RESEARCH REPORT

A Study of the Rainscreen Concept Applied to Cladding Systems on Wood Frame Walls

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A STUDY OF THE RAINSCREEN CONCEPT APPLIED TO CLADDING SYSTEMS ON WOOD FRAME WALLS

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This publication is one of the many items of information published by CMHC with the assistance of federal funds.

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EXECUTIVE SUMMARY

Morrison Hershfield Limited undertook to study and investigate the performance of the Rainscreen Principle applied to residential claddings on wood frame construction for the Canada Mortgage and Housing Corporation.

The study included a full scale simulation, in the laboratory, of the rain penetration control performance of three cladding types with each having a sealed and leaky air barrier system. The three cladding types include vinyl siding, stucco, and a brick veneer. All cladding systems were mounted on a conventional wood frame wall. The wood frame walls were equipped either with a flexible polyethylene air barrier system or a gypsum interior finish air barrier system. The walls were subjected to simulated wind driven rain from a water spray rack and a simulated wind pressure load. In addition, the test walls were subjected to steady state wind load conditions as well as variations in wind gusts. In the latter tests, the distribution of air pressure loads on the cladding elements and other components within the walls were recorded and analyzed.

The study also undertook an examination of the pressure equalization performance of one of the cladding systems on a construction model placed in a boundary layer wind tunnel, specifically the BLWT2 wind tunnel of Western University in London, Ontario. A fully compartmentalized cavity, a continuous cavity and other permutations of compartmentalizations were examined. This allowed for a detailed examination of the pressure equalization performance of the cladding system under real wind conditions and the compartmentalization requirements of the cavity behind the cladding system.

In addition, the study undertook to develop a simple mathematical model that simulates the pressure equalization performance of a rainscreen wall. The model was developed using the basic gas laws, for pressure, temperature and volume. It was designed to predict the cavity pressure and time response of the cavity for various gust load rates and magnitudes.

The laboratory investigations of the test walls have shown that the pressure equalization phenomenon reduces the amount of water that penetrates the cladding system.

This phenomenon is particularly evident with the brick veneer cladding system. It was found that the decrease in rain penetration can be as much as ten times depending on the cladding air pressure load difference. The stucco and vinyl cladding tests have shown little water penetration. Both cladding systems were substantially pressure equalized by the action of the sheathing and paper even though the air barrier systems were made leaky.

The compartmentalization study revealed that the pressure equalization of the cavity was dependent on the compartment seals. From the wind tunnel tests, the cavity pressures behind the cladding approached the exterior cladding surface pressures when the cavity was fully compartmented at the corners. It was noted from the study that the air pressure load on the air barrier varied between 10 and 100 percent. The compartment seals, on the other hand, were subjected to loads of two and three times the wind load pressure.

The mathematical model was developed, tested and computerized. It was found that the output of the model provided a satisfactory correlation between predicted results and the laboratory measurements for pressure equalization performance.

This study has revealed that the rainscreen principle applied to the design and construction of cladding systems on wood frame walls limits the penetration of rain more effectively than a non pressure equalized wall. To achieve rain penetration control, the rainscreen wall is dependent on certain design and construction features. These include an effective air barrier system within the wall, sufficiently rigid components, the air barrier system in particular, adequate venting and drainage of the cladding system, and effective compartment seals located at corners.

To further understand the requirements of the rainscreen principle and to quantify more fully the benefits, it is recommended that the study be extended to:

a) investigate the water penetration properties of a broader selection of wall systems to include systems constructed with insulated sheathings and other cladding types,

b) develop and test compartment seals to include the use of fibreglass, foams, tapes, plastic and metal compartment seals,

c) determine the effects of drips, flashings and capillary breaks on the reduction of water penetration in a rainscreen wall,

d) undertake a detailed study of various window systems designed on the rainscreen principle,

e) undertake a parametric study using the mathematical model to determine the optimum venting to volume ratios, venting area to leakage area ratios, volume to stiffness ratios and other permutations,

f) develop the math (computer model) to incorporate water penetration rates under simulated 15 minute, one hour and four hour rain storms.

Morrison Hershfield was pleased to have undertaken this important assignment on behalf of Canada Mortgage and Housing Corporation. The knowledge gained from this study will undoubtedly lead to innovations in the design and construction of exterior walls and cladding systems. These innovations should enhance rain penetration control while providing durable and cost effective cladding systems for the Canadian climate.

1. INTRODUCTION

It is believed that the rainscreen wall design principle was introduced, as early as 1960 and perhaps earlier, as an approach to the reduction of rain penetration problems. It was presented as an alternative to the traditional "face seal" approach. In the face seal approach, the control of rain penetration was achieved by completely sealing the exterior face of the building so that there were no openings through which rain water could penetrate. However, the climate conditions to which an exterior cladding is exposed to, in the Canadian climate, often result in premature deterioration of seals, thereby rendering the face seal ineffective.

Since the time of its inception, the rainscreen principle has been applied to most designs of exterior walls and windows, and recently even to roof systems. In its simplest form, the rainscreen wall system consists of an exterior cladding, drained and vented to the outside, a cavity behind the cladding, an inner plane called the air barrier system, and a set of compartment seals limiting the cavity to a modest size.

Wood frame construction employs the rainscreen concept with a variety of cladding systems. This concept is most frequently associated with brick veneer claddings that are drained and vented through weep holes, metal and plastic sidings that are drained and vented through punched openings and with stucco wall finishes that are drained and vented at horizontal joints. The air barrier system may be constructed of a sheet membrane, a gypsum board or other air impermeable material designed to prevent the flow of air from the cavity to the inside. The air barrier system must also support the wind pressure load.

Recent studies by the Institute for Research in Construction of the National Research Council of Canada were undertaken on pressure equalization performance of metal and glass curtain walls. Field measurements were also taken of air pressures in the cavity and on the face of the exterior walls of Place Air Canada building in Montreal; the Lethbridge Court House in Alberta, and one of the experiment[illegible]ouses of the Mark XI Energy Research Project in Orleans, Ontario. These studies have also revealed that most exterior wall systems lacked sufficient airtightness and adequate compartmentalization to support the pressure equalization performance required by a rainscreen wall design.

This study examined the performance characteristics of a rainscreen cladding on a wood frame wall. The work was divided into three parts. The first part of the work involved the laboratory investigation of various exterior cladding systems. These included a brick veneer cladding system, an exterior cladding of stucco and a vinyl cladding system. In the testing program, sample walls were subjected to simulated wind driven rain in an environmental chamber. The amount of water passing through the veneers was determined gravimetrically. During the tests, the walls were altered from air tight to leaky by creating an opening in the air barrier system. This caused the pressure equalized cladding to experience a difference in pressure and an increase in rain penetration. Subsequently, a broader set of sample wall systems were examined for pressure equalization performance only under simulated wind gust conditions.

The second part of the study involved an investigation of the compartmentalization requirement of the cavities behind the cladding. This study was done through the use of a full scale construction model installed in a wind tunnel.

The third part involved the development of a simulation model to predict the pressure equalization performance of various types of exterior cladding and wall systems. The parameters used for the simulation of a particular wall type included the vent areas required, air leakage areas, volume of the cavity, and stiffness or rigidity of the air barrier and the cladding elements.

2. TESTING OF RAINSCREEN WALLS

2.1 Introduction

In this part of the study, the performance characteristics of three types of cladding systems were determined; a wood frame wall with a vinyl siding, a wall with stucco and a wall with brick veneer. Samples walls were designed and constructed to fit a 2.4 m square opening of an environmental chamber. The sample walls were then pressurized to a predetermined level and wetted using a spray rack with narrowly spaced nozzles. Since visual observations of water penetration can be very subjective, a gravimetric method was developed to provide objective data.

In addition to the water spray tests, another series of tests was undertaken to determine the air pressure load distribution across the elements of the walls, when subjected to steady state pressure, varying gust rates and magnitudes. The dynamic loads were created by rapidly pressurizing and/or depressurizing the environmental chamber.

2.2 Description of Sample Walls

The exterior claddings studied were vinyl siding, stucco and brick veneer (Figures 5,12, and 14 of Appendix A). The test walls measured 2.4 m square and were mounted in an environmental test chamber as shown in Figure 1 of Appendix A. The wood framing consisted of 38 mm x 89 mm wood studs on 405 mm centres. The exterior or outboard side of the wood framing was sheathed with 7/16 standard fibreboard and covered with a standard construction paper. The inboard side of the wood framing was covered in either a polyethylene film air barrier system (fastened with battens and tapes) or with an air tight gypsum board. To provide a measurable leakage area through the air barrier systems, a 25 mm diameter hole was drilled in the gypsum board shown in Figure 1 of Appendix A.

The cladding part of each sample wall was positioned to face the interior of the test chamber where water and air were applied to the wall sample. Observations and measurements were made through sensors installed in each of the wall samples. These sensors included air pressure taps (small 1/8 inch diameter copper tubes installed through the wall construction layers to sample the air pressure) installed through the chamber and sample walls. All pressures were referenced to the inside or laboratory side.

2.3 Description of Test Chamber

The Environmental Test Chamber consisted of a wood frame structure constructed of nominal 38 mm x 280 mm joists for the walls, floor and ceiling. It provided a 3.1 m square clear frontal opening. The chamber was approximately 2 m deep and was lined with 24 gauge sheet steel to a plywood substrate. The sheet steel liner was made airtight and sealed from water leaks. The chamber had a centre partition (bulkhead) for pressure tests. In addition, the chamber was equipped with a rain rack. This rack was constructed of copper tubing mounted on two panels and hinged to the walls of the chamber. The spray nozzles were spaced at 610 mm on centre and were capable of delivering 5 US gal/hr/ft^2 over the sample to be tested. The chamber volume was 28.3 m^3 and was designed to withstand +/- 10 Kpa (200 lbs/ft^2).

The hydraulic system that provided water to the spray rack included a high pressure water pump and a reservoir located under the chamber. Water from the reservoir was pumped through the nozzles of the spray rack against the sample walls. The excess water was then drained back to the reservoir which was mounted on a roller supported at one end and two load cells at the other. These load cells were used to measure the change in weight of the water in the reservoir that was lost through the test walls.

To provide air pressurization or depressurization to the chamber, a commercial air pump, plastic piping, and air valves were used to pressurize or depressurize one or the other or both parts of the test chamber. Measurements of pressures were done using an MK6 Air Ltd. micromanometer for each of the channels which in turn were read directly by a data logger and scanner to produce and electronic real time recorder.

2.4 Procedures

The laboratory procedures consisted of a three part approach. The first part involved basic calibration measurements to qualify the conditions and characteristics of the wall samples. The second part involved a steady state pressurization and water test, and finally the third part involved a procedure for dynamic loading involving the buildup of gust pressures to determine the reaction load transfer path on the cladding and other components on the wall and the time duration of the pressure equalization process.

2.4.1 Air Leakage Test

The wall samples were mounted in the environmental test chamber and sealed at the perimeter. The wall samples were then covered with a polyethylene sheet taped at the perimeter edges to isolate the sample from the rest of the chamber. The chamber was then pressurized to determine the chamber air leakage prior to measurement of the wall leakage under test conditions. Once the chamber had been calibrated the polyethylene sheet was removed from the sample wall and the difference between the first measurement and the second measurement was the net air leakage rate through the sample wall. The air flow rates were measured at a pressure difference of 75 Pascals.

2.4.2 Water Test

The following test was adapted from the procedure listed in ASTM E-331. The water penetration test consisted of masking the wall sample (covering the wall sample with a water and airtight plastic sheet), and pressurizing the chamber to 250 Pa. The water spray rack was then turned on. Following a brief calibration period the test chamber door was opened momentarily, without stopping the water pump, and the polyethylene sheet was removed. The test chamber was immediately restored to a full air pressure setting. During the test activity the weight of the water consumed by the wall sample was noted in the weight change of the reservoir. The test was continued for a sufficient length of time until a steady state condition was obtained. At that point the air leakage characteristics of each wall was changed from airtight to leaky and the changes in water consumption of each cladding system was noted as well as the pressure difference across the cladding. The airtight barriers were made leaky by opening the one inch hole in the gypsum or the polyethylene sheet. The test was continued for a sufficient length of time until steady state conditions were achieved.

2.4.3 Gust Load Test

As shown in Figures 2 and 3 of Appendix A, the test walls were constructed in the test chamber with the cladding facing the inside of the chamber. The tests were conducted as per the procedures in ASTM E-330 - Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Air Pressure Difference. However, to produce the dynamic gust tests a dual chamber test setup was used as shown in Figure 1. By pressurizing the chamber furthest from the test wall a nominal pressure differential between 50 and 100 Pa was produced across the bulkhead. Then by rupturing a membrane in the bulkhead wall a sudden gust of pressure was produced in the chamber ahead of the bulkhead. Different gust rates were produced by using a different size of opening in which the membrane was mounted, three different opening sizes were used for each wall panel to produce initial gust rates between 1800 and 6300 Pa/s. In all cases the target or peak gust pressure level was 1000 Pa., with gust tests conducted under both positive and negative air pressure differentials (positive tests with the chamber air pressure above atmospheric). The gust rates were determined by measuring the initial slope of the gust rate curves noted from the recordings.

2.4.4. Instrumentation

The pressure differentials were measured at three pressure tap locations (Figures 2 and 3) using three MK6 Air Ltd digital micromanometers. The pressure readings were recorded with a Tecmar Labmaster A/D convertor board and an IBM PC/XT microcomputer at a rate of 0.015 s between sets of readings, with the duration of the "gusts" generally less than 2 s.

2.5 Results of Air Leakage Tests

The air leakage tests were performed on three cladding types and for variations involving furring and non furring cladding. The vinyl cladding wall system was mounted on furring and directly on paper and sheathing, and on an assembly of polyolefin building paper, and fibreboard. The stucco cladding was mounted on K-Lath building paper and fibreboard and directly to the stud wall face. The brick veneer wall was mounted one inch away from a building paper and fibreboard sheathing. All wall types were vented. In the six cases considered. each of the systems were either equipped with a 6 mil polyethylene air barrier or a gypsum board finish. The 6 mil. polyethylene was mounted over the studs using glazing tape on two edges and a furring bar. This technique would not normally be used in construction, however, for these purposes it was found to be satisfactory. The gypsum board on the other hand, was mounted in the normal manner with all joints taped and sealed, using conventional materials. A 25 mm diameter hole was drilled through the gypsum board to simulate a minor air leakage path. Basic measurements were undertaken at 75 Pa. Under these conditions, the air leakage rate through each assembly was measured and recorded.

TABLE 1: Summary of Air Leakage Rates Through Sample Wall Assemblies

	AIR BARRIER CONSTRUCTION		
CLADDING SYSTEM	**SEALED POLY**	**SEALED GYPSUM BD**	**1" HOLE IN GYPSUM BD**
Vinyl Cladding, Building Paper, Fibreboard (Fig. 4,5)	<.01 L/m²·s	<.01 L/m²·s	0.58 L/m²·s
Vinyl Cladding, Furring, Building Paper, Fibreboard (Fig. 6,7)	<0.01 L/m²·s	<0.01 L/m²·s	0.44 L/m²·s
Vinyl, Building Paper, Fibreboard, Tyvek, Fibreboard (Fig. 8)	<0.01 L/m²·s	<0.01 L/m²·s	0.40 L/m²·s
Stucco, K-lath, Building Paper, Fibreboard (Fig. 11,12)	<0.01 L/m²·s	<0.01 L/m²·s	0.37 L/m²·s
Stucco, K-lath, Building Paper (Fig. 9,10)	<0.01 L/m²·s	<0.01 L/m²·s	0.64 L/m²·s
Brick Veneer, 1" Air Space, Building Paper, Fibreboard (Fig. 13,14)	<0.01 L/m²·s	0.01 L/m²·s	0.53 L/m²·s

It is seen from the results in the table that all leakage values measured for the sealed 6 mil. polyethylene, and the sealed gypsum board were less than 0.01 L/s/m². This construction demonstrates that it is possible to achieve air leakage rates which are less than 0.1 L/m², the recommended value from the IRC/NRC values published in the proceedings of Building Science Insight 86. It is also to be noted that the air leakage rate increased substantially when the air barrier was unsealed at the 25 mm diameter hole. The air flows varied between 0.37 L/m^2.s for the Stucco wall to 0.58 L/m^2.s for the vinyl cladding.

2.6 Results of the Water Tests

The results of the water penetration tests were plotted for the vinyl, stucco, and brick veneer cladding. The test results are represented as water penetration in litres versus the time of wetting in minutes in Figures 15, 16, and 17 of Appendix A.

In the first test, it was observed that the vinyl cladding absorbed a small amount of water, less than 0.8 L/min for the duration of the test. During the test period, the air barrier was unsealed at the 60th minute. However, it was noted from the chamber and cavity pressure recordings that little if any drop in pressure occurred across the vinyl cladding. It was later discovered that the paper and fibreboard sheathing provided much of the resistance to the air pressure and thus sustained a pressure equalized vinyl siding throughout the test. The minor water leakage through the vinyl cladding was attributed to wetting by capillary action around the vinyl siding components.

The second rain penetration test involved the stucco cladding system. In Figure 16, it can be seen that the amount of water penetrating the cladding system was slightly more than that which was found on the vinyl system. The rate of penetration was approximately 0.2 L/min over a 60 minute period. When the air barrier system was unsealed, a noticeable difference occurred between the wall cavity pressure and the chamber pressure. This difference, approximately 150 Pa, should have caused a difference in the penetration of rain through the stucco. This did not occur. It was determined that because the stucco was monolithic over the entire sample wall surface, there were no cracks or joints for water to penetrate. Thus, the water penetration was limited to the absorption characteristics of the stucco material and it was not noticeably affected by the air pressure difference across the cladding.

The rain penetration test on the brick veneer cladding proved to be more conclusive. It was noted that following the unmasking of the sample wall, the brick veneer experienced a rapid absorption of approximately 0.53 L/min up to the time when the air barrier system was unsealed. At first the absorption rate was rapid, well over 15 litres in the first 10 minutes and it gradually tapered off after to about 60 minutes into the test. When the wall cavity pressure was dropped by unsealing the air barrier, the brick veneer experienced a significant pressure drop with a consequent increase in the water penetration rate. In Figure 18, the rain penetration values and the air pressure differences are shown on an expanded scale. It will be noted from the chart that the average water penetration rate, before the air barrier was unsealed, was considerably lower than that which occurred after. A calculation of the slopes have yielded a rate of approximately 1 L/hr/m^2 during pressure equalization stage and an increase to 8.7 L/hr/m^2 with an average pressure difference of 130 Pa across the brick veneer cladding.

2.7 Gust Load Test Results

Tests were undertaken on the sample walls to determine the structural response of the various layers to an imposed gust pressure load. The layers included the cladding, the sheathing, and the air barrier system. Various rate of loading were achieved using various orifice plate sizes. The tests were undertaken for positive and negative pressure configurations. The test results that follow include the most representative sample tests for presentation.

Figures 19 through 22 are plots of the results for the vinyl clad walls subjected to both positive and negative gust tests at the highest gust rates. Table 1 below is a summary of the peak loads recorded from the gust load tests on the vinyl clad walls. In all of these tests it is noted that most of the gust pressure is carried by the gypsum board air barrier with low air pressure differences carried by the sheathing and almost no pressure carried by the cladding (less than 2%).

TABLE 2: Summary Of Peak Air Pressures On Wall Components For The Vinyl Clad Walls

a) "Air Tight" Gypsum Board

Test No.	Initial Gust Rate (Pa/s)	Total Air Pressure Across Wall (Pa)	Across Air Barrier (Pa)	Across Sheathing (Pa)	Across Cladding (Pa)
1	1800	1070	1037	70	10
2	2700	1018	979	89	10
3	4100	1008	958	116	15
4	1900	-1059	-1022	-62	-2
5	3200	-1002	-962	-83	-18
6	5100	-1020	-961	-115	-17

b) 25mm dia hole in Gypsum Board

Test No.	Initial Gust Rate (Pa/s)	Total Air Pressure Across Wall (Pa)	Across Air Barrier (Pa)	Across Sheathing (Pa)	Across Cladding (Pa)
1	2100	1043	912	148	4
2	2800	1016	886	145	12
3	4400	1026	878	177	17
4	2100	-1006	-855	-150	-10
5	3100	-985	-834	-154	-17
6	4700	-984	-819	-172	-20

In Table 3 that follows, a summary of the peak loads is recorded for the brick veneer cladding wall tests. Figures 23 through 26 are plots of the results for the brick veneer wall gust testing, also for the highest gust rates. As with the vinyl siding walls the gust pressures carried by the air barrier is highest with relatively low pressures on the sheathing. However, the brick veneer cladding experienced significantly higher pressures compared to the vinyl clad wall tests. The reason for this is due to the smaller venting area in the brick compared to the vinyl siding. In addition the higher stiffness of the brick veneer will also have an effect.

TABLE 3: Summary Of Peak Air Pressures On Wall Components For The Brick Veneer Walls.

a) "Air Tight" Gypsum Board

Test No.	Initial Gust Rates (Pa/s)	Total Air Pressure Across Wall (Pa)	Across Air Barrier (Pa)	Across Sheathing (Pa)	Across Cladding (Pa)
1	2100	1055	1016	56	111
2	3800	1032	984	73	194
3	5000	985	928	83	253
4	2200	-998	-962	-53	-95
5	3300	-1028	-985	-71	-155
6	5800	-1043	-979	-88	-240

b) 25mm Diameter hole in Gypsum Board

Test No.	Initial Gust Rates (Pa/s)	Total Air Pressure Across Wall (Pa)	Across Air Barrier (Pa)	Across Sheathing (Pa)	Across Cladding (Pa)
1	2200	1038	883	131	132
2	3800	1045	883	145	219
3	4800	996	824	147	258
4	2200	-1010	-858	-128	-111
5	3500	-1070	-903	-145	-181
6	6300	-1054	-859	-155	-282

Other trends observed with both walls are as follows:

a) level of pressure carried by the outer layers of the construction increased as the gust rate increased.

b) level of pressure carried by the air barrier decreased as the air leakage of the wall was increased (pressure carried by other components increased).

c) no significant difference between negative and positive pressure performance for the brick wall but pressure carried by the sheathing on the vinyl siding walls were higher for the negative pressure tests.

Based on the design pressures for air barrier elements in exterior wood frame wall construction should be designed to resist the full design gust loads prescribed for the building site in the applicable building codes.

However, due to factors such as poor air tightness of the wall, and lack of compartmentalization, the design pressure loads for cladding elements are harder to establish. If the leakage area of the air barrier is high enough the cladding may see a significant level of pressure. In addition if the cavity space behind the cladding is connected to adjacent elevations of the building, the effect of pressure equalization across the cladding may be eliminated.

Therefore, in a rainscreen wall, it would appear necessary to design both the air barrier elements and the exterior cladding elements for the full peak gust loads.

To establish realistic design pressures for cladding elements, further research to measure pressure levels on wall elements is required. This should be done by instrumenting buildings in order to record the pressure distributions through the wall construction over an extended period of time.

2.8 Conclusion

The methods used for the air leakage tests, the rain penetration tests and the gust loading were satisfactory to characterize the rainscreen attributes of the test wall samples. All wall samples constructed were sufficiently airtight using the methods described above, specifically, glazing tape and furring for polyethylene and conventional construction for gypsum board. The rain penetration tests illustrated that a pressure equalized brick veneer resists water penetration better than a non pressure equalized wall. The gust load tests were useful in determining that the wind pressure will transfer to the inner component of the wall. Thus a functional rainscreen wall requires; a vented and drained cladding, a structurally supported air barrier system, and a cavity defined by compartment seals.

In the water tests as well as the gust load tests the sheathing and the construction paper carried an unexpected proportion of the air pressure loads. This was attributed to the low air permeability of the combination of the fibreboard sheathing and the construction paper. These attributes may occur with other construction materials in wall systems and should be considered in the performance of any rainscreen wall design.

3. COMPARTMENTALIZATION

3.1 Introduction

The rainscreen wall is comprised of a vented and drained cladding system, a cavity behind the cladding, an air barrier to contain the cavity pressure and a compartment seal. A compartment may be defined as a cavity bound horizontally and vertically by compartment seals at the corners and along the floor and ceiling plane if the compartment is limited to one storey. The perimeter sealing is usually referred to as compartmentalization. When a cavity exists behind a vented cladding and it communicates around the building, it is referred to as a continuous cavity. In this case, the cavity pressure on the windward side will be rapidly transmitted around the corners of the building and prevent the cladding from pressure equalizing. Thus the need for compartmentalization is defined.

This part of the project examines the effects of air pressure distribution and wind pressure load distribution with and without compartmentalization of the cavity on a full scale model in a wind tunnel. Various cavity compartment were examined and included a fully compartmentalized cavity at the four corners, a continuous cavity, a cavity compartmentalized at the diagonal corners and a cavity compartmentalized on one face, the other three cavities connected continuously. The pressure distributions on the faces of the model and in the cavities of each configuration was examined to determine the cladding load as well as the load transfer of the wind pressures to other components within the wall systems.

3.2 Description of Model

The wood frame model consisted of a square plan room, 1.22 m long per side, and 1.22 m high. (Figures 1 and 2 of Appendix B). It was constructed using 38 mm x 89 mm studs at 406 mm on centre, with a 4x4 horizontal vinyl siding over an exterior construction sheathing paper, a 7/16 in. fibre board sheathing and finished with an interior 12 mm gypsum board air barrier system. All four elevations were constructed in a similar manner. The four walls were capped by a top and bottom platform. They were sheathed in plywood, air sealed on the inboard faces to enclose the test walls. The corners of the model were constructed to permit easy connecting and disconnecting of the wall cavities. In this way various combinations of compartmentalization were achieved through the opening or closing of ports connecting the various cavities.

3.3 Instrumentation

The model was instrumented with pressure taps throughout the construction. These consisted of small diameter metal tubes inserted through the interior gypsum board into the cavity of the wall as well as through the wall to the cavity behind the vinyl and through the wall to the outside. These metal tubes (taps) were then connected with plastic tubbing to a central data collection system. In addition, the model building was equipped with a set of perimeter penny taps on the exterior sidings to augment data collection on the exterior pressures around the test model. The location of these taps will be found in Fig. 19 of Appendix B. The reference pressure tap for all measurements was the static port of a pitot tube upstream of the test model in the wind tunnel.

3.4 Description of Wind Tunnel

The model was tested in the boundary layer wind tunnel at the Faculty of Engineering and Science of the University of Western Ontario. The wind tunnel is a closed circuit system and has both a low as well as high speed testing section. BLWT2 wind tunnel is 64 m long, 15 m wide and approximately 6 m high. The low speed section is 53 m long, 5 m wide and 4 m high. It is serviced by a 2.5 m "8 ft " diameter, 10 blade fan, 215 kilowatt "280 horsepower " variable speed, DC drive (Figure 18). The test model was installed in the wind tunnel on a turn table. Pitot tubes were located upstream and over the model to measure wind velocities in the free stream and over the model.

3.5 Method of Test

The first part of the test consisted of calibrating the test model pressure taps. To do this the model was wrapped in a plastic sheet and subsequently pressurized. In this way each tap could be calibrated electronically through a scanner and transducer to determine if it was clear and unobstructed prior to testing in the tunnel.

The second part involved the use of the wind tunnel. The wind tunnel was activated to obtain about 30 feet per second wind at or near the test model. The static pressures were read for all penny taps as well as all other pressure taps. Each tap was read through the scanner for a period of approximately 60 seconds. Following measurements of all taps, the orientation of the model was changed to a 45^{o} right rotation, and a new test was begun. After each normal and rotated position of the model a new configuration of compartmentalization was arranged, the procedure was then repeated as described above. The results of each test series has been illustrated tabulated in Appendix B.

3.6 Test Results

The model building was compartmentalized in five ways and oriented in two directions for a total of 10 tests. The model was oriented one face normal to the wind, 0^{o} (Figure 6), and alternately with a 45^{o} rotation to the right (Figure 7). The compartmentalization modes included fully compartmented cavity, Figures 6, 7, 8, and 9, a continuous cavity through the stud space, Figures 10 and 11, diagonal compartments, Figures 12, 13 and 14, and single elevation compartments with three other stud spaces connected. Figures 15, 16, 17.

The diagrams of Figures 8 through 17 illustrate the average pressures coefficient measured at the face of each elevation, the pressures coefficient in the cavity between the siding and the sheathing, the pressure coefficient in the stud cavity and the resultant pressure to the interior of the model. All measurements are reported as a fraction of the full wind speed stagnation relative to the Pitot measurement made upstream from the model.

The percentage figure on the diagrams indicate the percentage of the wind load pressure difference that occurred at the specific plane of materials or that would had occurred at the compartment seals. These values were derived by taking the difference in the pressure coefficients on either side of a plane and multiplying by 100. The variations in pressure coefficients in areas of symmetry are attributed to the small differences in leakage area between compartment zones. Variation in surface coefficient are due to imperfect symmetry of the model.

Figures 6 and 7 of Appendix B illustrate the external surface pressure coefficient distribution obtained from the pressure tap around the model with 30 feet per second frontal wind velocity. It will be noted that the front surface coefficient are positive and exhibit a value of approximately 1. Both sides of the model exhibit negative pressures and are slightly higher near the front on side A but symmetric on side B. Leeward surface pressures exhibit uniformity around 0.7.

Note the resultant interior pressure coefficient of -0.37. It is the sum of all flows in from the front elevation through the cracks and imperfections minus the flows outwardly from the model to the other three sides from similar imperfections.

In Figure 8 the model is fully compartmentalized at the corners. The figure illustrates the resultant pressures in each of the individual cavities. The cavity in the front elevation exhibits positive coefficients while the other three sides all have negative pressures reflecting the conditions of the wind pressures near their respective surfaces. It should be noted that the vinyl cladding of the windward side only sees 2% of the wind load. Simultaneously the sheathing sees 29%, and the gypsum board 101% of the wind stagnation pressure. Further, it is interesting to note that the pressure loads at the stud cavity compartment seals notably between the front and side (A) is considerably higher than stagnation; 170% on the inside while the outer seal experiences a 213% load.

In Figure 9 the fully compartmentalized model was rotated 45^{o} to the right so that the wind impinged on both side B and front elevation only. For the same velocity of wind, the surface pressure coefficients exhibited an average of 0.4 while the two leeward faces experienced negative pressure coefficients of -1.04 and -1.12 respectively. In this orientation there is a reduction of the interior pressure and a modest reduction in the load on the gypsum air barrier and the compartment seals.

In Figure 10, the compartment seals of the model were removed to obtain a continuous cavity around the perimeter walls. The orientation of the model was set to 0^{o} and the wind test was repeated using approximately the same wind velocities. With this configuration significant changes were noted in the pressure coefficient of the wall cavities. First, the interior pressure dropped to -0.54 and all cavities surrounding the interior space experienced negative pressures between -0.42 to -0.72. The gypsum board air barrier system experienced a maximum wind load of 15% while the exterior sheathing and building paper at the front elevation supported 150%. Although the paper and sheathing were not intentionally chosen for their airtightness, it exhibited considerable more resistance than expected. This behavior might explain why interior air barriers in non-compartmentalized floor plans have not been found to break away from fastenings on interior surfaces. Note also the very small load, 5 percent, on the vinyl siding of side (A). This presumably is because the sheathing in the cavity is relatively airtight compared with the vinyl siding and at the compartment seal surrounding the vinyl edge is satisfactory.

In Figure 11, the continuous cavity model was rotated 45°. In this orientation the pressure within the cavities vary less than in the normal orientation. The air barrier loads are small less than 30% but a significant load appears at the siding compartment edges and seals. The primary load appears again to be supported by sheathing and paper on all elevations.

In Figures 12, 13 and 14, the cavity is divided diagonally and rotated in three orientations. In all cases the vinyl siding load is less than 20% of the full wind load. The load on the compartment seals between the stud cavities in Figures 12 and 13 are large but are effectively neutralized in Figure 14. This is due to the symmetry of the loading with respect to the location of the compartment seals. In Figure 13, the cavity towards the wind side of the tunnel is positive whereas the cavity pressure on the leeward side is negative. This results in high loads on the compartment seals and air barriers.

In Figure 15, the wall cavity is compartmentalized on the front elevation only. As with the fully compartmentalized case, the front elevation sheathing and air barrier, but not the cladding, exhibit a high load, while the remainder of the elevations exhibit a lower pressure difference from outside to inside and a more evenly distributed load across all members of the construction.

In Figures 16 as with most other figures turned 45°, the siding cavity pressure appears slightly higher than the outside pressures. This is due to the averaging process that was used with respect to the single numbers at the outside of each facade. It is likely that the pressure load that the cavity sees is affected by the joints and vents in the siding which are distributed along the length of the siding pieces.

In Figure 17 the single compartment is at the rear of the model and it is readily apparent from the load distribution that the condition does not influence the adjacent cavities whether compartmented or not. Once again it can be seen that the primary load is carried by the sheathing and construction paper.

3.7 Conclusion

It appears from the results of the wind tunnel study that the compartmentalization of the wall cavities tends to transfer the air pressure load to the air barrier system. It was also noted from the test results that compartment seals should be designed to withstand loads in excess of 2.0 times the wind design load. Although the construction paper and exterior fiberboard sheathing were not intended to be the air barrier, its air permeability and stiffness attributes significantly influenced the distribution of pressures within the walls and on the air barrier in particular. This pressure distribution also depended on whether the cavity was compartmentalized or not.

It was noted from the non compartmentalized cases that pressures are dissipated around the cavities.. This form of equilibrium also occurs because air can flow around the cavity more liberally than when it is compartmentalized. This would also tend to entrain moisture penetration. Nevertheless, the test results demonstrate clearly that compartmentalization is required to reduces the air pressure loads on the outer layer of construction, and the sheathing and siding. Alternatively it will transfer the wind load to the air barrier and compartment seals. Further work will be required to determine the velocity of air movements in the cavities as well as the load distributions in other systems not using construction paper and fibre board sheathing but rather insulated sheathing having different attributes.

3.8 Recommendations

1. It is recommended therefore that a fully compartmentalized approach be favoured. However due consideration must be given to the construction details and types of compartment seals to be used.

2. It is recommended that wind tunnel testing of models of various construction to include wood siding, metal siding, brick veneer, stucco in combination with exterior insulated sheathing or rigid insulations should be undertaken.

3. Investigate the performance of a model with various test openings through the air barrier system to determine the effects on the interior pressure.

4. The development of compartment seals should be undertaken for wood frame construction and for various types of cladding systems to determine the leakage characteristics and the practicality of the details.

5. Investigate the velocity of air in cavity simultaneously with pressure distributions.

4. A SIMULATION MODEL

4.1 Introduction

To design a rainscreen wall the following physical parameter of the wall must be determined and they include; the volume of the cavity, the area of venting, the stiffness criteria of both cladding and the air barrier material and the leakage area of the air barrier system. It is also understood that the cavity volume is bound by compartment seals that must be leak proof.

To assist the designer, a simulation model can be used to determine the pressure equalization performance for the above noted features and characteristics. The simulation model developed predicts the pressure equalization behavior of a wall system in terms of structural air pressure load distribution and pressure equalization time. The simulation model was developed using the fundamental gas laws and basic equations of fluid dynamics.

4.2 Development of the Model

The simulation model that follows was developed to simulate the behavior of a single cavity compartment, with one plane exhibiting cladding features and one plane exhibiting air barrier attributes. In all simulations it is assumed that the inside pressure is the reference pressure, and various loading rates and initial conditions of cavity pressure are chosen for the simulation.

Previous research has shown that the loading pattern typically exhibited by gusting wind most closely resembles a triangular pulse function. However, to simulate the behavior of the laboratory tests, the model uses an exponential equation to generate the loading on the wall. The rate at which the load is applied can be adjusted by changing the value of the exponent in the equation.

The response of the cavity pressure in a rainscreen wall is a function of the basic gas law:

$$P = \frac{nRT}{V} \qquad \text{.............................(2.1)}$$

where
$P =$ absolute pressure (Pa)
$V =$ volume (m^3)
$n =$ no. of moles of air (moles)
$R =$ gas constant (J/(mole ·°K))
$T =$ absolute temperature (°K)

In the development of the simulation model, it was assumed that temperature would be constant; a value of 20 °C or 293 °K has been established as the standard condition. It was also assumed that the gas constant would not change significantly.

To understand how pressure equalization occurs, consider the situation where a positive pressure is applied to the wall surface. Pressure equalization will occur when the pressure in the cavity rises or falls to match the applied pressure. Movement of air into the cavity is one mechanism to increase the pressure in the cavity. The mass of air required to achieve equalization depends on the volume of the cavity. The rate at which equalization occurs depends on the rate at which the air can enter the cavity, which is given by the following equation:

$$Q = CA \left(\frac{2\Delta P}{D}\right)^n \qquad \text{... (2.2)}$$

where
$Q =$ air leakage rate (m^3/s)
$C =$ discharge coefficient (unitless)
$A =$ total area of opening (m^2)
$\Delta P =$ pressure difference (Pa)
$D =$ density of air (kg/m^3)
$n =$ exponent (between .5 and 1)

The rate of air flow into the cavity is constantly changing. As air flows in, the pressure difference across the cavity changes and the pressure difference across the cavity is the driving force which dictates the rate of air entering or leaving the cavity.

Another parameter that causes the pressure in the cavity to increase or decrease is related to deformation of the volume of the cavity. Depending on their rigidity (or flexibility), both the cladding and the air barrier will deflect under the applied load and will change the volume of the cavity. If the cladding deflects more than the air barrier, the cavity volume will decrease and the cavity pressure will increase without the flow of air into the cavity.

In actual situations, a combination of air movement and cavity volume change caused by deflections of the cladding and air barrier will occur. The program attempts to model these simultaneous occurrences. The resulting equation which must be solved takes the following form:

$$P_c = \frac{287 \cdot T \left[Vo \cdot de + (A_1 \cdot Cd \cdot T_s \cdot \sqrt{(2 \cdot de \cdot (P_e - P_c))} - (A_2 \cdot Cd \cdot T_s \cdot \sqrt{(2 . d_e \cdot (P_c - P_i))} \right]}{Vo - k_1 (P_e - P_c) + k_2 (P_c - P_i)} \quad ......(2.3)$$

where	Pc	= absolute cavity pressure (Pa)
	T	= absolute temperature (°K)
	Vo	= initial cavity volume (m^3)
	de	= density of air (kg/m^3)
	Ai	= area of cladding leakage (m^2)
	Cd	= discharge coefficient (unitless)
	Ts	= time interval (sec.)
	A2	= area of air barrier leakage (m^2)
	Pi	= interior pressure (Pa)
	k1	= flexibility constant of cladding (m^3/Pa)
	k2	= flexibility constant of air barrier (m^3/Pa)

The resulting equation proved too unwieldy to analyze directly so it was divided into smaller segments and solved numerically through a computer program using an iterative procedure. A listing of the computer program will be found in Appendix C. The program is also available on computer diskette, with instructions for use, and will be provided by CMHC upon request.

4.3 Input Parameters

When the program is executed, the following parameters must be input by the user:

- Test No.
- Volume of cavity (m^3)
- PF X1 (m^3/Pa)
- PF X2 (m^3/Pa)
- VA1 (m^2)
- VA2 (m^2)
- Time (s)
- Inc. (s)

Each of these parameters is discussed below.

Test No.

This is a dimensionless number input to identify the run no.

Volume

This is the initial volume of the cavity assuming the wall is in an equilibrium condition at an absolute pressure of 101000 Pa.

PFX1

This is the flexibility constant of the cladding. A flexibility constant equal to zero represents a rigid cladding which does not deflect under load. The units are m^3/Pa and represent the volumetric displacement of a plane of materials subjected to a pressure difference.

PFX2

This is the flexibility constant of the air barrier. A flexibility constant of 0.00005 m^3/pa represents a very flexible material, such as 4 mil polyethylene film spanning 405 mm in a wood frame wall.

VA 1

This is the total leakage and vent area of the cladding. A typical value for an 8 ft. by 8 ft. brick wall vented at the head joints every 24 in. o.c. would be 0.0024 m^2.

VA 2

This is the total leakage area of the air barrier. This value should be zero or very close to zero.

Time and Inc.

These numbers define the duration of the simulation. Inc. is the increment of time assumed to have passed before the equalization equation is solved. The default increment is 0.05 s. Time is the total number of seconds of real time for the simulation.

There are a number of other parameters which can be changed within the program. For the most part, these parameters were assigned constant values and are described below:

Loading

The program was designed to simulate a wind loading pattern having an exponential decay from an absolute positive pressure of 101000 Pa. Atmospheric pressure is assumed to be 100,000 Pa. The equation for the loading rate takes the following form:

$$P = 1000\, e^{-nt}$$

where $n = 5$

t = time (s)

Decreasing the variable n reduces the rate of change of pressure or decreases the rate of loading. A value of 5 was selected for the standard value of n because previous research indicated that this loading rate is most representative of a medium speed gust pressure change.

4.4 Output Results

The output from the computer program is dumped into a data file in a columnar format as follows:

Column 1: Iteration Number

Column 2: Time (sec.)

Column 3: Absolute wind pressure (Pa)

Column 4: Absolute Cavity pressure (Pa)

Column 5: Pressure difference across the cladding (Col 4 - Col 3) (Pa)

Column 6: Pressure difference across air barrier (Co/4-Pi) (Pa)

Column 7: Volume of cavity (m^3)

Column 8: Mass of air in cavity (kg)

Column 9: Flow of air through cladding (l/s)

Column 10: Flow of air through air barrier (l/s)

This data can be imported into a spreadsheet program, such as Lotus 1-2-3, for further manipulation or graphing.

The data which are important to designers are the time to equalization and the peak load on the exterior cladding. These values can be obtained by scanning Column 4 of the data file. The peak load is easily discernable by scanning this column of data. It is somewhat more difficult to establish the time to equalization.

4.5 Comparative Validation

To validate the simulation model, it was necessary to compare it's output with the measured performance of other systems. The output results of significance are peak load air pressure difference on cladding and equalization time for a particular type and duration of wind gust. The output of the simulation model, was compared with the measured performance of a metal and glass curtain wall system. The performance of the latter was reported in a paper in the 1987 CSCE Centennial Conference Proceedings, May 19 - 22, 1987, or IRC/NRC reprint number 1547.

From the above noted publication, it was determined that the following features characterized the elements and geometry of the metal glass curtain wall tested. The volume of the cavity was 0.15 m^3, the area of leakage was 0.00023 m^2, no leakage through the back-pan, and an estimated stiffness of 0.000002 m^3/Pa for the glass spandrel and 0.000005 m^3/Pa for the back-pan. These parameters were input to our simulation model along with an exponential load exhibiting a 4000 Pa/sec decay. It will be noted from the comparison of the measured and computed results, that the results closely approximate each other. There is noted difference in the slope of decay but the peak loads and duration times are approximately the same under similar loading conditions.

Steady State Characteristics

The simulation model was developed primarily to simulate gust loading conditions. However, for steady state conditions, it was found by experiment, that the pressure distribution across the cladding (vinyl, stucco, brick) and the air barrier system (sheathing, gypsum) may be determined from the following equations.

$$CL = \frac{La^2(Pe-Pi)}{La^2+Va^2} \qquad \text{........(2.5)}$$

or

$$AL = \frac{Va^2(Pe-Pi)}{La^2+Va^2} \qquad \text{........(2.6)}$$

where CL = cladding load (Pa)
AL = air barrier load (Pa)
La = air barrier leakage (m^2)
Va = vent area (m^2)
Pe = external absolute pressure (Pa)
Pi = interior absolute pressure (Pa)

For example, if a sample wall has a .001 m^2 vent area through the brick weep holes, and it has .001 m^2 leakage area through the air barrier system, the wind load (Pe - Pi) of approximately 500 Pa would exhibit 250 Pa on the cladding and 250 Pa on the air barrier system. There would also be a flow of air corresponding to the actual size of the leakage, usually referred to as infiltration. It is to be noted that the flexibility or stiffness of the cladding or of the air barrier system is of no importance or consequence to the distribution pressures under steady state conditions, however, the deflections of the cladding components or air barrier systems under steady state loads may prove unacceptable.

Thus, the steady state pressure distribution in an exterior wall is easily determined from the known characteristics of leakage areas through the various systems in a compartmentalized wall, or can be obtained from field measurements of pressure and one other parameter, the leakage or vent area of the cladding, or the leakage of the air barrier system.

Dynamic Load Characteristics

Dynamic loads on the cladding and the resultant distribution of pressures within the wall is more difficult to predict and is the subject of our simulation model. First, to simulate a gust effect or transient load, our experimental methods involved pressurizing a chamber and releasing the pressure suddenly by means of a special orifice valve and membrane to cause a rapid change in pressure. The rate of change of pressure of the chamber is set to fast, medium, or slow by means of various orifice sizes and membrane selection. The pressure drop/increase using this method was found to decay along an exponential curve and therefore could be analyzed and simulated.

While simulated gust pattern does not mimic wind behavior, it exhibits all the dynamics of wind effects, and for this reason was deemed suitable to validate the simulation model. Thus, the simulation uses an exponential load formula for this purpose. It is to be noted that the simulation can also be executed using a triangular pulse load of varying amplitude and frequency and/or a sinusoidal load of any frequency and amplitude. See program listing #1 and #2 as well as Figures 10 and 11 of Appendix C.

A sensitivity analysis of the effect of the parameters is undertaken in the next section. While we believe that the model provides a good first approximation of the dynamic behavior of the cavity pressure for the noted characteristics, it should be compared with the results of other assemblies notably masonry cavity wall systems, precast sandwich wall panels, and similar structural components and elements to determine if size or scale effects exhibit a significant influence.

It is to be noted that the math model does not consider the resonance effects of the air in the chamber or the frequency response of materials in terms of possible dynamic oscillations of the mass of air or other components comprising the metal and glass curtain wall. Measurements made of the system described have indicated the cavity pressure decayed without any oscillatory behavior.

4.6 Example Simulations

To demonstrate the use of the program and the effect of changing the input parameters, a number of example simulations were executed. First, some basic conditions were established. These would be typical of a brick veneer wall 2438 mm by 2438 mm with a 19 mm cavity and a concrete back-up wall. Both the cladding components and the air barrier system are assumed to be rigid. The value of the input parameters used in the simulation are summarized in the first line of Table 2.1. Then, each input parameter was varied as indicated in Table 4.1 The results are shown on Graphs in Figures 1 thru 7 in Appendix C.

TABLE 4: INPUT PARAMETERS FOR EXAMPLE SIMULATIONS

Example	VOL m^3	PFX1 m^3/Pa	PFX2 m^3/Pa	VA1 m^2	VA2 m^2	RUN TIME (sec)	INC (sec)
Basic Conditions	0.1	0	0	.0001	0	4	.05
Cavity Volume Increased	**0.5**	0	0	.0001	0	4	.05
Cladding Flexibility increased	0.1	**5x10-6**	0	.0001	0	4	.05
Air Barrier Flexibility Increased	0.1	0	**1x10-6**	.0001	0	4	.05
Cladding Leakage Increased	0.1	0	0	**.0005**	0	4	.05
Air Barrier Leakage Increased	0.1	0	0	.0001	**.0001**	4	.05

4.7 Discussion

Parametric Analysis

Increasing the initial volume significantly increased both the peak load on the cladding and the time to equalization. This result is expected because the larger volume requires that more air must be exhausted to attain equalization. However, the fixed vent area limits the rate at which the air can be exhausted from the cavity.

Increasing the flexibility of the cladding reduced the peak load on the cladding but increased the time to equalization. This is attributed to the elastic deformation of the cladding which cause the cavity pressure to follow the outside pressure. However, as the load diminishes, the deformed cladding will sustain a difference until it has returned to rest position.

Increasing the flexibility of the air barrier increased the peak load response on the cladding and increased the time to equalization.

Increasing the vent area (or the cladding leakage) reduced both the peak load and the time to equalization. This result was expected because more air could move out of the cavity in the same period of time.

Increasing the leakage through the air barrier decreased the peak loading and lightly increased the time to equalization. In this situation, the cavity pressure decays both outwardly and inwardly in the simulation to accelerate pressure equalization. In a pressure buildup condition, we could expect leakage through the air barrier to have the reverse effect.

The example simulations, although limited in number, demonstrate the sensitivity that model has with respect to each variable. Verification of the model against actual test results is done in Section 6.1.

4.8 Limitations and Further Development

Unpredictable results may be output from the simulation when the input parameters are not within realistic limits. The input parameters of leakage area and flexibility coefficient may be difficult to determine when trying to design a wall. More test data is needed to establish typical ranges for these parameters.

Further development of the model could include the following:

1) allowing user to input description of construction materials and let the computer generate the flexibility constants;

2) expand the simulation model to provide conditions using a steady state wind pressure;

3) expand user flexibility with respect to gust rate loadings;

4) develop a single number concept to define the peak load and pressure equalization; response for a rainscreen wall system;

5) Expand the model to include a rain penetration index from the Climatic Data (Weather Index).

6) Develop model further to predict rain penetration index for 15 min., one hour and four hour storms.

5. DISCUSSION

5.1 Rain Penetration

Rain penetration is one of the oldest problems building owners have had to deal with, yet it still occurs all too frequently. The penetration of rain can not only damage interior finishes and materials, but it can also damage the structure of the walls themselves.

A notable reference on the topic of rain penetration is Canadian Building Digest CBD 40 "Rain Penetration and its Control", by Kirby Garden. This document was published in 1963 and is one of the earliest references on the rainscreen principles. In fact, the term "Open rainscreen" was coined in this paper. The following discussion on rain penetration is based on the information contained in CBD 40.

Rain penetration results when a combination exists of water at the surface of the wall, openings through which it can pass, and a force to move the water through these openings. The elimination of any one of these three conditions could prevent the occurrence of rain penetration. While wide roof overhangs may help to shelter the walls of a low-rise building, it is not likely that rain will never reach the walls. Therefore one of the remaining two conditions must be eliminated to prevent rain penetration.

The face seal approach attempts to eliminate all the openings in the wall through which water can pass. However, the materials used to seal all these openings are exposed to extremes of weather and to movements of the building. Even if the problems of job site inaccuracies and poor workmanship can be overcome and a perfect seal can be achieved, the in-service weather conditions will eventually cause the deterioration and failure of these seals, creating openings in the wall through which water can pass. Unfortunately, these openings can be extremely tiny and difficult to identify, so that even an extensive maintenance program may not keep the building free of openings.

The alternate approach to controlling rain penetration is to eliminate the forces which drive or draw water into the wall. There are typically considered to be four such forces: kinetic energy, capillarity, gravity and wind pressure differences. Each of these forces is explained below.

Kinetic Energy

For a wind driven rain storm, rain droplets can be blown directly into large openings in the wall. However, if there is no direct path to the interior, the rain droplets will not pass deeply into the wall. Where large openings, such as joints, are unavoidable, the use of battens, splines, baffles or overlaps has been successful in minimizing rain penetration caused by the kinetic energy of the rain drops.

Capillarity

Due to the surface tension of water, voids in a material will tend to draw in a certain amount of moisture until the material approaches saturation. If capillaries pass from the exterior to the interior, water can move through the wall due to the action of capillary suction. While partial water penetration of a wall by capillarity is characteristic of porous cladding material, the introduction of a discontinuity or air gap can prevent through-wall movement of water.

Gravity

The force of gravity will cause water to move down the face of the wall and into any downward sloped passages into the wall. To prevent gravity induced movement through joints, they are typically designed to slope upwards from the exterior. Unintentional cracks or openings are more difficult to control. If there is a cavity directly behind the exterior face of the wall, any water that does flow through the wall will then be directed downward, by gravity, on the inboard face of the exterior wall. At the bottom of the cavity, the water can then be drained back to the outside through the use of sloped flashings.

Air Pressure Difference

An air pressure difference across the wall of a building is created by stack effect, wind and/or mechanical ventilation. If the pressure on the exterior face of the wall is higher than on the interior of the wall, water can be forced through tiny openings in the wall. Research has shown that the amount of rain moved through the cladding by this mechanism is the most significant. This force can be eliminated or reduced by the use of the pressure-equalized cavity. This concept is discussed in detail in the following section.

5.2 Principles of Pressure Equalization

The theory of the pressure equalized cladding is that it neutralizes the air pressure difference across the cladding (caused by wind) which causes water penetration (the wind). It is impossible to prevent wind from blowing on a house but it is possible to counteract the pressure of the wind so that the pressure difference across the exterior cladding of the wall is close to zero. If the pressure difference across the cladding is zero, one of the main forces of rain penetration is eliminated.

A rainscreen wall incorporates two layers on wythes separated by an air space or cavity. The outer layer or cladding is vented to the outside. When wind blows on the building facade, a pressure difference would be created across the cladding; however, if the cavity behind the cladding is vented to the outside, some of the wind blowing on the wall enters the cavity, causing the pressure in the cavity to increase until it equals the exterior pressure. This concept of pressure equalization presupposes that the inner wythe of the wall is airtight. This inner wythe, which includes an air barrier, must be capable of sustaining the wind loads in order for pressure equalization to occur. If there are openings in the air barrier, the pressure in the cavity will not equalize and rain penetration may occur.

A further advantage to consider is that the wind load will not be imposed on the exterior cladding. Potentially, it is possible to design the exterior cladding of a rainscreen wall to be much lighter than it has been traditionally and thus economies in construction could be realized.

The concept of pressure equalization is readily understood when steady-state conditions are considered. However, the wind is dynamic and the exterior wind pressures impinging on a building facade are in a constant state of flux. Previous research has shown that there is typically a time lag between the application of the exterior load and pressure equalization in the cavity. As a result of this time lag, a pressure difference does occur across the exterior cladding. For the rainscreen concept to be effective, this time lag should be as short as possible. Therefore, when we examine the performance of a rainscreen wall, one of the primary factors considered is the time to equalization. Another is the load distribution on the exterior cladding. The higher the load, the higher the driving force moving rain to the interior, and the longer the time to equalization, more rain is likely to penetrate.

Some rain penetration through the exterior cladding can be tolerated because the cavity should be designed to drain. However, it is still desirable to the overall function of the wall to minimize any penetration of rain. Therefore, the "ideal" rainscreen wall would equalize instantly and the exterior cladding would never experience any wind load. In reality, this is almost impossible to achieve. We therefore expect rainscreen walls to have a short equalization time and small proportion of the peak wind load on the cladding.

At first consideration, the time to equalization seems a reasonable intuitive question. The most simplest definition would be the length of time required after application of an exterior load for the cavity to attain the same pressure. However, from our research, it was found that while the pressure across the cladding may approach zero, the equalization follows exponential decay and therefore never occurs. It may be more appropriate therefore to define the time to equalization as the time it takes for the cavity to reach a certain percentage of the applied load or the difference between the applied load pulse and the response load.

5.3 Factors Affecting Pressure Equalization

There are a number of wall parameters that affect the rate at which pressure equalization will occur, including:

- leakage area of the air barrier system
- area of vent openings
- cavity volume
- stiffness of the air barrier system
- stiffness of the cladding
- sealing of cavity perimeter (compartmentalization)

The rate of the applied load and the magnitude of the applied load will also affect the time to equalization. Each of these factors is discussed below.

5.4 The Air Barrier System

If the air barrier is perfectly tight, when a pressure is applied to the wall, all air entering the cavity through the vented cladding will remain in the cavity to cause the pressure in the cavity to increase. If there is leakage through the air barrier, air will move from the cavity to the interior of the building, and equalization does not occur. The ratio of the air pressure difference across the wall to the air pressure difference across the cladding will depend on the relative tightness of the cladding and the air barrier. Ideally, the air barrier should not leak, both for the rainscreen to function to its maximum level and also to prevent the exfiltration of indoor air and the infiltration of outdoor air.

5.5 Area of Vent Openings

Pressure equalization depends partly on air movement into/out of the cavity. The rate at which air can move through the cladding depends on the area of openings through the cavity. If only one small opening exists, equalization may be slow, whereas if there are many openings, equalization will occur much faster. Research has indicated that the area of vent openings required depends on the cavity volume and the stiffness of the cladding system and the air barrier system.

5.6 Cavity Volume

A larger cavity will require more air to move into or out of the cavity to cause pressure equalization. Therefore, given the same area of vent openings, a smaller cavity will equalize faster than a larger cavity. Thus, in designing a rainscreen wall, consideration must be given to the proportion of vent area in relation to cavity volume.

5.7 Stiffness of the Air Barrier Plane

If the air barrier material is flexible and a positive pressure is applied to it, it will deflect. The result of this deflection will be an increase in the volume of the cavity and a larger volume takes longer to pressure equalize. Thus, the more flexible the air barrier, the longer it will take for the cavity pressure to reach outdoor conditions. This causes the cladding to experience dynamic loads. Therefore, in designing a rainscreen wall, the air barrier should be designed to be as rigid as possible.

5.8 Stiffness of the Cladding

If the cladding is flexible, the cladding will deflect inwards, reducing the cavity volume, when a positive load is applied. Thus, the cavity will tend to pressure equalize faster than normal from the compression effects of the cladding deflection.

But, the cladding deflection will cause the cavity pressure difference to linger longer. This characteristic of the cladding tends to dampen the gust loads on the facade. From the result of our pressure tests, it can be seen that a flexible cladding experiences a small but longer lasting air pressure difference.

5.9 Compartmentalization

In designing a building with the rainscreen approach, consideration must be given to the pressure variations over the surface of the building. When the wind impinges on a building facade, it tends to flow around and over the top of the building producing variations in pressure on the surface of the buildings. In some areas the pressure will be negative. If the cavity behind the cladding is continuous around the building, the pressures on the surface of the cladding may induce lateral air movement within the cavity from ingress of air at the front to exit along the sides and back. This was demonstrated in the compartmentalization tests, Chapter 3.

Air will move within the cavity from a region of positive pressure to the region of negative pressure at the sides of the building; as a result of this movement of air, pressure equalization will not occur within the stud cavity. Therefore, it is important to "compartmentalize" the cavity. By Compartmentalization we mean dividing the wall cavity into smaller individual cavities through the use of strategically positioned, airtight seals. It is particularly important that these compartments do not extend around the corner of a building.

In addition it is important to note that compartment seals are not the same as baffles. Such techniques as stuffing fiberglass in a crack, or gluing rigid foam pieces that do not fit tightly is not satisfactory. A compartment seal may be an elastomeric membrane, a sheet steel angle, or foamed in urethane insulation.

5.10 Wind Loading

Two conditions of wind must be considered with the pressure equalized wall, the steady state condition and the gust effect. While gusting presents a dynamic loading, it is the time average pressure over the surface which exhibits the most influence on rain penetration. For this reason, water penetration tests were conducted at a steady state pressure while the dynamics of gusting was examined for structural effects.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The rainscreen wall concept is a viable solution to water penetration control but it requires the effort of more than the cladding system alone. The rainscreen must be complimented by an effective air barrier system capable of supporting steady state as well as dynamic wind loads. The cavity volume must be of minimum size and satisfactorily compartmentalized to prevent the flow of air from escaping from one part of the cavity to the next, particularly around corners.

The rainscreen concept was examined in reference to wood frame construction. The principles however have been applied to numerous commercial types of exterior wall systems. These include: precast, sheet steel wall systems, and metal and glass curtain walls. The concept has also been applied satisfactorily to the design of window frames and window sashes. Many new designs incorporate the vented and drained cavity within the sash and these systems have existed in commercial windows for well over 25 years.

6.2 Laboratory Testing

The method of test developed for the determination of water penetration under simulated wind driven rain has proven satisfactory and quite dependable. This method has eliminated the need for subjective impressions of wetting, soaking and water penetration with the more objective measurements determined by the gravimetric analysis.

It was noted with the vinyl clad wall systems, the stucco cladding systems, and even the brick cladding sample walls, that the fibreboard and building paper provided more airtightness and structural support than expected. This was found during the water tests as well as in the wind tunnel tests undertaken on the wood frame model.

The results of the water testing have shown that given adequate venting and drainage and an effective air barrier system on the inside of the stud face, the brick veneer wall does benefit by the pressure equalization phenomenon. With a difference in air pressure across the cladding of 130 Pa, our test results have indicated a tenfold increase in water penetration from a fully pressurized cavity to a cladding subjected to a significant air pressure difference.

The dynamic load testing has illustrated that the air barrier system must be designed to carry the full wind load pressures. In addition, due consideration must be given to the gust strength factor. Some rainscreen wall systems will transmit steady state and dynamic pressures to the air barrier system within the wall.

It was also found from our testing that pressurization or depressurization exhibited symmetry in a distribution of the load path from the air pressure difference. In other words, whether a wall was negatively pressurized or positively pressurized from a gust, the loads on the air barrier and other components of the wall were approximately the same.

6.3 Compartmentalization

From the results of the compartmentalization testing, it was clear that without corner seals, a continuous cavity behind the cladding and around the building does not support pressure equalization. With compartmentalization at diagonally opposite corners, the performance of the cavity will be relative to the direction of the wind. When the wind faces one of the corners which does not have compartmentalization, the cavities will divide into two zones, a negatively pressurized zone in the leeward side of the wind, and a positively pressurized zone on the windward side. This results in high pressure loads on the seals and baffles. On the other hand, when the wind faces one corner which is compartmentalized and the other is diametrically opposed, little performance improvement is obtained as the symmetry is similar to a fully continuous cavity. The optimum situation is when all four corners are suitably compartmentalized. In this configuration, each face of the cube model exhibited the pressure signs and characteristics of the wind pressures applied to that face.

It was noted from the results of all permutations and combinations of orientation and compartmentalization that the vinyl cladding was essentially pressure equalized under most conditions. This was due primarily to the unsuspected contribution of the building paper and fibreboard sheathing which provided more airtightness than the cladding system but less than the air barrier system.

6.4 Mathematical Modelling

The mathematical model can be used to predict the dynamic conditions of pressure equalization and the cavity performance of a rainscreen wall system. The model was validated against lab examples and found to correlate reasonably well with measured results. The input parameters of the model should be realistic otherwise the output becomes somewhat unpredictable.

The stiffness of claddings and air barriers has a significant effect on the distribution of gust wind loads to the structural element. From the simulation results, it is recommended that the stiffness of the air barrier be as high as possible, whereas the cladding should have a stiffness somewhat less than the air barrier for a better load distribution and minimum pressure difference across the cladding.

6.5 Recommendations

Numerous recommendations were presented following the conclusions of each chapter. They are summarized here for convenience. To review the detailed recommendations see chapters 2, 3 and 4.

It is recommended that additional water tests be undertaken on simple cladding elements to augment the sample data base on rain penetration performance for walls. It would be noteworthy to determine the difference between the vinyl siding with fibreboard as a sheathing, and vinyl siding fastened to a glass clad insulation. It is suspected that these two types of sheathings and air barrier systems would alter the performance of the cladding system and its behavior as a pressure equalized rainscreen system.

Gust load transfer within a wall can now be predicted satisfactorily using a computer model. However, some research is needed to determine the structural properties of various types of sheathings and air barrier systems to ensure long term performance of the rainscreen wall.

Wind tunnel testing was both practical and revealing. The wind load profiles on the face, sides, and leeward parts of the model building would appear to follow the classic patterns. However, the significant variation in pressure distribution between fully compartmentalized and fully continuous cavities necessitates further research.

A similar investigation should be undertaken using different types of exterior sheathing systems. In addition, the investigation should be directed to determining the sensitivity of the indoor air pressure to imperfection on the air barrier system.

The results of the compartmentalization tests illustrated that the design and construction of the compartment seals goes beyond providing a simple baffle. These seals must be designed to withstand high air pressure loads, and to be effective, must connect the cladding to the air barrier system.

The mathematical model developed to simulate pressure equalization provides a satisfactory first order capability. However, it is recommended that a parametric study be undertaken to determine the effects and ratios of such items as vent area to volume ratio, absolute and relative stiffness of air barrier in cladding system, the distribution of pressure loads in a multi-plane system of wall component. The model should be developed to incorporate the results of the water penetration rates of different cladding types.

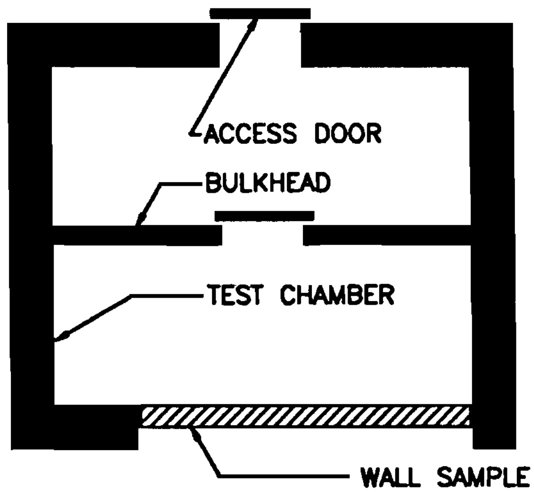
APPENDIX A

FIGURES OF LABORATORY TEST APPARATUS,

CONSTRUCTION DRAWINGS OF TEST WALLS

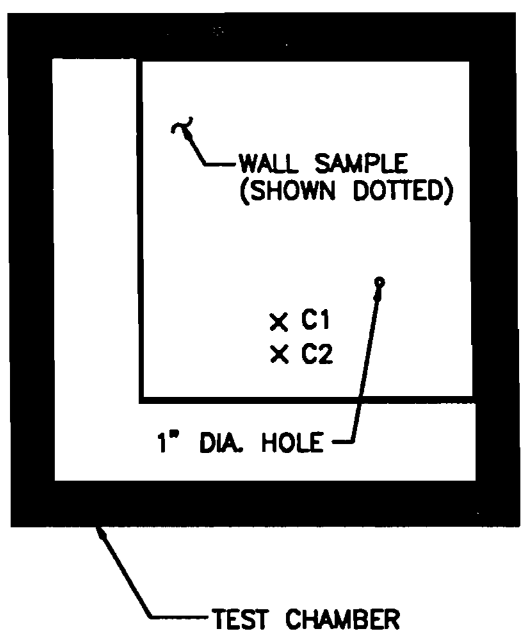
AND

CHARTS OF TEST RESULTS



PLAN

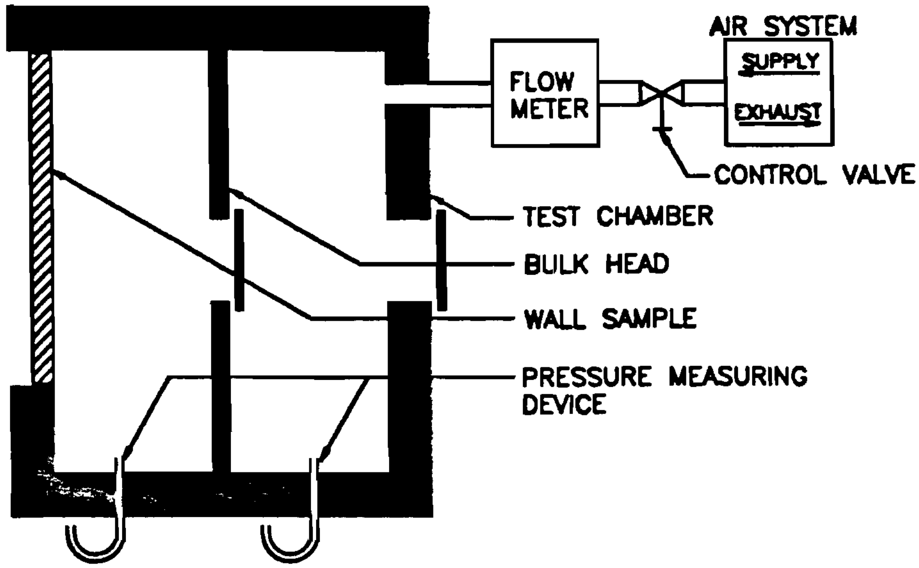
TEST CHAMBER



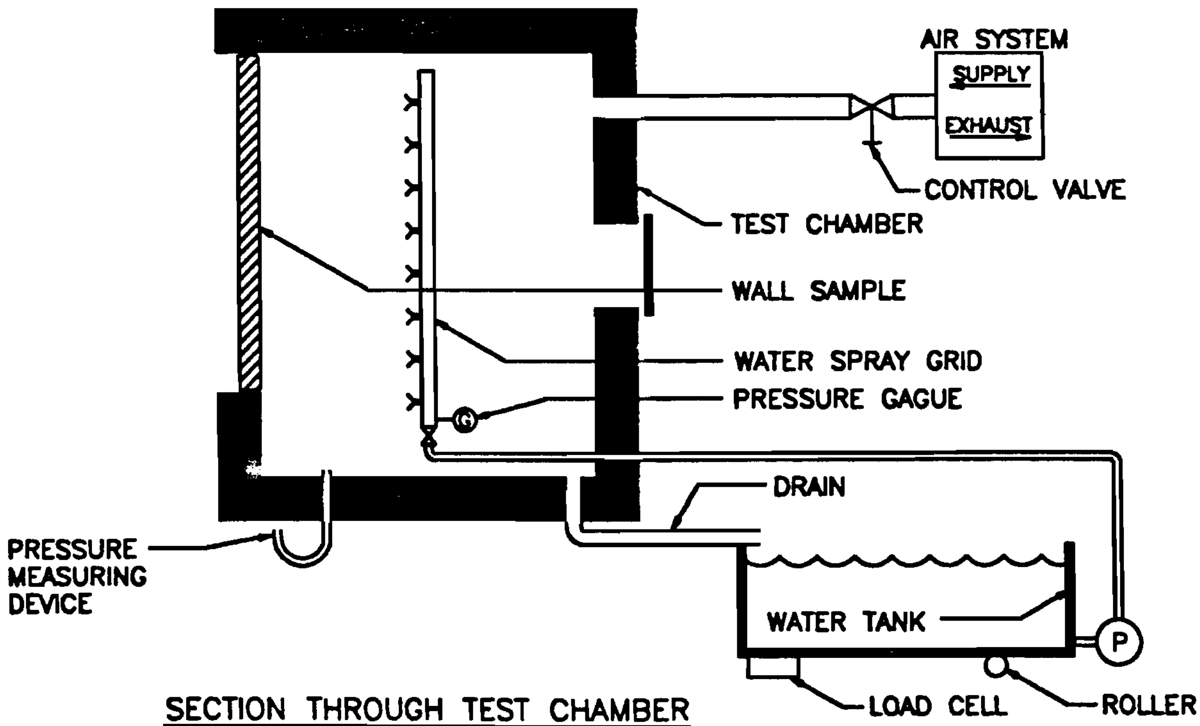
ELEVATION

TEST CHAMBER

FIGURE 1

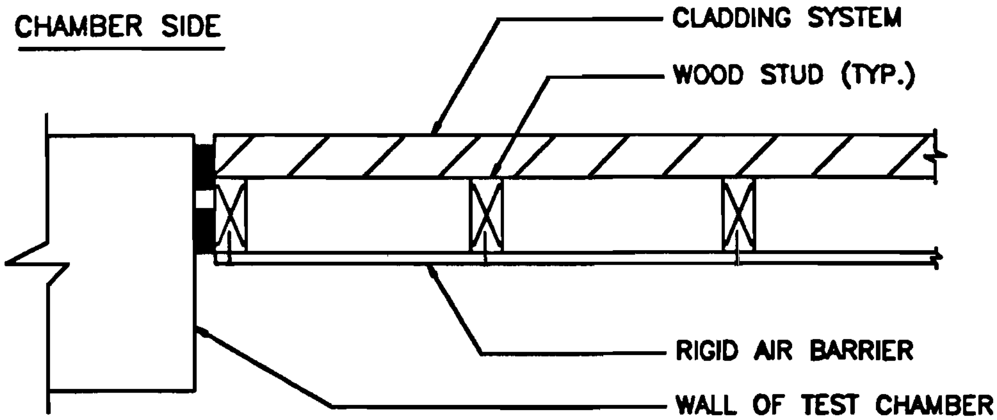


SECTION THROUGH TEST CHAMBER SHOWING GENERAL AIR LEAKAGE & PRESSURE EQUALIZATION SET-UP

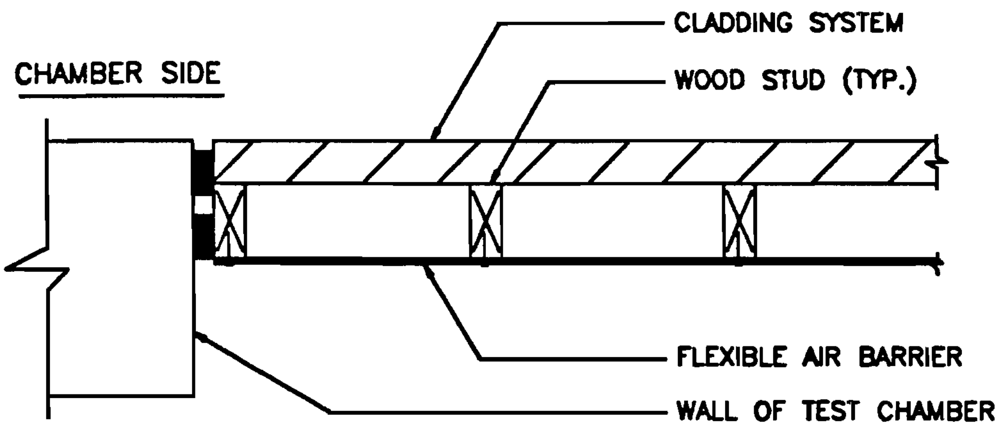


SECTION THROUGH TEST CHAMBER SHOWING GENERAL WATER LEAKAGE SET-UP

FIGURE 2

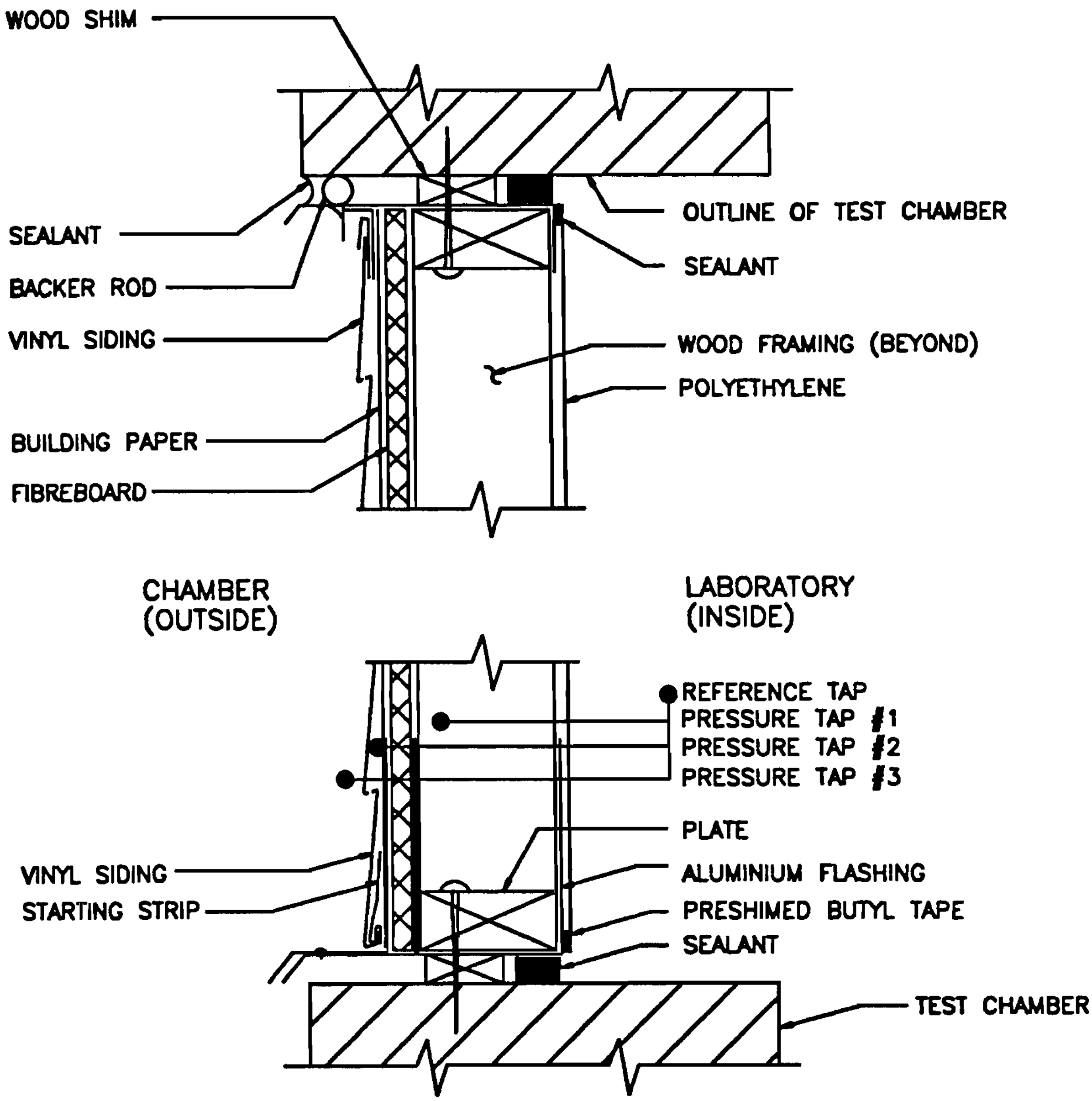


DETAIL OF JUNCTION BETWEEN WALL SAMPLE AND TEST CHAMBER
FOR RIGID AIR BARRIER



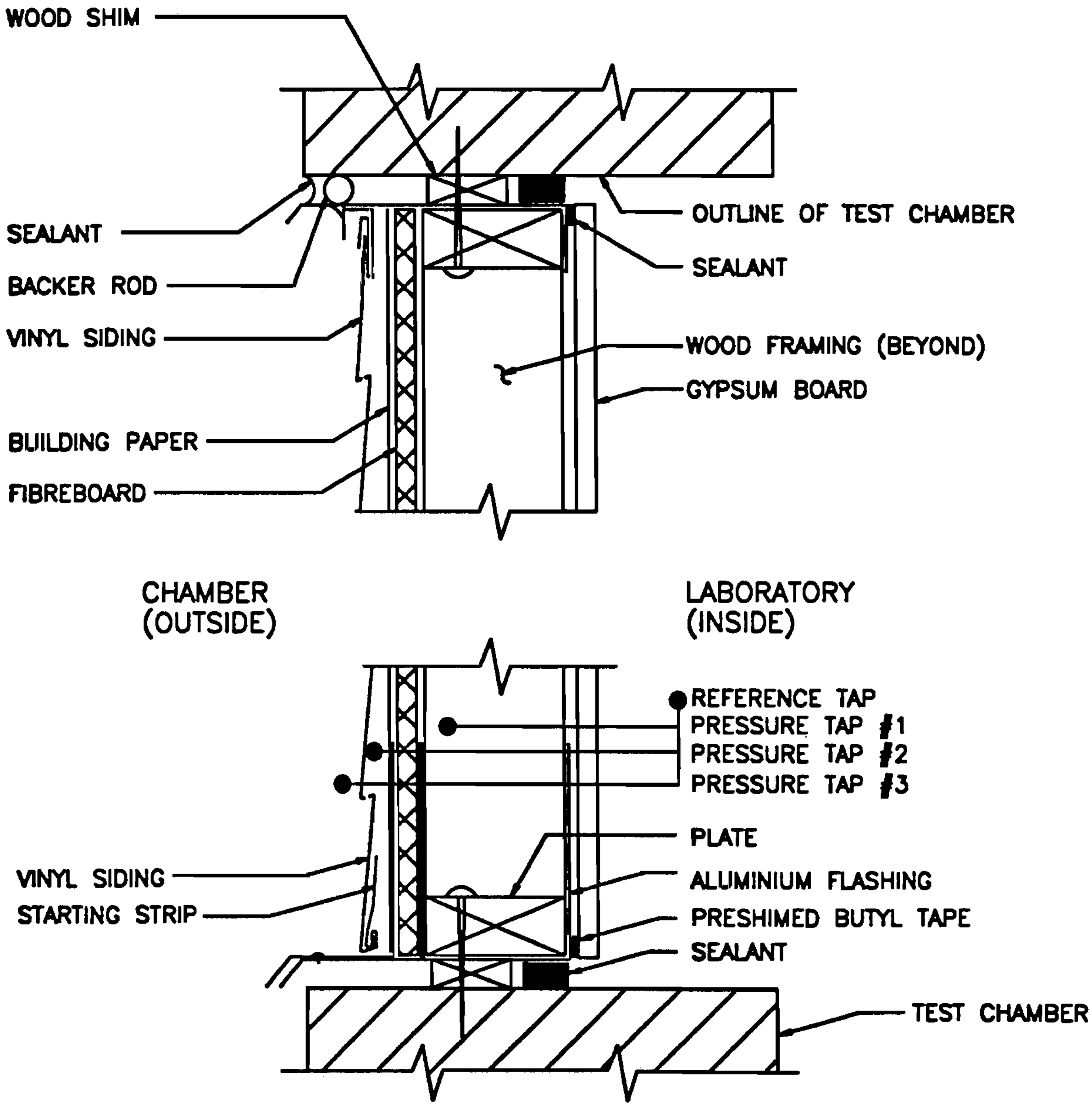
DETAIL OF JUNCTION BETWEEN WALL SAMPLE AND TEST CHAMBER
FOR FLEXIBLE AIR BARRIER

FIGURE 3



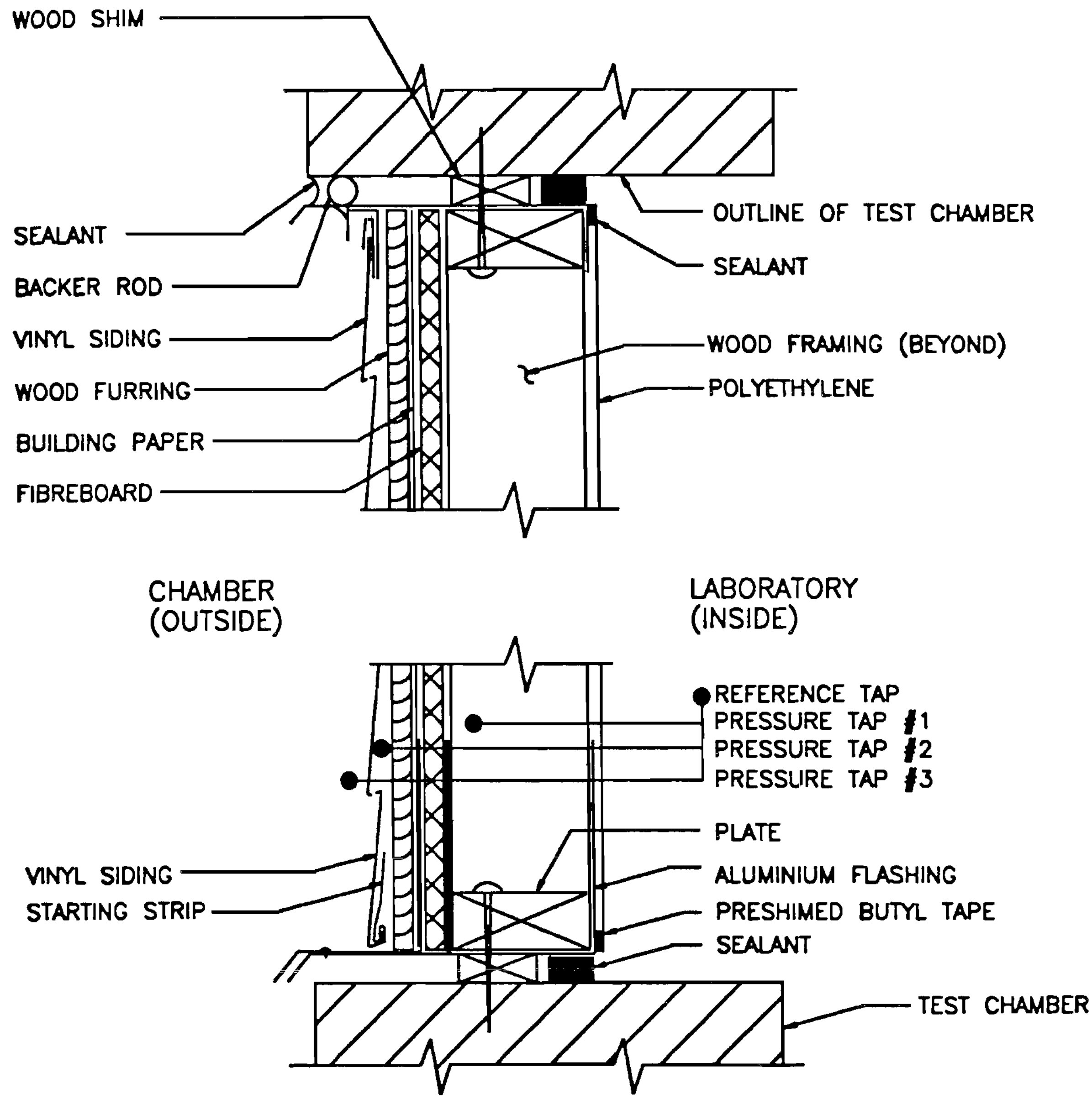
SECTION THROUGH VINYL CLAD
EXTERIOR WOOD FRAME WALL
POLY AIR BARRIER NO
FURRING UNDER SIDING

FIGURE 4



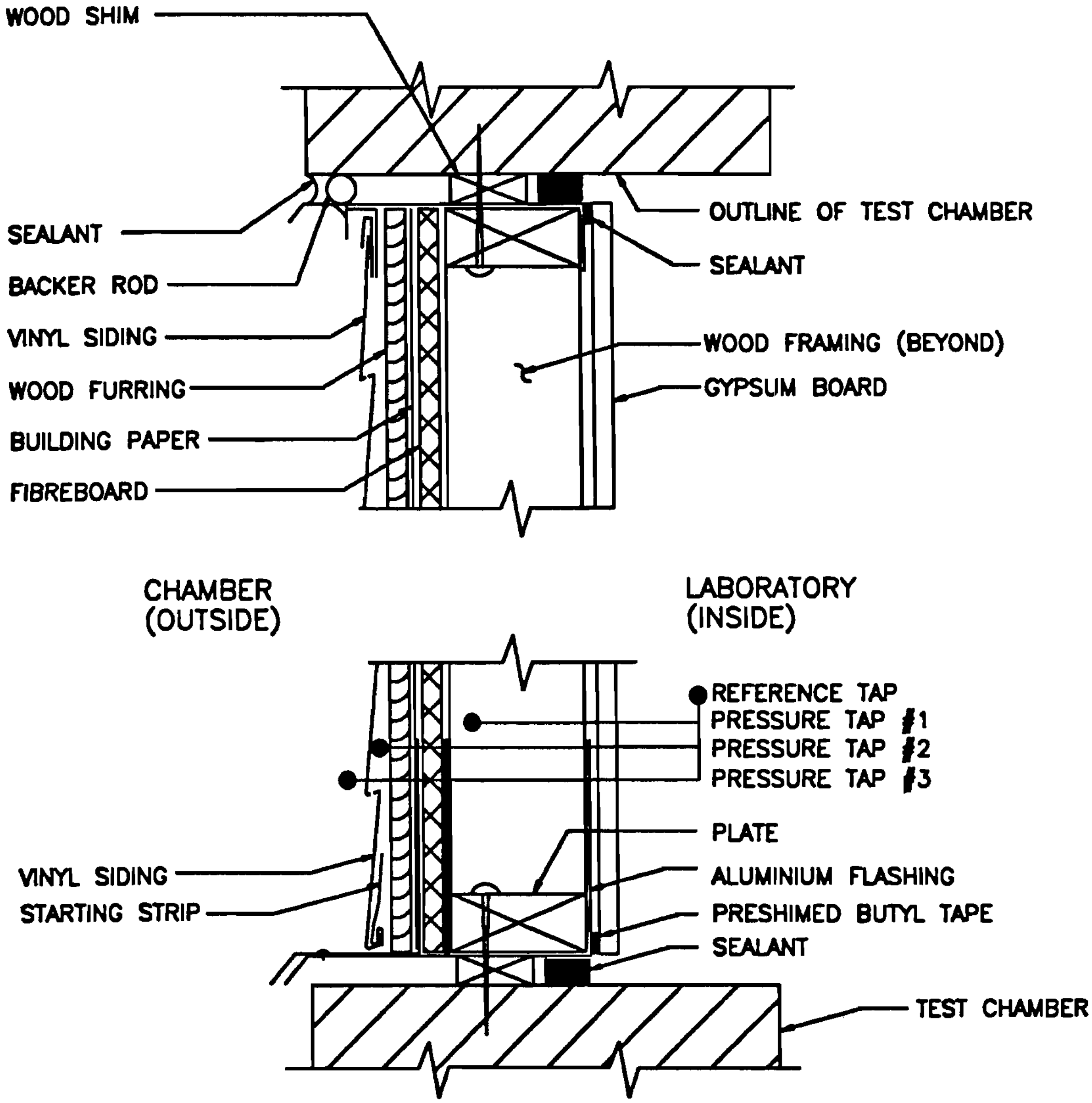
SECTION THROUGH VINYL CLAD EXTERIOR WOOD FRAME WALL GYPSUM AIR BARRIER NO FURRING UNDER SIDING

FIGURE 5



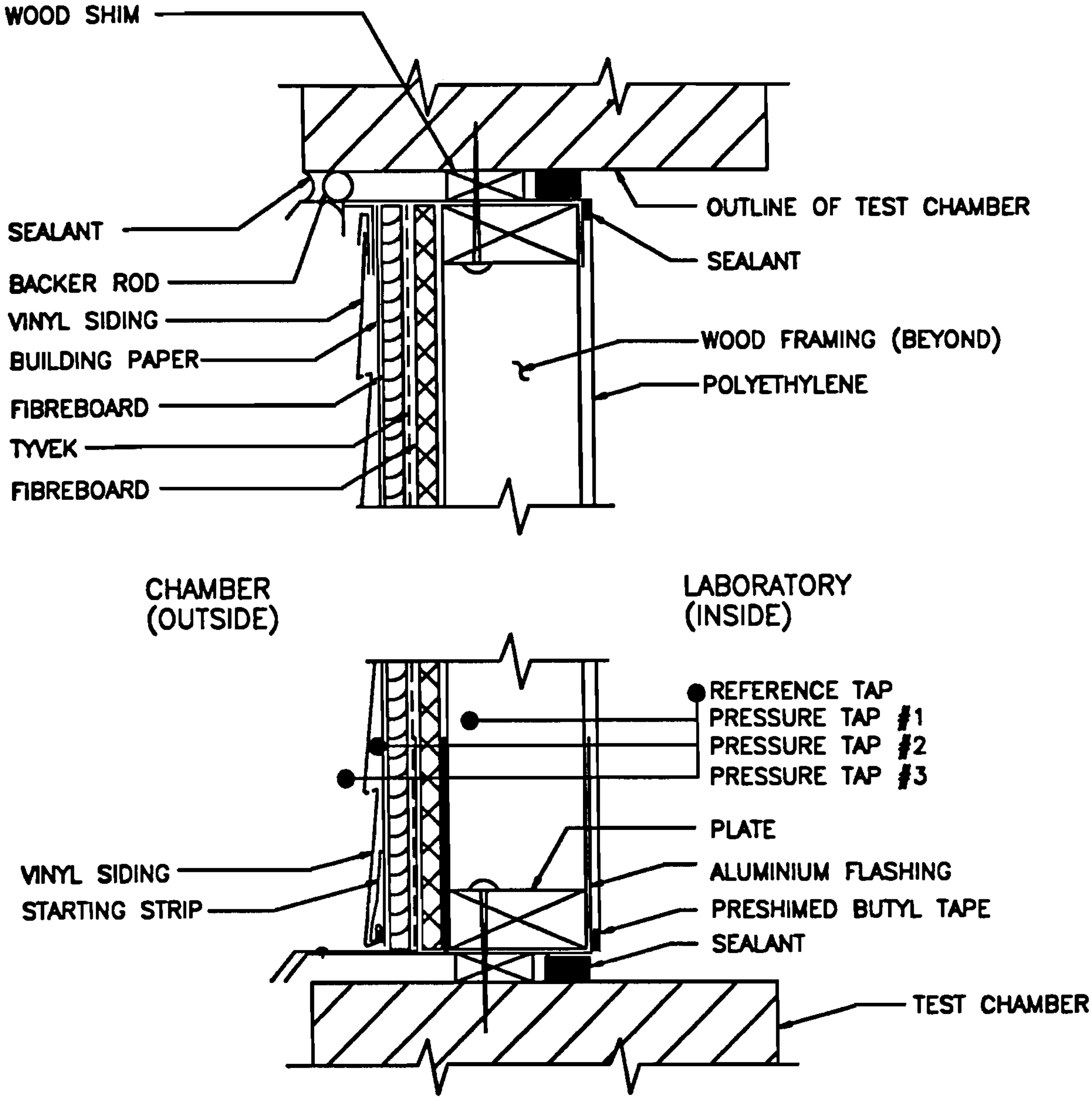
SECTION THROUGH VINYL CLAD EXTERIOR WOOD FRAME WALL POLY AIR BARRIER - WITH FURRING UNDER SIDING

FIGURE 6



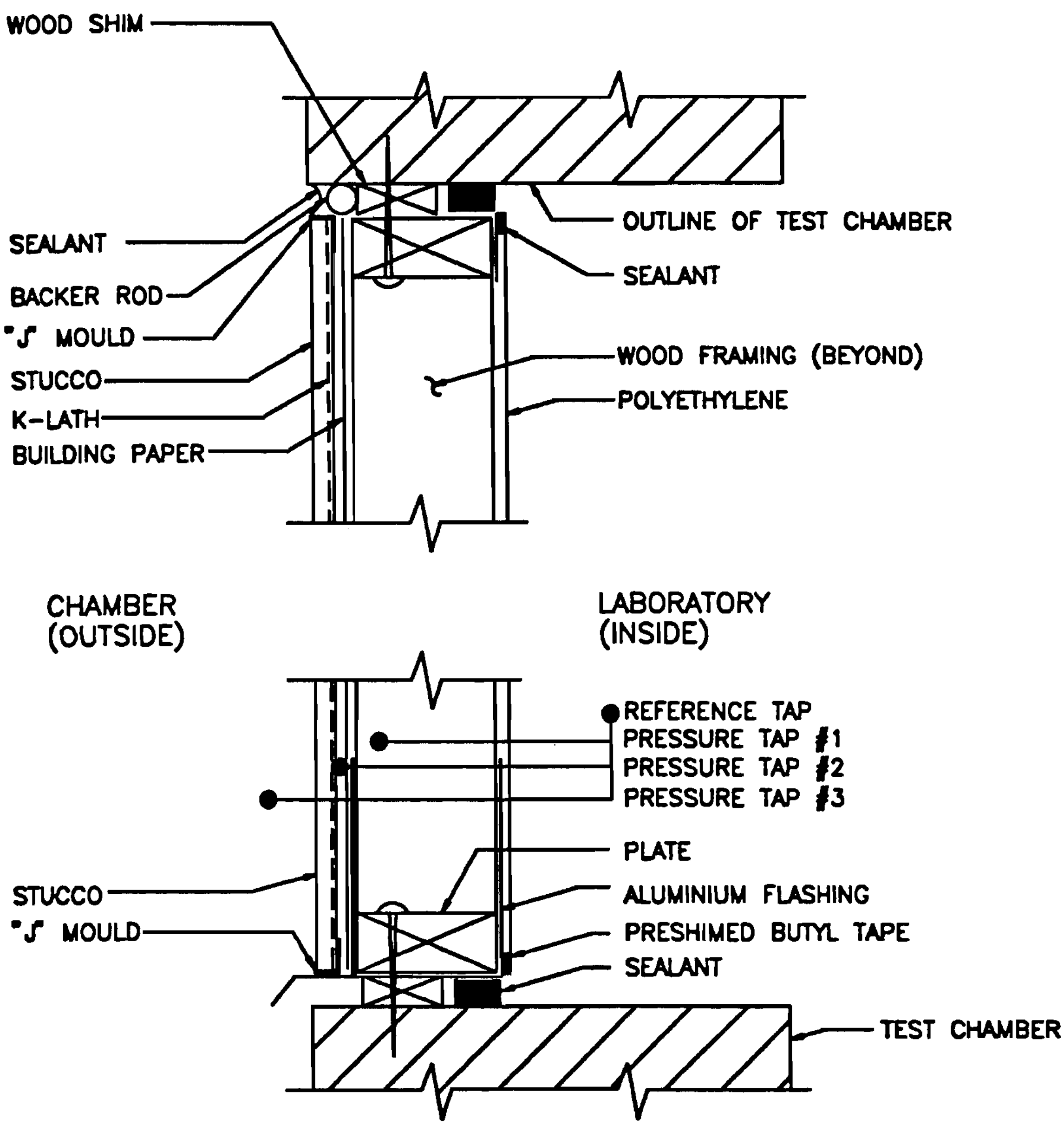
SECTION THROUGH VINYL CLAD EXTERIOR WOOD FRAME WALL GYPSUM AIR BARRIER - WITH FURRING UNDER SIDING

FIGURE 7



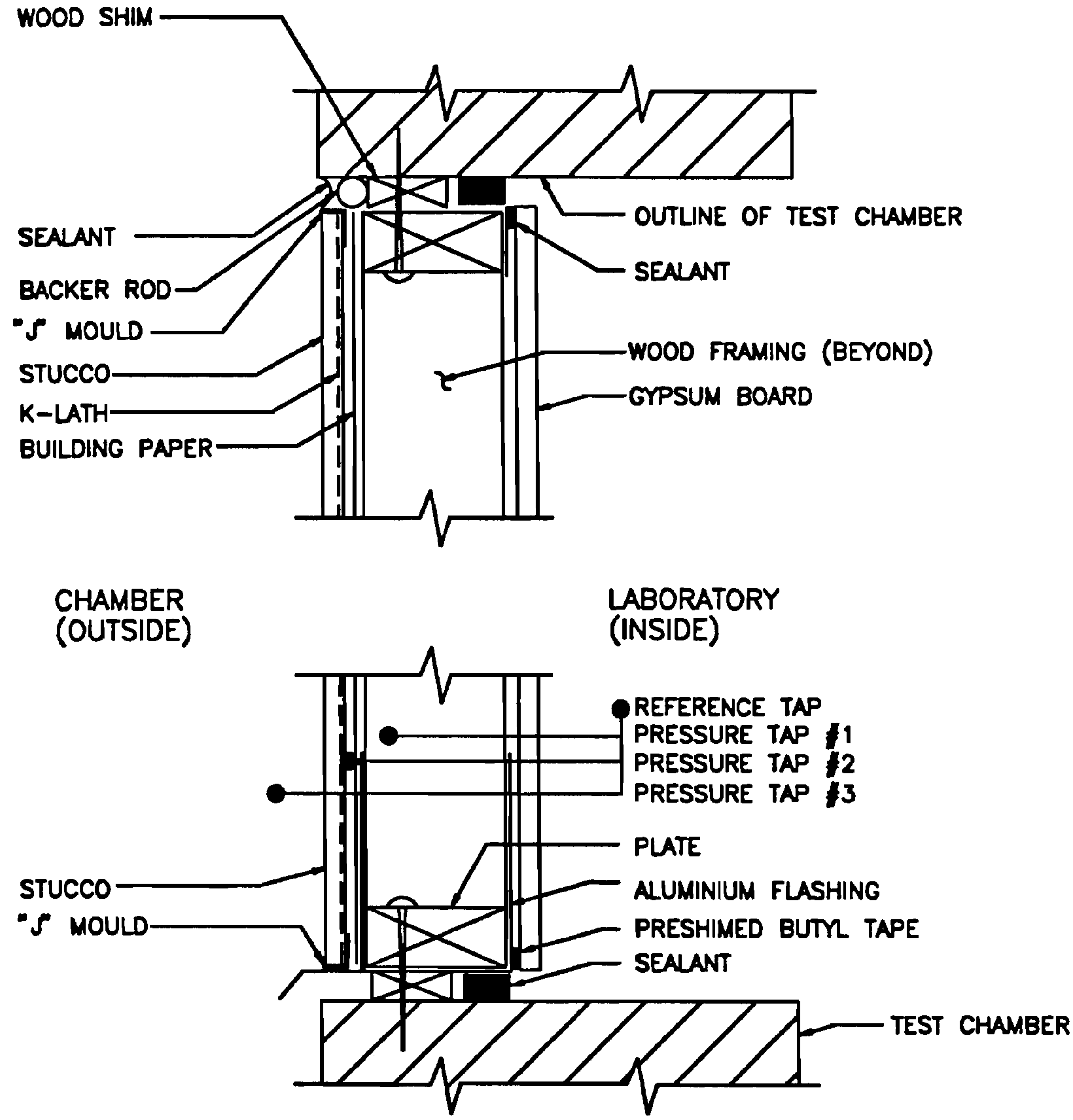
SECTION THROUGH VINYL CLAD EXTERIOR WOOD FRAME WALL WITH FIBREBOARD, TYVEK, FIBREBOARD AIR BARRIER - NO FURRING UNDER SIDING

FIGURE 8



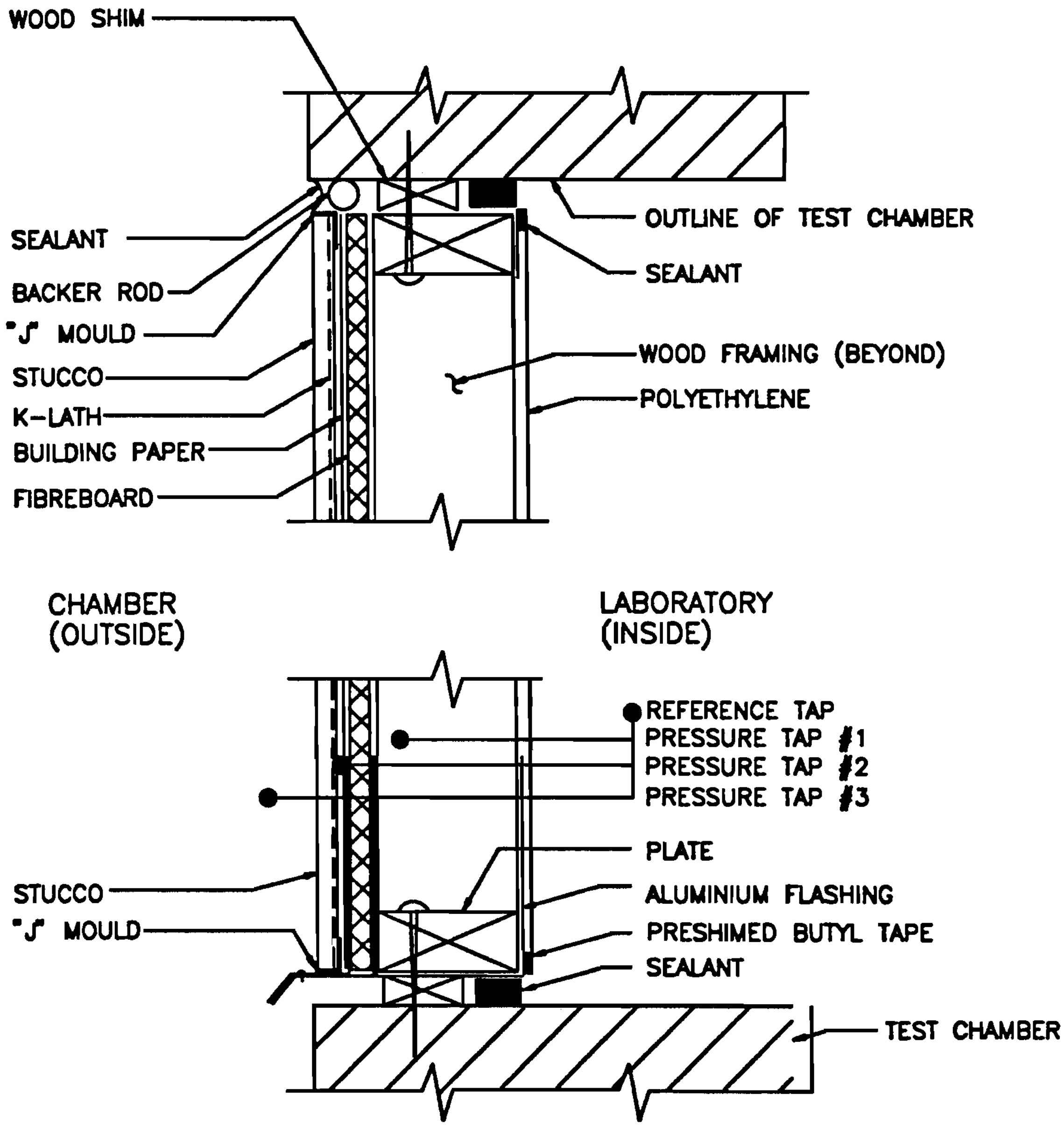
SECTION THROUGH STUCCO CLAD EXTERIOR WOOD FRAME WALL POLY AIR BARRIER - NO SHEATHING BEHIND STUCCO

FIGURE 9



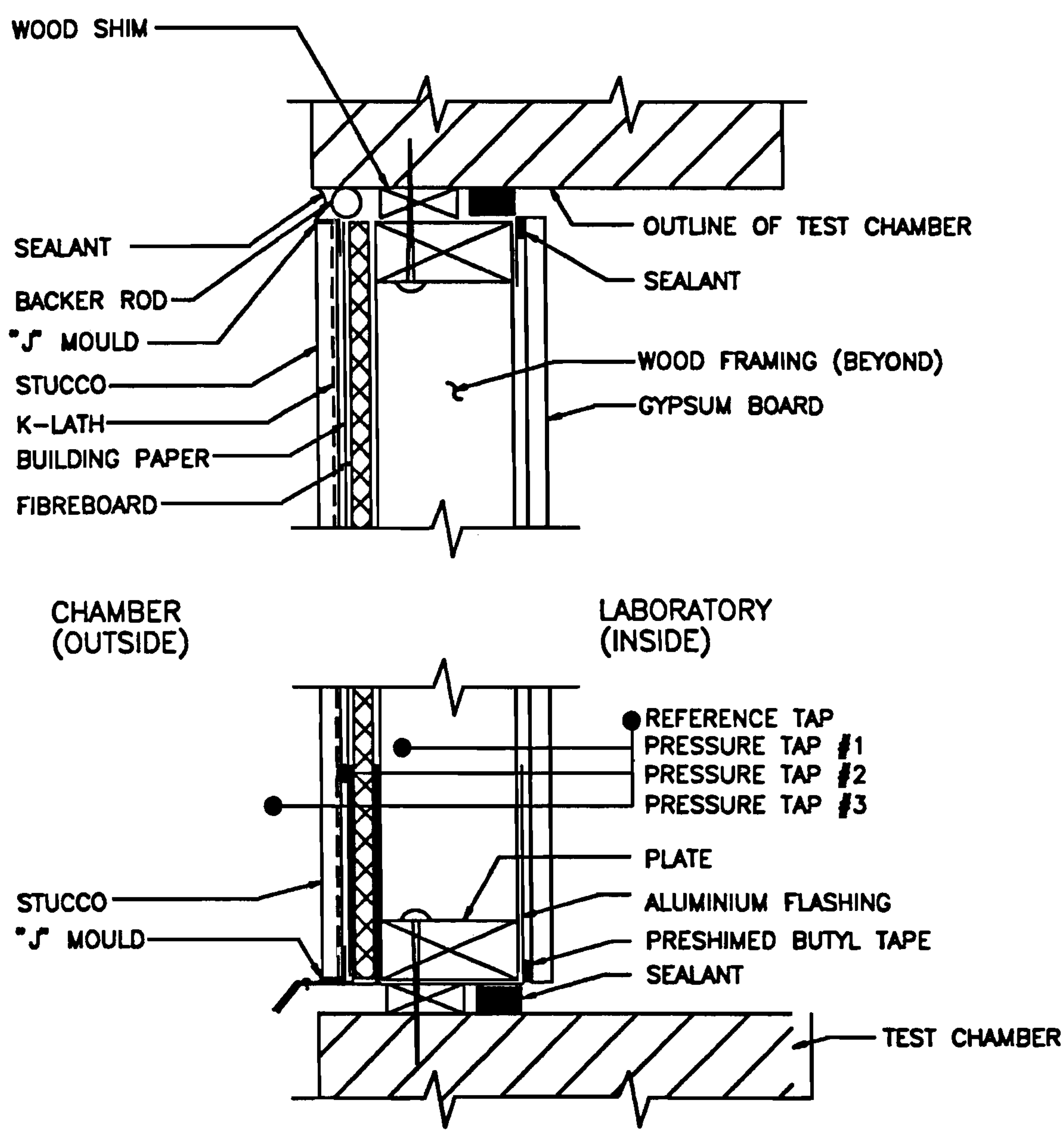
SECTION THROUGH STUCCO CLAD
EXTERIOR WOOD FRAME WALL
GYPSUM AIR BARRIER - NO
SHEATHING BEHIND STUCCO

FIGURE 10



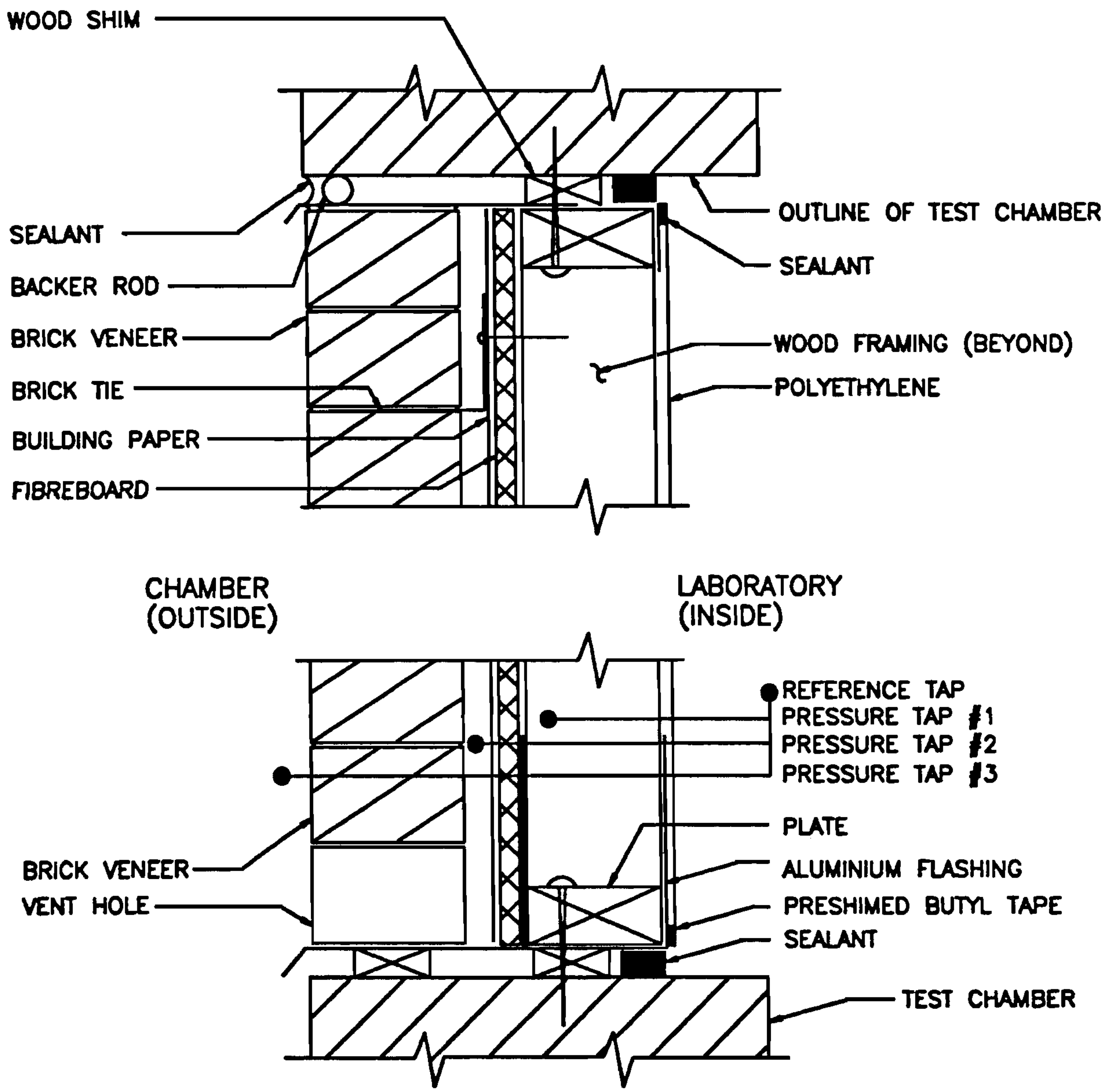
SECTION THROUGH STUCCO CLAD EXTERIOR WOOD FRAME WALL POLY AIR BARRIER - WITH SHEATHING BEHIND STUCCO

FIGURE 11



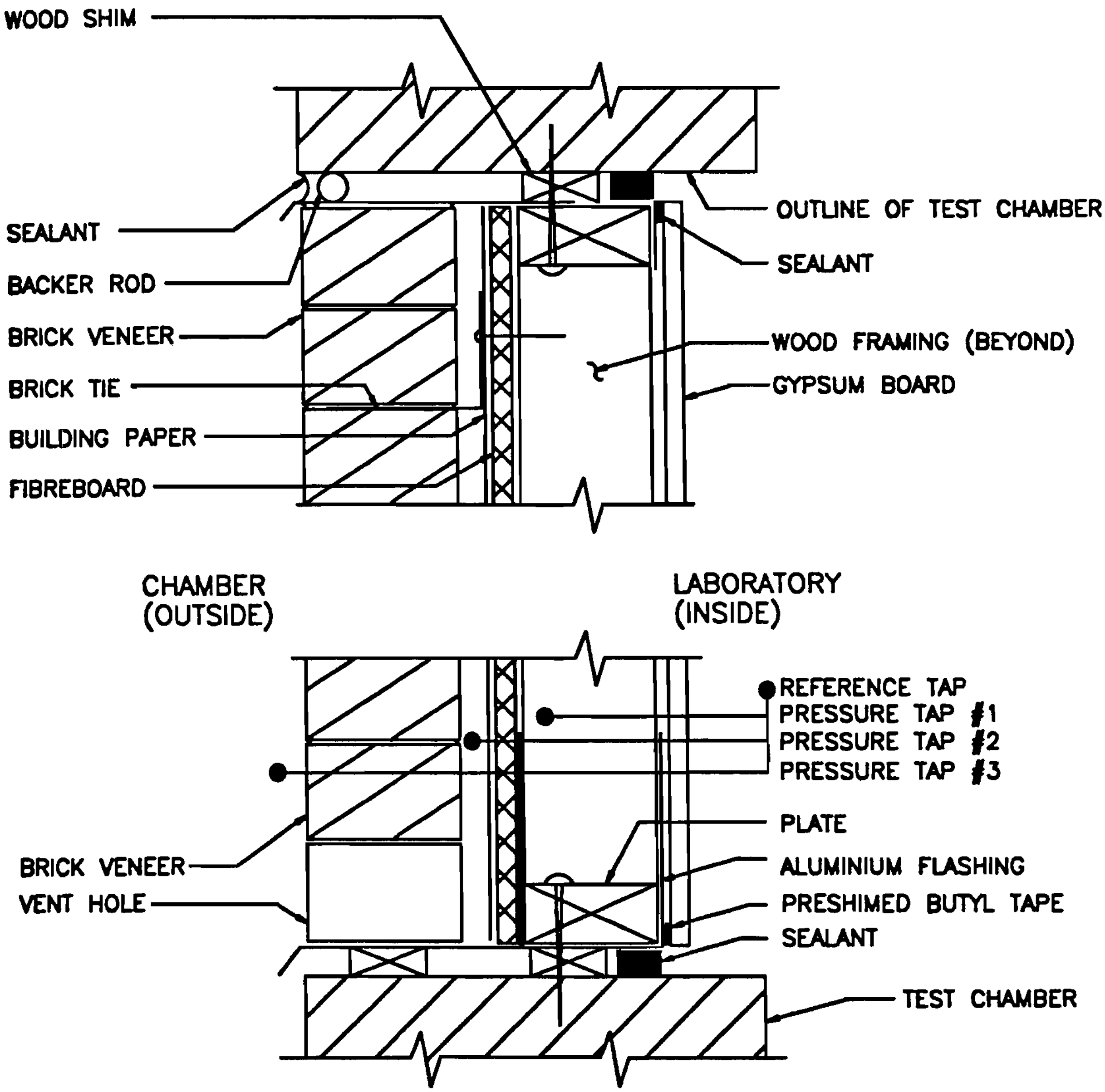
SECTION THROUGH STUCCO CLAD EXTERIOR WOOD FRAME WALL - WITH GYPSUM AIR BARRIER AND FIBREBOARD SHEATHING

FIGURE 12



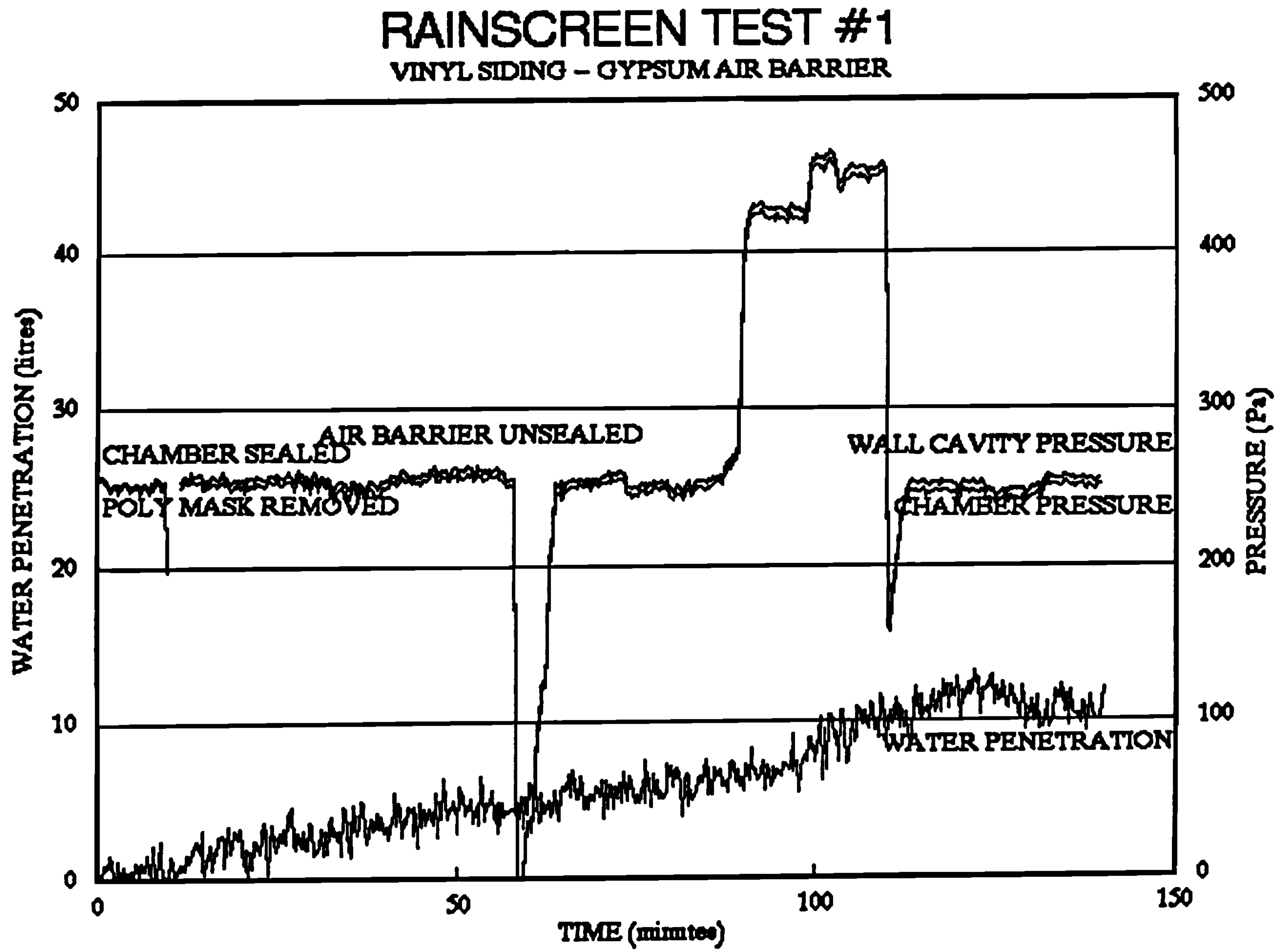
SECTION THROUGH BRICK VENEER EXTERIOR WOOD FRAME WALL WITH POLY AIR BARRIER - AND FIBREBOARD SHEATHING

FIGURE 13



SECTION THROUGH BRICK VENEER
EXTERIOR WOOD FRAME WALL
WITH GYPSUM AIR BARRIER
AND FIBREBOARD SHEATHING

FIGURE 14



RAINSCREEN TEST #1
VINYL SIDING – GYPSUM AIR BARRIER
WATER PENETRATION (litres)
PRESSURE (Pa)
TIME (minutes)
50
40
30
20
10
0
500
400
300
200
100
0
0
50
100
150
CHAMBER SEALED
AIR BARRIER UNSEALED
POLY MASK REMOVED
WALL CAVITY PRESSURE
CHAMBER PRESSURE
WATER PENETRATION

FIGURE 15

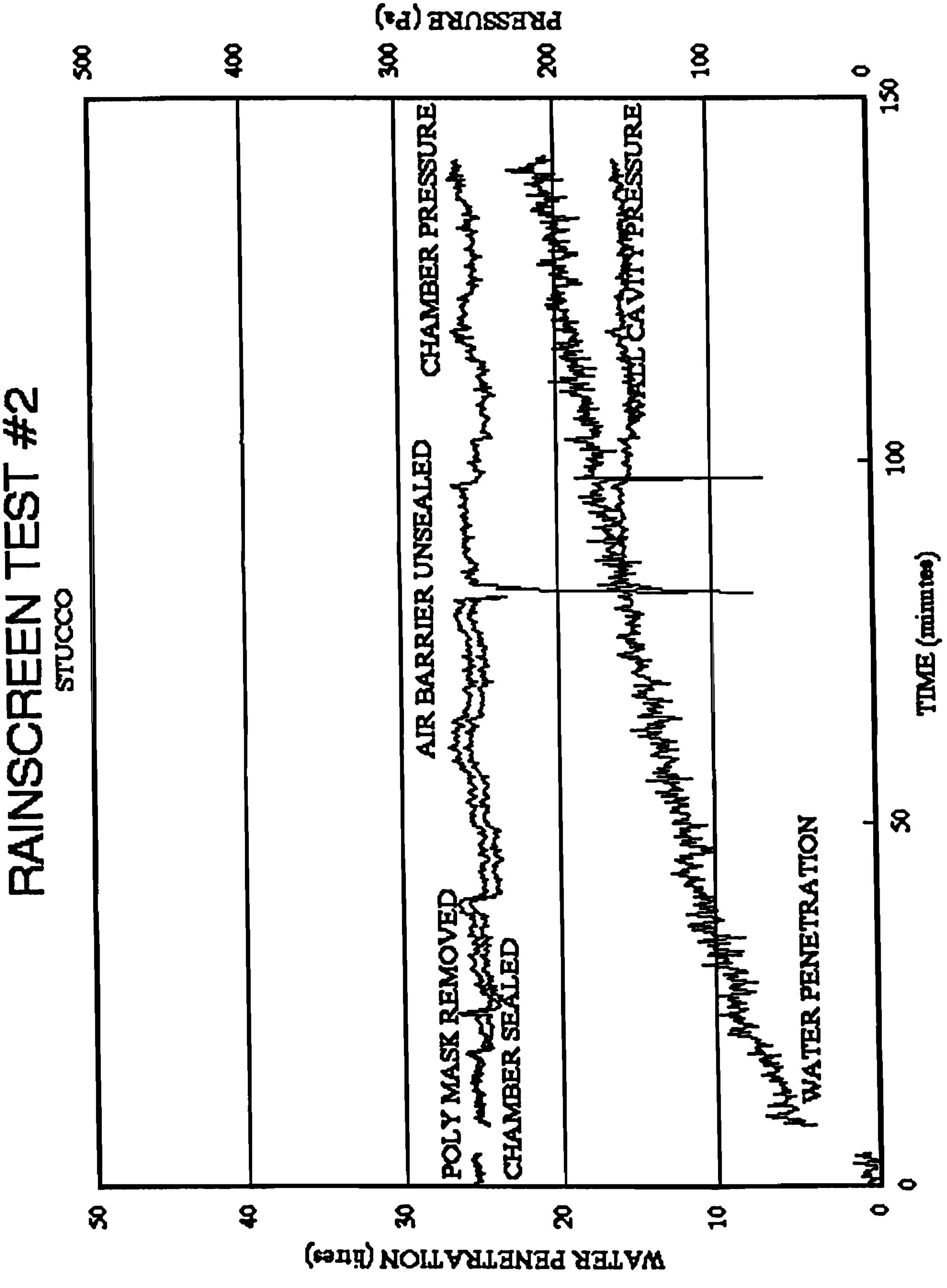

RAINSCREEN TEST #2
STUCCO
PRESSURE (Pa)
500
400
300
200
100
0
CHAMBER PRESSURE
AIR BARRIER UNSEALED
POLY MASK REMOVED
CHAMBER SEALED
WALL CAVITY PRESSURE
WATER PENETRATION
0
50
100
150
TIME (minutes)
WATER PENETRATION (lines)
50
40
30
20
10
0

FIGURE 16

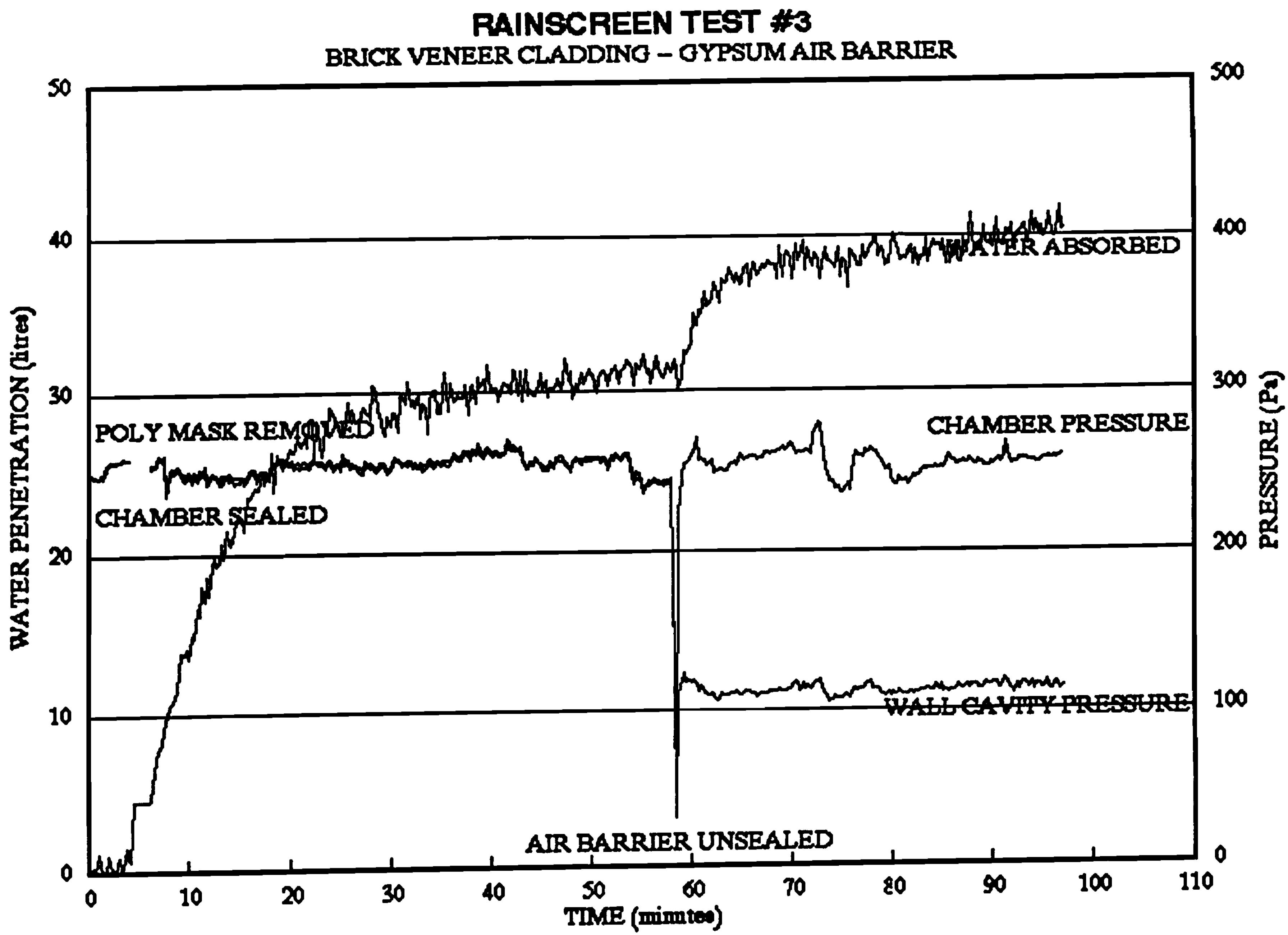

RAINSCREEN TEST #3
BRICK VENEER CLADDING – GYPSUM AIR BARRIER
WATER PENETRATION (litres)
PRESSURE (Pa)
TIME (minutes)
WATER ABSORBED
CHAMBER PRESSURE
POLY MASK REMOVED
CHAMBER SEALED
WALL CAVITY PRESSURE
AIR BARRIER UNSEALED
0
10
20
30
40
50
60
70
80
90
100
110
200
300
400
500

FIGURE 17

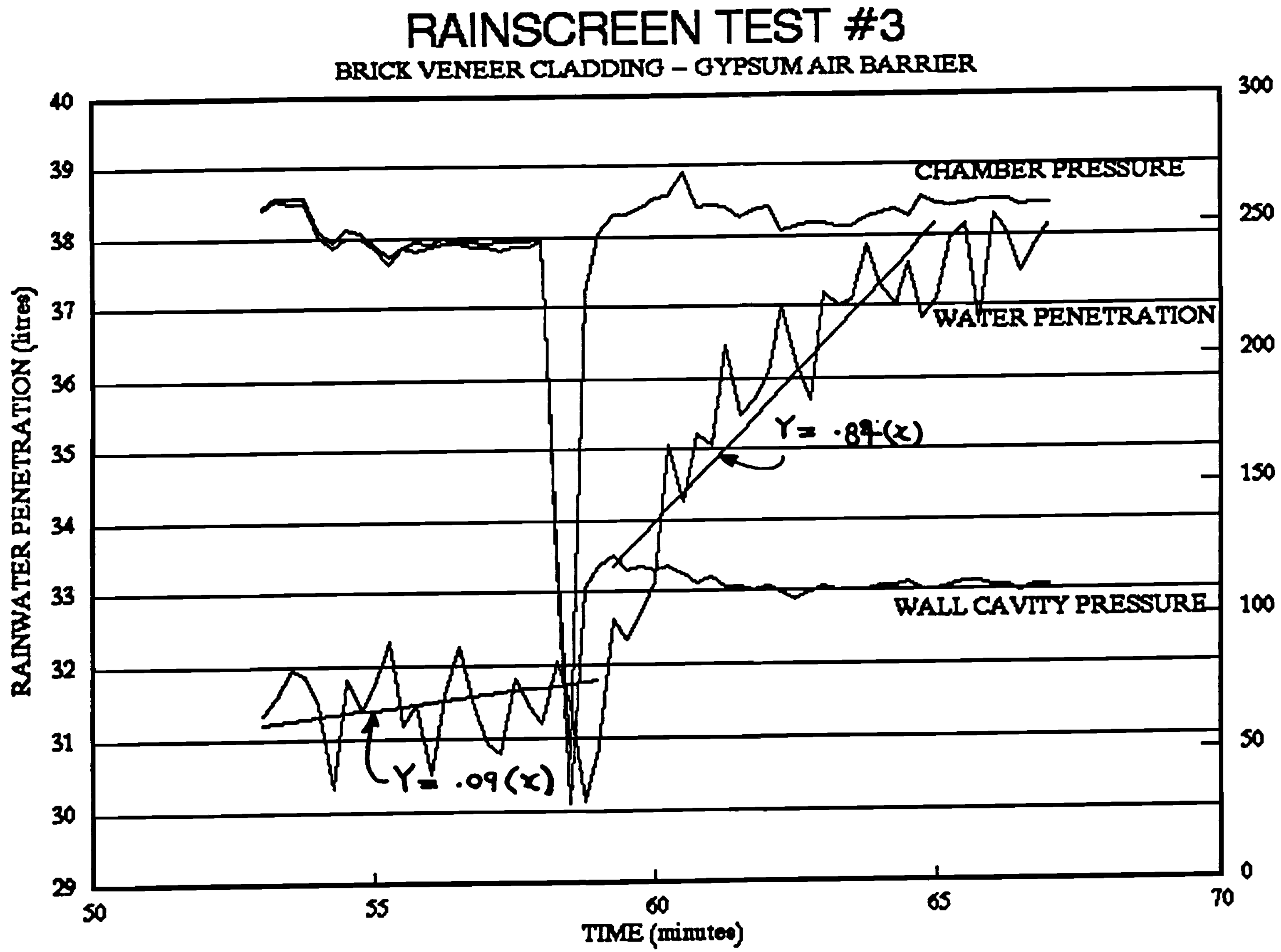
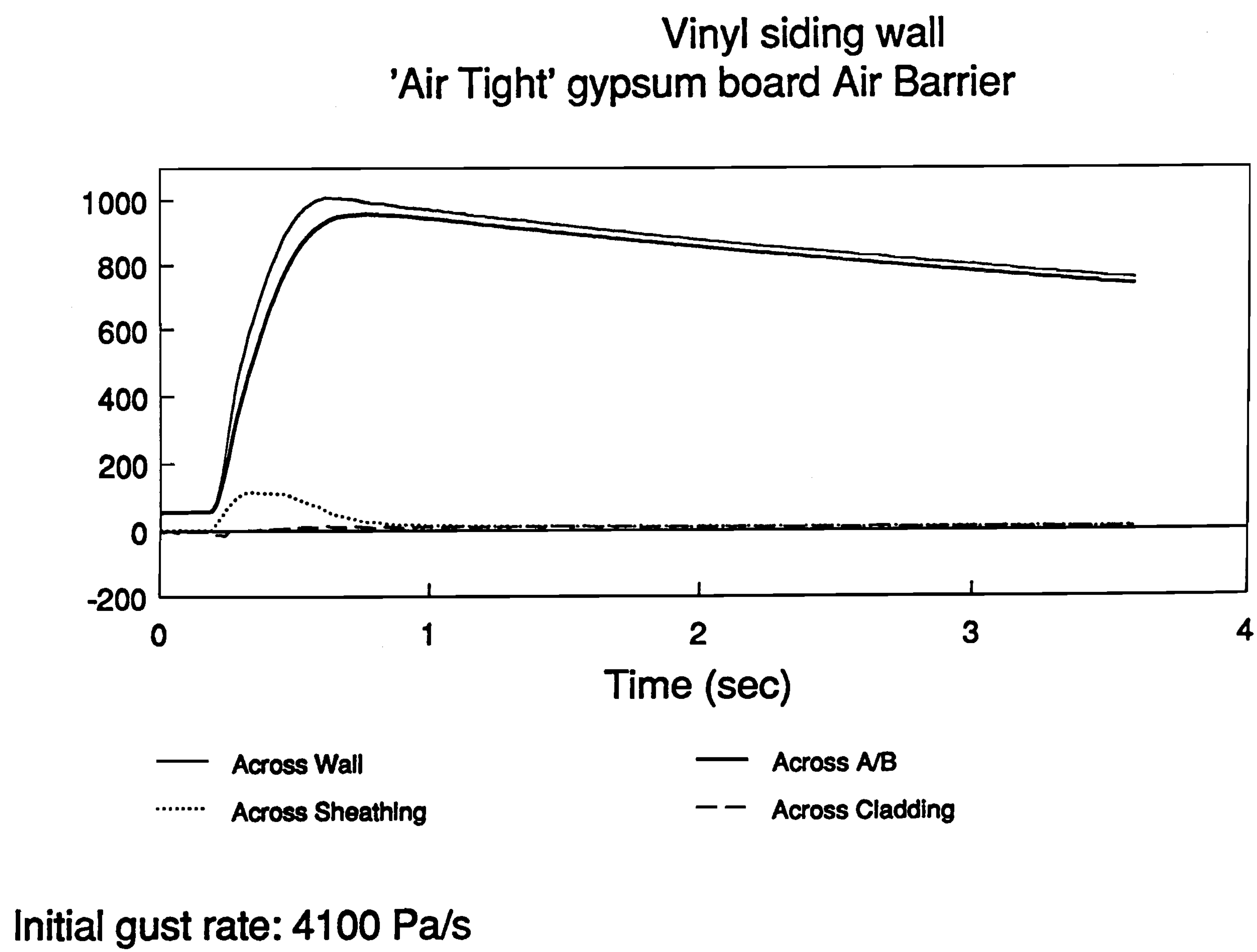

RAINSCREEN TEST #3
BRICK VENEER CLADDING – GYPSUM AIR BARRIER
CHAMBER PRESSURE
WATER PENETRATION
WALL CAVITY PRESSURE
Y= .09(x)
RAINWATER PENETRATION (litres)
PRESSURE (Pa)
TIME (minutes)
40
39
38
37
36
35
34
33
32
31
30
29
300
250
200
150
100
50
0
50
55
60
65
70

FIGURE 18



Vinyl siding wall
'Air Tight' gypsum board Air Barrier
1000
800
600
400
200
0
-200
0
1
2
3
4
Time (sec)
Across Wall
Across A/B
Across Sheathing
Across Cladding
Initial gust rate: 4100 Pa/s

FIGURE 19

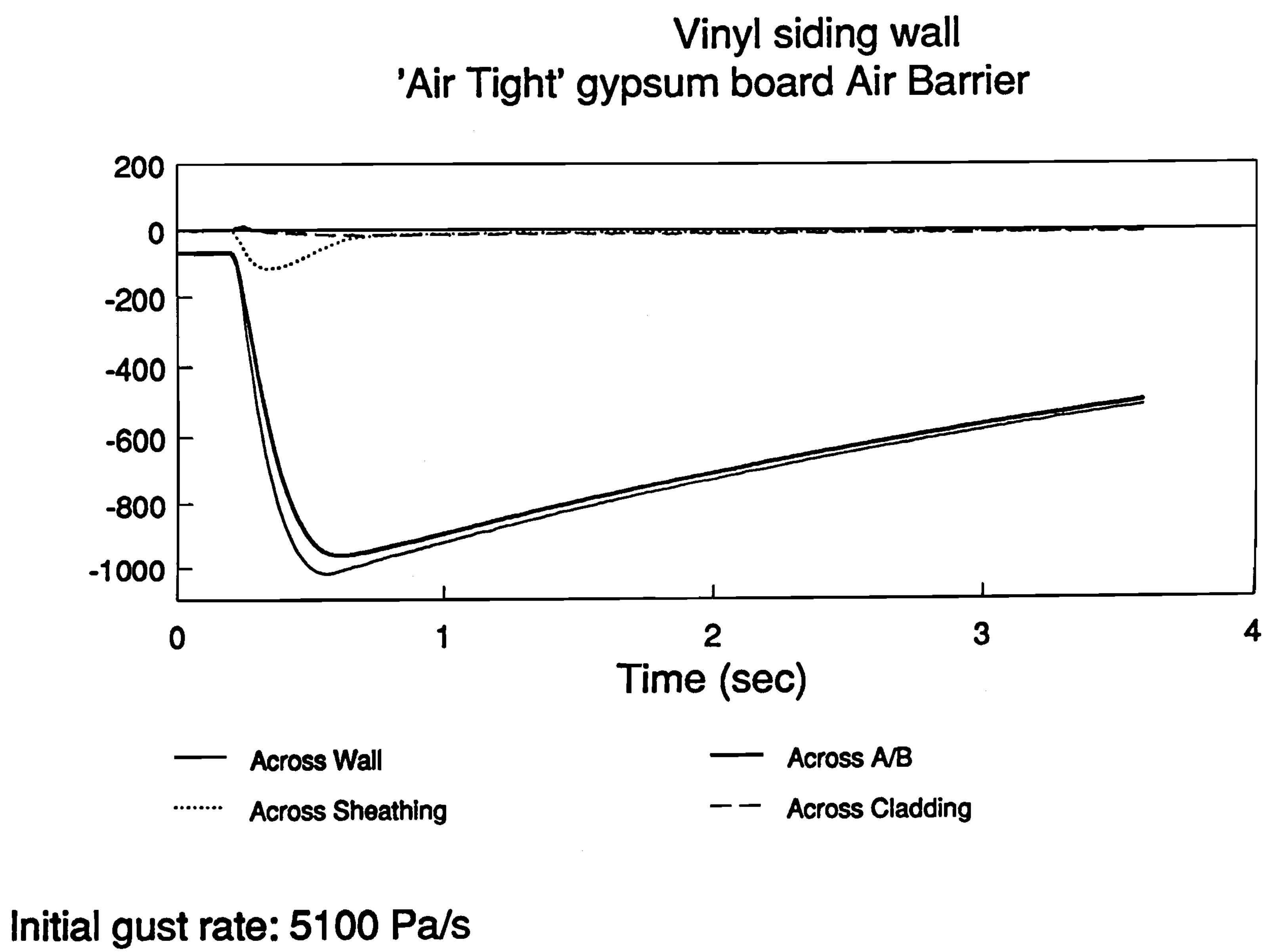

Vinyl siding wall
'Air Tight' gypsum board Air Barrier
200
0
-200
-400
-600
-800
-1000
0
1
2
3
4
Time (sec)
Across Wall
Across Sheathing
Across A/B
Across Cladding
Initial gust rate: 5100 Pa/s

FIGURE 20

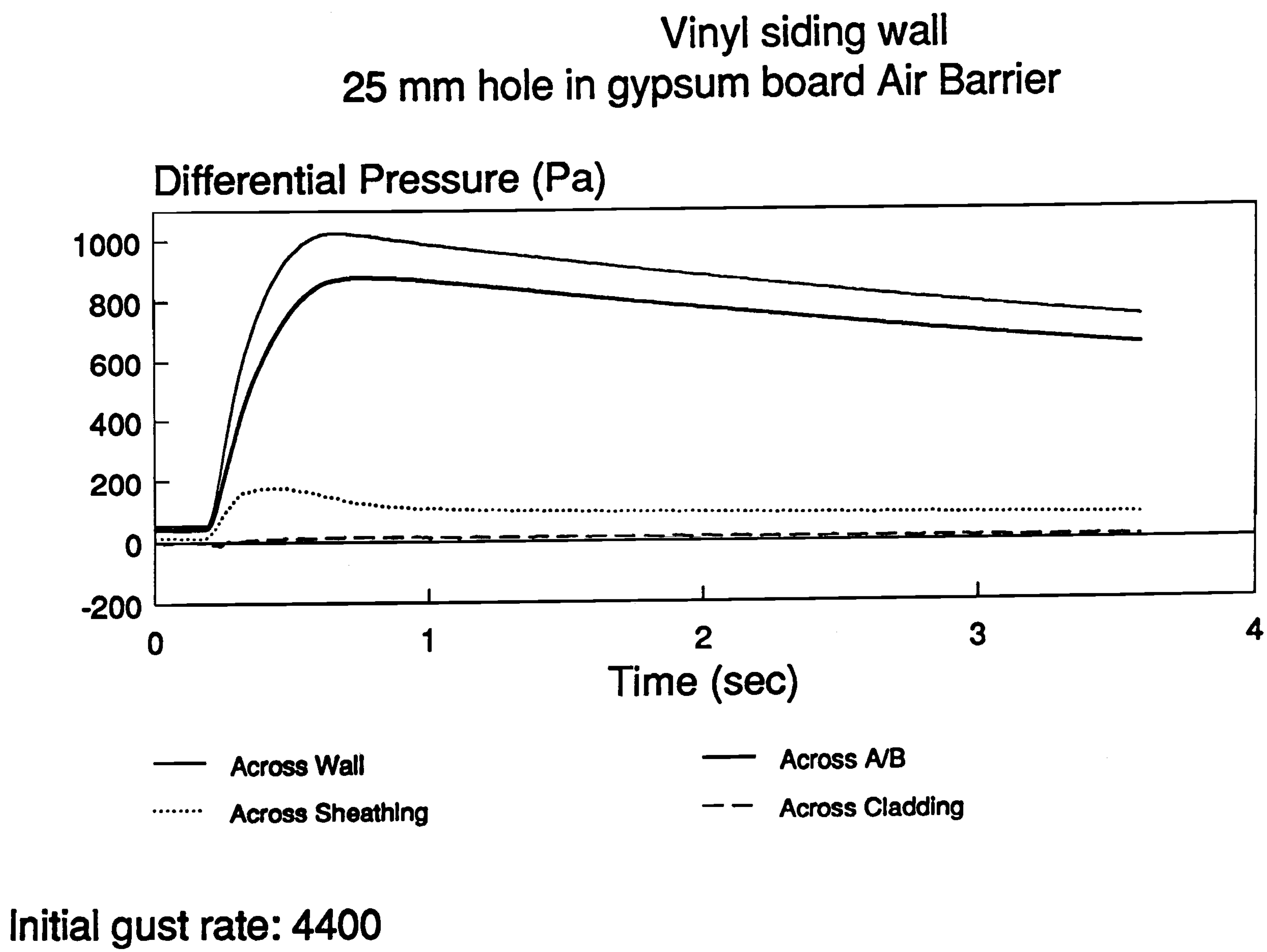

Vinyl siding wall
25 mm hole in gypsum board Air Barrier
Differential Pressure (Pa)
1000
800
600
400
200
0
-200
0
1
2
3
4
Time (sec)
Across Wall
Across Sheathing
Across A/B
Across Cladding
Initial gust rate: 4400

FIGURE 21

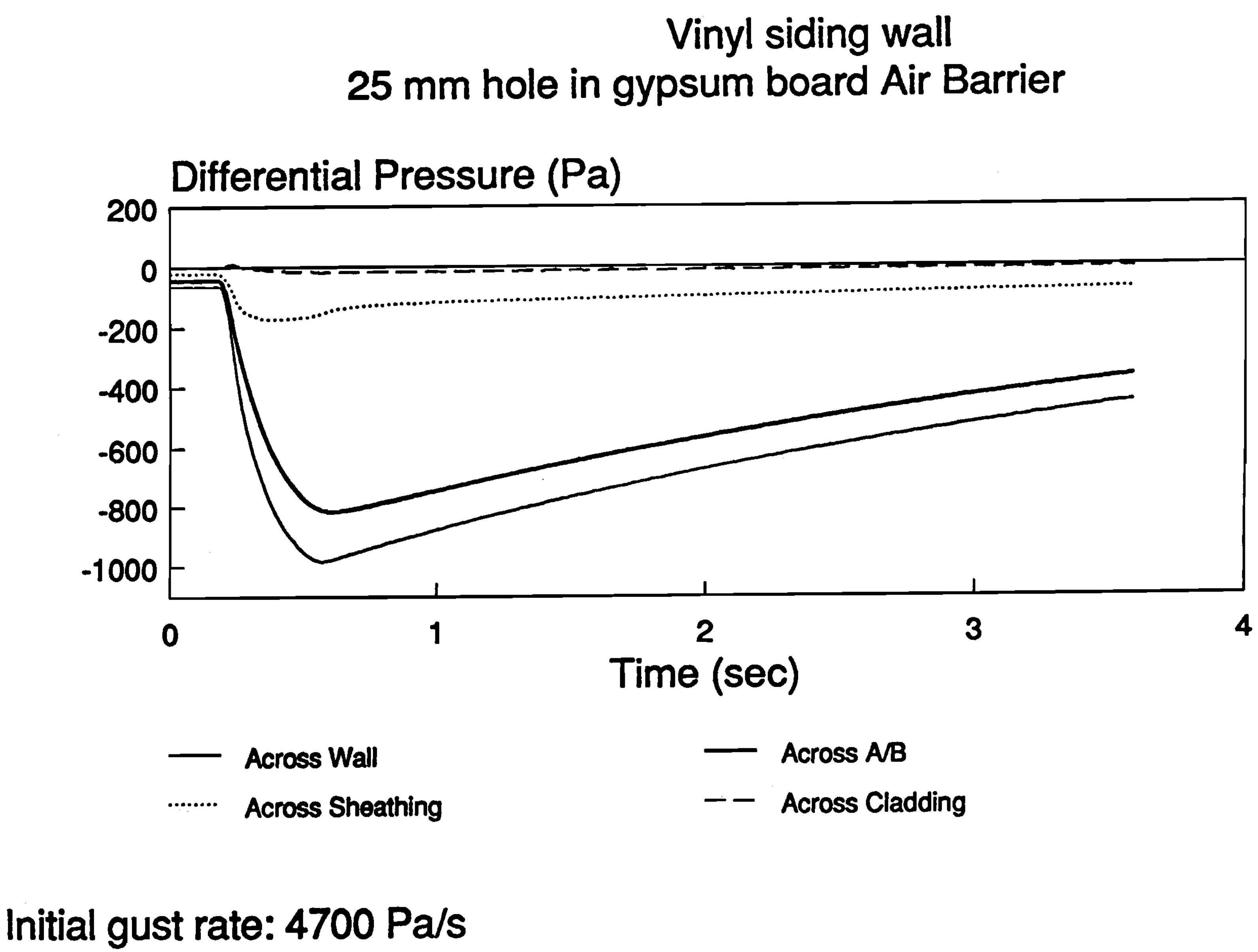

Vinyl siding wall
25 mm hole in gypsum board Air Barrier
Differential Pressure (Pa)
200
0
-200
-400
-600
-800
-1000
0
1
2
3
4
Time (sec)
Across Wall
Across Sheathing
Across A/B
Across Cladding
Initial gust rate: 4700 Pa/s

FIGURE 22

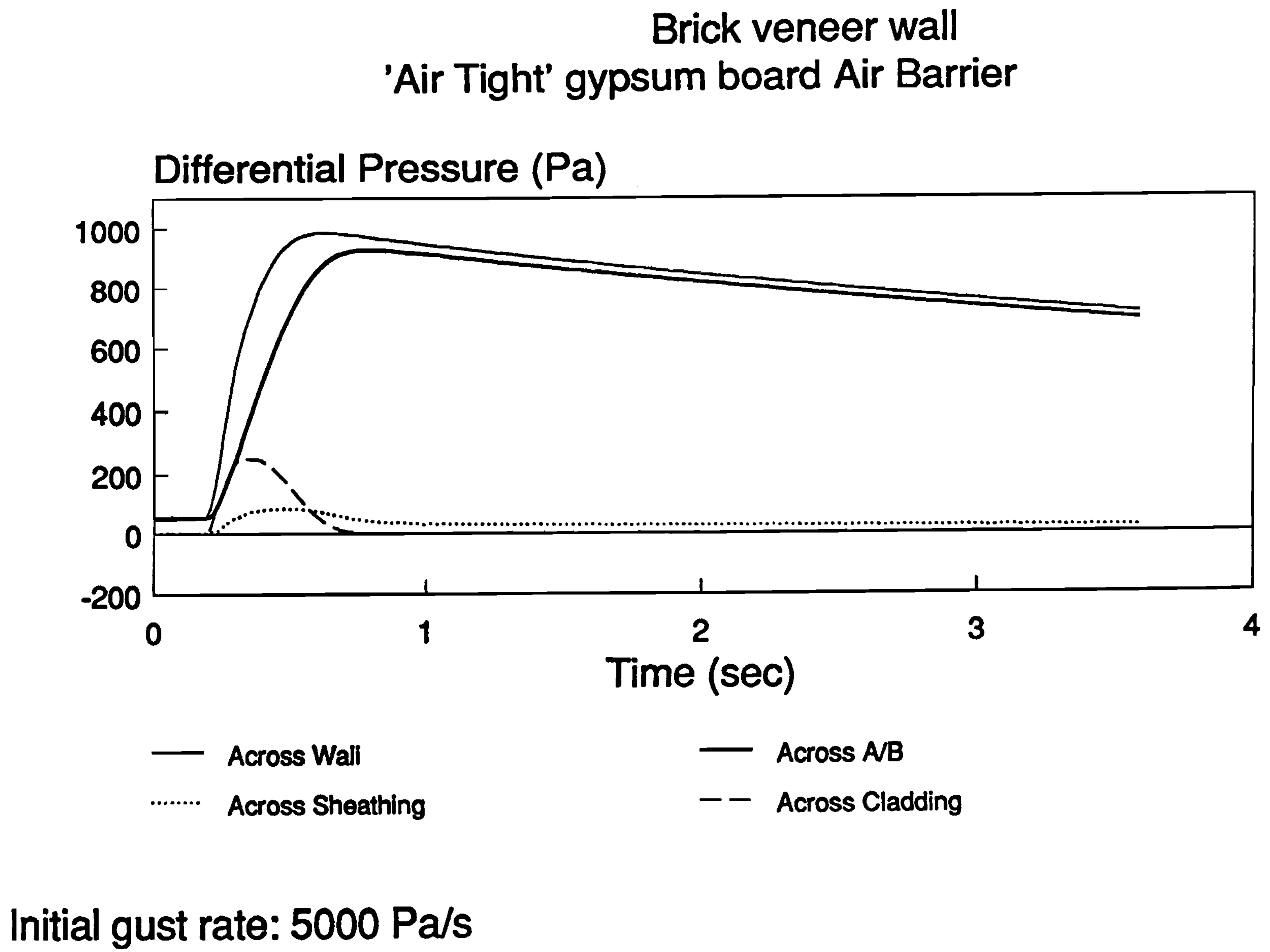

Brick veneer wall
'Air Tight' gypsum board Air Barrier
Differential Pressure (Pa)
1000
800
600
400
200
0
-200
0
1
2
3
4
Time (sec)
Across Wall
Across Sheathing
Across A/B
Across Cladding
Initial gust rate: 5000 Pa/s

FIGURE 23

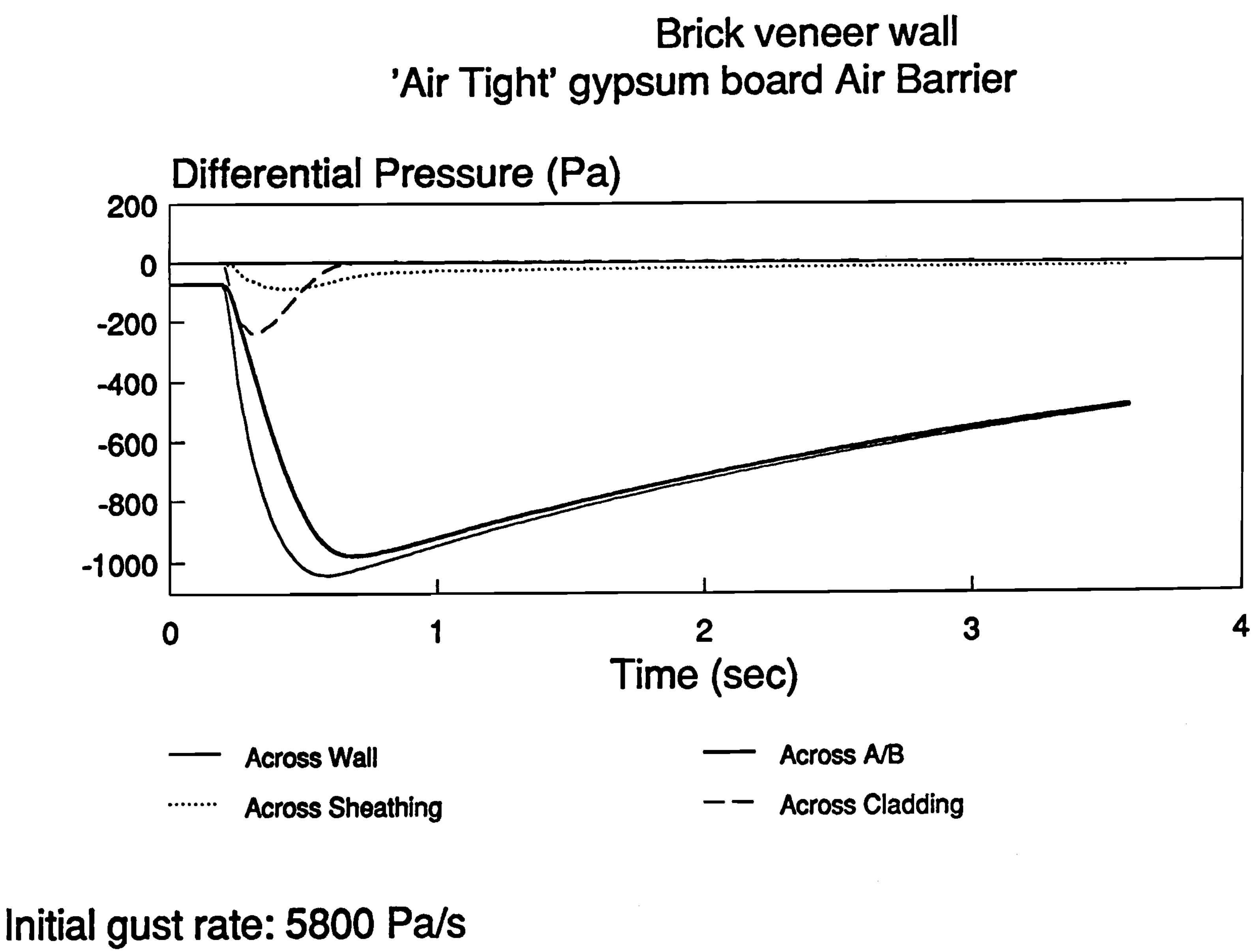

Brick veneer wall
'Air Tight' gypsum board Air Barrier
Differential Pressure (Pa)
200
0
-200
-400
-600
-800
-1000
0
1
2
3
4
Time (sec)
Across Wall
Across A/B
Across Sheathing
Across Cladding
Initial gust rate: 5800 Pa/s

FIGURE 24

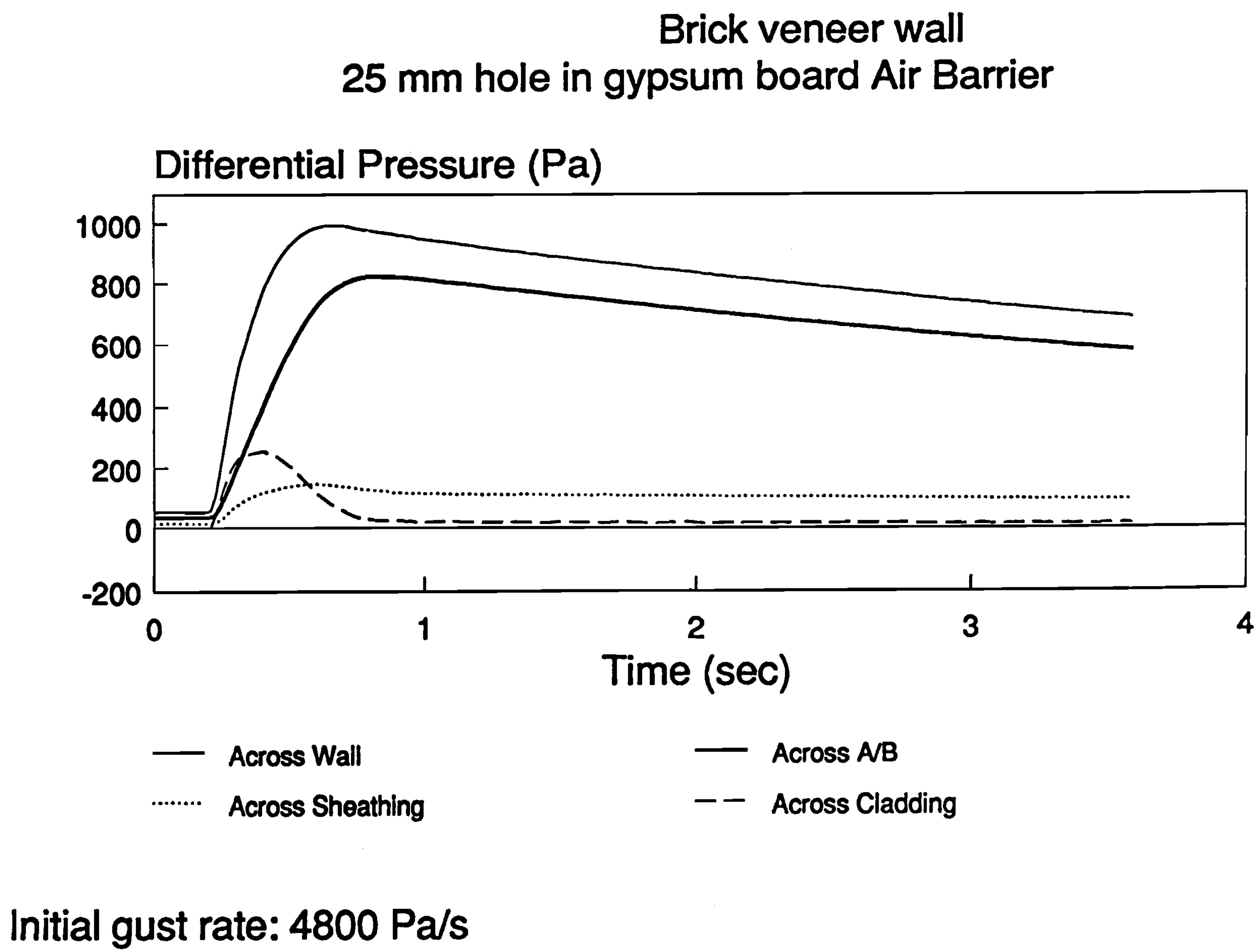

Brick veneer wall
25 mm hole in gypsum board Air Barrier
Differential Pressure (Pa)
1000
800
600
400
200
0
-200
0
1
2
3
4
Time (sec)
Across Wall
Across A/B
Across Sheathing
Across Cladding
Initial gust rate: 4800 Pa/s

FIGURE 25

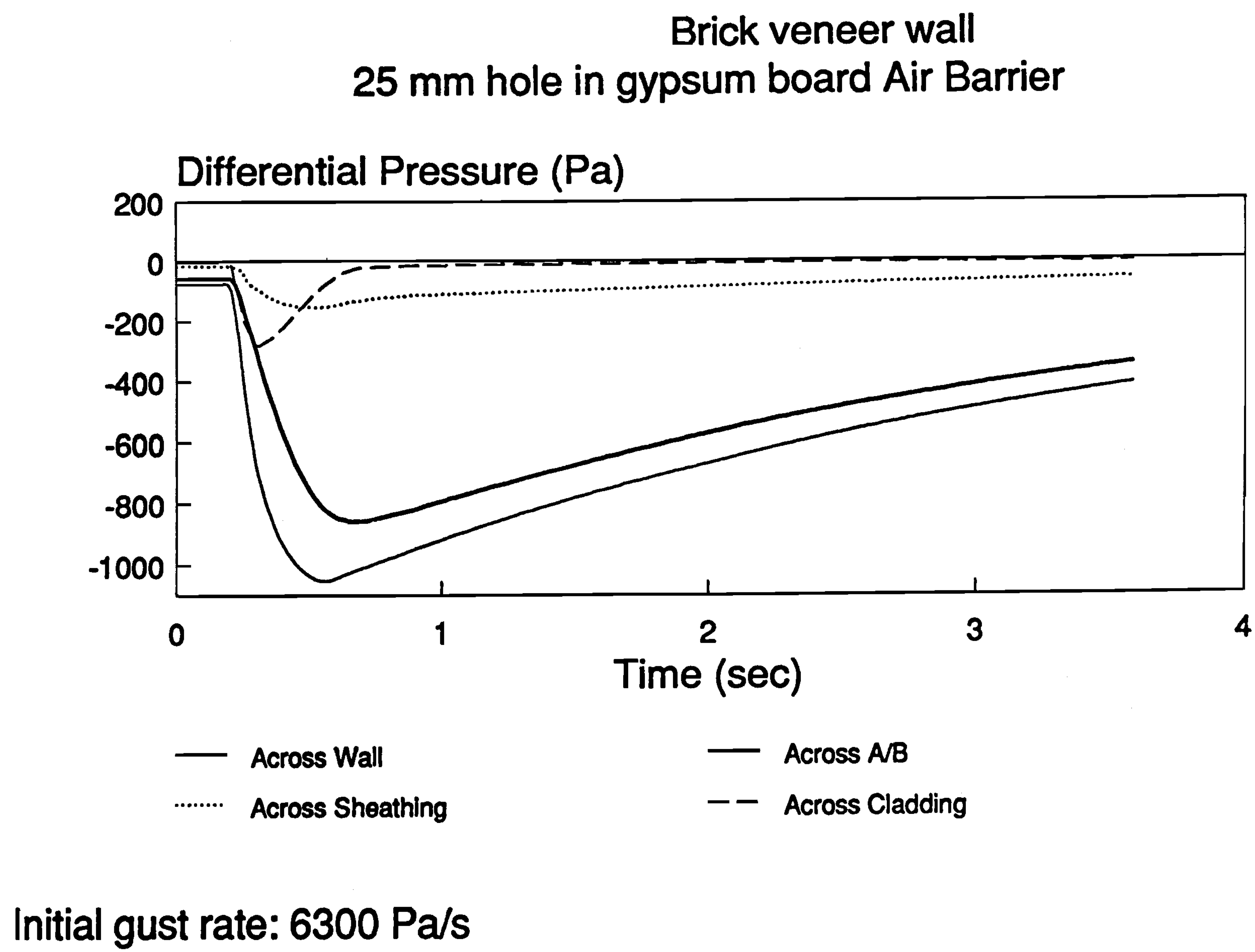

Brick veneer wall
25 mm hole in gypsum board Air Barrier
Differential Pressure (Pa)
200
0
-200
-400
-600
-800
-1000
0
1
2
3
4
Time (sec)
Across Wall
Across Sheathing
Across A/B
Across Cladding
Initial gust rate: 6300 Pa/s

FIGURE 26

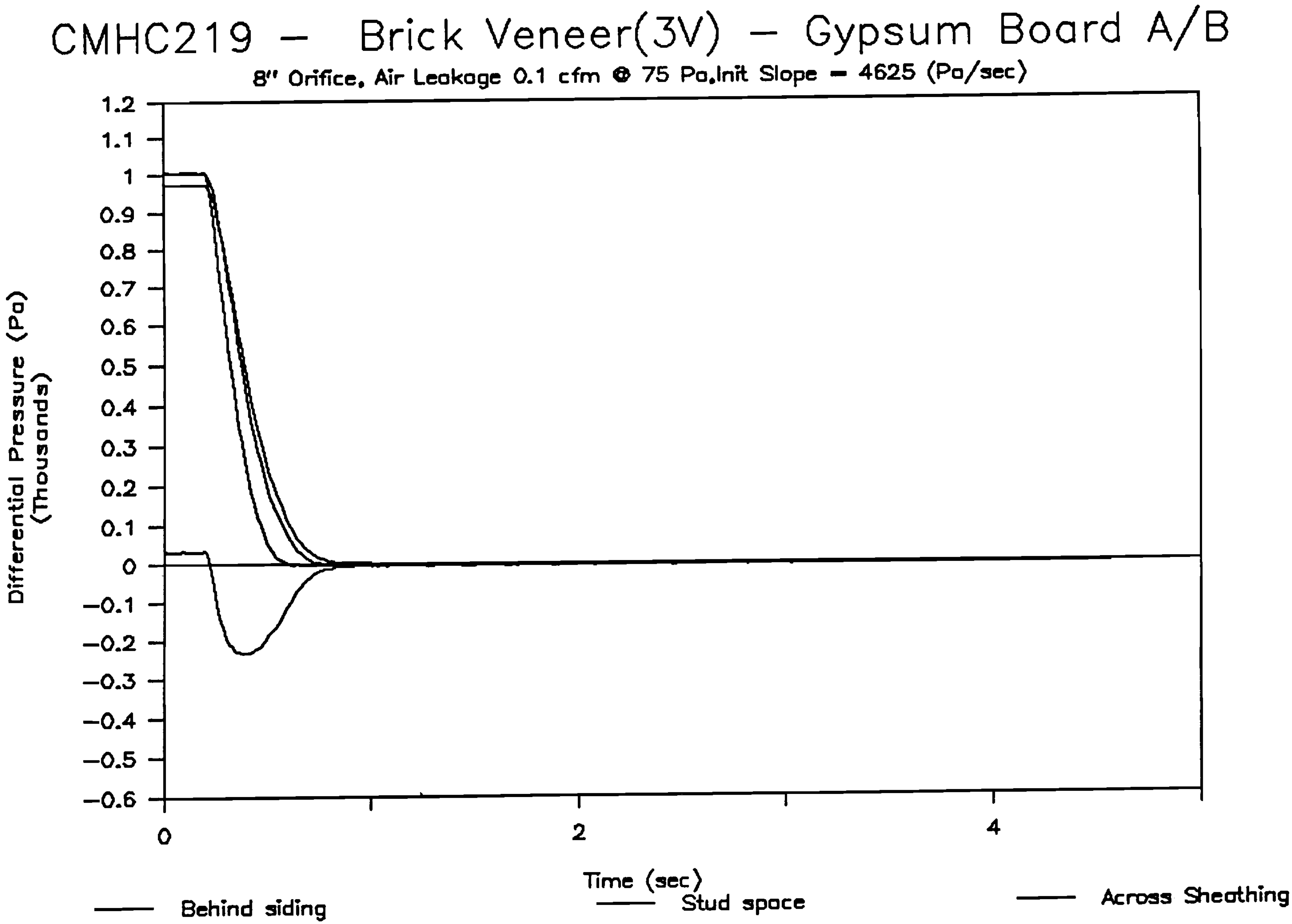

CMHC219 – Brick Veneer(3V) – Gypsum Board A/B
8" Orifice, Air Leakage 0.1 cfm @ 75 Pa, Init Slope = 4625 (Pa/sec)
Differential Pressure (Pa)
(Thousands)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
–0.1
–0.2
–0.3
–0.4
–0.5
–0.6
0
2
4
Time (sec)
Behind siding
Stud space
Across Sheathing

FIGURE 27

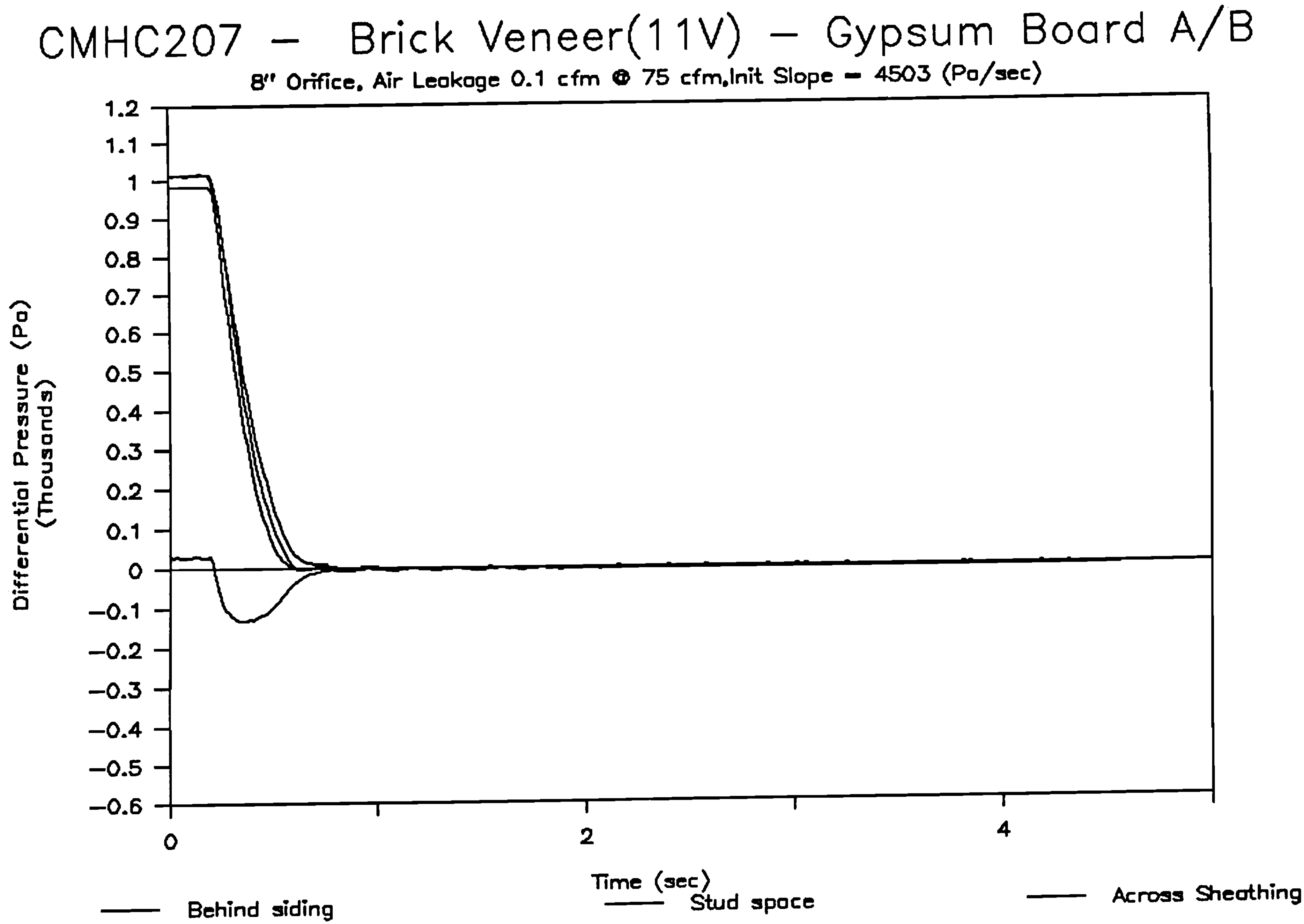

CMHC207 – Brick Veneer(11V) – Gypsum Board A/B
8" Orifice, Air Leakage 0.1 cfm @ 75 cfm,Init Slope = 4503 (Pa/sec)
Differential Pressure (Pa)
(Thousands)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
0
2
4
Time (sec)
Behind siding
Stud space
Across Sheathing

FIGURE 28

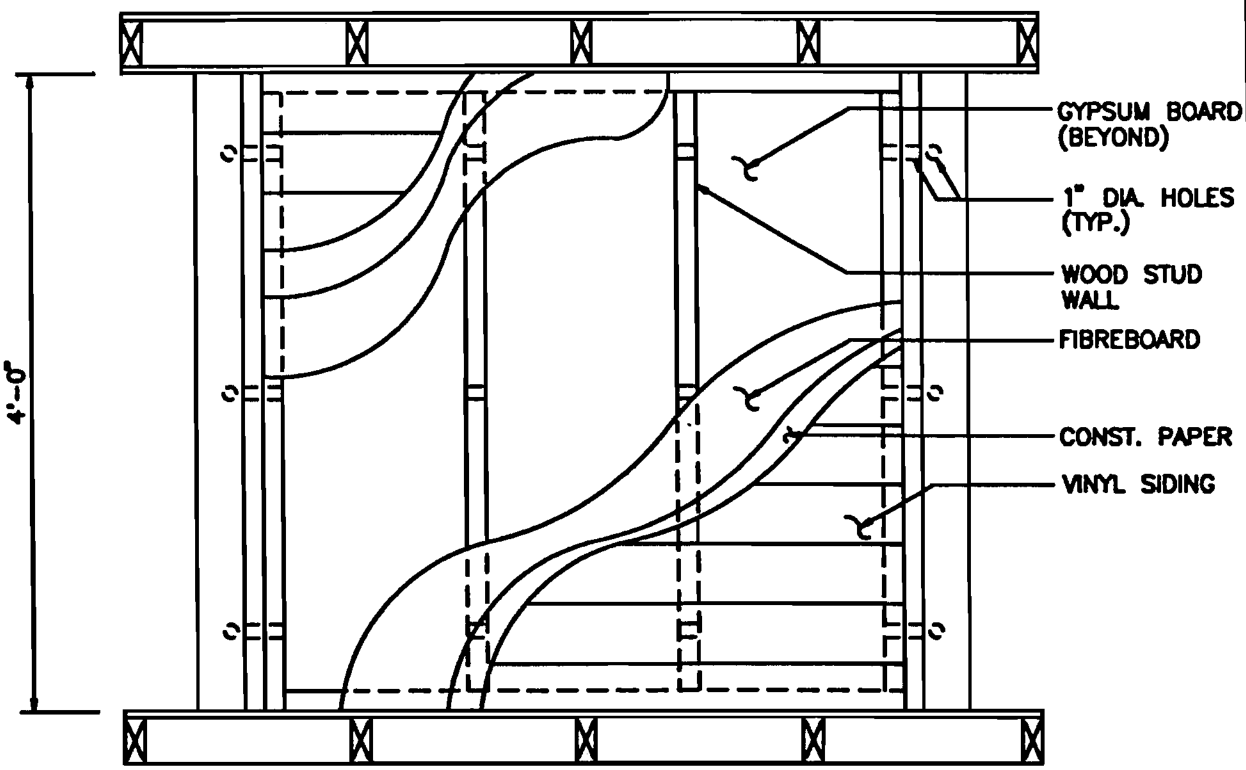
APPENDIX B

CONSTRUCTION DRAWINGS OF

COMPARTMENTALIZATION MODEL,

TABLES AND FIGURES OF

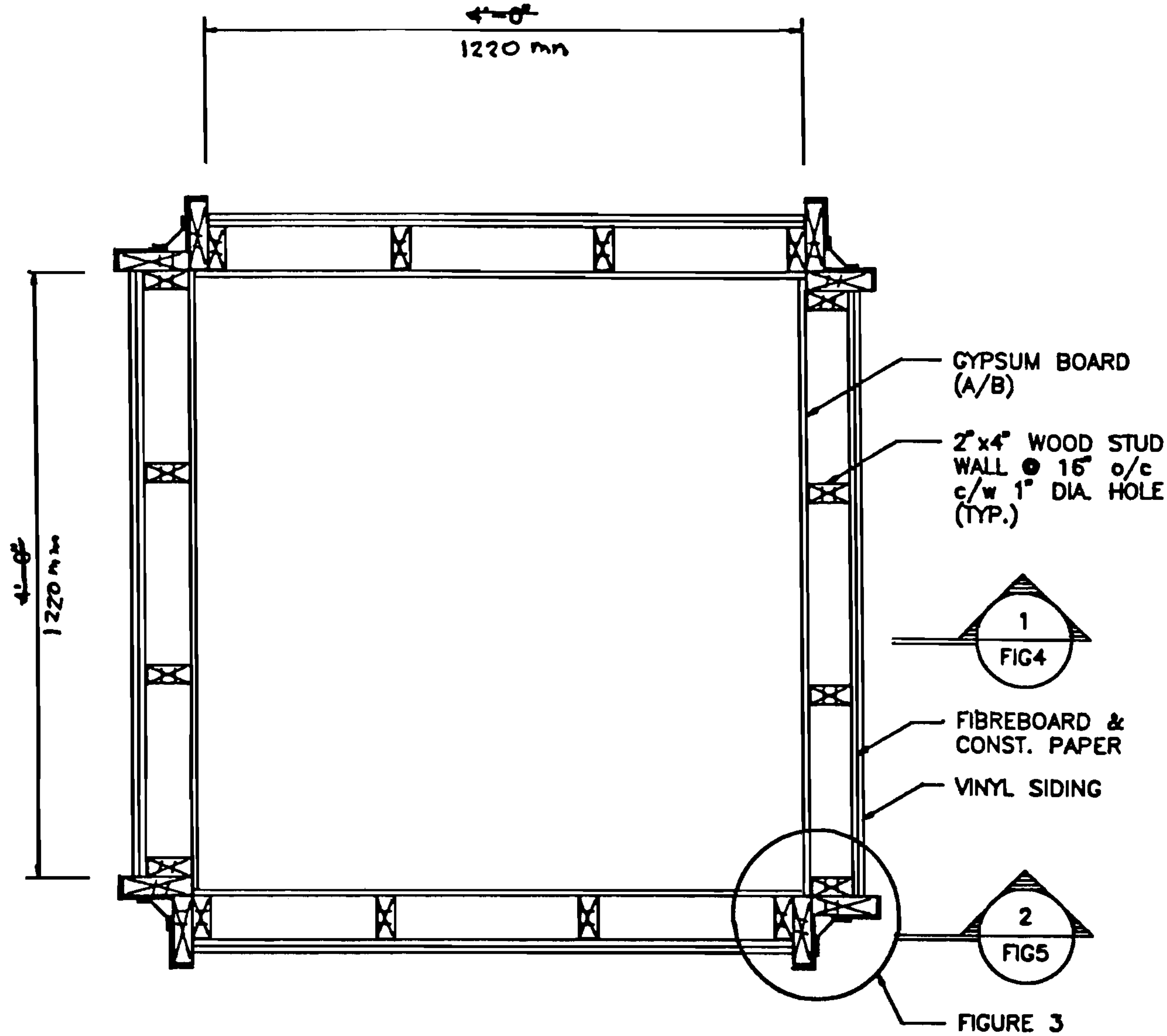
WIND TUNNEL TEST RESULTS



ELEVETION

COMPARTMENTALIZATION MODEL

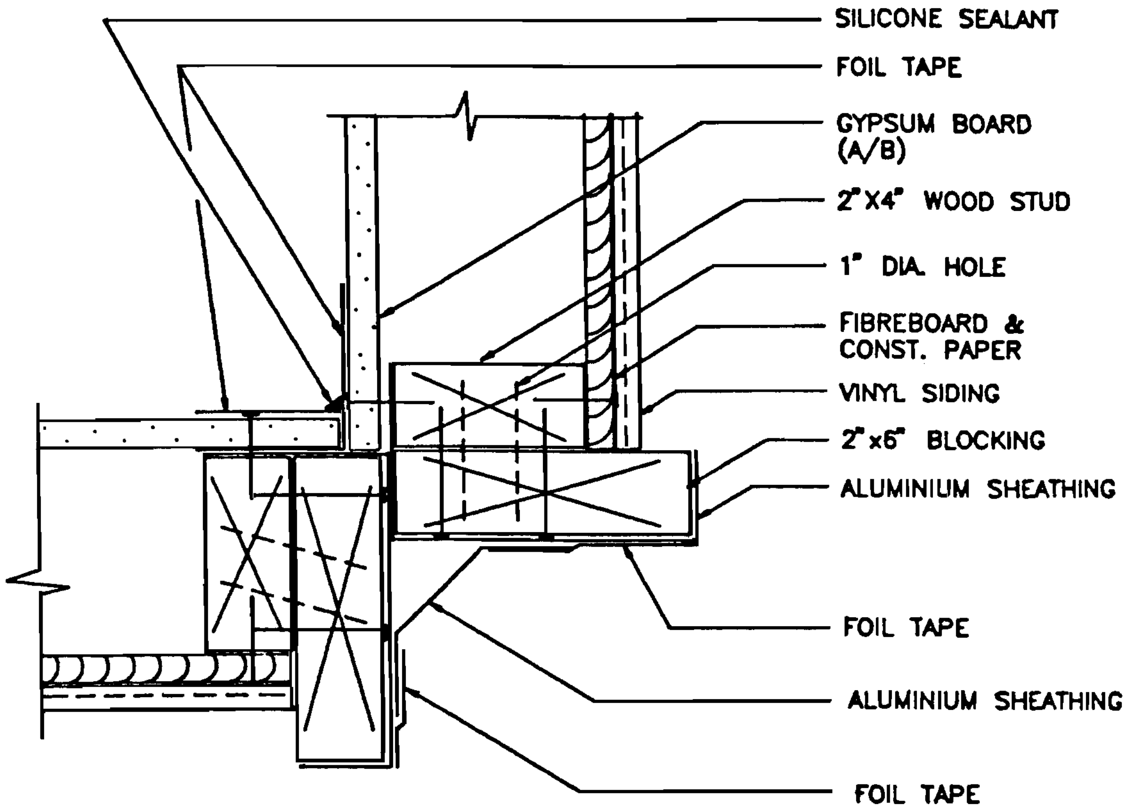
FIGURE 1



PLAN

COMPARTMENTALIZATION MODEL

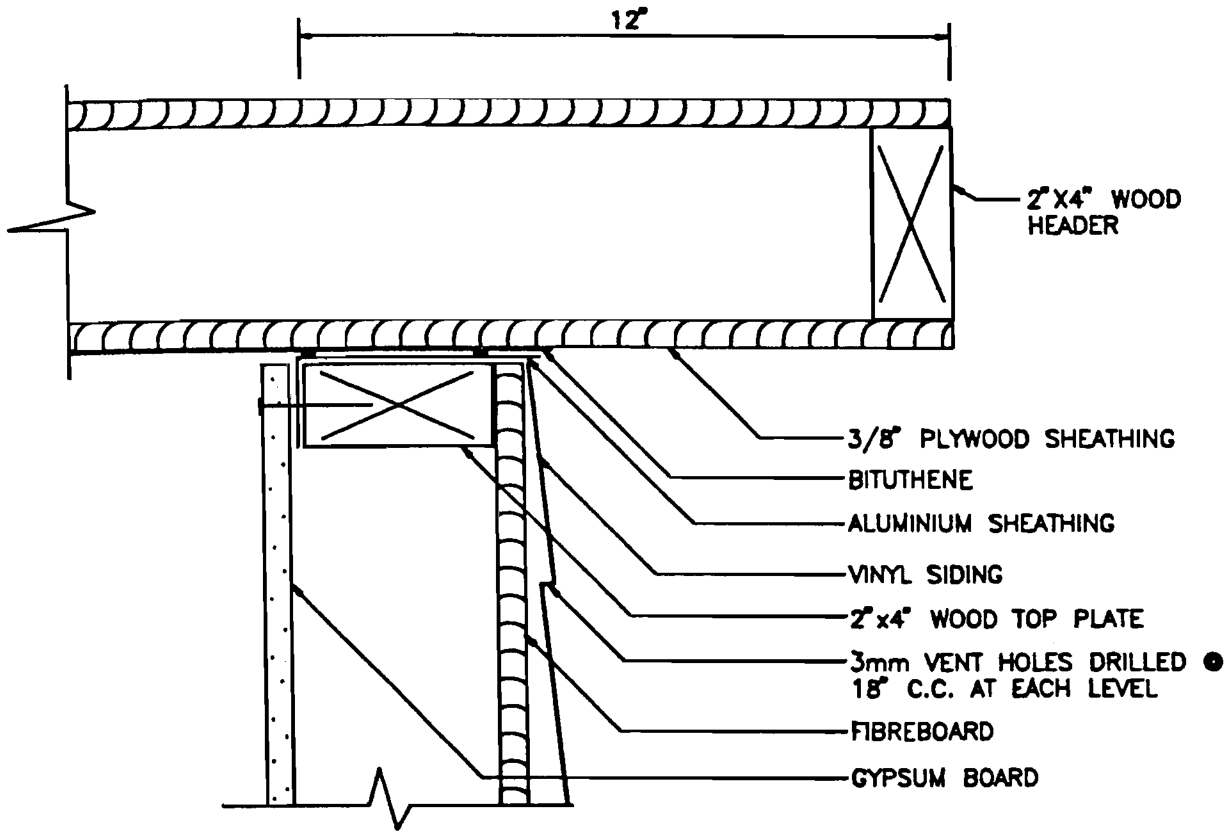
FIGURE 2



PLAN OF CORNER DETAIL

COMPARTMENTALIZATION MODEL

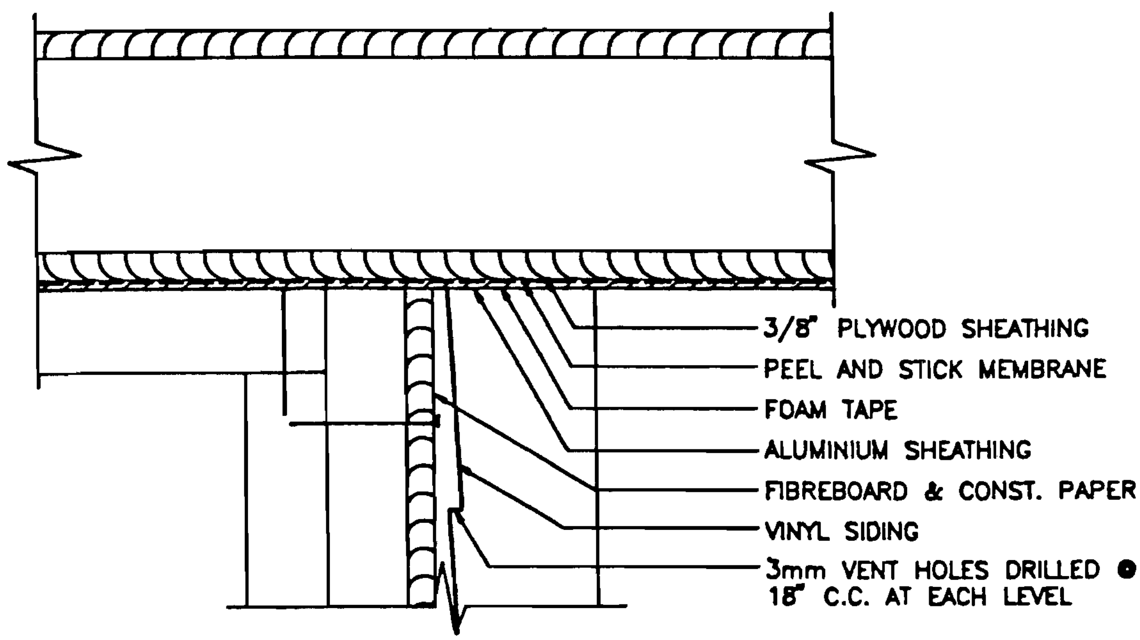
FIGURE 3



SECTION THROUGH EDGE OF CUBE LID AND BASE

SECTION 2 / FIG.2

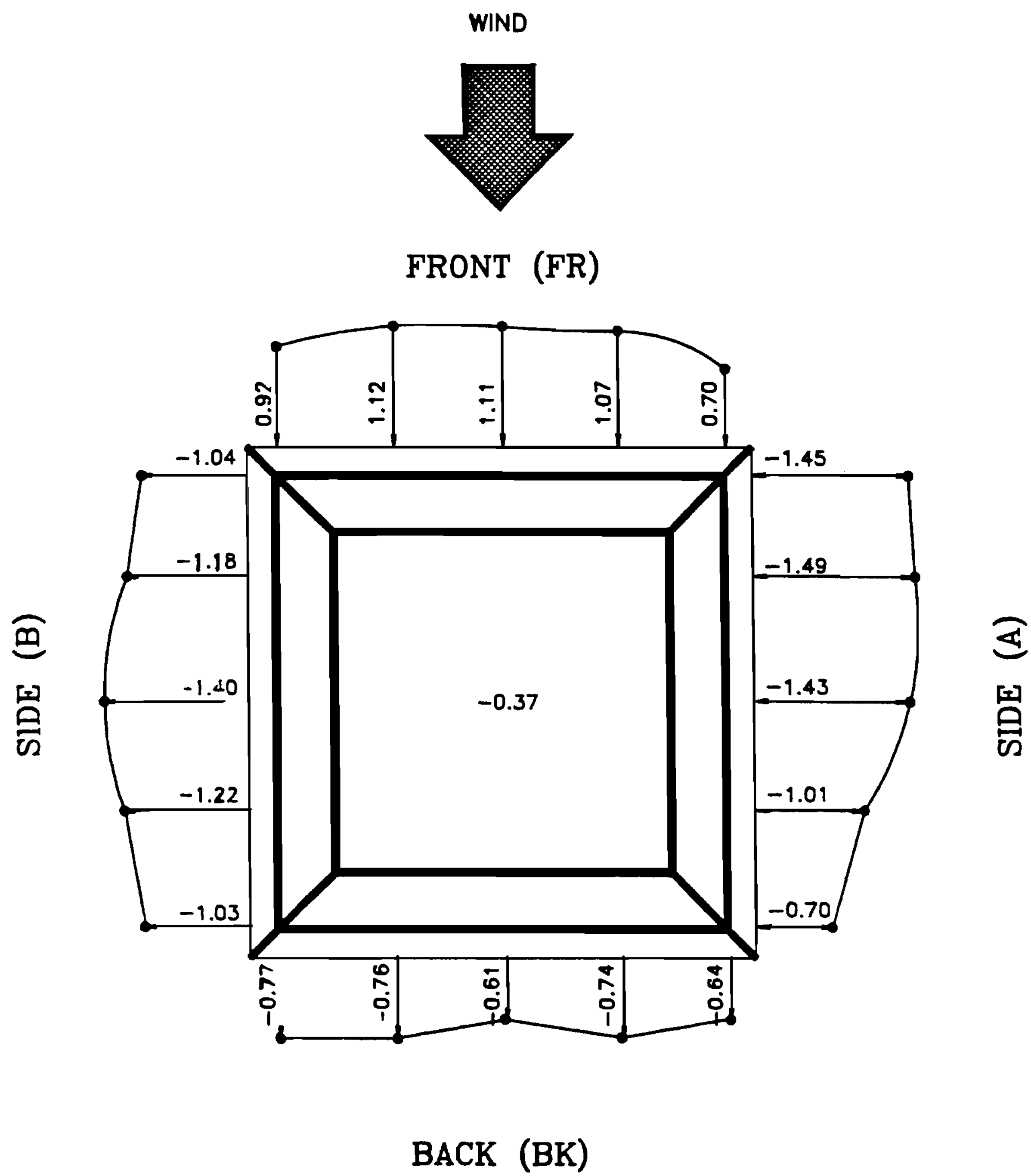
FIGURE 4



ELEVATION THROUGH EDGE OF CUBE LID AND BASE

SECTION 2 / FIG.2

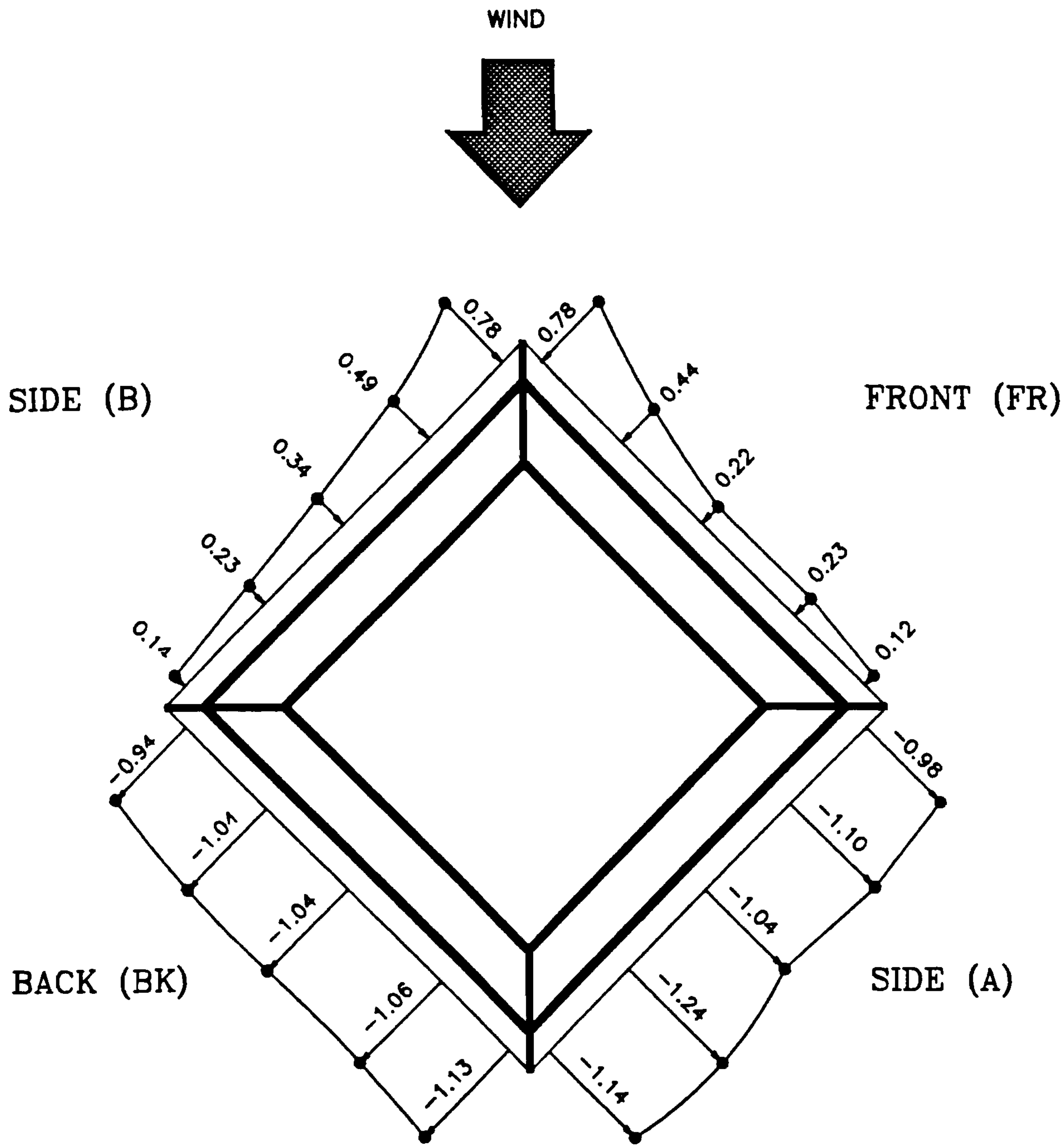
FIGURE 5



EXTERIOR PRESSURE COEFFICIENTS

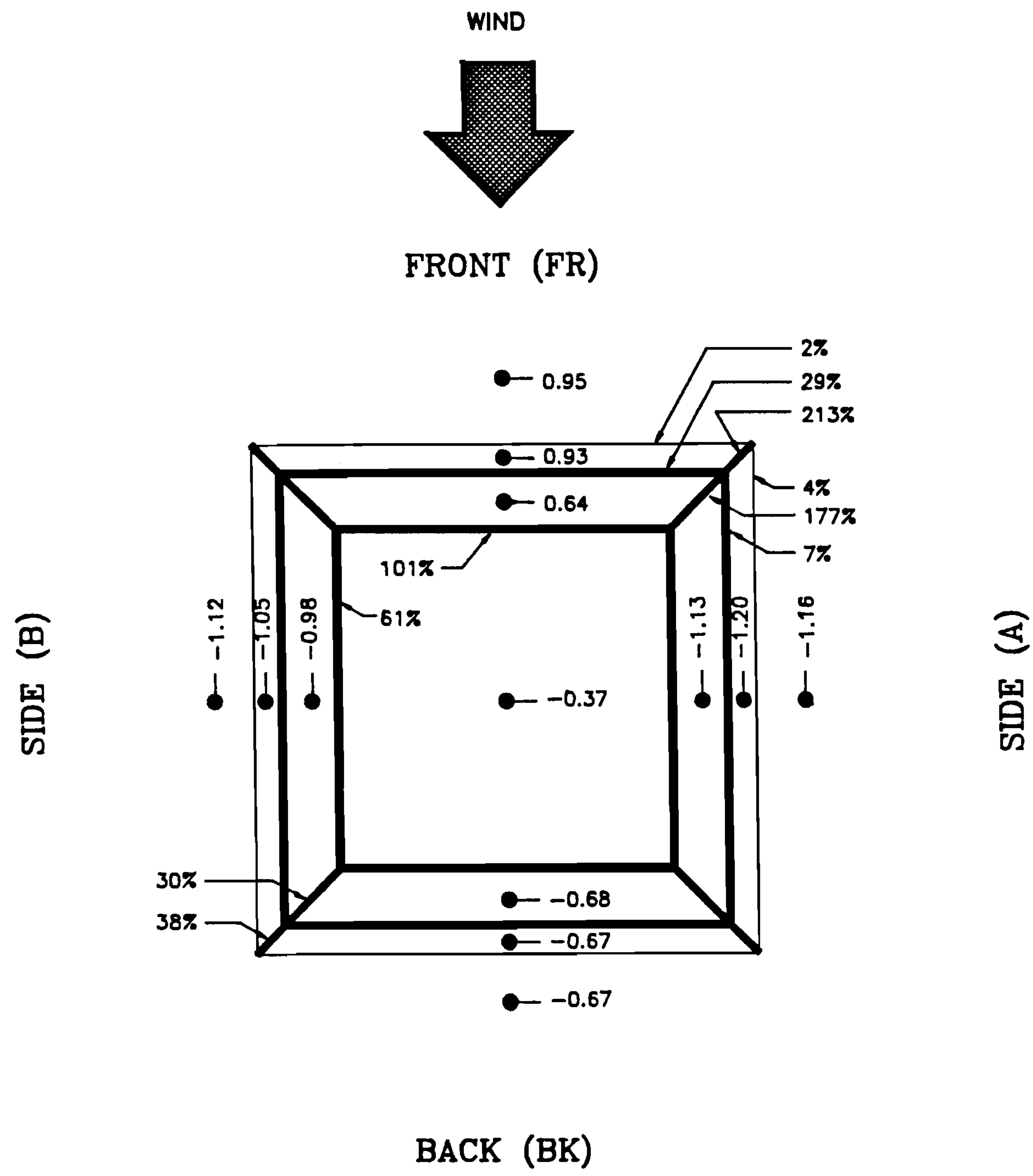
0° WIND

FIGURE 6



EXTERIOR PRESSURE COEFFICIENTS
45° WIND

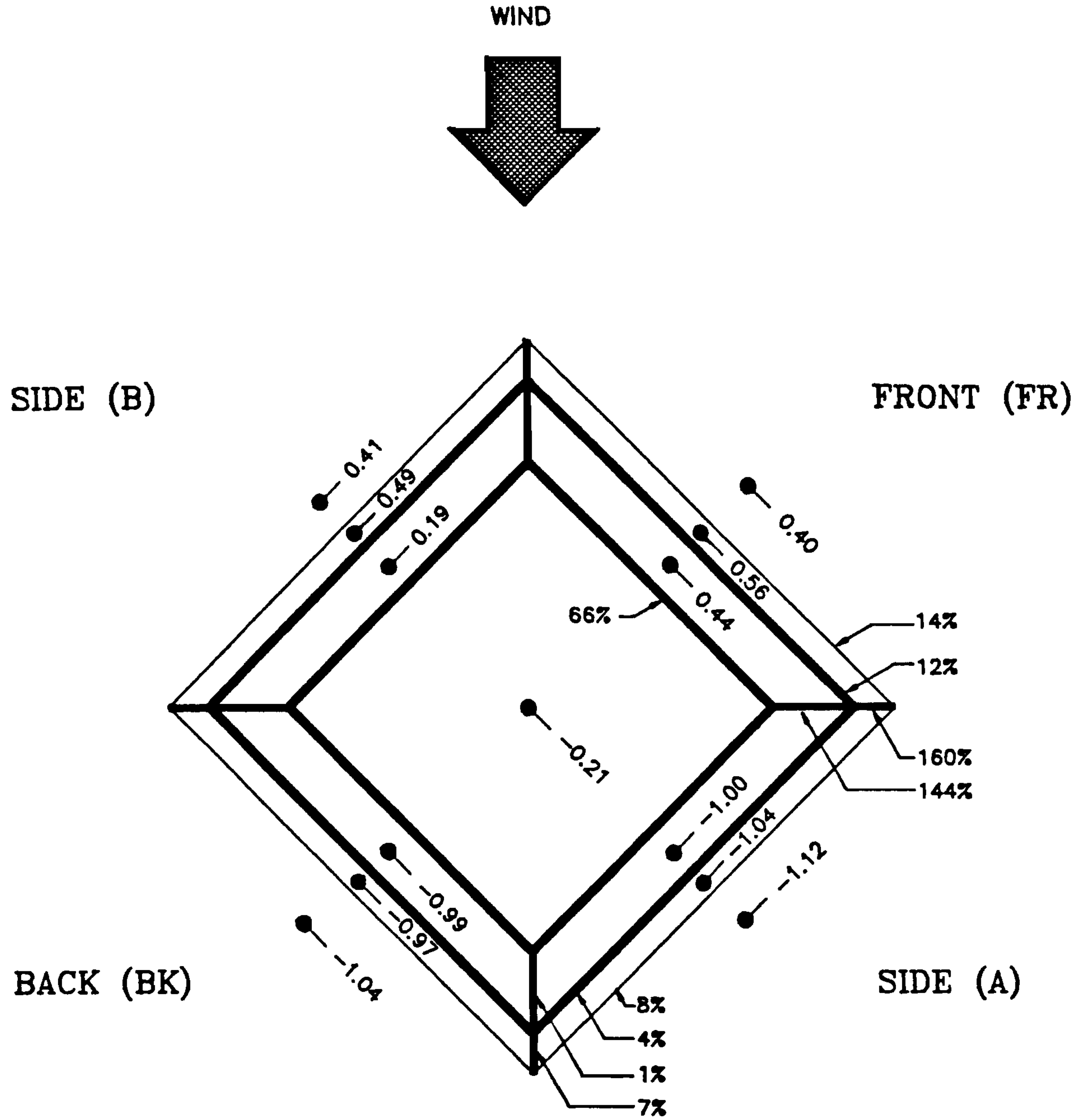
FIGURE 7



FULLY COMPARTMENTED AT ALL CORNERS

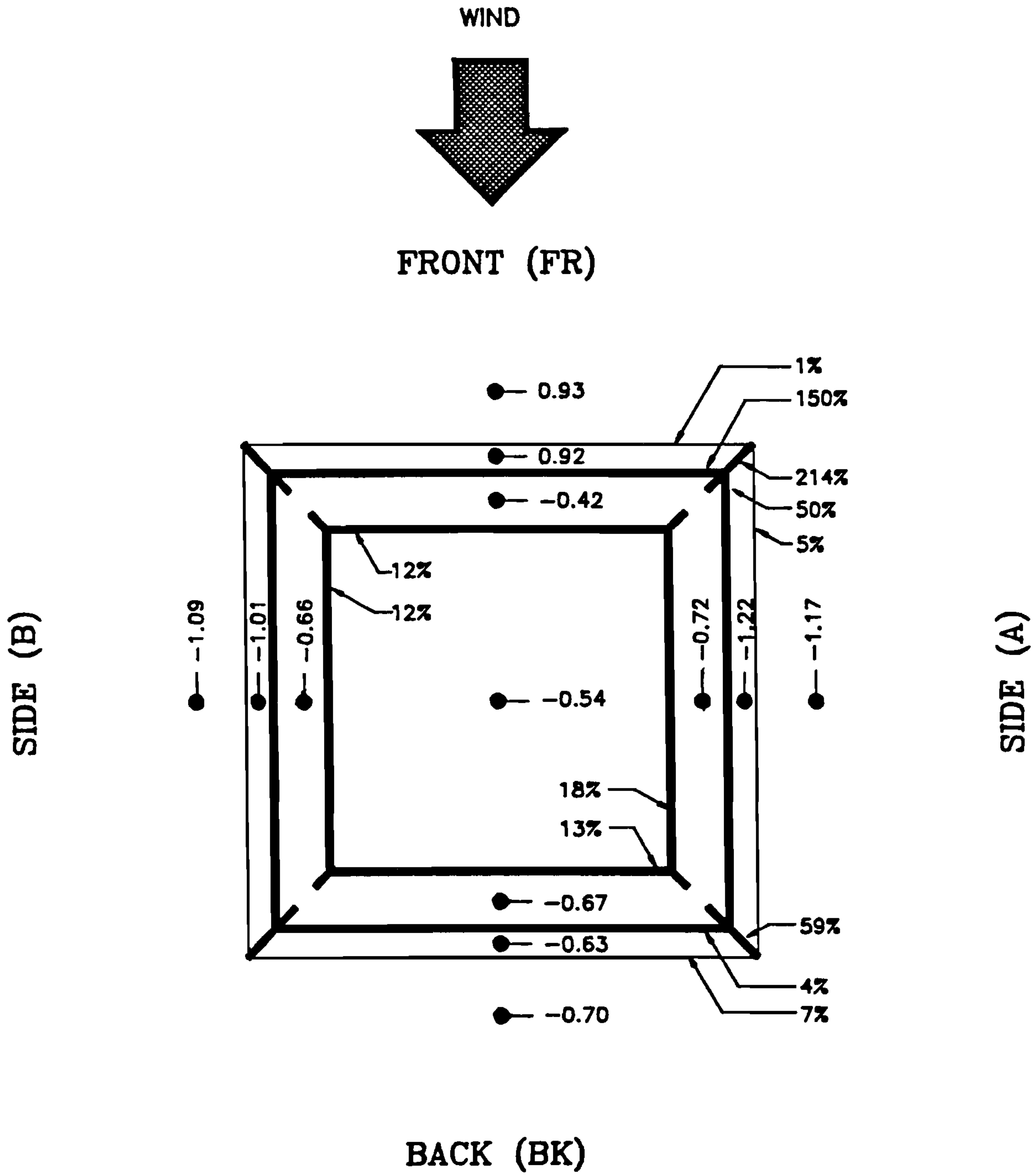
0° WIND ATTACK

FIGURE 8



FULLY COMPARTMENTED AT ALL CORNERS
45° WIND ATTACK

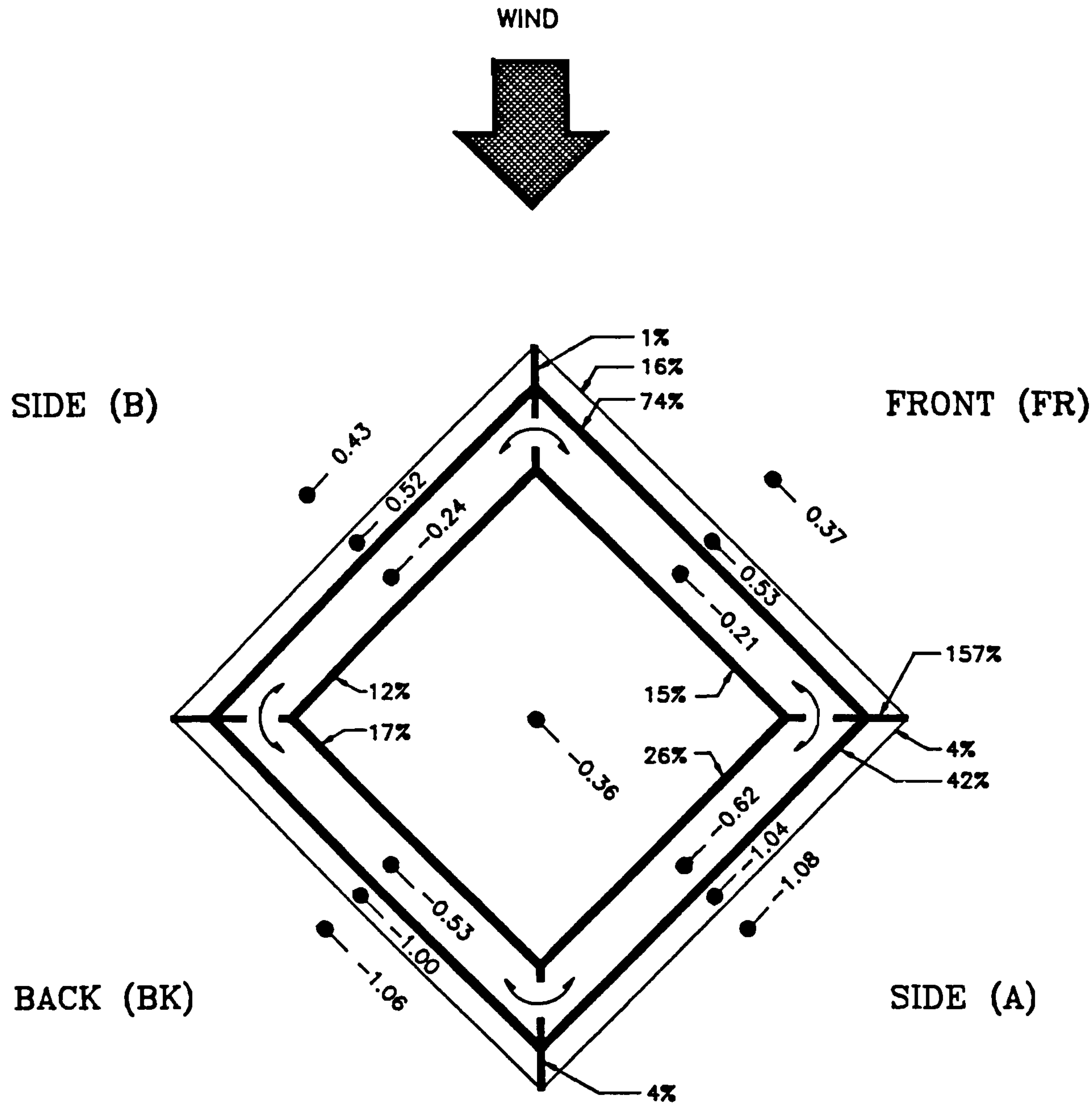
FIGURE 9



CONTINUOUS CAVITY. NO COMPARTMENTS

0° WIND

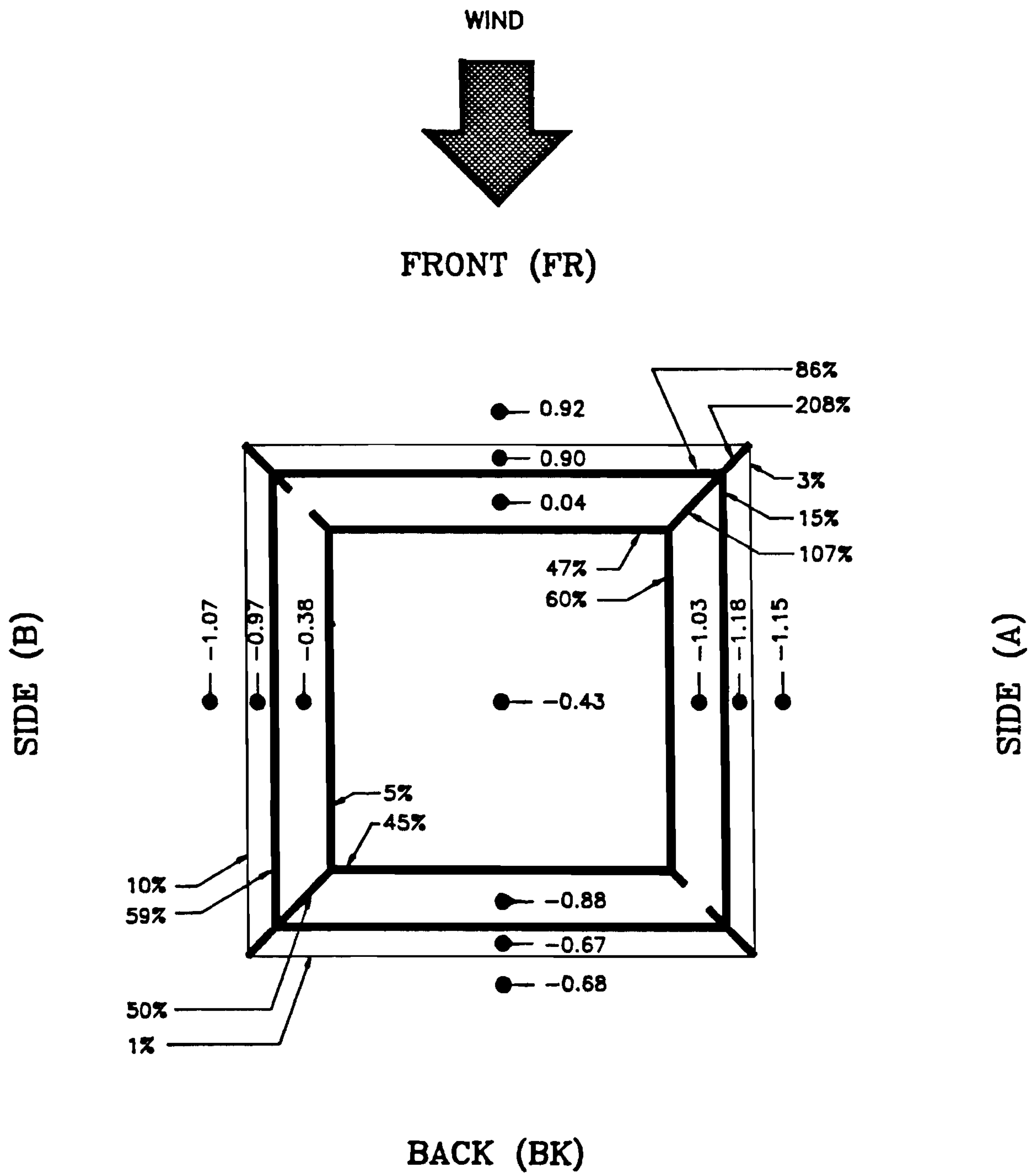
FIGURE 10



CONTINUOUS CAVITY. NO COMPARTMENTS

45° WIND

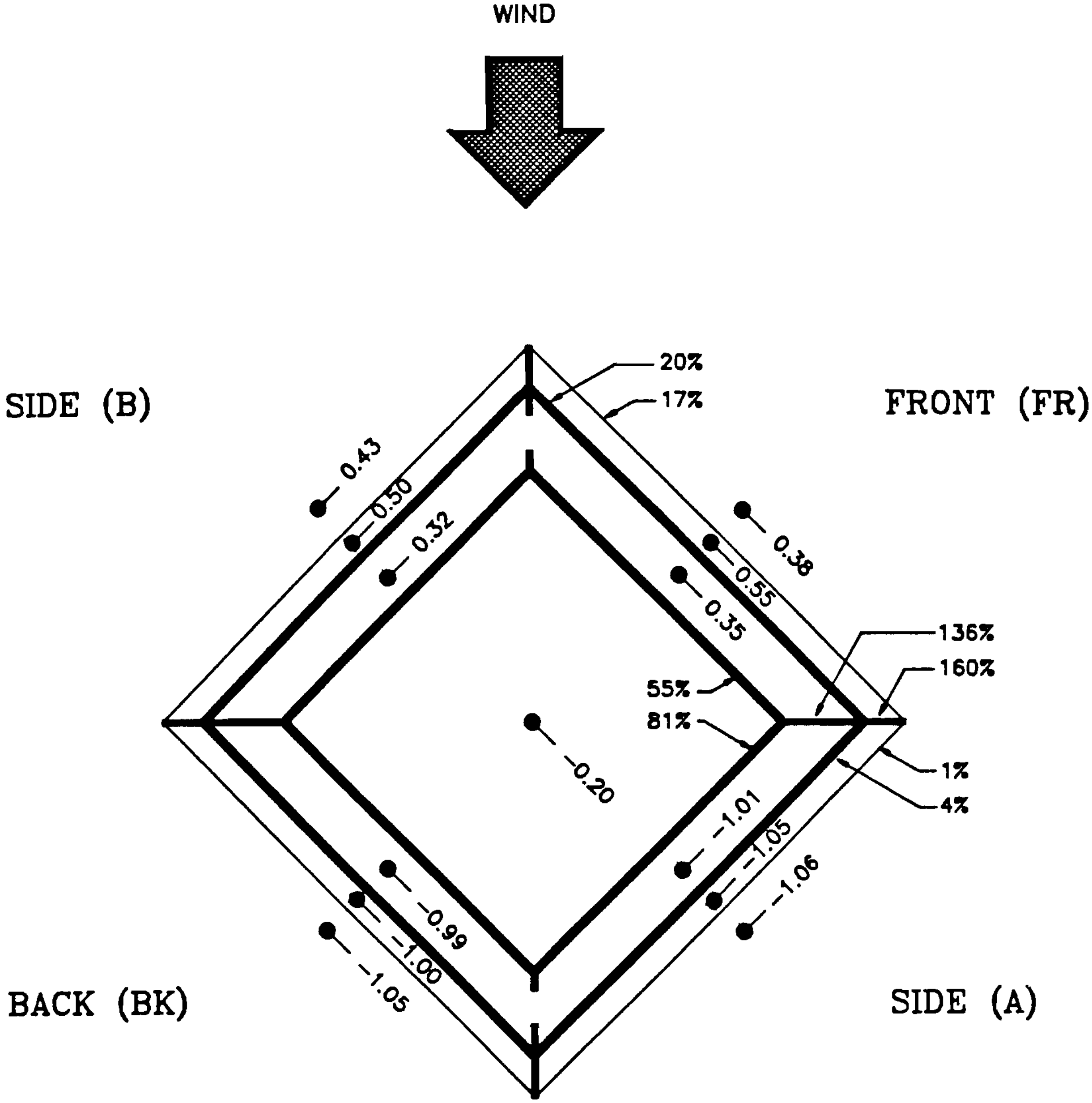
FIGURE 11



DIAGONALLY OPPOSED (RIGHT) COMPARTMENTS

0° WIND

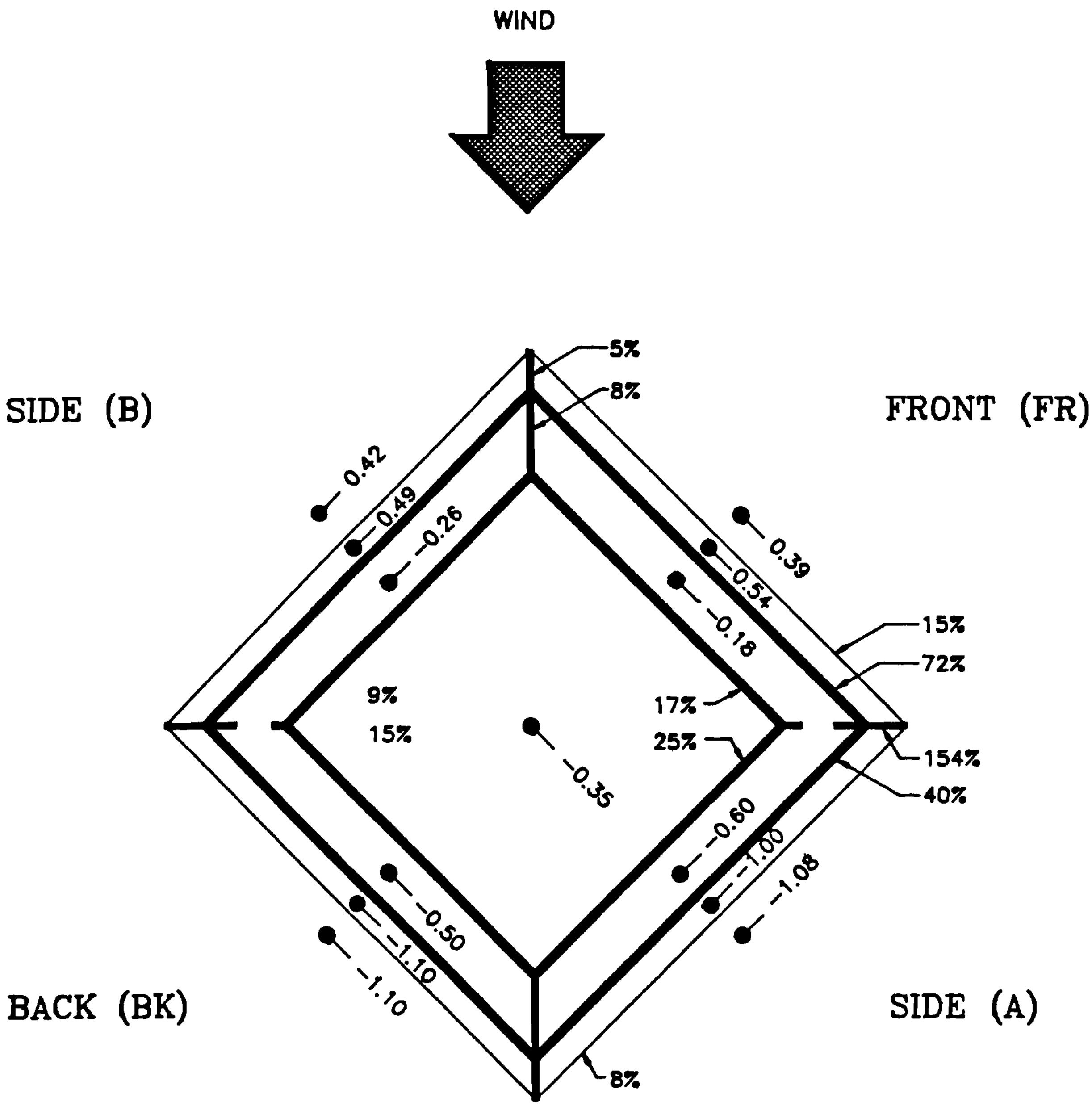
FIGURE 12



DIAGONALLY OPPOSED (RIGHT) COMPARTMENTS

45° WIND

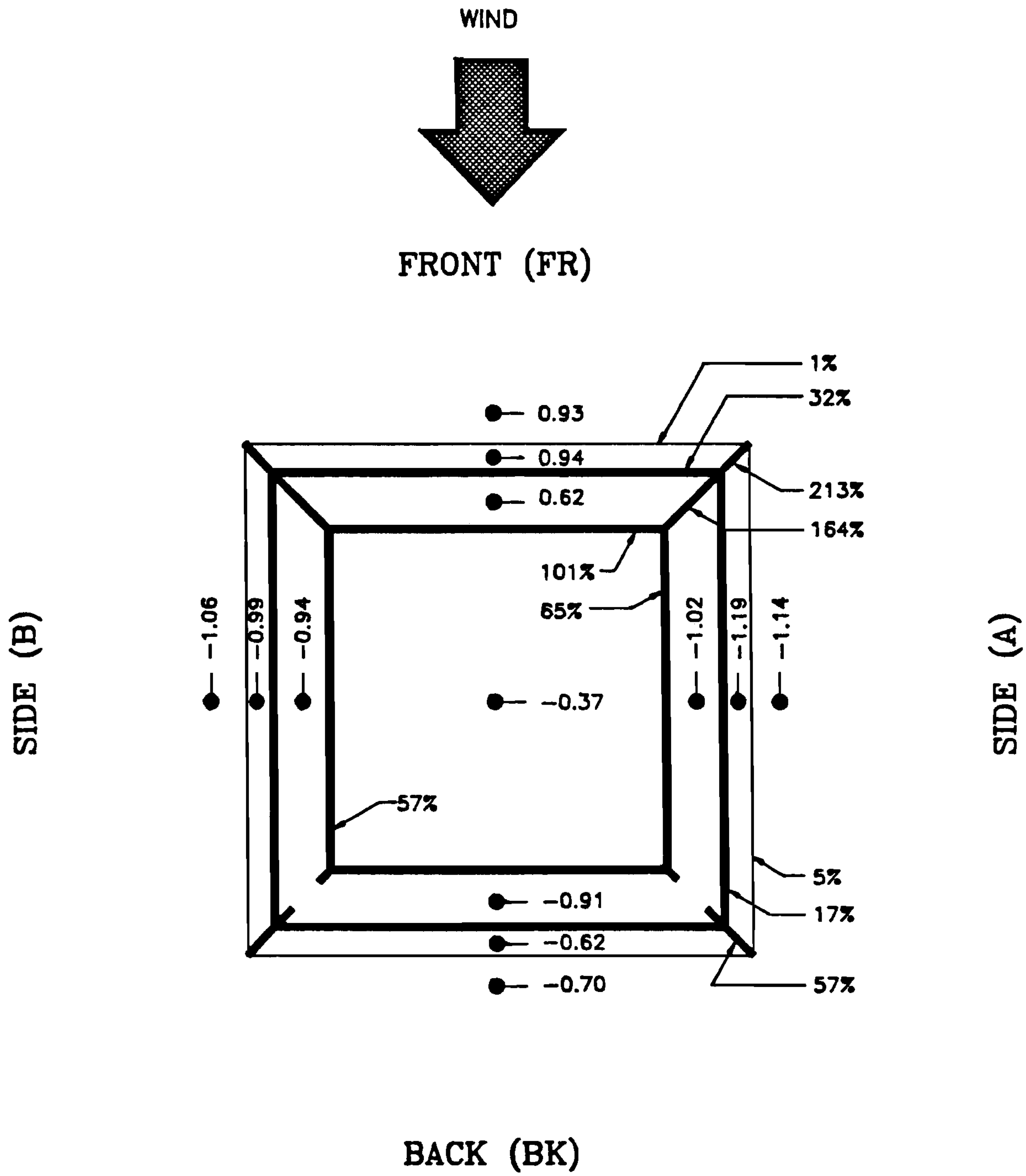
FIGURE 13



DIAGONALLY OPPOSED 9LEFT) COMPARTMENTS

45° WIND

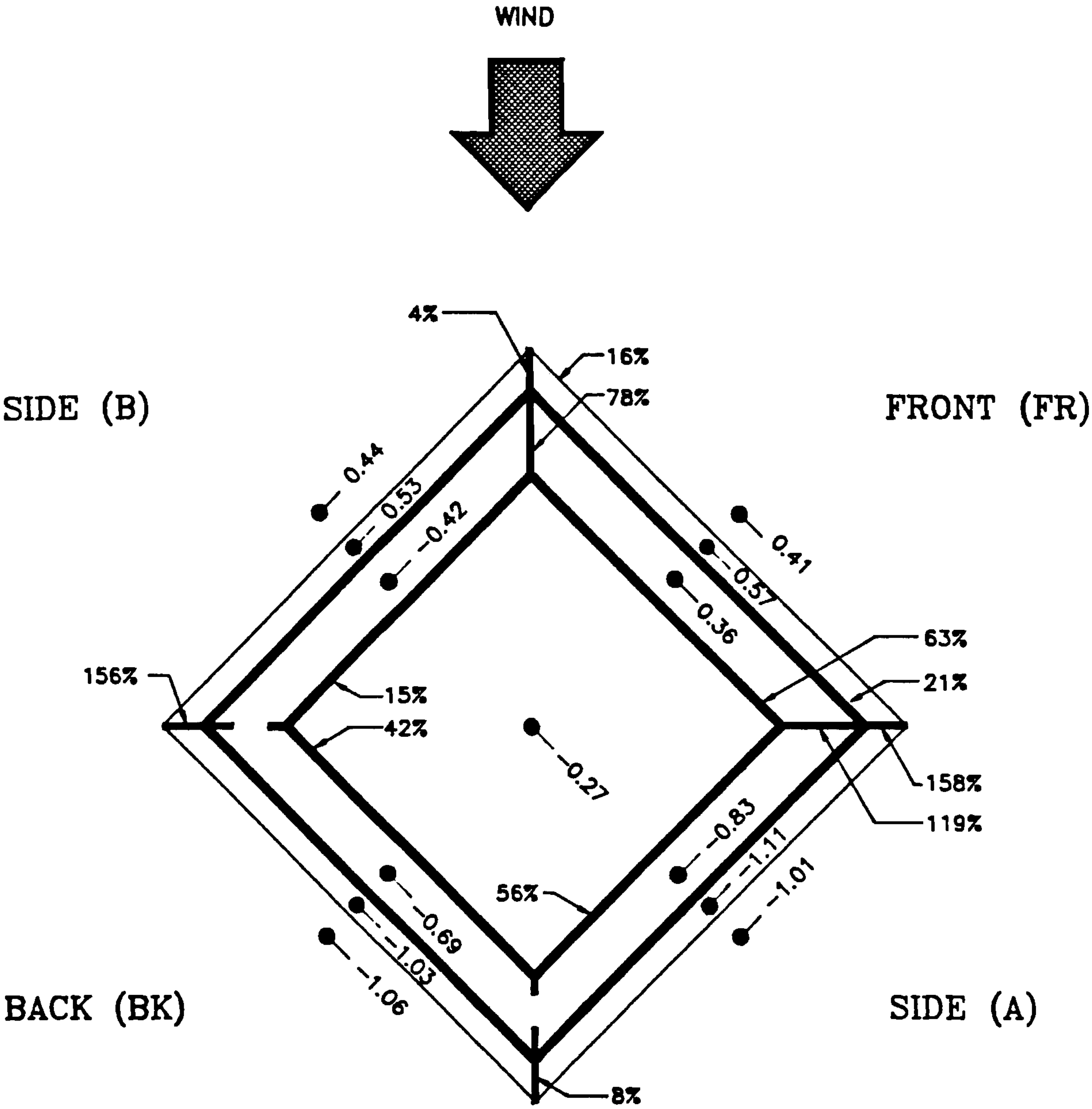
FIGURE 14



FRONT ELEVATION COMPARTMENTALIZED

B-BK-A CONTINUOUS- 0° WIND

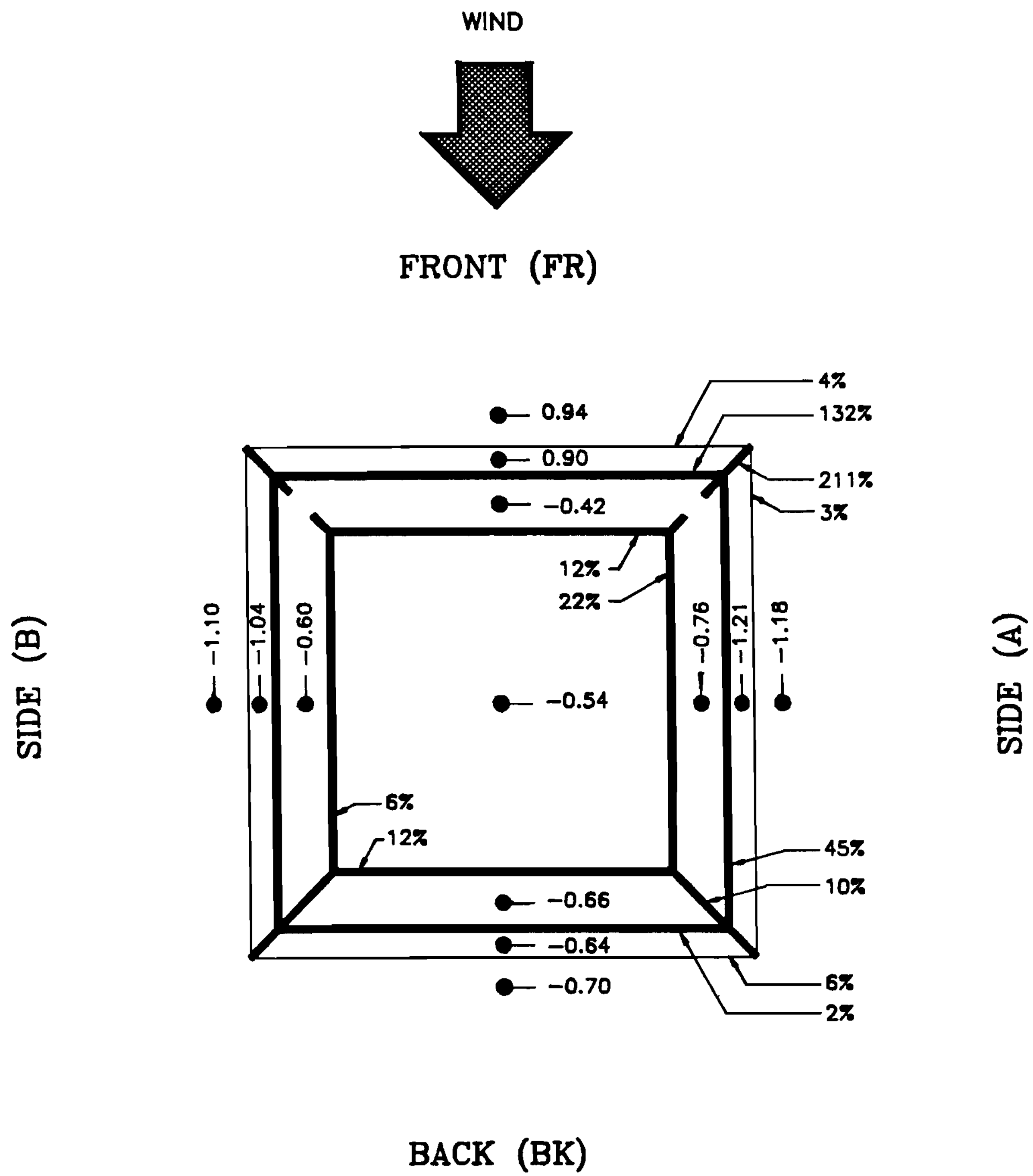
FIGURE 15



FRONT ELEVATION COMPARTMENTALIZED

B-BK-A CONTINUOUS- 45° WIND

FIGURE 16



BACK ELEVATION COMPARTMENTALIZED
B-FR-A CONTINUOUS- 0° WIND

FIGURE 17

	LENGTH m (ft)	WIDTH m (ft)	HEIGHT m (ft)	MAX. SPEED km/hr (mph)
OVERALL SIZE	64 (210)	15 (49)	6 (20)	— —
HIGH SPEED TEST SECTION	39 (128)	3.4 (11)	2.5 (8)	100 (62)
LOW SPEED TEST SECTION	52 (171)	5 (16)	4 (13)	36 (22)
WATER CHANNEL	52 (171)	5 (16)	2 (6.5)	— —

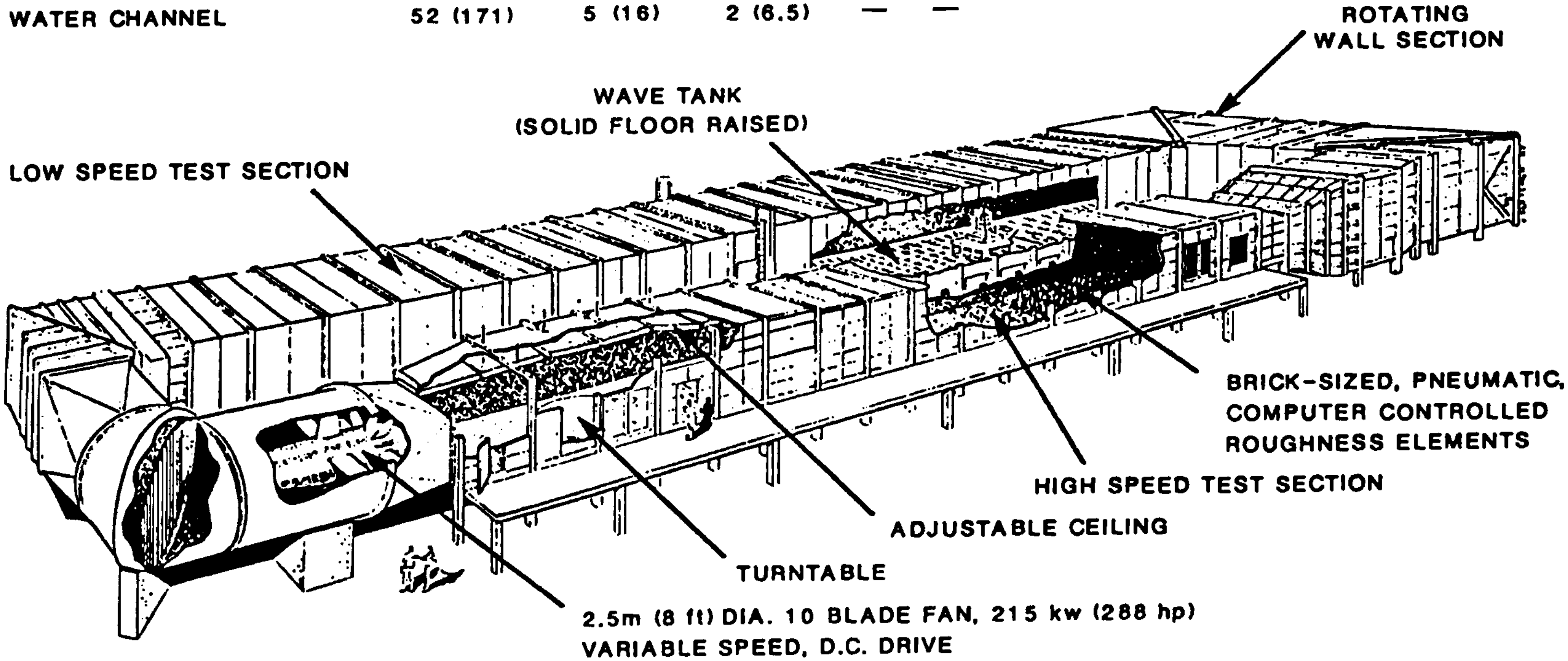
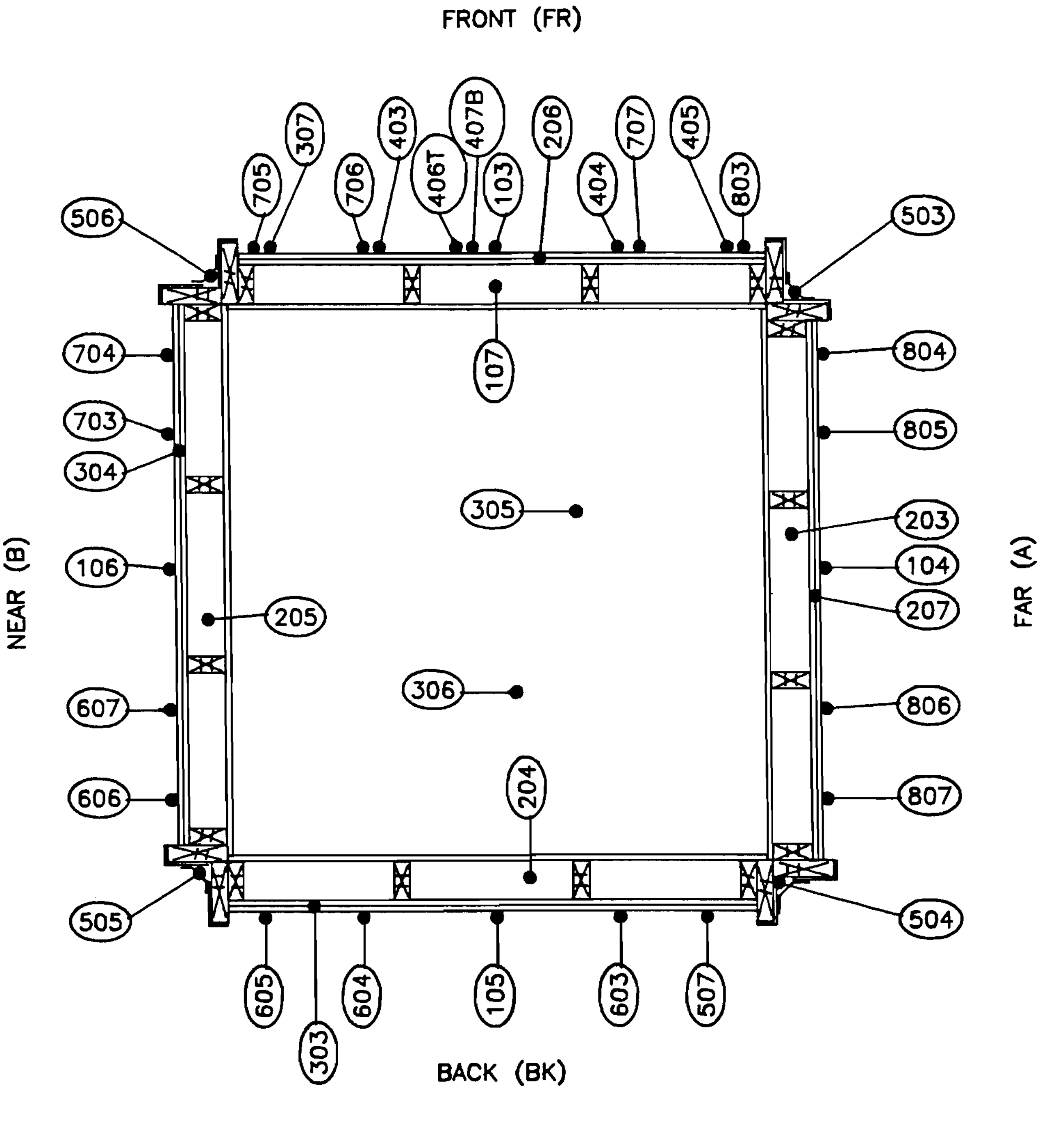


EXHIBIT 2 : BLWT II

THE BOUNDARY LAYER WIND TUNNEL LABORATORY

FIGURE 18



PLAN
COMPARTMENTALIZATION MODEL

FIGURE 19

TABLE 1

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHA101
Description: ALL CHAMBERS SEPARATE, 0 DEG., FIRST RUN (CONTROL)

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	1.127		
2	A OUT	104	-1.283	Avg MH Fr:	0.859
3	BK OUT	105	-0.554	Fr Top+Bot	1.110
4	B OUT	106	-1.376	Avg WT Fr:	0.943
5	FR STUD	107	0.607	Avg Fr:	0.970
6	A STUD	203	-1.110	MH Back:	-0.554
7	BK STUD	204	-0.672	Avg WT Bk:	-0.685
8	B STUD	205	-0.937	Avg Back:	-0.620
9	FR SIDING	206	0.922		
10	A SIDING	207	-1.248	MH A Side:	-1.283
				Avg WT A:	-1.146
11	BK SIDING	303	-0.413	Avg A Side:	-1.215
12	B SIDING	304	-1.016		
13	INSIDE FR	305	-0.339	MH B Side:	-1.376
14	INSIDE BK	306	-0.338	Avg WT B:	-1.075
15	OUT FR, B	307	0.678	Avg B Side:	-1.226
16	OUT FR, IN	403	1.114	Avg Int:	-0.339
17	OUT FR, IN	404	0.992		
18	OUT FR, A	405	0.383		
19	FR TOP	406	1.105		
20	FR BOT	407	1.114		
21	FR-A CORNER	503	-1.266		
22	A-BK CORNER	504	-0.677		
23	BK-B CORNER	505	-0.828		
24	B-FR CORNER	506	-0.873		
25	BK PENNY	507	-0.653		
26	BK PENNY	603	-0.672		
27	BK PENNY	604	-0.712		
28	BK PENNY	605	-0.703		
29	B PENNY	606	-1.001		
30	B PENNY	607	-1.182		
31	B PENNY	703	-1.107		
32	B PENNY	704	-1.011		
33	FR PENNY	705	0.915		
34	FR PENNY	706	1.118		
35	FR PENNY	707	1.047		
36	FR PENNY	803	0.692		
37	A PENNY	804	-1.652		
38	A PENNY	805	-1.529		
39	A PENNY	806	-0.795		
40	A PENNY	807	-0.608		

TABLE 2

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHA102

Description: ALL CHAMBERS SEPARATE, 45 DEG., FIRST RUN (CONTROL)

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.151		
2	A OUT	104	-1.096	Avg MH Fr:	-0.045
3	BK OUT	105	-1.114	Fr Top+Bot	0.020
4	B OUT	106	0.320	Avg WT Fr:	0.413
5	FR STUD	107	0.442	Avg Fr:	0.129
6	A STUD	203	-1.028	MH Back:	-1.114
7	BK STUD	204	-0.981	Avg WT Bk:	-1.071
8	B STUD	205	0.174	Avg Back:	-1.092
9	FR SIDING	206	0.581		
10	A SIDING	207	-1.089	MH A Side:	-1.096
				Avg WT A:	-1.117
11	BK SIDING	303	-0.915	Avg A Side:	-1.106
12	B SIDING	304	0.512		
13	INSIDE FR	305	-0.222	MH B Side:	0.320
14	INSIDE BK	306	-0.228	Avg WT B:	0.414
15	OUT FR, B	307	0.624	Avg B Side:	0.367
16	OUT FR, IN	403	0.367	Avg Int:	-0.225
17	OUT FR, IN	404	-0.204		
18	OUT FR, A	405	-0.861		
19	FR TOP	406	0.246		
20	FR BOT	407	-0.206		
21	FR-A CORNER	503	-0.888		
22	A-BK CORNER	504	-1.056		
23	BK-B CORNER	505	-0.568		
24	B-FR CORNER	506	0.770		
25	BK PENNY	507	-1.113		
26	BK PENNY	603	-1.157		
27	BK PENNY	604	-1.012		
28	BK PENNY	605	-1.000		
29	B PENNY	606	0.115		
30	B PENNY	607	0.250		
31	B PENNY	703	0.479		
32	B PENNY	704	0.811		
33	FR PENNY	705	0.802		
34	FR PENNY	706	0.463		
35	FR PENNY	707	0.268		
36	FR PENNY	803	0.119		
37	A PENNY	804	-1.067		
38	A PENNY	805	-1.052		
39	A PENNY	806	-1.164		
40	A PENNY	807	-1.183		

TABLE 3

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott — April 2 1990

Test File Name: MHA103

Description: ALL CHAMBERS SEPARATE, 0 DEG.

	Tap Loc	Scani #	Cp (MEAN)
1	FR OUT	103	1.099
2	A OUT	104	-1.429
3	BK OUT	105	-0.610
4	B OUT	106	-1.401
5	FR STUD	107	0.641
6	A STUD	203	-1.134
7	BK STUD	204	-0.676
8	B STUD	205	-0.982
9	FR SIDING	206	0.933
10	A SIDING	207	-1.199
11	BK SIDING	303	-0.665
12	B SIDING	304	-1.045
13	INSIDE FR	305	-0.371
14	INSIDE BK	306	-0.373
15	OUT FR, B	307	0.738
16	OUT FR, IN	403	1.045
17	OUT FR, IN	404	0.976
18	OUT FR, A	405	0.438
19	FR TOP	406	1.079
20	FR BOT	407	1.117
21	FR-A CORNER	503	-1.164
22	A-BK CORNER	504	-0.680
23	BK-B CORNER	505	-0.824
24	B-FR CORNER	506	-0.873
25	BK PENNY	507	-0.643
26	BK PENNY	603	-0.736
27	BK PENNY	604	-0.756
28	BK PENNY	605	-0.771
29	B PENNY	606	-1.033
30	B PENNY	607	-1.223
31	B PENNY	703	-1.184
32	B PENNY	704	-1.043
33	FR PENNY	705	0.918
34	FR PENNY	706	1.122
35	FR PENNY	707	1.073
36	FR PENNY	803	0.695
37	A PENNY	804	-1.450
38	A PENNY	805	-1.489
39	A PENNY	806	-1.010
40	A PENNY	807	-0.701

Avg MH Fr:	0.859
Fr Top+Bot	1.098
Avg WT Fr:	0.952
Avg Fr:	0.970
MH Back:	-0.610
Avg WT Bk:	-0.727
Avg Back:	-0.668
MH A Side:	-1.429
Avg WT A:	-1.163
Avg A Side:	-1.296
MH B Side:	-1.401
Avg WT B:	-1.121
Avg B Side:	-1.261
Avg Int:	-0.372

TABLE 4

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHA104

Description: ALL CHAMBERS SEPARATE, 45 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.156		
2	A OUT	104	-1.037	Avg MH Fr:	-0.037
3	BK OUT	105	-1.031	Fr Top+Bot	0.016
4	B OUT	106	0.341	Avg WT Fr:	0.403
5	FR STUD	107	0.444	Avg Fr:	0.127
6	A STUD	203	-1.004	MH Back:	-1.031
7	BK STUD	204	-0.988	Avg WT Bk:	-1.039
8	B STUD	205	0.189	Avg Back:	-1.035
9	FR SIDING	206	0.556		
10	A SIDING	207	-1.040	MH A Side:	-1.037
				Avg WT A:	-1.114
11	BK SIDING	303	-0.965	Avg A Side:	-1.075
12	B SIDING	304	0.490		
13	INSIDE FR	305	-0.216	MH B Side:	0.341
14	INSIDE BK	306	-0.212	Avg WT B:	0.412
15	OUT FR, B	307	0.621	Avg B Side:	0.377
16	OUT FR, IN	403	0.377	Avg Int:	-0.214
17	OUT FR, IN	404	-0.147		
18	OUT FR, A	405	-0.880		
19	FR TOP	406	0.222		
20	FR BOT	407	-0.191		
21	FR-A CORNER	503	-0.876		
22	A-BK CORNER	504	-1.044		
23	BK-B CORNER	505	-0.521		
24	B-FR CORNER	506	0.787		
25	BK PENNY	507	-1.126		
26	BK PENNY	603	-1.059		
27	BK PENNY	604	-1.038		
28	BK PENNY	605	-0.934		
29	B PENNY	606	0.142		
30	B PENNY	607	0.232		
31	B PENNY	703	0.494		
32	B PENNY	704	0.781		
33	FR PENNY	705	0.778		
34	FR PENNY	706	0.437		
35	FR PENNY	707	0.275		
36	FR PENNY	803	0.121		
37	A PENNY	804	-0.986		
38	A PENNY	805	-1.093		
39	A PENNY	806	-1.235		
40	A PENNY	807	-1.140		

TABLE 5

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott — April 2 1990

Test File Name: MHC101

Description: ALL CHAMBERS CONNECTED, 0 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	1.097		
2	A OUT	104	-1.365	Avg MH Fr:	0.844
3	BK OUT	105	-0.600	Fr Top+Bot	1.099
4	B OUT	106	-1.367	Avg WT Fr:	0.934
5	FR STUD	107	-0.418	Avg Fr:	0.959
6	A STUD	203	-0.723	MH Back:	-0.600
7	BK STUD	204	-0.672	Avg WT Bk:	-0.700
8	B STUD	205	-0.658	Avg Back:	-0.650
9	FR SIDING	206	0.924		
10	A SIDING	207	-1.220	MH A Side:	-1.365
				Avg WT A:	-1.166
11	BK SIDING	303	-0.628	Avg A Side:	-1.266
12	B SIDING	304	-1.006		
13	INSIDE FR	305	-0.552	MH B Side:	-1.367
14	INSIDE BK	306	-0.526	Avg WT B:	-1.087
15	OUT FR, B	307	0.709	Avg B Side:	-1.227
16	OUT FR, IN	403	1.064	Avg Int:	-0.539
17	OUT FR, IN	404	0.992		
18	OUT FR, A	405	0.357		
19	FR TOP	406	1.084		
20	FR BOT	407	1.113		
21	FR-A CORNER	503	-0.648		
22	A-BK CORNER	504	-0.713		
23	BK-B CORNER	505	-0.687		
24	B-FR CORNER	506	-0.517		
25	BK PENNY	507	-0.654		
26	BK PENNY	603	-0.695		
27	BK PENNY	604	-0.711		
28	BK PENNY	605	-0.741		
29	B PENNY	606	-1.001		
30	B PENNY	607	-1.177		
31	B PENNY	703	-1.149		
32	B PENNY	704	-1.019		
33	FR PENNY	705	0.892		
34	FR PENNY	706	1.121		
35	FR PENNY	707	1.049		
36	FR PENNY	803	0.673		
37	A PENNY	804	-1.564		
38	A PENNY	805	-1.583		
39	A PENNY	806	-0.878		
40	A PENNY	807	-0.639		

TABLE 6

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHC102
Description: ALL CHAMBERS CONNECTED, 45 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.232		
2	A OUT	104	-1.033	Avg MH Fr:	-0.096
3	BK OUT	105	-1.097	Fr Top+Bot	-0.091
4	B OUT	106	0.377	Avg WT Fr:	0.372
5	FR STUD	107	-0.209	Avg Fr:	0.062
6	A STUD	203	-0.616	MH Back:	-1.097
7	BK STUD	204	-0.530	Avg WT Bk:	-1.056
8	B STUD	205	-0.242	Avg Back:	-1.077
9	FR SIDING	206	0.534		
10	A SIDING	207	-1.042	MH A Side:	-1.033
				Avg WT A:	-1.077
11	BK SIDING	303	-0.997	Avg A Side:	-1.055
12	B SIDING	304	0.515		
13	INSIDE FR	305	-0.366	MH B Side:	0.377
14	INSIDE BK	306	-0.358	Avg WT B:	0.431
15	OUT FR, B	307	0.564	Avg B Side:	0.404
16	OUT FR, IN	403	0.293	Avg Int:	-0.362
17	OUT FR, IN	404	-0.234		
18	OUT FR, A	405	-0.873		
19	FR TOP	406	0.087		
20	FR BOT	407	-0.268		
21	FR-A CORNER	503	-0.502		
22	A-BK CORNER	504	-0.602		
23	BK-B CORNER	505	-0.397		
24	B-FR CORNER	506	-0.209		
25	BK PENNY	507	-1.133		
26	BK PENNY	603	-1.093		
27	BK PENNY	604	-0.999		
28	BK PENNY	605	-1.000		
29	B PENNY	606	0.133		
30	B PENNY	607	0.254		
31	B PENNY	703	0.502		
32	B PENNY	704	0.836		
33	FR PENNY	705	0.756		
34	FR PENNY	706	0.423		
35	FR PENNY	707	0.236		
36	FR PENNY	803	0.074		
37	A PENNY	804	-1.015		
38	A PENNY	805	-1.014		
39	A PENNY	806	-1.146		
40	A PENNY	807	-1.132		

TABLE 7

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHF101

Description: TWO CORNERS OPEN, FRONT-B AND BACK-A, 0 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	1.072		
2	A OUT	104	-1.384	Avg MH Fr:	0.842
3	BK OUT	105	-0.585	Fr Top+Bot	1.079
4	B OUT	106	-1.384	Avg WT Fr:	0.922
5	FR STUD	107	0.039	Avg Fr:	0.948
6	A STUD	203	-1.025	MH Back:	-0.585
7	BK STUD	204	-0.877	Avg WT Bk:	-0.682
8	B STUD	205	-0.377	Avg Back:	-0.634
9	FR SIDING	206	0.904		
10	A SIDING	207	-1.182	MH A Side:	-1.384
				Avg WT A:	-1.151
11	BK SIDING	303	-0.673	Avg A Side:	-1.268
12	B SIDING	304	-0.970		
13	INSIDE FR	305	-0.426	MH B Side:	-1.384
14	INSIDE BK	306	-0.433	Avg WT B:	-1.066
15	OUT FR, B	307	0.724	Avg B Side:	-1.225
16	OUT FR, IN	403	1.016	Avg Int:	-0.430
17	OUT FR, IN	404	0.992		
18	OUT FR, A	405	0.407		
19	FR TOP	406	1.040		
20	FR BOT	407	1.118		
21	FR-A CORNER	503	-1.201		
22	A-BK CORNER	504	-0.908		
23	BK-B CORNER	505	-0.817		
24	B-FR CORNER	506	-0.170		
25	BK PENNY	507	-0.611		
26	BK PENNY	603	-0.733		
27	BK PENNY	604	-0.667		
28	BK PENNY	605	-0.718		
29	B PENNY	606	-0.991		
30	B PENNY	607	-1.154		
31	B PENNY	703	-1.152		
32	B PENNY	704	-0.968		
33	FR PENNY	705	0.899		
34	FR PENNY	706	1.088		
35	FR PENNY	707	1.052		
36	FR PENNY	803	0.649		
37	A PENNY	804	-1.496		
38	A PENNY	805	-1.533		
39	A PENNY	806	-0.941		
40	A PENNY	807	-0.634		

TABLE 8

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHF102

Description: TWO CORNERS OPEN, FRONT-B AND BACK-A, 45 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.234		
2	A OUT	104	-0.985	Avg MH Fr:	-0.079
3	BK OUT	105	-1.102	Fr Top+Bot	-0.082
4	B OUT	106	0.377	Avg WT Fr:	0.380
5	FR STUD	107	0.345	Avg Fr:	0.073
6	A STUD	203	-1.008	MH Back:	-1.102
7	BK STUD	204	-0.989	Avg WT Bk:	-1.050
8	B STUD	205	0.315	Avg Back:	-1.076
9	FR SIDING	206	0.549		
10	A SIDING	207	-1.045	MH A Side:	-0.985
				Avg WT A:	-1.059
11	BK SIDING	303	-0.999	Avg A Side:	-1.022
12	B SIDING	304	0.495		
13	INSIDE FR	305	-0.207	MH B Side:	0.377
14	INSIDE BK	306	-0.201	Avg WT B:	0.429
15	OUT FR, B	307	0.573	Avg B Side:	0.403
16	OUT FR, IN	403	0.281	Avg Int:	-0.204
17	OUT FR, IN	404	-0.199		
18	OUT FR, A	405	-0.815		
19	FR TOP	406	0.100		
20	FR BOT	407	-0.263		
21	FR-A CORNER	503	-0.884		
22	A-BK CORNER	504	-0.990		
23	BK-B CORNER	505	-0.452		
24	B-FR CORNER	506	0.341		
25	BK PENNY	507	-1.055		
26	BK PENNY	603	-1.094		
27	BK PENNY	604	-1.060		
28	BK PENNY	605	-0.990		
29	B PENNY	606	0.140		
30	B PENNY	607	0.272		
31	B PENNY	703	0.498		
32	B PENNY	704	0.804		
33	FR PENNY	705	0.757		
34	FR PENNY	706	0.441		
35	FR PENNY	707	0.244		
36	FR PENNY	803	0.078		
37	A PENNY	804	-0.976		
38	A PENNY	805	-0.988		
39	A PENNY	806	-1.126		
40	A PENNY	807	-1.148		

TABLE 9

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHB102

Description: TWO OPEN CORNERS, FR-A, AND BACK-B, 45 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.182		
2	A OUT	104	-1.008	Avg MH Fr:	-0.076
3	BK OUT	105	-1.013	Fr Top+Bot	-0.005
4	B OUT	106	0.351	Avg WT Fr:	0.387
5	FR STUD	107	-0.178	Avg Fr:	0.102
6	A STUD	203	-0.599	MH Back:	-1.013
7	BK STUD	204	-0.501	Avg WT Bk:	-1.096
8	B STUD	205	-0.257	Avg Back:	-1.054
9	FR SIDING	206	0.542		
10	A SIDING	207	-1.004	MH A Side:	-1.008
				Avg WT A:	-1.084
11	BK SIDING	303	-1.098	Avg A Side:	-1.046
12	B SIDING	304	0.489		
13	INSIDE FR	305	-0.350	MH B Side:	0.351
14	INSIDE BK	306	-0.349	Avg WT B:	0.416
15	OUT FR, B	307	0.586	Avg B Side:	0.383
16	OUT FR, IN	403	0.327	Avg Int:	-0.350
17	OUT FR, IN	404	-0.209		
18	OUT FR, A	405	-0.901		
19	FR TOP	406	0.222		
20	FR BOT	407	-0.231		
21	FR-A CORNER	503	-0.436		
22	A-BK CORNER	504	-0.861		
23	BK-B CORNER	505	-0.366		
24	B-FR CORNER	506	0.761		
25	BK PENNY	507	-1.124		
26	BK PENNY	603	-1.236		
27	BK PENNY	604	-1.078		
28	BK PENNY	605	-0.944		
29	B PENNY	606	0.123		
30	B PENNY	607	0.263		
31	B PENNY	703	0.467		
32	B PENNY	704	0.809		
33	FR PENNY	705	0.752		
34	FR PENNY	706	0.436		
35	FR PENNY	707	0.250		
36	FR PENNY	803	0.109		
37	A PENNY	804	-1.005		
38	A PENNY	805	-1.091		
39	A PENNY	806	-1.117		
40	A PENNY	807	-1.123		

TABLE 10

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott   April 2 1990

Test File Name: MHD101

Description: FRONT CHAMBER CLOSED, 0 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	1.086		
2	A OUT	104	-1.383	Avg MH Fr:	0.847
3	BK OUT	105	-0.600	Fr Top+Bot	1.070
4	B OUT	106	-1.334	Avg WT Fr:	0.926
5	FR STUD	107	0.615	Avg Fr:	0.947
6	A STUD	203	-1.018	MH Back:	-0.600
7	BK STUD	204	-0.912	Avg WT Bk:	-0.703
8	B STUD	205	-0.941	Avg Back:	-0.652
9	FR SIDING	206	0.937		
10	A SIDING	207	-1.188	MH A Side:	-1.383
				Avg WT A:	-1.143
11	BK SIDING	303	-0.619	Avg A Side:	-1.263
12	B SIDING	304	-0.998		
13	INSIDE FR	305	-0.391	MH B Side:	-1.334
14	INSIDE BK	306	-0.340	Avg WT B:	-1.057
15	OUT FR, B	307	0.713	Avg B Side:	-1.195
16	OUT FR, IN	403	1.038	Avg Int:	-0.366
17	OUT FR, IN	404	0.969		
18	OUT FR, A	405	0.428		
19	FR TOP	406	1.059		
20	FR BOT	407	1.080		
21	FR-A CORNER	503	-1.203		
22	A-BK CORNER	504	-0.957		
23	BK-B CORNER	505	-0.931		
24	B-FR CORNER	506	-0.872		
25	BK PENNY	507	-0.683		
26	BK PENNY	603	-0.690		
27	BK PENNY	604	-0.690		
28	BK PENNY	605	-0.749		
29	B PENNY	606	-0.948		
30	B PENNY	607	-1.168		
31	B PENNY	703	-1.113		
32	B PENNY	704	-0.998		
33	FR PENNY	705	0.867		
34	FR PENNY	706	1.108		
35	FR PENNY	707	1.018		
36	FR PENNY	803	0.709		
37	A PENNY	804	-1.448		
38	A PENNY	805	-1.454		
39	A PENNY	806	-0.959		
40	A PENNY	807	-0.712		

TABLE 11

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHD102

Description: FRONT CHAMBER CLOSED, 45 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	-0.151		
2	A OUT	104	-1.101	Avg MH Fr:	-0.033
3	BK OUT	105	-1.156	Fr Top+Bot	-0.062
4	B OUT	106	0.353	Avg WT Fr:	0.407
5	FR STUD	107	0.362	Avg Fr:	0.104
6	A STUD	203	-0.833	MH Back:	-1.156
7	BK STUD	204	-0.690	Avg WT Bk:	-1.057
8	B STUD	205	-0.415	Avg Back:	-1.107
9	FR SIDING	206	0.571		
10	A SIDING	207	-1.111	MH A Side:	-1.101
				Avg WT A:	-1.108
11	BK SIDING	303	-1.029	Avg A Side:	-1.104
12	B SIDING	304	0.529		
13	INSIDE FR	305	-0.255	MH B Side:	0.353
14	INSIDE BK	306	-0.278	Avg WT B:	0.437
15	OUT FR, B	307	0.617	Avg B Side:	0.395
16	OUT FR, IN	403	0.408	Avg Int:	-0.267
17	OUT FR, IN	404	-0.195		
18	OUT FR, A	405	-0.843		
19	FR TOP	406	0.138		
20	FR BOT	407	-0.262		
21	FR-A CORNER	503	-0.789		
22	A-BK CORNER	504	-0.799		
23	BK-B CORNER	505	-0.558		
24	B-FR CORNER	506	0.772		
25	BK PENNY	507	-1.125		
26	BK PENNY	603	-1.097		
27	BK PENNY	604	-0.992		
28	BK PENNY	605	-1.014		
29	B PENNY	606	0.101		
30	B PENNY	607	0.270		
31	B PENNY	703	0.536		
32	B PENNY	704	0.841		
33	FR PENNY	705	0.801		
34	FR PENNY	706	0.453		
35	FR PENNY	707	0.246		
36	FR PENNY	803	0.128		
37	A PENNY	804	-1.081		
38	A PENNY	805	-1.014		
39	A PENNY	806	-1.133		
40	A PENNY	807	-1.202		

TABLE 12

CMHC RAINSCREEN COMPARTMENTALIZATION TESTS

BLWT WIND TUNNEL RUNS

Michael A. Scott April 2 1990

Test File Name: MHE101

Description: BACK CHAMBER CLOSED, 0 DEG.

	Tap Loc	Scani #	Cp (MEAN)		
1	FR OUT	103	1.114		
2	A OUT	104	-1.365	Avg MH Fr:	0.850
3	BK OUT	105	-0.577	Fr Top+Bot	1.077
4	B OUT	106	-1.394	Avg WT Fr:	0.935
5	FR STUD	107	-0.417	Avg Fr:	0.954
6	A STUD	203	-0.760	MH Back:	-0.577
7	BK STUD	204	-0.661	Avg WT Bk:	-0.704
8	B STUD	205	-0.602	Avg Back:	-0.640
9	FR SIDING	206	0.895		
10	A SIDING	207	-1.208	MH A Side:	-1.365
				Avg WT A:	-1.180
11	BK SIDING	303	-0.640	Avg A Side:	-1.273
12	B SIDING	304	-1.042		
13	INSIDE FR	305	-0.534	MH B Side:	-1.394
14	INSIDE BK	306	-0.545	Avg WT B:	-1.095
15	OUT FR, B	307	0.713	Avg B Side:	-1.244
16	OUT FR, IN	403	1.070	Avg Int:	-0.540
17	OUT FR, IN	404	0.973		
18	OUT FR, A	405	0.382		
19	FR TOP	406	1.049		
20	FR BOT	407	1.105		
21	FR-A CORNER	503	-0.606		
22	A-BK CORNER	504	-0.654		
23	BK-B CORNER	505	-0.788		
24	B-FR CORNER	506	-0.516		
25	BK PENNY	507	-0.640		
26	BK PENNY	603	-0.717		
27	BK PENNY	604	-0.741		
28	BK PENNY	605	-0.716		
29	B PENNY	606	-1.014		
30	B PENNY	607	-1.187		
31	B PENNY	703	-1.141		
32	B PENNY	704	-1.037		
33	FR PENNY	705	0.911		
34	FR PENNY	706	1.098		
35	FR PENNY	707	1.058		
36	FR PENNY	803	0.674		
37	A PENNY	804	-1.634		
38	A PENNY	805	-1.576		
39	A PENNY	806	-0.882		
40	A PENNY	807	-0.629		

APPENDIX C

COMPUTER PROGRAM LISTINGS

AND

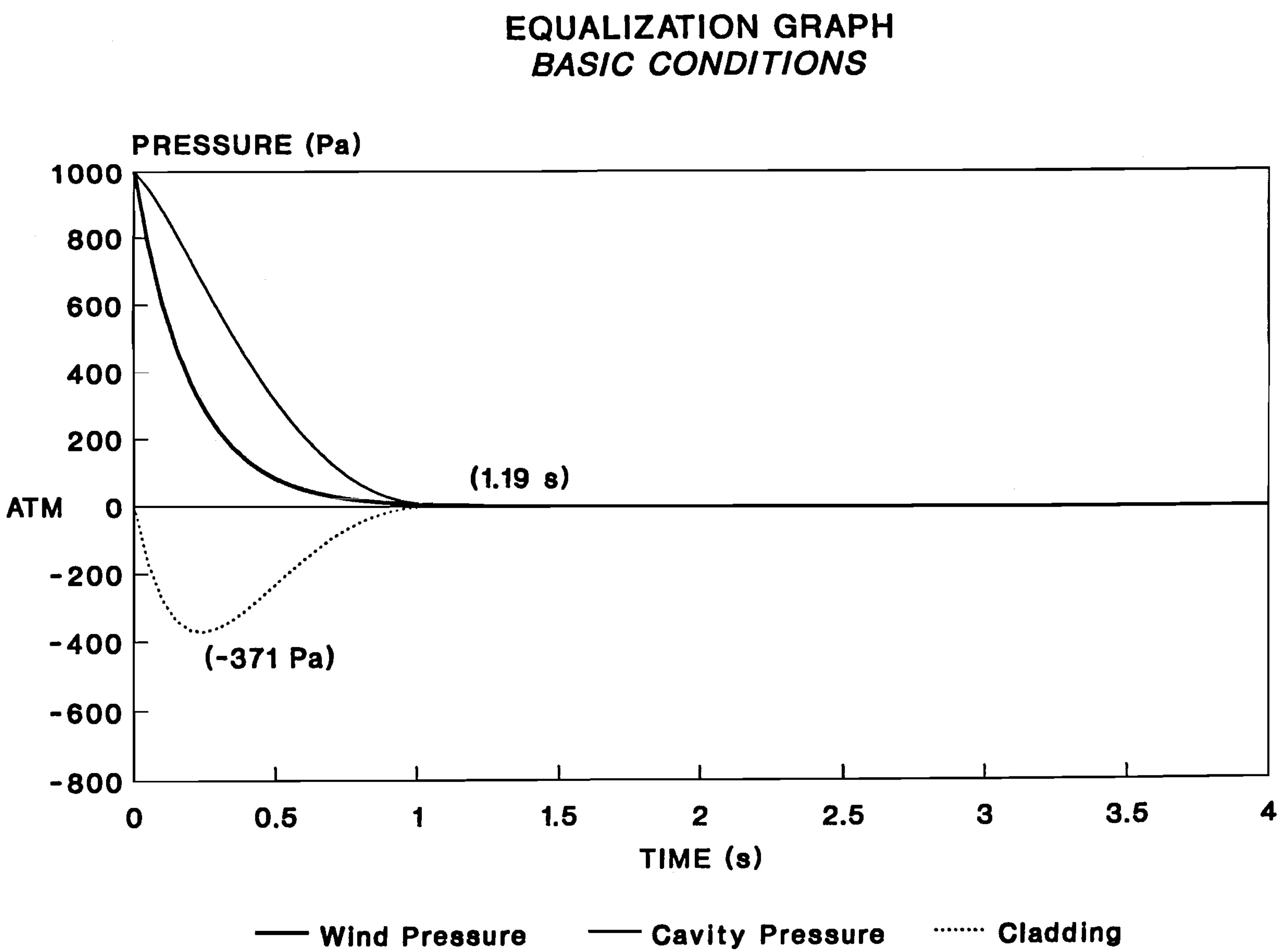
GRAPH SIMULATION RESULTS

PROGRAM LISTING #1

```
5  CLS
8  PRINT"                    *******   RNSCRN5     ********* "
10 PRINT"            -*THIS PGM COMPUTES THE PRESSURE EQUALIZATION*-"
15 PRINT"                -*PERFORMANCE OF A RAINSCREEN WALL*-"
16 PRINT
17 PRINT"                    EXPONENTIAL DECAY OF WIND GUST "
18 PRINT"                    PRESSURE DROPS FROM 101000 PA"
20 INPUT"                      ***TEST No.= ";WW$
50 INPUT"                      ***VOL(m3)= ";VV:IF VV=0 THEN LET VV=1
55 INPUT"                      ***PFX1(m3/pa)=";K1
60 INPUT"                      ***PFX2(m3/pa)=";K2
65 INPUT"                      ***VA1(m2)=";A1
70 INPUT"                      ***VA2(m2)=";A2
71 INPUT"                      ***CYCLES?=";JJ:IF JJ=0 THEN LET JJ=50
72 INPUT"                      ***INT(s)?=";TS:IF TS=0 THEN LET TS=.05
73 PRINT"    ----------------------------------------------------    "
74 REM ***********************************************************
76 PE=101000!:PC=101000!:PX=100000!
78 DE=1.20108:GC=287:TK=293:Y1=PC
80 CD=.61:T=0:J=0
82 V5=VV-K1*(PE-PC)+K2*(PC-PX):YD=V5
84 MO=(PC*V5)/(GC*TK)
90 OPEN "c:\[illegible]\lotus123\files\rsd1.dat" FOR OUTPUT AS #1
98 GOSUB 800:T=TS
100 REM  ********************************************************
110 GOSUB 605
127 REM  ********************************************************
130 Q1=A1*CD*TS*SQR(2*DE*ABS(PE-X1)):IF X1>PE THEN LET Q1=-Q1
132 Q2=A2*CD*TS*SQR(2*DE*ABS(X1-PX)):IF X1>PX THEN LET Q2=-Q2
134 YN=GC*TK*(MO+Q1+Q2)
136 YD=V5-(K1*AA)+(K2*BB):IF K1=0 THEN LET YD=V5
138 Y1=YN/YD
140 X$=INKEY$:IF X$="s" GOTO 400
147 IF (ABS(X1-Y1)<.05 OR I<.005) THEN 220
150 ON F1 GOTO 160,170
160 IF X1>Y1 THEN X1=X1-I:GOSUB 700:GOTO 130
165 F1=2:I=I/1.5:GOTO 170
170 IF X1<Y1 THEN X1=X1+I:GOSUB 700:GOTO 130
175 F1=1:I=I/1.5:GOTO 160
200 REM  ********************************************************
220 V5=VV-(K1*AA)+(K2*BB)
230 MO=MO+Q1+Q2
235 GOSUB 800
240 T=T+TS
260 J=J+1:IF J=JJ+1 THEN 400
300 REM  ********************************************************
325 GOSUB 605
329 REM  ********************************************************
330 GOTO 130
400 REM  ********************************************************
415 PRINT "    +++++++NO. of CYCLES =";J;"     END of SIMULATION+++++++"
450 CLOSE
500 END
600 REM  ********************************************************
605 REM subroutine no 1
610 I=50:F1=1:F2=1
615 X1=(PE+PX)/2
620 AA=PE-X1:BB=X1-PX      -5
625 PE=100000!+1000*EXP(-6*T)
640 PRINT "----------------------------"
650 RETURN
699 REM  ********************************************************
700 REM subroutine no 2
720 AA=PE-X1:BB=X1-PX
730 RETURN
800 REM  ********************************************************
805 ZZ=INT(T*100)/100:PP=INT(PE):YY=INT(Y1)
806 CL=INT(PP-YY):AB=INT(YY-PX)
810 PRINT "**T,=";ZZ,"**PE=";PP,"**PC=";YY,"**Cl=";CL;"**ABL=";AB
815 PRINT "    *VOL=";YD;"*MO=";MO;"*AF1=";Q1;"AF2=";Q2
816 PRINT
820 PRINT#1,J;",";ZZ;",";PE;",";Y1;",";CL;",";YD;",";MO
825 RETURN
```

PROGRAM LISTING #2

```
3  PRINT"                    ****** RNSCRN6  ********"
5  CLS
10 PRINT"          -*THIS PGM COMPUTES THE PRESSURE EQUALIZATION*-"
15 PRINT"              -*PERFORMANCE OF A RAINSCREEN WALL*-"
16 PRINT
17 PRINT"                  SINUSOIDAL LOAD CYCLE - 2SEC
18 PRINT"                  PRESURE RISES FROM 100000 PA"
20 INPUT"                    ***TEST No.= ";WW$
50 INPUT"                    ***VOL(m3)= ";VV:IF VV=0 THEN LET VV=1
55 INPUT"                    ***PFX1(m3/pa)=";K1
60 INPUT"                    ***PFX2(m3/pa)=";K2
65 INPUT"                    ***VA1(m2)=";A1
70 INPUT"                    ***VA2(m2)=";A2
71 INPUT"                    ***CYCLES?=";JJ:IF JJ=0 THEN LET JJ=50
72 INPUT"                    ***INT(s)?=";TS:IF TS=0 THEN LET TS=.05
73 PRINT"   ------------------------------------------------   "
74 REM ************************************************************
76 PE=100000!:PC=100000!:PX=100000!
78 DE=1.20108:GC=287:TK=293:Y1=PC:Y2=Y1
80 CD=.61:T=0:J=0
82 V5=VV-K1*(PE-PC)+K2*(PC-PX):YD=V5
84 MO=(PC*V5)/(GC*TK)
90 OPEN "c:\goodstuf\lotus123\files\rsdl.dat" FOR OUTPUT AS #1
98 GOSUB 800:T=TS
100 REM  **********************************************************
110 GOSUB 605
127 REM  **********************************************************
130 Q1=A1*CD*TS*SQR(2*DE*ABS(PE-X1)):IF X1>PE THEN LET Q1=-Q1
132 Q2=A2*CD*TS*SQR(2*DE*ABS(X1-PX)):IF X1>PX THEN LET Q2=-Q2
134 YN=GC*TK*(MO+Q1+Q2)
136 YD=V5-(K1*AA)+(K2*BB):IF K1=0 THEN LET YD=V5
138 Y1=YN/YD:Y2=Y1
140 X$=INKEY$:IF X$="s" GOTO 400
147 IF (ABS(X1-Y1)<.05 OR I<.005) THEN 220
150 ON F1 GOTO 160,170
160 IF X1>Y1 THEN X1=X1-I:GOSUB 700:GOTO 130
165 F1=2:I=I/1.5:GOTO 170
170 IF X1<Y1 THEN X1=X1+I:GOSUB 700:GOTO 130
175 F1=1:I=I/1.5:GOTO 160
200 REM  **********************************************************
220 V5=VV-(K1*AA)+(K2*BB)
230 MO=MO+Q1+Q2
235 GOSUB 800
240 T=T+TS
260 J=J+1:IF J=JJ+1 THEN 400
300 REM  **********************************************************
325 GOSUB 605
329 REM  **********************************************************
330 GOTO 130
400 REM  **********************************************************
415 PRINT "    +++++++NO. of CYCLES =";J;"     END of SIMULATION+++++++"
450 CLOSE
500 END
600 REM  **********************************************************
605 REM subroutine no 1
610 I=50:F1=1:F2=1
615 X1=(PE+PX)/2
620 AA=PE-X1:BB=X1-PX
625 PE=100000!+1000*SIN(T*2*90*.017453):PRINT PE
627 RETURN
699 REM  **********************************************************
700 REM subroutine no 2
720 AA=PE-X1:BB=X1-PX
730 RETURN
800 REM  **********************************************************
805 ZZ=INT(T*100)/100;PP=INT(PE);YY=INT(Y1)
806 CL=INT(Y1-PE):AB=INT(Y1-PX)
810 PRINT "**T.=";ZZ,"***PE=";PP,"***PC=";YY,"**C1=";CL;"***ABL=";AB
815 PRINT "   *VOL=";YD;"*MO=";MO;"*AF1=";Q1;"AF2=";Q2
816 PRINT
820 PRINT#1,J;",";ZZ;",";PP-100000!;",";YY;",";CL
825 RETURN
```



EQUALIZATION GRAPH
BASIC CONDITIONS
PRESSURE (Pa)
1000
800
600
400
200
ATM
0
-200
-400
-600
-800
(1.19 s)
(-371 Pa)
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 1

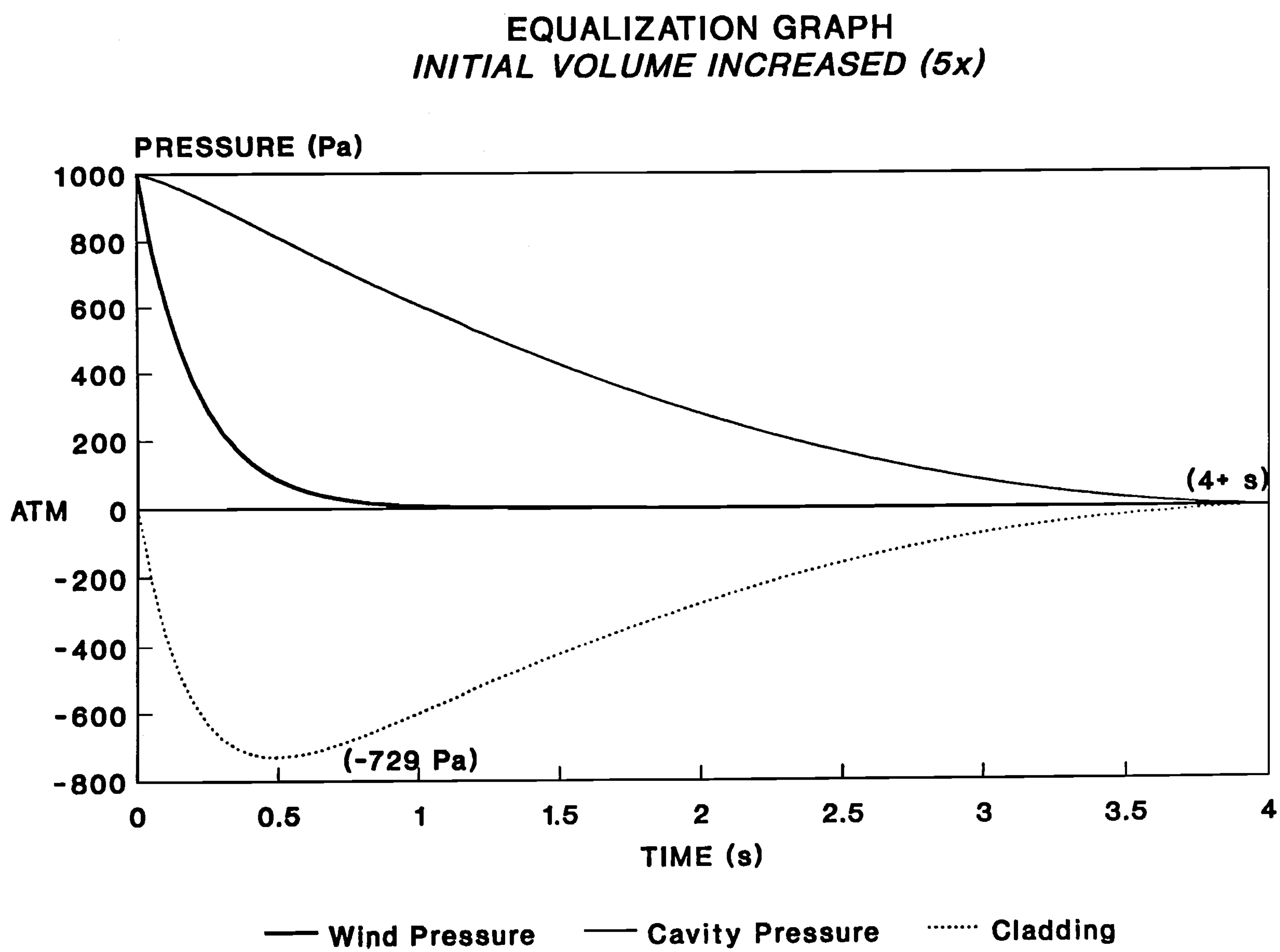
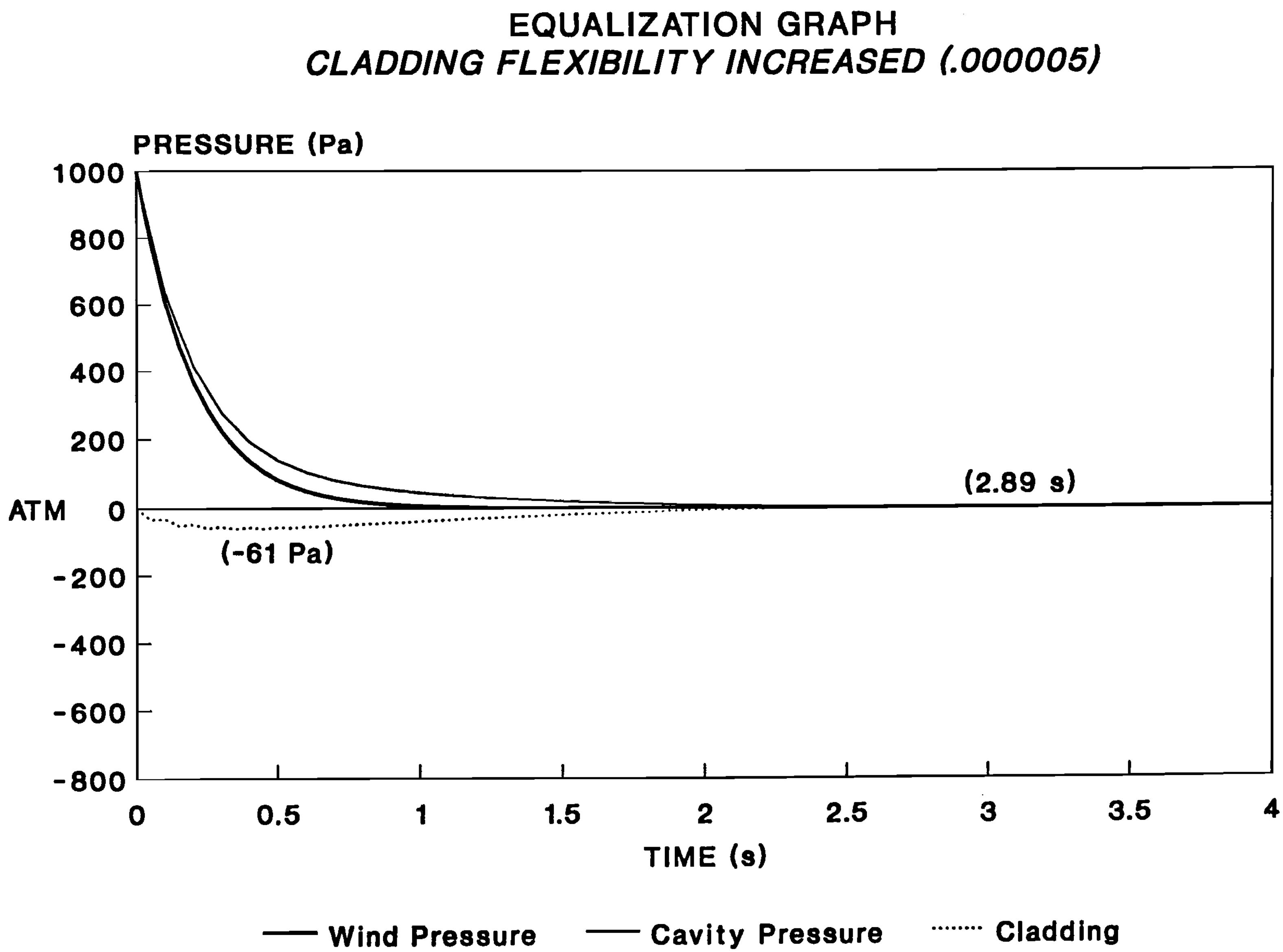

EQUALIZATION GRAPH
INITIAL VOLUME INCREASED (5x)
PRESSURE (Pa)
1000
800
600
400
200
ATM 0
-200
-400
-600
-800
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)
(4+ s)
(-729 Pa)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 2



EQUALIZATION GRAPH
CLADDING FLEXIBILITY INCREASED (.000005)
PRESSURE (Pa)
1000
800
600
400
200
ATM
0
-200
-400
-600
-800
(2.89 s)
(-61 Pa)
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 3

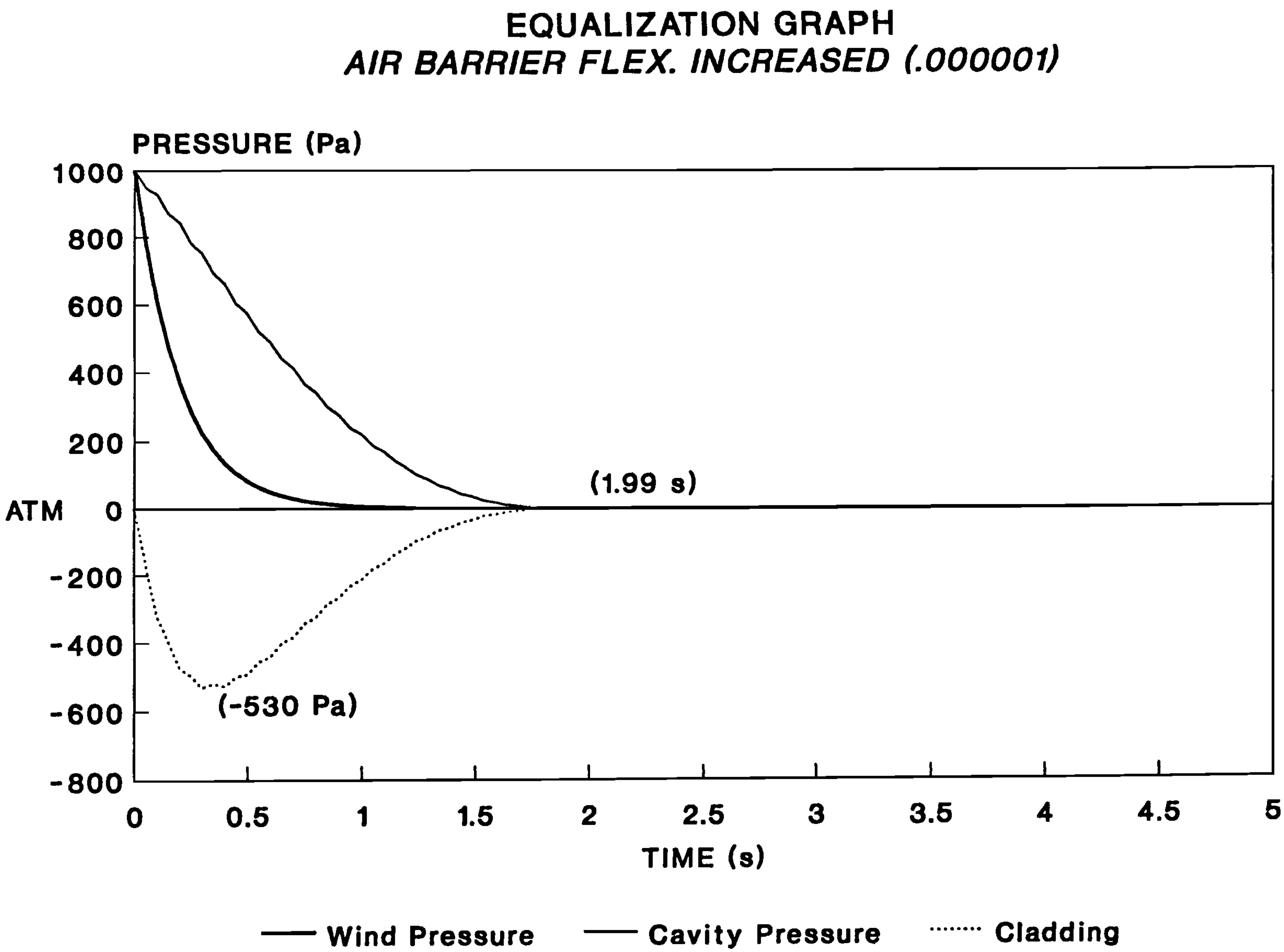

EQUALIZATION GRAPH
AIR BARRIER FLEX. INCREASED (.000001)
PRESSURE (Pa)
1000
800
600
400
200
ATM
0
-200
-400
-600
-800
(1.99 s)
(-530 Pa)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
TIME (s)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 4

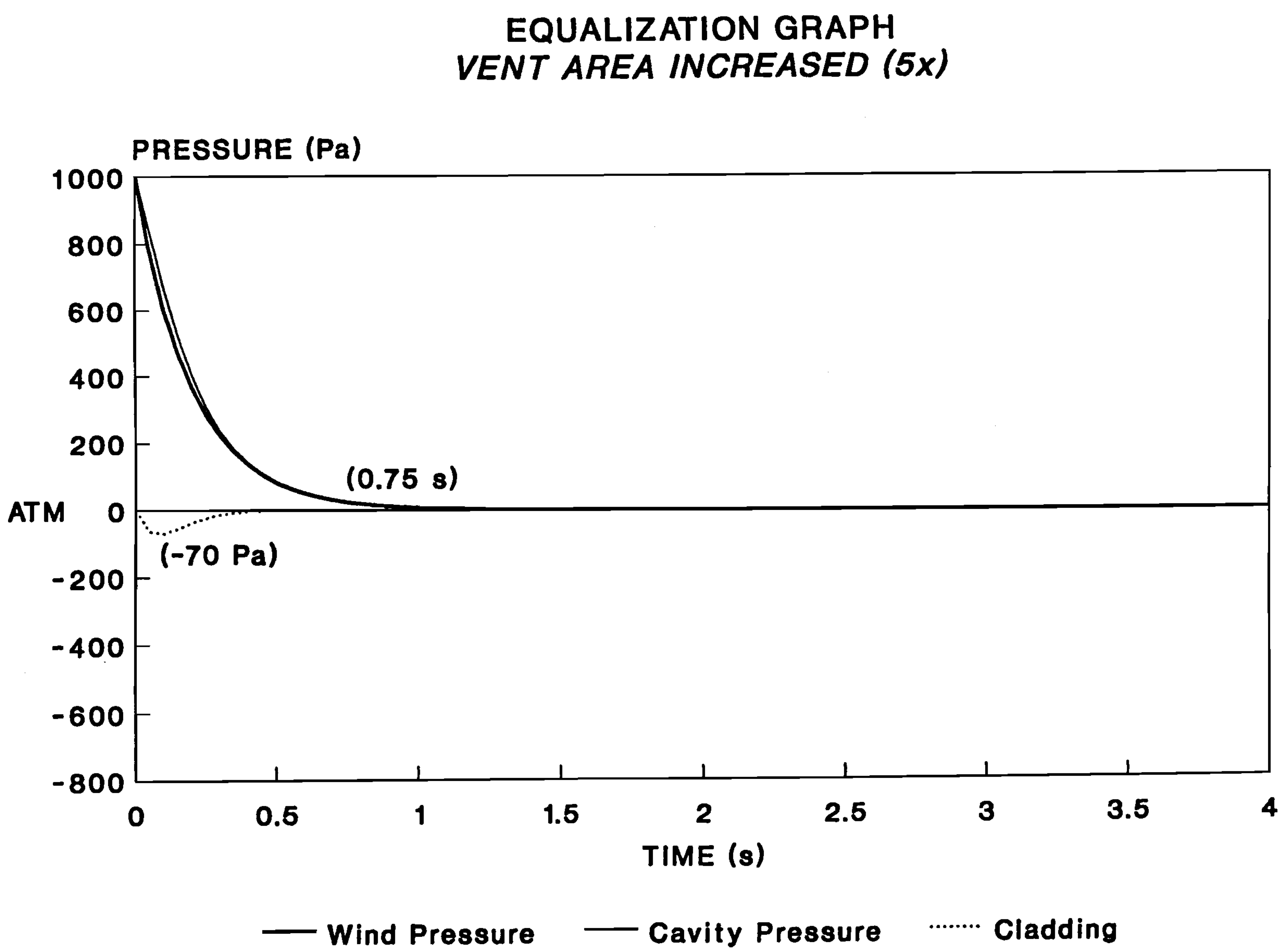

EQUALIZATION GRAPH
VENT AREA INCREASED (5x)
PRESSURE (Pa)
1000
800
600
400
200
ATM
0
-200
-400
-600
-800
(0.75 s)
(-70 Pa)
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 5

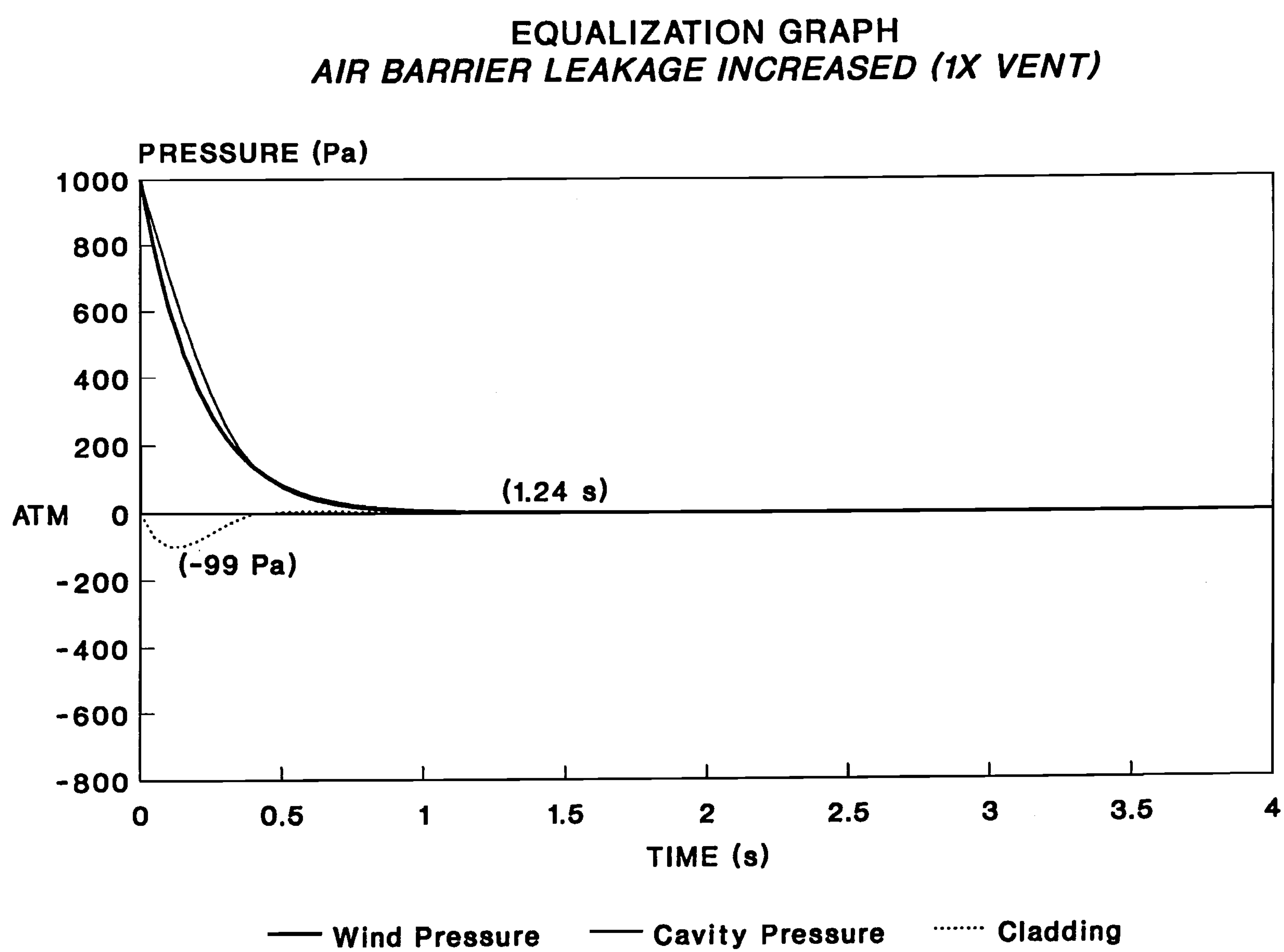

EQUALIZATION GRAPH
AIR BARRIER LEAKAGE INCREASED (1X VENT)
PRESSURE (Pa)
1000
800
600
400
200
ATM 0
-200
-400
-600
-800
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)
(1.24 s)
(-99 Pa)
Wind Pressure
Cavity Pressure
Cladding

FIGURE 6

EQUALIZATION GRAPH
AIR BARRIER LEAKAGE INCREASED (5x VENT)

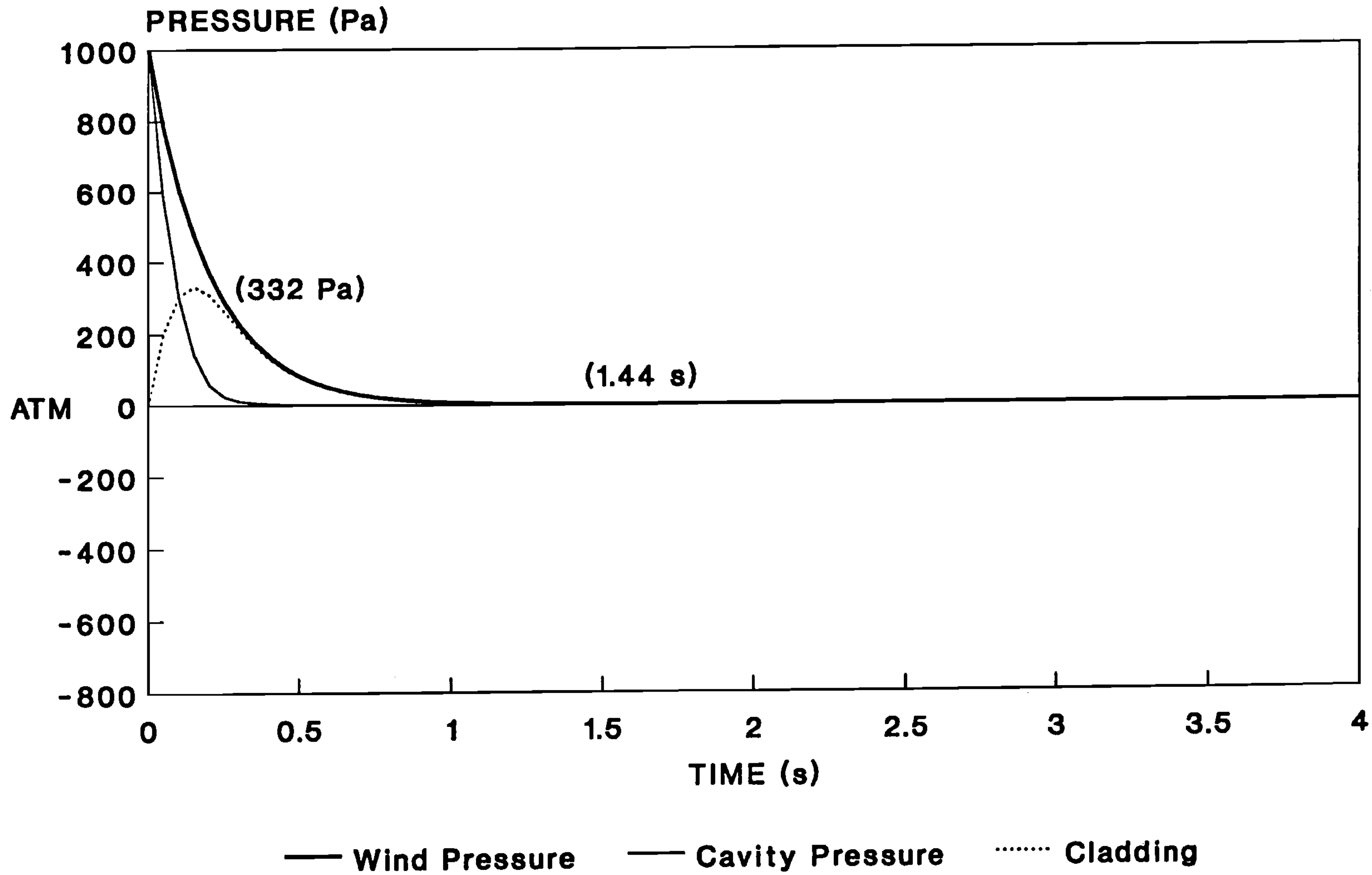
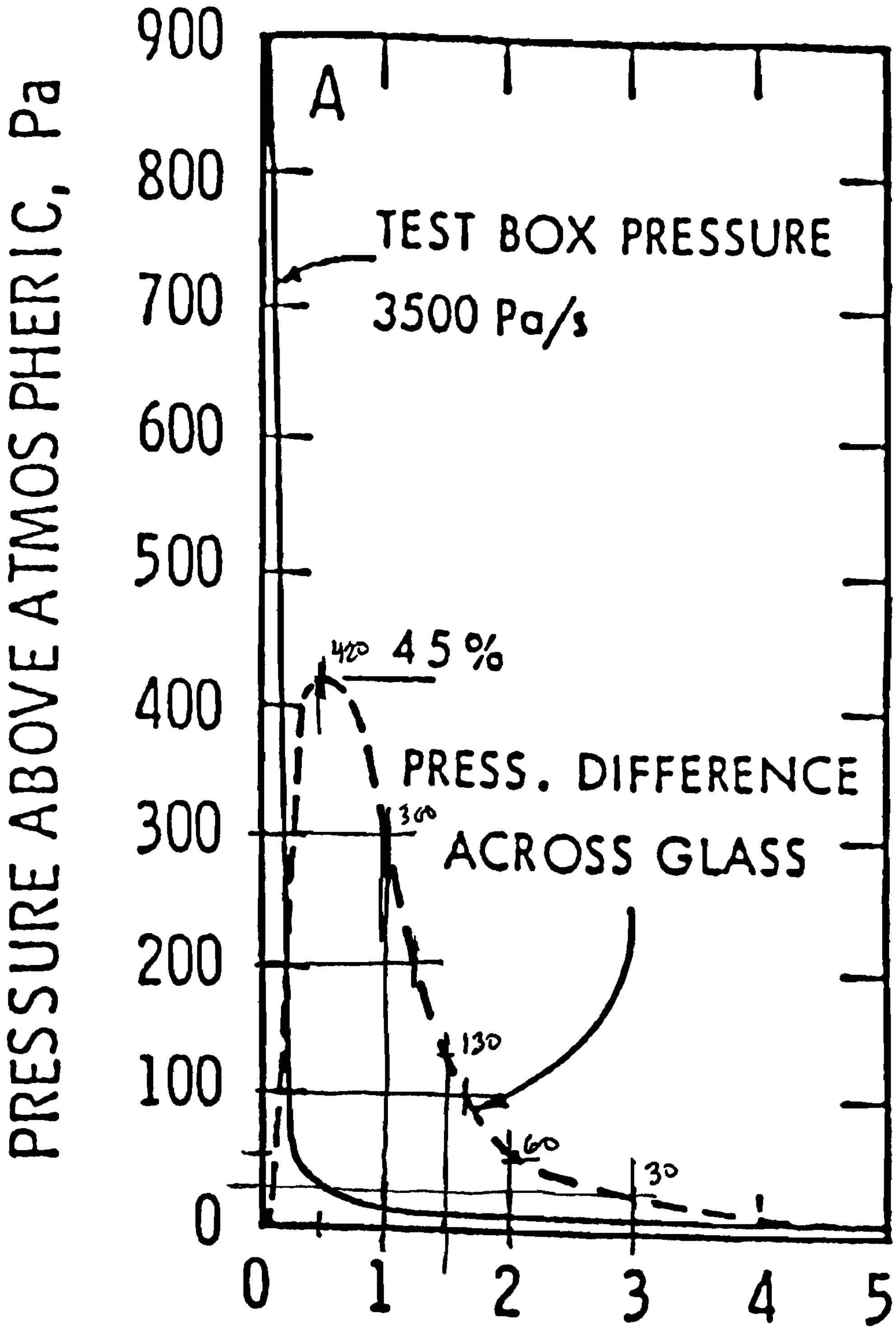


FIGURE 7



PRESSURE ABOVE ATMOSPHERIC, Pa
900
800
700
600
500
400
300
200
100
0
A
TEST BOX PRESSURE
3500 Pa/s
420
45 %
PRESS. DIFFERENCE
ACROSS GLASS
360
130
60
30
0
1
2
3
4
5

FIGURE 8

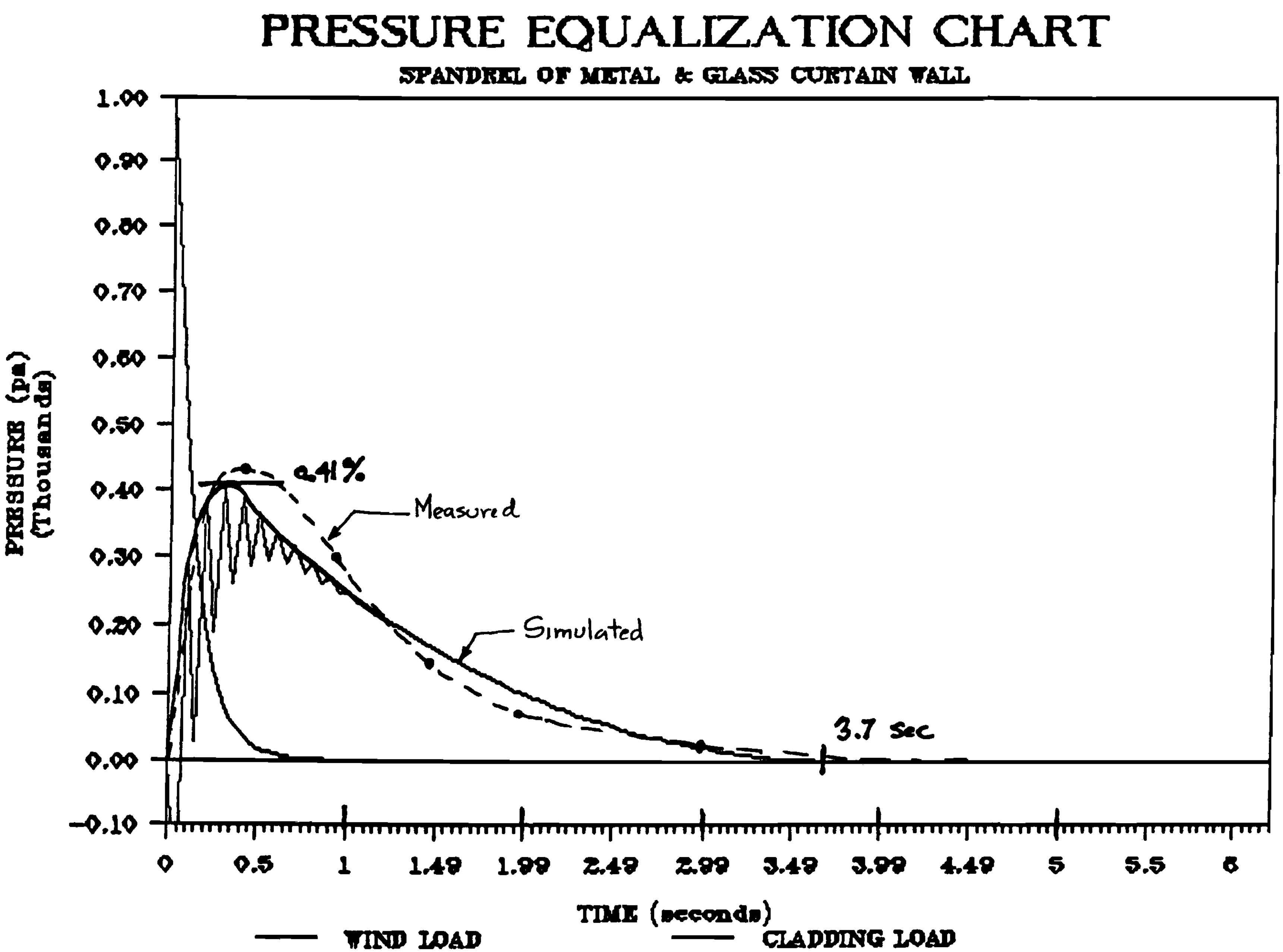

PRESSURE EQUALIZATION CHART
SPANDREL OF METAL & GLASS CURTAIN WALL
PRESSURE (pa)
(Thousands)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
0.41%
Measured
Simulated
3.7 sec
0
0.5
1
1.49
1.99
2.49
2.99
3.49
3.99
4.49
5
5.5
6
TIME (seconds)
WIND LOAD
CLADDING LOAD

FIGURE 9

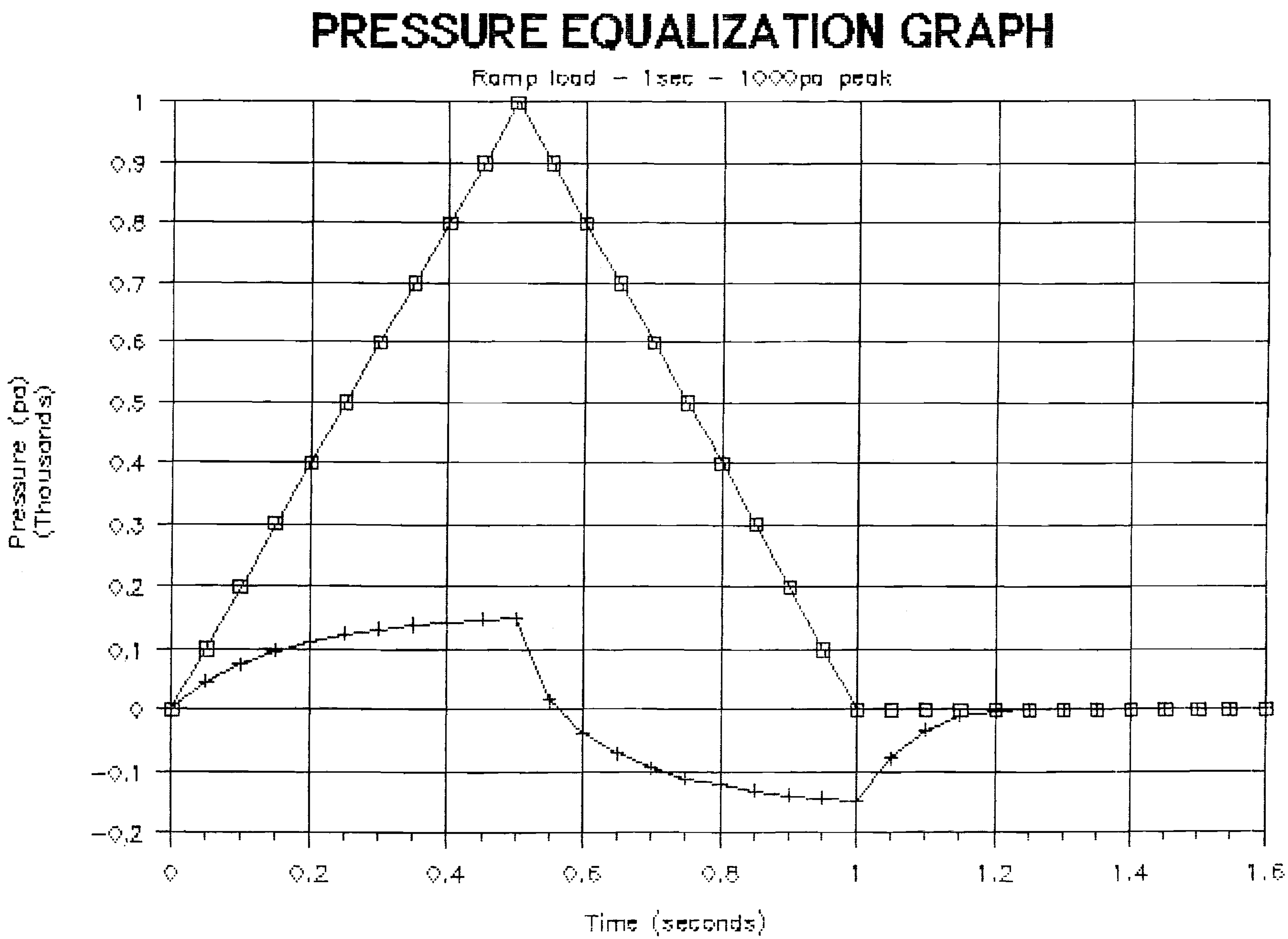

PRESSURE EQUALIZATION GRAPH
Ramp load - 1sec - 1000pa peak
Pressure (pa)
(Thousands)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Time (seconds)

FIGURE 10

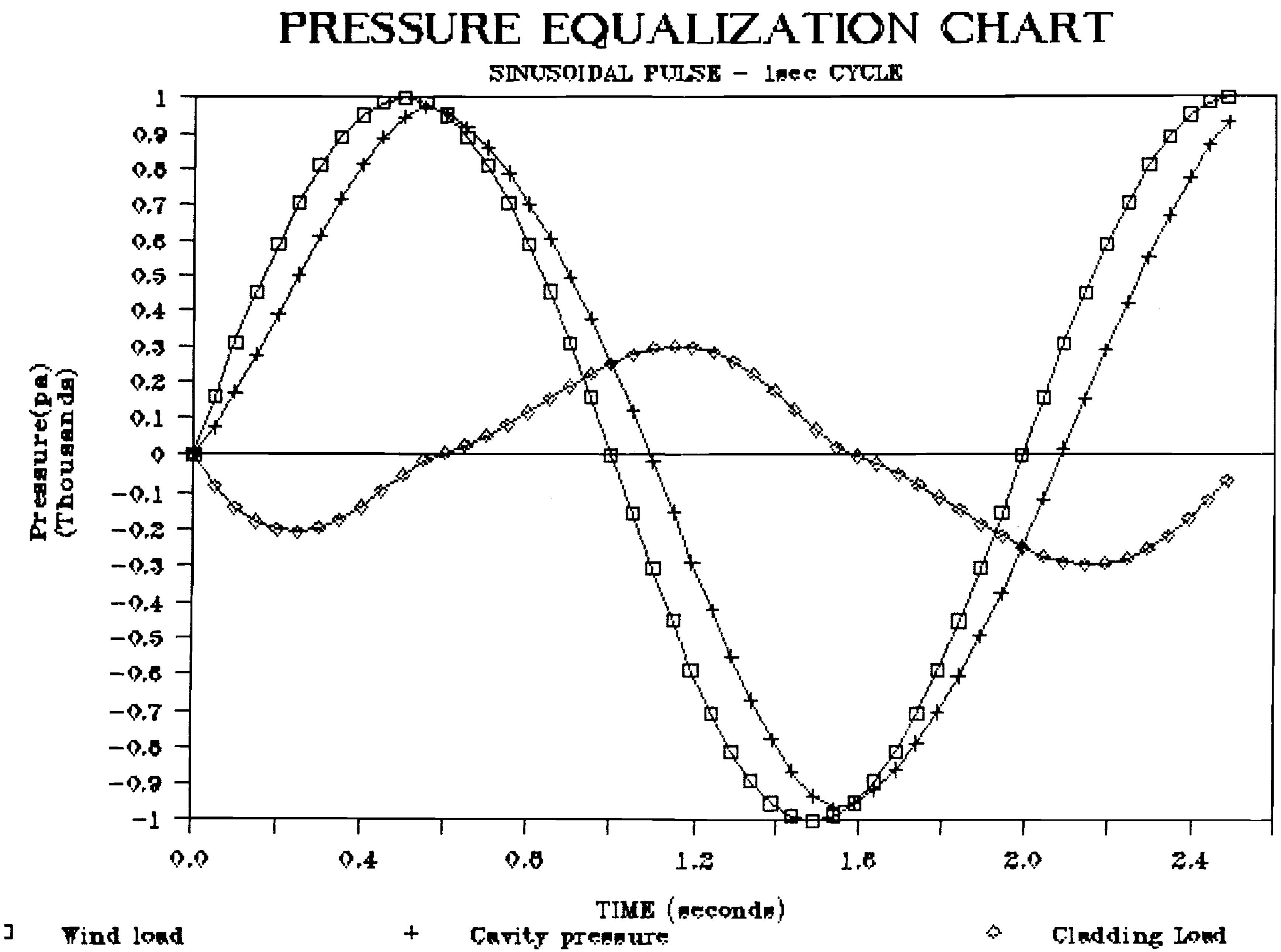

PRESSURE EQUALIZATION CHART
SINUSOIDAL PULSE – 1sec CYCLE
Pressure(pa)
(Thousands)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
–0.1
–0.2
–0.3
–0.4
–0.5
–0.6
–0.7
–0.8
–0.9
–1
0.0
0.4
0.8
1.2
1.6
2.0
2.4
TIME (seconds)
Wind load
Cavity pressure
Cladding Load

FIGURE 11