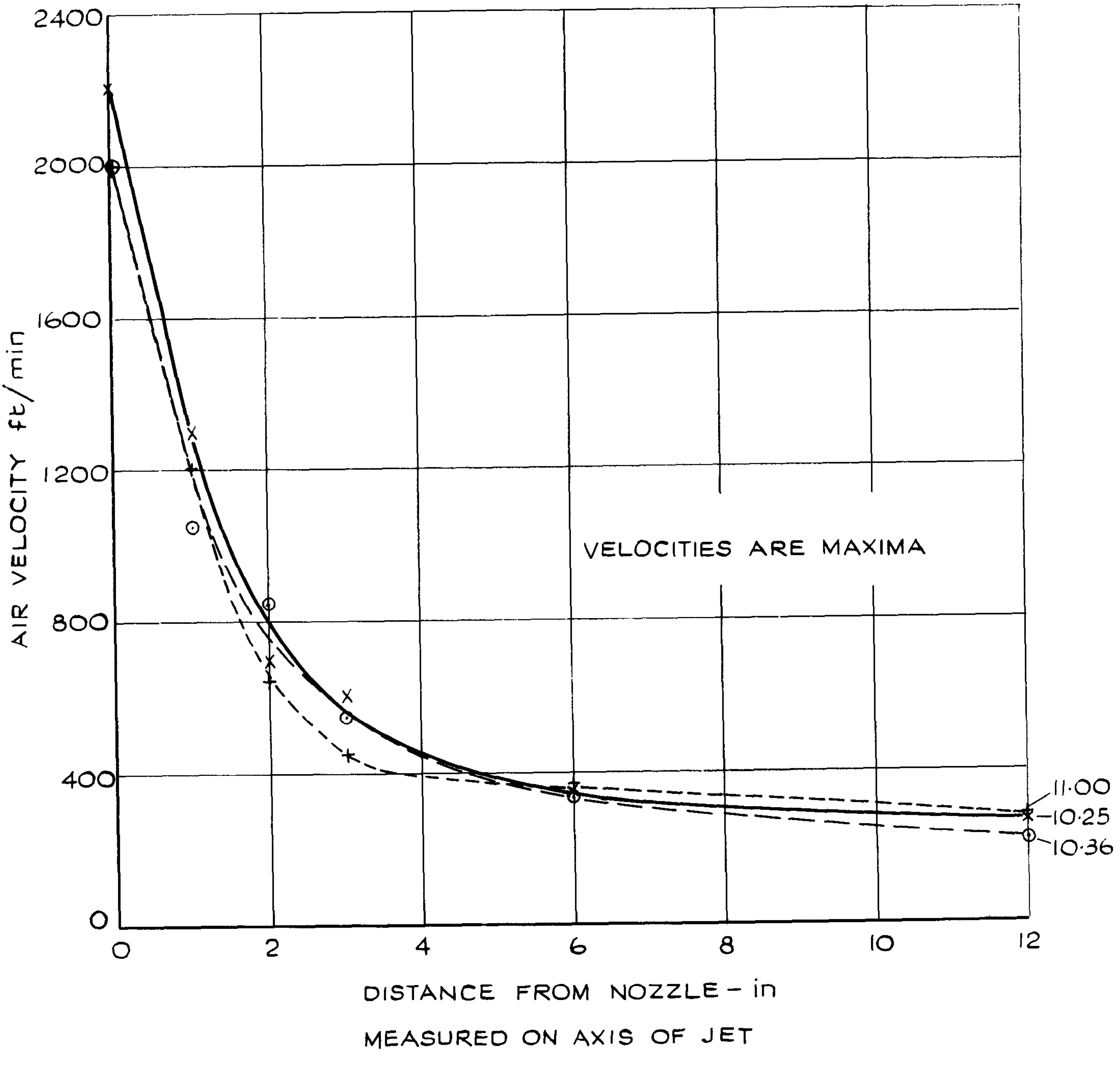


FIG. E.2 JET VELOCITY PROFILES - TEST RUN No 7

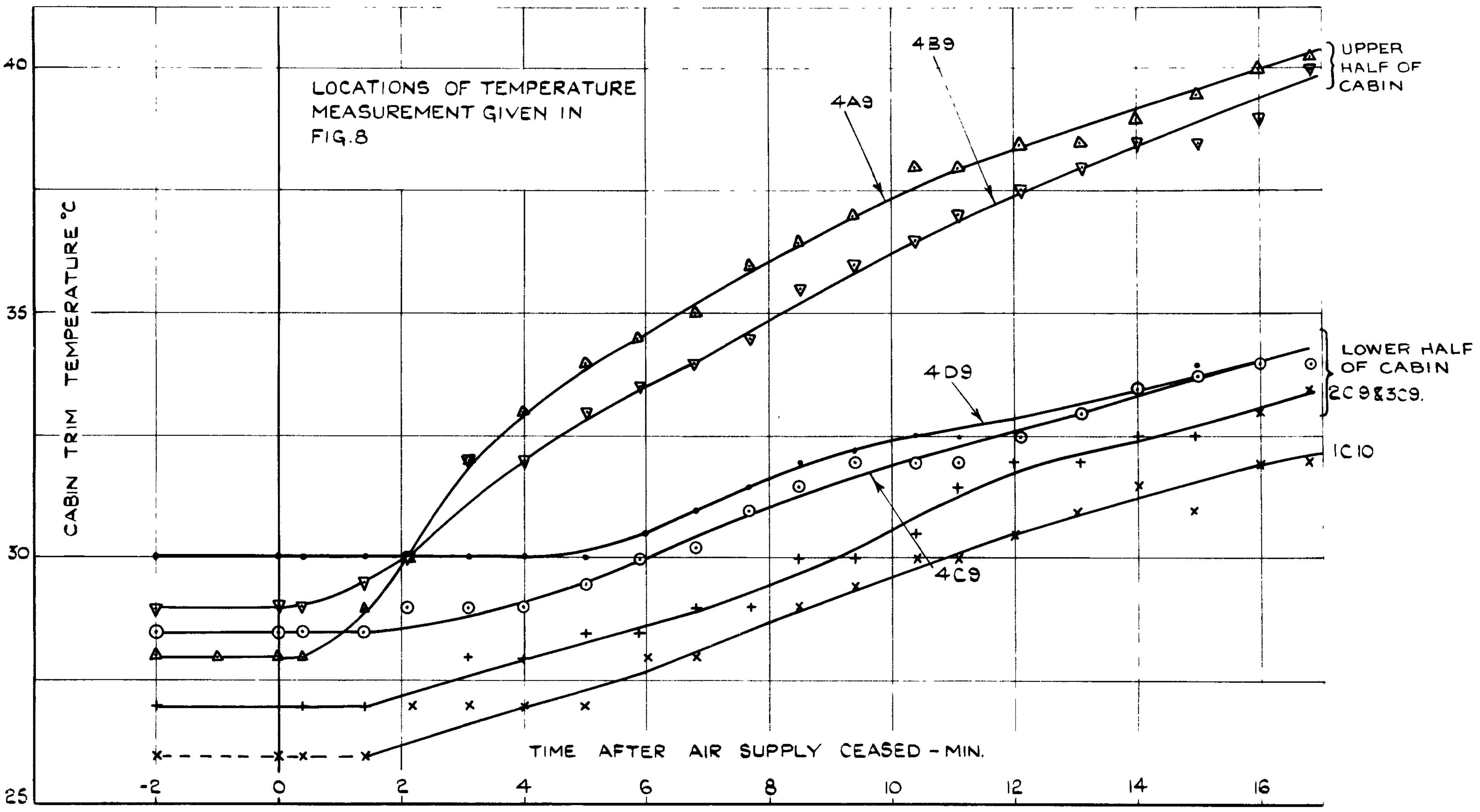


FIG. F2 TRIM TEMPERATURES AFTER AIR SYSTEM FAILURE

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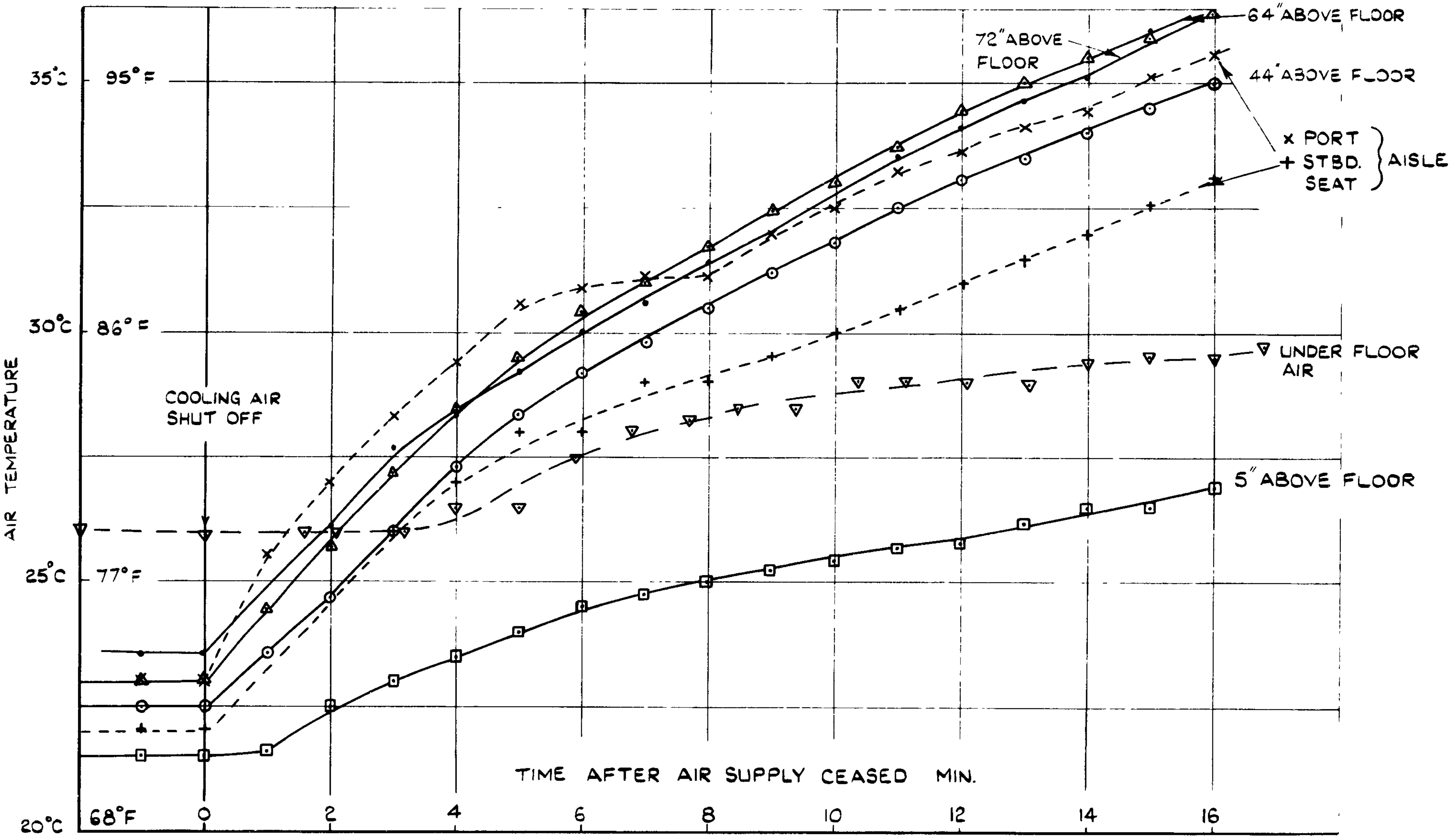
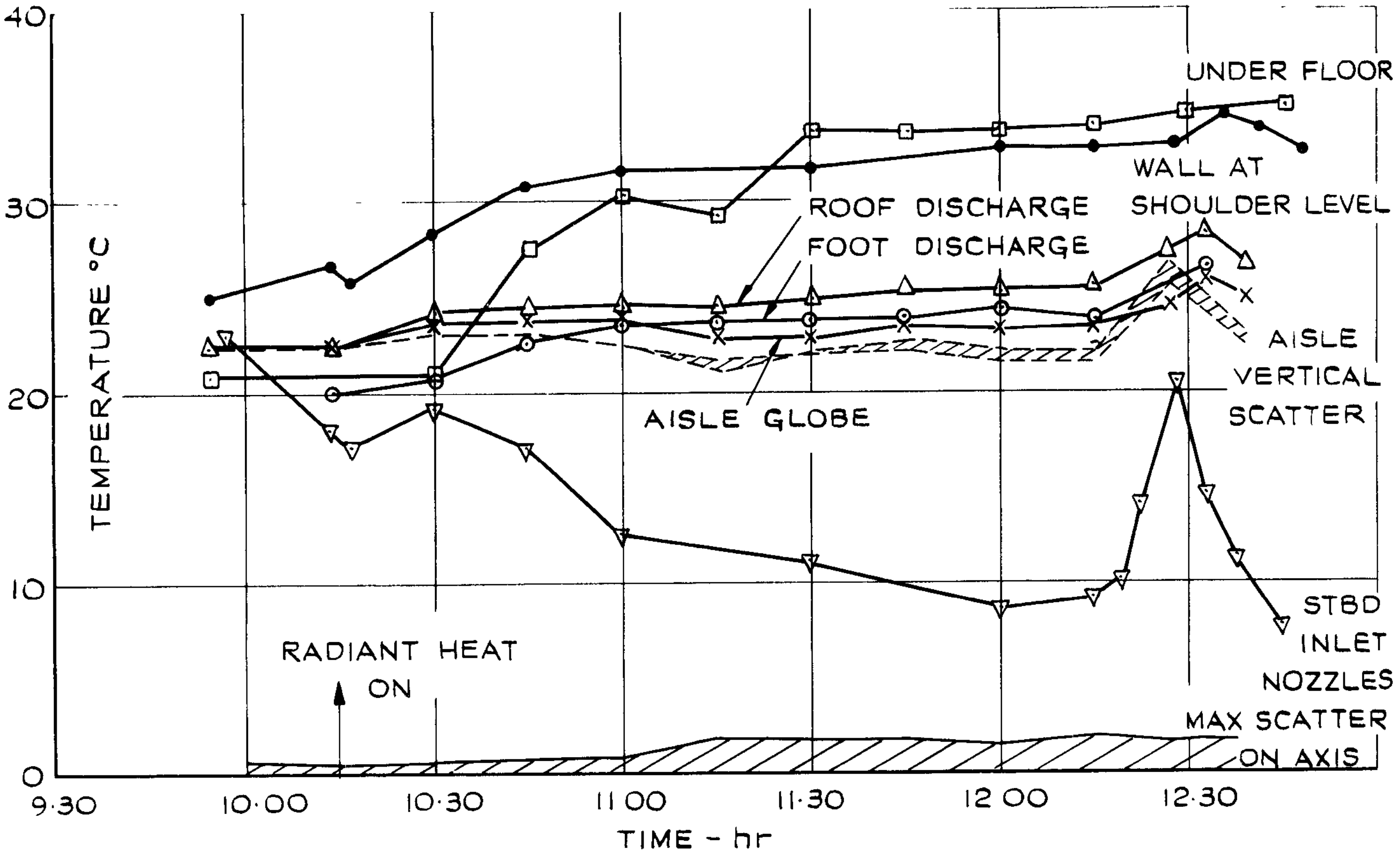
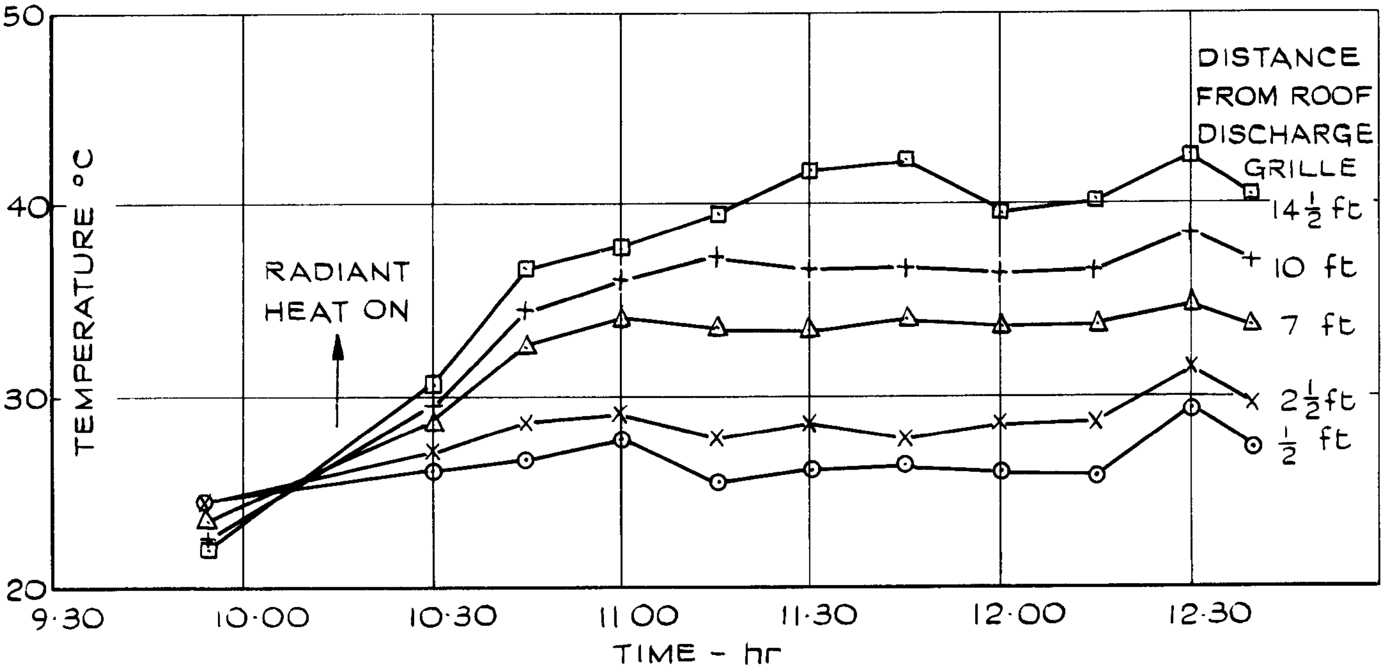


FIG. F1 CABIN AIR TEMPERATURE AFTER 'SYSTEM FAILURE'

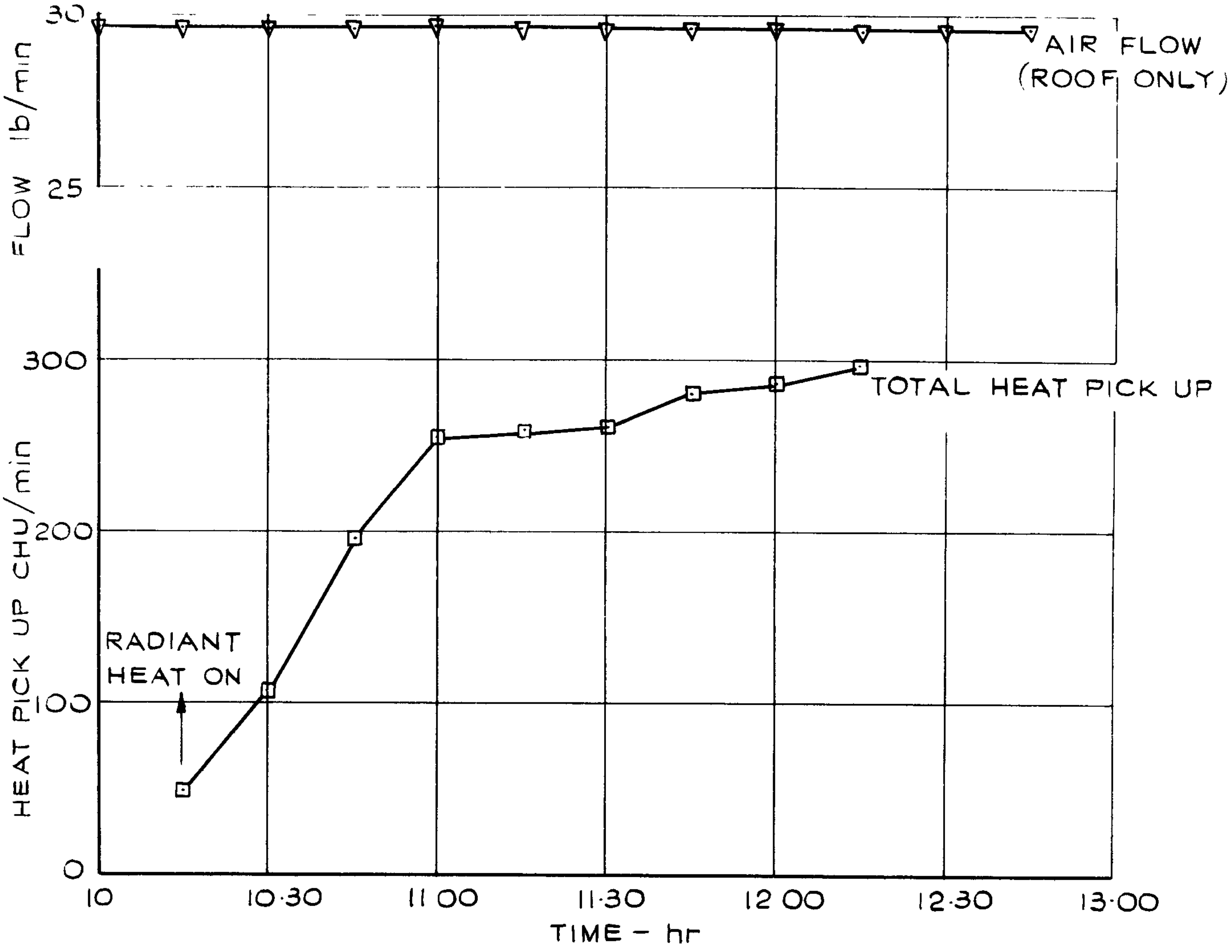


CABIN CONDITIONS



WALL DUCT TEMPERATURES

FIG. E.12 TEST 9 CABIN AND WALL DUCT AIR TEMPERATURES



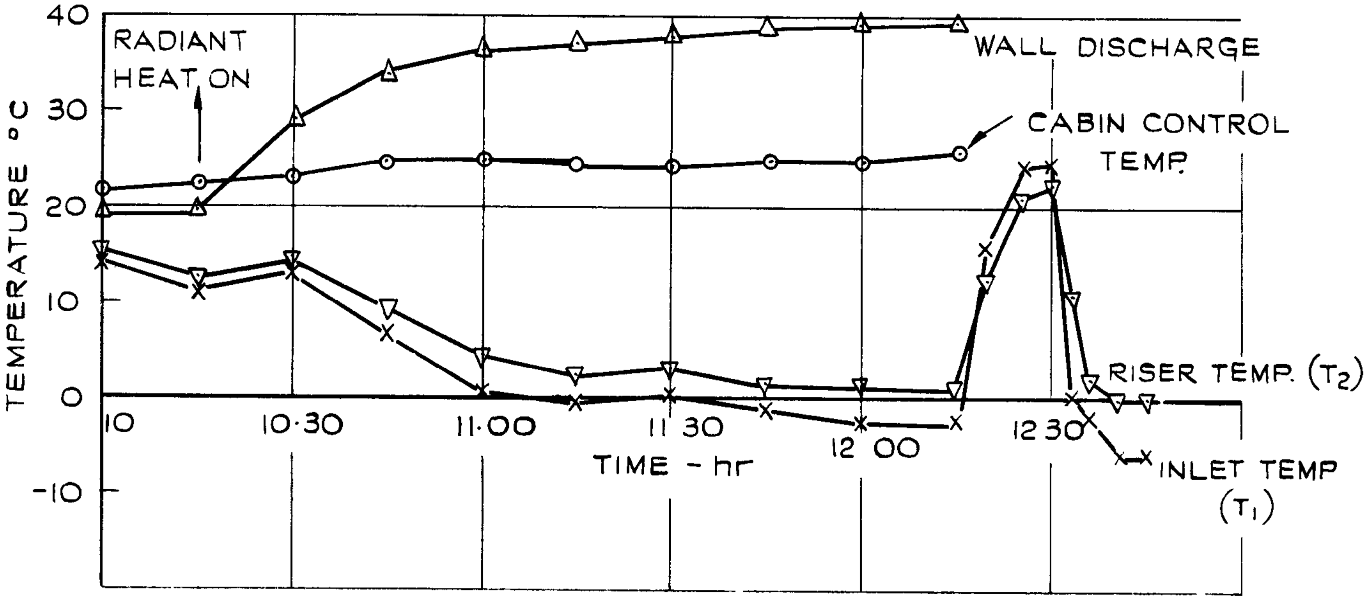
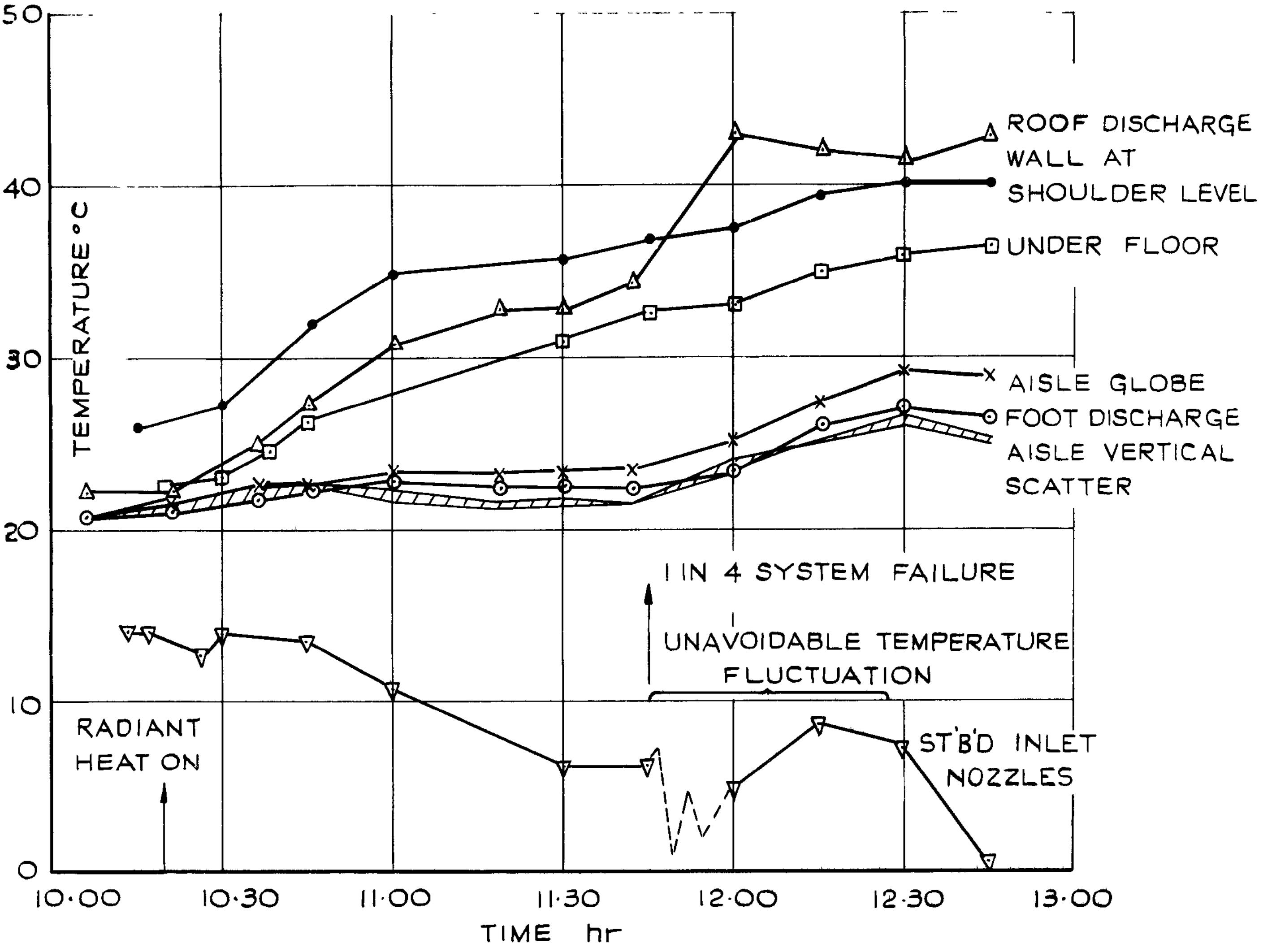
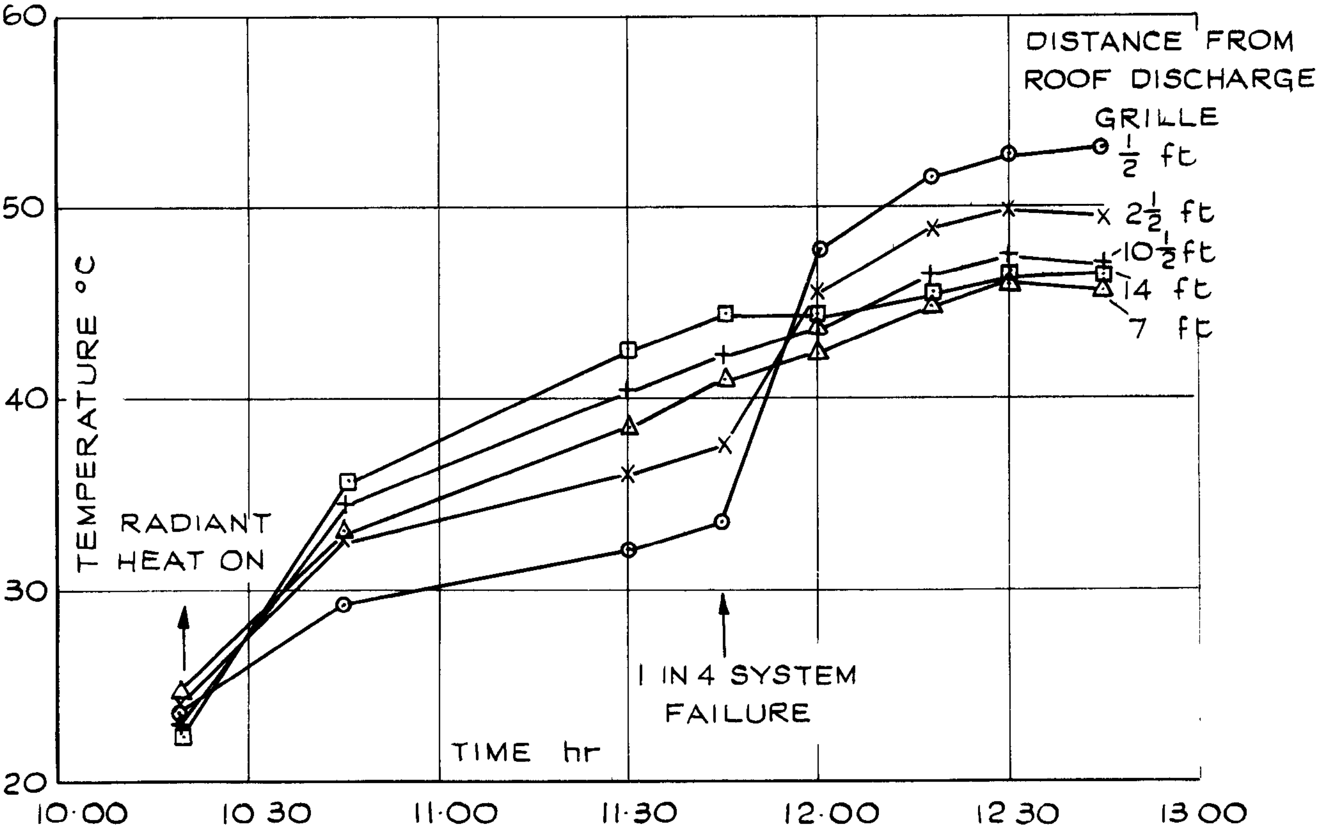


FIG.E.11 TEST 9 TEST CONDITIONS AND HEAT PICK-UP

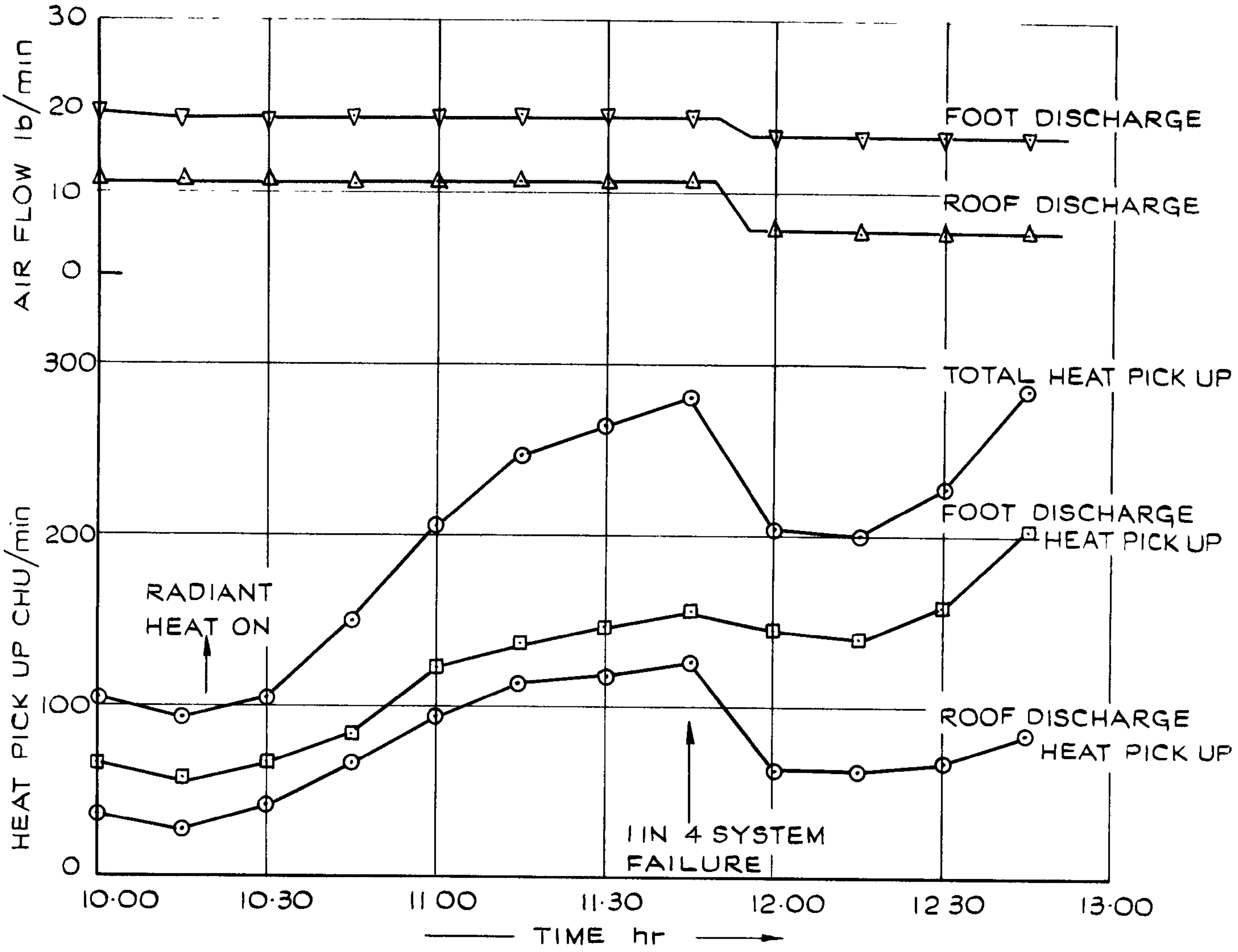


CABIN TEMPERATURES

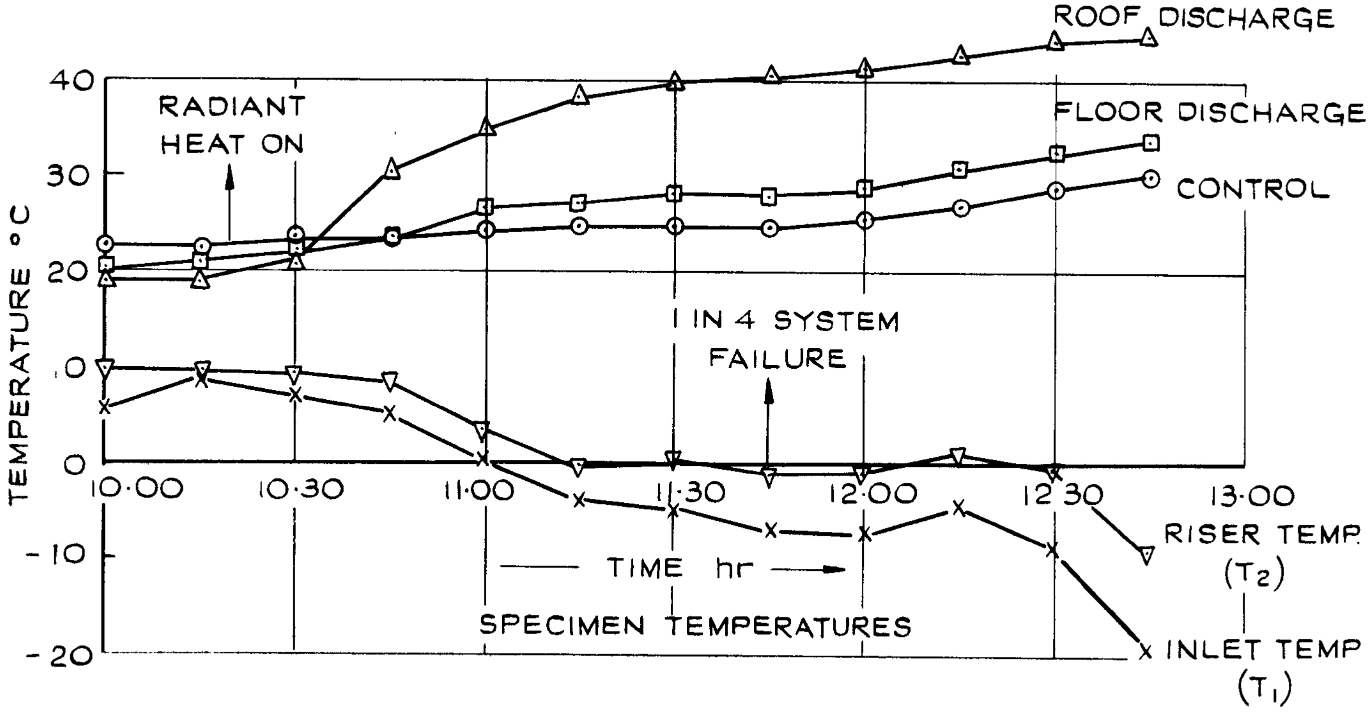


WALL DUCT TEMPERATURES

FIG. E.10 TEST 7 CABIN AND WALL DUCT AIR TEMPERATURES

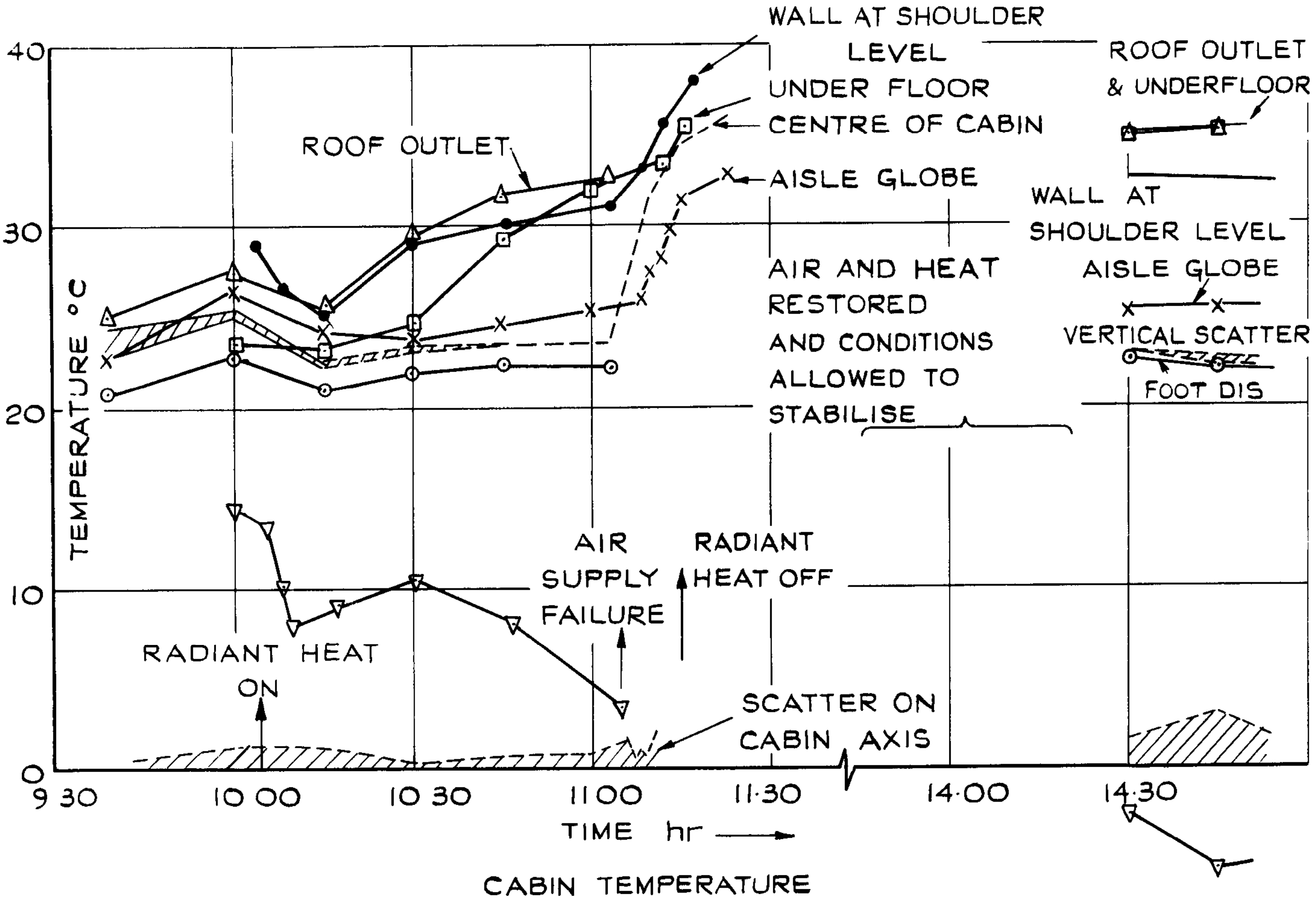


HEAT PICK UP
MEAN SKIN TEMPERATURE 128 °C

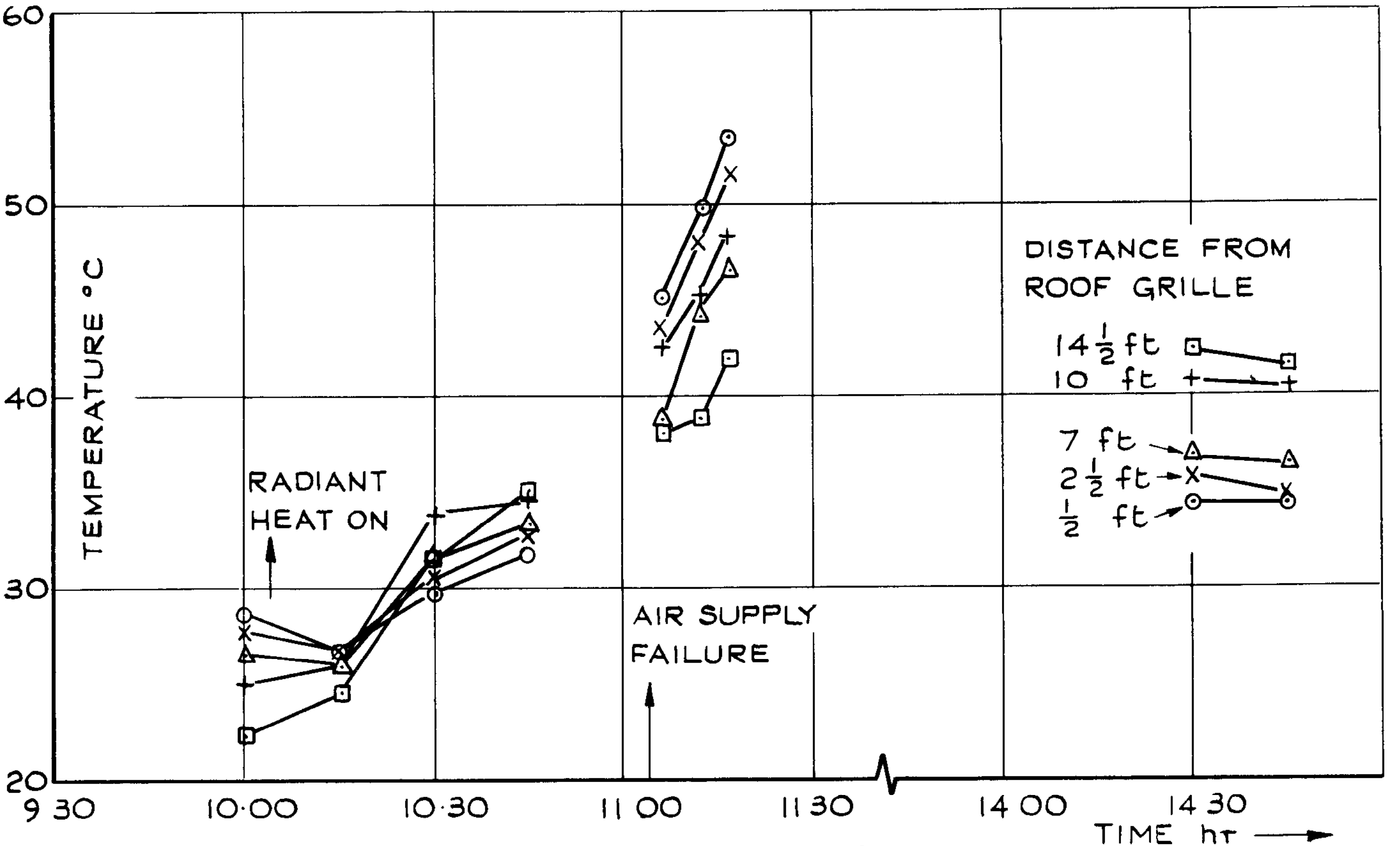


SPECIMEN TEMPERATURES

FIG. E 9 TEST 7 TEST CONDITIONS AND HEAT PICK-UP



CABIN TEMPERATURE



WALL DUCT TEMPERATURE

FIG. E.8 TEST 4 CABIN AND WALL DUCT AIR TEMPERATURES
TOTAL FLOW 23 lb/min

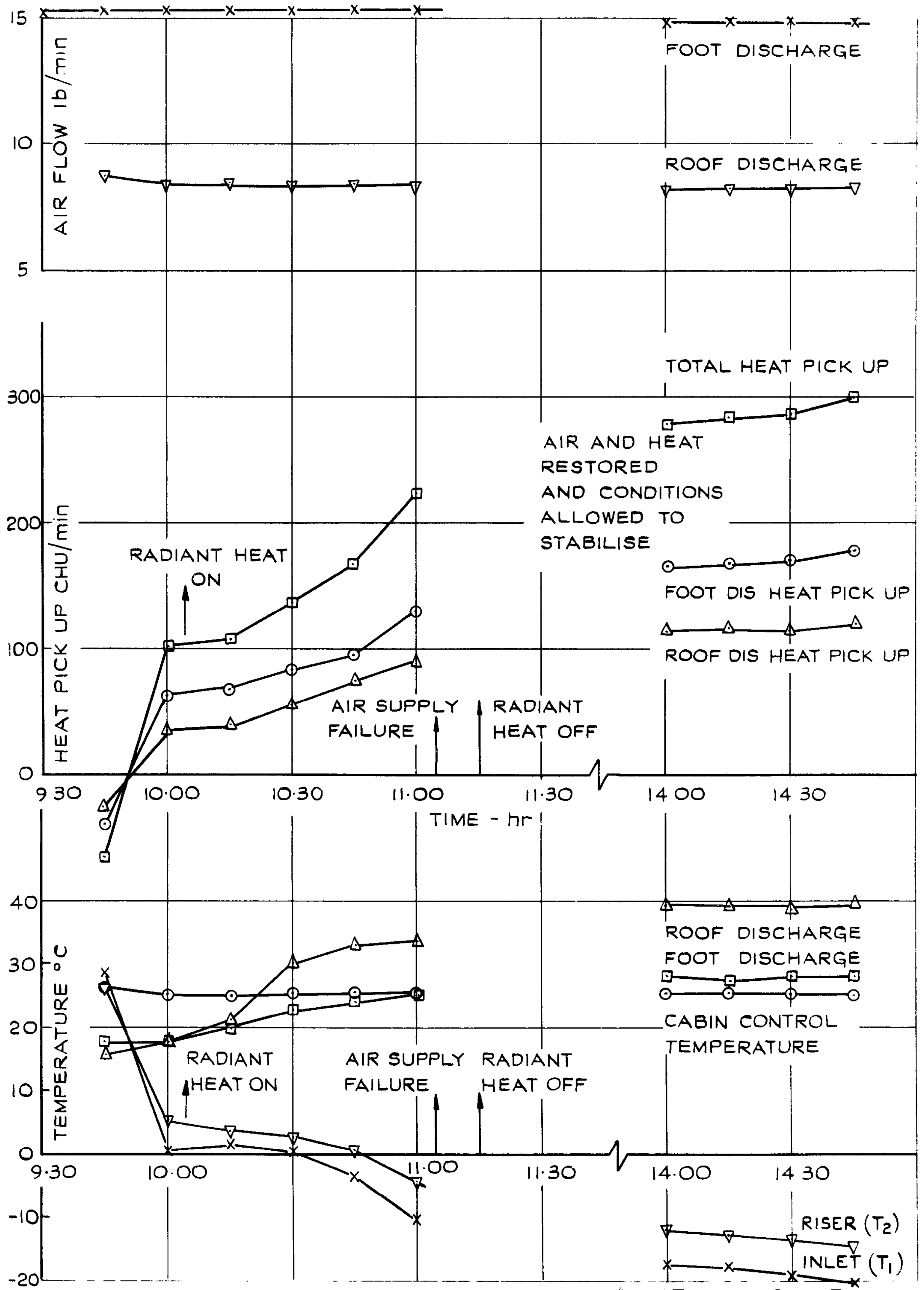


FIG. E.7 TEST 4 TEST CONDITIONS AND HEAT PICKUP
TOTAL FLOW 23 lb/min

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April 1966

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Timby, E.A.

CABIN CONDITIONING TESTS ON A SIMULATED M 2.2 TRANSPORT AIRCRAFT CABIN

629.137.1 :
533.6.011.5 :
629.13.067.2 :
629.13.012.112 :
5.001.58

This paper describes tests made to investigate a cabin insulation scheme and to determine cooling air distribution requirements for a supersonic (M 2.2) passenger transport aircraft. Thermal conditions of flight were simulated in a ground rig with a section of aircraft fuselage equipped as a cabin.

Several methods of introducing air into the cabin were tested. That employing the principle of jet entrainment was found to be the most

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(Over)

DETACHABLE ABSTRACT CARDS

economical in cooling air mass flow, to provide overall passenger thermal comfort.

The insulation and cooling scheme for the cabin wall was evaluated and the amount of heat leakage in the test specimen established.

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