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AIR-PERMEABILITY MEASUREMENTS IN MULTIZONE BUILDINGS

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ABSTRACT

The fan pressurization technique is widely used to determine the air permeability of single-family detached houses. This technique uses a large door-mounted fan to blow air into or suck air out of a building to determine the air flow at various pressure differences across the building's shell. Whereas the technique to measure the leakage characteristics is already available for single-zone structures, for multizone buildings, with their internal air flow paths, these techniques are just being developed. This paper focuses on the comparison of two techniques to obtain leakage data for multizone buildings needed as input for multizone infiltration models, using standard equipment designed for single-zone applications.

Keywords:

Infiltration, air leakage, blower door, multizone buildings.

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1. NOMENCLATURE

m	pressure exponent for nozzle type blower [–]
n	pressure exponent for crack flow [–]
k	exponent [–]
t	flow length inside a crack $[m]$
$\Delta p_{friction}$	frictional losses $[Pa]$
Δp_{head}	head losses $[Pa]$
Δp_{in}	pressure difference across internal walls $[Pa]$
Δp_{nozzle}	static pressure difference between blower door nozzle and undisturbed air $[Pa]$
Δp_{out}	pressure difference between considered zone and outside $[Pa]$
Δp_{tot}	total pressure loss $[Pa]$
v	velocity $[m/s]$
A	effective leakage area, flow coefficient [-]
B	flow coefficient [-]
C	coefficient for nozzle type blower $[m^3/h\ Pa^m]$
C, C_1, C_2	constant values
D	air permeability $[m^3/h\ Pa^n]$
D_{eq}	equivalent diameter $[m]$
D_{in}	air permeability for internal walls $[m^3/h\ Pa^n]$
D_{out}	air permeability for external walls $[m^3/h\ Pa^n]$
D_{tot}	total air permeability $[m^3/h\ Pa^n]$
Q	air flow rate $[m^3/h]$
Re	Reynold's Number [–]
λ	friction factor [–]
μ	dynamic viscosity $[kg/(s\ m)]$
ν	viscosity $[m^2/s]$
ρ	density $[kg/m^3]$
ζ	fitting loss coefficient [–]

2. INTRODUCTION

With improved insulation of the building envelope, heat loss due to ventilation has become a rather significant fraction of the building's overall energy balance. In order to reduce heat loss due to the random air flow of outside air through unintentional openings (infiltration), standards for new buildings call for a tight construction [1, 2, 3]. This tightening of building envelopes, however, can lead to poor indoor air quality, causing health problems and building damage. Therefore, it is very important to determine the infiltration rate associated with a given air tightness.

There are two fundamental approaches to determine the infiltration rate of a building. The most straightforward method is to measure infiltration directly, e.g. by using the tracer gas technique. An inert gas, which is normally neither present in the atmosphere nor in the measured environment, is released and thoroughly mixed with the air of the considered zone. The concentration is measured according to the chosen tracer gas technique. The dilution of the tracer gas is associated with the exfiltration of air [4].

Whereas the direct measurement of air exchange gives a value for infiltration under the prevailing weather conditions (snap shot), the indirect method can be used to determine values of infiltration for all climatic combinations. This second technique uses mathematical models. Several computer programs have been developed to calculate the air flow distribution in buildings. The first multizone infiltration program developed is probably the NRC-model [5]. Since its appearance in 1973 many more models have been developed. A literature review undertaken in 1984 [6] produced 26 papers describing 15 different programs developed in eight countries. The latest evolvement in this course is the COMIS model, which is under development at Lawrence Berkeley Laboratory (LBL) by participants from eight countries (China, France, Italy, Japan, Netherlands, Sweden, Switzerland, and USA).

Mathematical models require a large amount of input data to properly treat the true complexity of air flows in multizone buildings. Input parameters are the permeability of the building's envelope and its internal partitions, the distribution of the permeability, the pressure coefficients to determine the pressure field around the building as well as the wind speed, wind direction, indoor and outdoor temperatures. The determination of the building's interzonal permeability characteristics is especially very difficult and bothersome.

This report describes and compares two techniques to determine the permeability characteristics of building components in multizone structures, using standard equipment designed for single-zone applications.

3. AIR PERMEABILITY OF BUILDING COMPONENTS

3.1 General

Work on air permeability measurements has been going on for many years. Tests on building components like windows and doors were already performed in the early twenties of this century. Since building standards call for tight building components, a major part of the air permeability is related to the connection of these building components with the walls. Therefore, to determine the air permeability as input data for mathematical models, measurements ought to be done in-situ rather than using laboratory determined component leakage data. Besides the permeability of the building's envelope, the knowledge of internal leakage paths is very important to determine the air flow distribution.

3.2 Physical Fundamentals of Crack Flow

The air permeability of the building's envelope is dependent on the number and size of cracks, windows, doors, and gaps between building components. In addition to these visually observable flow paths, there is the background leakage caused by the porosity of the building material.

Although, component leakage measurements were already performed in the early 1920s, the effort to understand the physical fundamentals of crack flow is relatively new. For laminar crack flow, a dependence of the friction factor on the Reynolds number, analogous to pipe flow, was found [7]. Data obtained from measurements on a crack model show that, for turbulent crack flow, the mathematical description of the friction factor is identical to the one found for conduit flow with smooth walls [8, 9].

Additional to the pressure losses in cracks with infinite crack lengths, real cracks have head losses due to geometric flow separations, which occur at the sharp crack entrance as well as for sudden expansion at the exit.

The total pressure loss Δp_{tot} across a building component can be described by:

$$\Delta p_{tot} = \Delta p_{friction} + \Delta p_{head} \tag{1}$$

with the head pressure loss:

$$\Delta p_{head} = \Sigma \, \zeta \, \tfrac{1}{2} \, \rho \, v^2 \tag{2}$$

and:

$$\zeta \neq f(v) \tag{3}$$

The friction losses can be expressed by the following equation:

$$\Delta p_{friction} = \lambda \left[\left[\frac{t}{D_{eq}} \right]^k \right] \tfrac{1}{2} \, \rho \, v^2 \tag{4}$$

with λ for fully laminar flow:

$$\lambda = \frac{C}{\text{Re}} = C \left[\frac{\nu}{D_{eq} v} \right] \tag{5}$$

and λ for fully turbulent flow [8]:

$$\lambda = (2 \log (Re\ \lambda^{1/2}) - 0.8)^{-2} \tag{6}$$

Based on turbulent flow concepts for conduit flow, the equivalent diameter D_{eq} for crack flow is a function of the flow area and the wetted perimeter. For cracks, the value of D_{eq} is roughly twice the height of the crack.

From the equations above, we learn that the head loss as well as the friction loss for fully turbulent flow are a function of v^2, whereas the friction loss for fully laminar flow is a function of v.

For practical applications, results of permeability measurements are usually described by the empirical power-law equation:

$$Q = D \Delta p^n \tag{7}$$

with values for the exponent between n = 0.5 for fully turbulent jets or turbulent flow and n = 1.0 for fully laminar flow. However, due to the head losses, which are directly dependent on the square of the velocity, n = 1.0 cannot be reached in reality. Due to the change in flow regimes with the driving pressure difference, this power-law equation can only describe the flow characteristics for a limited pressure range. This range is dependent on the configuration of the crack design.

The second most commonly used mathematical description for flow through building components is the square root law, which applies to turbulent jets through thin plate orifices. This led to the institution of the *effective leakage area* A, with:

$$Q = A \sqrt{\frac{2 \Delta p}{\rho}} \tag{8}$$

For a number of reasons, this equation does not fit the available data very well [10]. In order to describe the different possible flow regimes in a crack, the quadratic equation was introduced [11].

$$\Delta p = A\ Q + B\ Q^2 \tag{9}$$

This relationship between air flow and the pressure difference gives the correct descriptions for the developed laminar flow and the developed turbulent flow, however, it disregards the transition flow between the two extremes [12].

As described above, almost all of the data obtained from blower door measurements are fitted to the power-law equation (see Eq. 7). Therefore, the data acquired from the experiments described in this paper were also treated to fit this curve.

For blower door measurements performed at other than standard conditions ($T = 20°C, p_o = 1.013\ 10^5\ Pa$), the air permeability has to be corrected according to the equations given by the ISO proposal for the blower door measurement standard [13]:

$$D_o = D\left[\frac{\mu}{\mu_o}\right]^{2n-1}\left[\frac{\rho}{\rho_o}\right]^{1-n} \tag{10}$$

3.3 Methods to Determine the Air Permeability

3.3.1 Single-Zone Structures

The standard way to determine the air permeability of a construction is to pressurize or depressurize all or part of it with a large variable speed fan. This fan is usually installed in a doorway in the envelope of the considered building part. The permeability characteristics is then obtained from the measured air flows versus the measured pressure differences. The device used for this kind of measurements is commonly known as a blower door. Commercially available blower doors use fans with free flow capacities up to 12,500 m^3/h [14].

The fan pushes air into or draws air out of the building to create a pressure difference between the inside and the outside. The air flow necessary to maintain a specific pressure difference across the envelope is obtained indirectly by measuring either the fan speed (in RPM) or the difference in static pressure between the undisturbed air and a pressure tap at the nozzle-type inlet of the fan. Consequently, one distinguishes between nozzle-type doors and RPM-doors [14]. By measuring pressure differences created by the fan and the appropriate air flows at different over- or under-pressures, one can determine the permeability characteristics of the building's shell. These permeability characteristics can be expressed using the empirical power-law equation (see Eq. 7). The permeability coefficient and the pressure exponent can be obtained from the measured data by using the linear regression method.

Several standards that require different procedures both for measurement and data analysis have evolved for single-zone structures (see [15]). These standards allow tolerances up to ± 6% for the flow measurement and up to ± 2.5 Pa for the pressure measurement device [16].

Environmental conditions influence blower door measurements through distortions in pressure and air flow measurements. Whereas there is no measure to compensate for the stack effect due to indoor/outdoor temperature differences, the effects of wind pressure on the blower door test can be minimized by either taking both pressurization and depressurization data or by using four outside pressure taps together with a pressure averaging container. However, these measures can only reduce the wind influence, not eliminate it [17]. Therefore, blower door standards give upper limits for the allowable wind speed.

The dilemma of blower door tests is, that the most accurate results are obtained for high pressure differentials, whereas the air flows caused by natural forces will occur at relatively small pressure differences. Therefore, the determination of the pressure exponent is very important.

This description shows, that the precision of single-zone blower door measurements is already somewhat limited. Using the equipment designed for single-zone blower door tests for multizone blower door tests will introduce even larger errors [27].

3.3.2 Multizone Structures

3.3.2.1 Guarded Zone Method

Whereas the blower door technology for single zone buildings was developed some ten years ago, comparable techniques were not available for multizone buildings. The conventional single-zone blower door technique cannot distinguish between the permeability of the outside wall and the permeability of the walls between zones.

In order to assign the values of permeability to the internal and external walls of each zone, Modera et al [18] have simultaneously used six blower doors in a three story Minneapolis building. To determine the permeability of the external walls only, all zones were pressurized to the same pressure level, eliminating the internal flow paths (*guarded zone method*). The differences between the air flows measured by the single zone method for each zone and the measurements using the six blower doors simultaneously was used to separate the permeability of the different flow paths.

The improved version of this *guarded zone method* uses only two blower doors, measuring only pairs of zones rather than all zones simultaneously [15, 19]. To determine the permeability of internal walls using the guarded zone method, the guarded zone is pressurized, with the adjacent zones either pressurized to the same pressure level (guarding zone) or kept at outdoor pressure (outside pressure zone). The differences between the air flows measured for various configurations can be used to separate the permeability of the different flow paths (see Figs. 1a) and 1b)). In these Figures, the guarded zone is labelled A and the guarding zone, B. Figure 1a) shows the situation when the adjacent zones are pressurized to the same pressure level and Figure 1b) the situation when one part of the adjacent zones is kept at outdoor pressure. The difference between the air flows provides information on the permeability of the partition between the two small rooms.

Fig. 2a) gives an example of the use of the guarded zone method. It shows the air flows, which would theoretically be obtained for a zone with the characteristics given in Table 1. One series of blower door tests without the guarding zone provides the data to calculate the permeability of the whole envelope (exterior and interior walls) of this zone. A second series of measurements with a guarding zone leads to the characteristics of the envelope reduced by the portion which separates the guarded zone and the guarding zone. The shaded area between the two curves represents the properties of the internal walls between the considered zones.

Table 1: Flow Characteristics for the Example given in Fig. 2a) and Fig. 2b)		
Wall Section	Permeability D $[m^3/h\ Pa^n]$	Pressure Exponent n [-]
envelope	79.0	0.59
external walls only	50.6	0.50
internal walls only	31.5	0.67

Due to the non-linear function between air flows and the driving pressure difference, even smallest difference in pressure between the guarded zone and the guarding zone introduces significant flows, which cannot be neglected (see Eq. 7). Therefore, particular care has to be taken with the pressure difference between the two zones. As the pressures influence each other, this test procedure requires constant adjustment of the speed of the two fans to reach the pressure equilibrium. When achieved, this condition can be easily disturbed by wind action. Consequently, a computer controlled pressurization unit has been developed at the EPFL to overcome these problems [20].

3.3.2.2 Deduction Method

In practice, it is almost impossible to keep adjacent zones exactly at the same pressure level and an alternative to the *guarded zone method* was, therefore, sought. The resulting technique, called the *deduction method*, also allows the determination of the permeability of internal and external walls in a multizone building.

While keeping one zone at a constant pressure difference against the outside (constant pressure zone, e.g., zone A in Fig. 1c); pressure difference usually kept at 50 Pa), the pressures in the adjacent zones are either kept at outside pressure (outside pressure zone) or are pressurized in steps from the outside pressure level to the level of the pressure in the constant pressure zone (floating pressure zone, e.g., zone B in Fig. 1c)). With increasing pressure in the floating pressure zone, the blower door has to supply less air to keep the pressure in the constant pressure zone at the required level. Deducting the air flow for the case of pressure equilibrium between the two considered zones from the overall air flow for a given pressure difference between the two pressurized zones results in the air flow of the flow paths between these two zones at this pressure difference.

The permeability characteristics of the interior wall can then be calculated by using the linear regression method. Fig. 2b) shows the curves describing this measurement technique for the example given in Table 1.

In order to avoid the problems connected with trying to keep the two zones at the same pressure level (see *guarded zone method*), the air flow to be deducted can be calculated by averaging the air flows obtained by measurements taken at pressures in the floating pressure zone, which are equidistant below and above the pressure in the constant pressure zone (e.g. $\Delta p_{guard.} = 50\ Pa$; $45\ Pa \le \Delta p_{float.} \le 55\ Pa$).

Whereas the result of a test performed using the guarded zone method determines the permeability coefficient of the "outside walls" directly, the deduction method defines the flow characteristics of the walls separating the constant pressure zone and the floating pressure zone with a single set of measurements.

Independently of the method used, the data pairs taken from blower door tests are converted into permeability coefficients and pressure exponents to fulfill Eq. 7. For building components which cannot be measured directly, these indicators are calculated either from flow rate differences obtained from different measurements, or by subtracting the curves, which are fitted to the data points. The latter method always shows correlation coefficients, r, close to 1.0. This is, however, only a measure of the accuracy of the curve fitting for ideal data points and does not indicate the quality of the data used to obtain the permeability characteristics for the two measurements in the first place.

Besides these methods using two blower doors, advanced single fan pressurization methods for multizone buildings are in discussion [21]. The disadvantage of these methods is the precise pressure readings necessary to gain meaningful results. This requires, not only very sensitive pressure gauges, but even more important, very calm weather conditions.

3.4 Multizone Blower Door Tests

3.4.1 Measurement Equipment

The two blower door techniques for multizone structures were tested on three buildings at the Joint Research Centre (JRC) of the European Communities in Ispra, Italy. The equipment used were two sets of the "Minneapolis Blower Door", commercially available in the US. Each set consists of an adjustable door frame with a nylon fabric door panel, a "custom calibrated" nozzle-type fan with a solid-state speed controller (± 5% accuracy), a pressure gauge (range 0 - 60 Pa) to measure the pressure difference between inside/outside and two pressure gauges (0 - 125 Pa and 0 - 500 Pa) to measure the difference in static pressure between the undisturbed air and the mouth of the nozzle. The accuracy of the pressure gauges is not mentioned by the manufacturer of the blower doors.

As a special "sensitive" pressure gauge or a "flow finder" [22] adds easily the price of a whole blower door set to the overall equipment cost, no additional pressure gauge or other expensive equipment will be used by professional engineers in the field. Therefore, all tests have been performed with standard equipment, originally developed for the purpose of single-zone measurements.

The method used to fit the data by a curve describing the power-law function (see Eq. 7) is given in Ref. 21.

3.4.2 Tests Performed

3.4.2.1 Blower Door Tests at ENEA Building

A three story building with several passive and active solar features was erected by the Italian Agency for Nuclear and Renewable Sources of Energy (ENEA) on the site of the Joint Research Centre in Ispra (see Figs. 3a and 3b). The structure, with an in-situ concrete frame and prefabricated building components of glassfiber reinforced concrete, has a total floor area of 3,500 m^2 in four building parts: Corpo A with a lecture hall and offices for the director and administration, Corpo B with the computer room, laboratories and offices for researchers and support staff, Corpo D with a workshop and the exchangeable heat storage, and Corpo C which functions as entrance hall. The south facade of Corpo A is inclined (60°) and covered by 290 m^2 of air collectors. The entrance hall connects the administration offices with the rest of the building. Its south facade is closed by a three polycarbonate layer surface. Corpo B utilizes solar chimneys to reduce the heating and cooling load for its offices and laboratories. The south pitch of the roof sheds of the two office blocks are covered with water solar collectors [24, 25].

The zones used for comparison of the two blower door techniques are located in Corpo B (see Fig. 3c). This part of the building is ventilated by means of exhaust ventilation, using openings in the facade to supply the necessary outdoor air. The mechanical system is designed to exhaust a specific air flow of about 1 m^3/m^3h from the offices and the laboratories. Solar chimneys on the south facade of the building are designed to heat air from the rooms facing south and supply the heated air via ducts to the rooms facing north. To allow circulation between rooms, the internal doors to the corridor are equipped with grills.

Underneath the considered zone (zone #1) is a meeting room; above is an electronics laboratory. The internal walls of the building are made of sheet rock. Whereas the east wall of the zone has no visible flow paths to the adjacent zone (zone #2), the west wall contains a door, which connects zone #1 with zone #4. Furthermore, there is a visible crack between this internal wall and the facade.

In order to determine the leakage of the ceiling, the laboratory located above zone #1 was pressurized from outside pressure to 50 Pa while keeping zone #1 at a constant pressure of 50 Pa. No flow adjustments were necessary to keep zone #1 at the desired pressure level. From this measurement we learned that the permeability of the ceiling is negligible.

For all tests the outside air supply opening in the facade of zone #1 was set to its normal (open) position. The grill of the mechanical exhaust ventilation system and the opening of the solar chimney in zone #1 as well as the grills in all doors facing the common corridor were taped. The latter was necessary to separate zones from each other and to be able to pressurize the guarding zone (floating pressure zone) up to 60 Pa.

In order to determine the permeability of the outside wall as well as of the walls separating the considered office from the adjacent zones on the same floor, both, the guarded zone method and the deduction method were tested. The air flow for the guarded zone (respectively the constant pressure zone) was supplied by a blower door installed in the frame of the corridor door of the office (zone #1). The guarding zone (floating pressure zone) was pressurized using a blower door installed in the fire door of the corridor. Both fans were in a series arrangement. This gives the most stable conditions for the air flow of zone #1, because the fan provides the air flow at very small pressure differences. The size of the guarding zone (floating pressure zone) was changed by opening or closing doors and windows in the adjacent offices. Thus, an adjacent zone either belonged to the guarding zone (floating pressure zone) or to the outside.

To minimize the wind influence, measurements were not taken at wind speeds above 1 m/s and the outside pressure probe was located in a box with four holes in its perimeter. The box itself was placed approximately 30 m away on the windward side of the building. According to numerical investigations, this probe arrangement produces pressure coefficients between $-0.1 \leq cp \leq +0.1$ [26]. For the deduction method, the uncertainty in the measured leakage coefficient of the common wall between the two zones associated with these low wind speeds is in the range of 1% [27].

The calculated permeability coefficients, D, the pressure exponents, n, and the correlation coefficients, r, are shown in Table 2. The section covered by walls #2 and #3 is almost air tight; this leads to very confusing results. As the air flow through this section of the internal wall is in the range of the accuracy of the blower door measurements, no reasonable results could be obtained by either method.

Even if the results for the walls #2 and #3 are disregarded, the pressure exponents obtained from the regression method vary in a broad range for the different sections of the envelope as well as for the different techniques.

Except for the above mentioned case, the exponents obtained by the deduction method are consistently between 0.59 and 0.62, which is in good agreement with the single-zone test (all walls). Those exponents obtained by the guarded zone method vary between 0.53 and 0.78. The differences in the calculated permeability characteristics between all internal walls (walls #2, #3 and #4) and the same section but without wall #2 show the problems associated with the guarded zone method. When plotting the data, one finds that air flow calculated for the smaller section of the internal walls is larger than the one for the whole internal wall (see Fig. 2c).

According to the results obtained from the deduction method, the outside wall represents 64% of the overall leakage of the considered zone. This permeability can cause significantly higher air flows than those caused by the exhaust ventilation system. Most of the rest of the permeability is located in the west wall of the zone (wall #4), which contains the visible openings of the internal walls.

3.4.2.2 Blower Door Tests at the Solar Laboratory (Casa Solare)

To study the control of a direct gain passive solar system, the "Non Nuclear Energies Programme" of the Joint Research Centre has built a single story building, consisting of a 12 year old test structure, formerly used for active solar systems, and a sun-space added to the south side of the building. The overall floor area of the building amounts to 260 m^2, including the 90 m^2 of the sun-space. In the building there is a hall, a meeting room, a bathroom and a room for the equipment. The sun-space is used as library and

Table 2: Pressurization Measurements; Results for zone #1 in Corpo B of the **ENEA** Building; Inside/Outside Temperature = 26/28°C.

CASE/ Technique *)	Method	D [m^3/h Pa^n]	n [-]	Corr. Coeff. [-]
all walls single zone	direct	79.0	0.59	0.9976
outside wall				
guarded zone	direct	64.4	0.56	0.9934
deduction method	ΔQ	69.9	0.50	0.9999
deduction method	D & n	50.6	0.59	1.0000
walls #2 and #3				
guarded zone	ΔQ	55.4	-0.14	0.2291
guarded zone	D & n	4.4	0.55	0.9999
deduction method	direct	24.0	0.10	0.2786
walls #3 and #4				
guarded zone	ΔQ	31.9	0.53	0.8299
guarded zone	D & n	23.5	0.60	0.9999
deduction method	direct	24.8	0.62	0.9824
walls #2, #3 and #4				
guarded zone	ΔQ	11.1	0.78	0.9769
guarded zone	D & n	16.0	0.69	0.9999
deduction method	direct	28.4	0.60	0.9840

***) Remarks:**

Case:	describes selected walls and the test method used to obtain the data. Wall number refers to the wall separating zone #1 from the zone with the wall number.
Method:	describes the mathematical way to obtain the data to calculate coefficients and exponents. **direct**: data points are obtained from one single blower door test. **ΔQ**: data points are differences of data points of two different blower door tests. **D & n** : data points are calculated from two sets of coefficients and exponents.
Corr. Coeff:	measure of the quality of the curve fit; best fit results in correlation coefficient of 1.0

exhibition room (see Figs. 4a and 4b) [28].

The walls facing North, East and West are made of two layers of brick with 12 cm insulation between them; the south facade is completely covered with low emissivity double glazing. The former south facade (now interior east wall of the sun-space) and the roof are made of wooden girders with insulation covered by boards between them. The building is built slab on grade.

The test house is conditioned by fan coil units and ventilated by means of a mechanical exhaust ventilation system. For the permeability tests, the exhaust grills were taped.

Both blower door techniques were used to determine the permeability of the internal walls separating the meeting room and the bathroom from the rest of the building. A second set of tests was performed, treating the wall between the meeting room and the sun-space as an outside wall. One of the two blower doors was installed in the emergency exit of the meeting room (East wall), whereas the second door replaced one of the two door panels at the exit on the west facade. The two doors were installed in a parallel arrangement.

Except for the door between the meeting room and the hall, all internal doors were kept open for the first set of tests. The two major internal leakages, detected by the eye, are the slit below the door panel (between 1.0 and 1.5 cm) and the cracks of the four-piece sliding window, which forms the upper part of the wall between the meeting room and the hall. Openings having the dimensions of the slit below the door panel usually cause turbulent jets [8]. Therefore, the flow exponent for the internal walls can be expected to be close to $n = 0.5$.

The results of the first set of blower door tests are shown in Table 3a. No significant differences can be seen for the air flows obtained by the first set of measurements for the two techniques. The blower door tests done for the arrangement with the sun-space belonging to the outside, show similar results (see Table 3b). Again, both techniques show reasonable results for the outside walls and the internal walls. As the second set of tests was done after "removing" a very tight section of the internal wall and "adding" it to the outside wall, the value of the pressure exponent for the inside wall will be governed even more by the visible cracks. Therefore, the value of the pressure exponent for the internal wall ought to decrease with the reduction of the wall area. This effect, however, can only be seen for the deduction method. The guarded zone method shows the opposite effect; the exponent for the reduced section of the internal wall is significantly higher than the one for the whole internal wall.

3.4.2.3 Blower Door Tests at Building 26A

Building 26A is a single story wooden barrack built above a crawl space (for details see Figs. 5a and 5b). The internal surface of the outside walls as well as the internal walls are covered by hardboard. The joints are covered by moldings. The outside surface is made of wood siding. The building appears to be very leaky.

Table 3a: Pressurization Measurements; Results for Internal Walls of Casa Solare (Building 45e); Inside/Outside Temperature = 29/32°*C*.				
CASE/ Technique	Method	D [m^3/h Pa^n]	n [-]	Corr. Coeff. [-]
all walls single zone	direct	567.6	0.58	0.9962
outside walls				
guarded zone	direct	238.8	0.62	0.9881
deduction method	ΔQ	281.4	0.59	0.9203
deduction method	D & n	264.7	0.60	1.0000
walls #2, #3 and #4				
guarded zone	ΔQ	355.6	0.53	0.9457
guarded zone	D & n	332.2	0.55	1.0000
deduction method	direct	304.0	0.56	0.9748

Table 3b: Pressurization Measurements; Results for Internal Walls (except Sunspace) of Casa Solare (Building 45e).				
CASE/ Technique	Method	D [m^3/h Pa^n]	n [-]	Corr. Coeff. [-]
all walls single zone	direct	567.6	0.58	0.9962
outside walls				
guarded zone	direct	427.5	0.52	0.9887
deduction method	ΔQ	249.6	0.65	0.9840
deduction method	D & n	275.4	0.62	1.0000
walls #3 and #4				
guarded zone	ΔQ	174.2	0.66	0.9605
guarded zone	D & n	158.7	0.68	0.9999
deduction method	direct	296.4	0.54	0.9969

The building contains two rows of offices, separated by a common corridor. The offices are air conditioned, using duct work to supply conditioned air into the offices. The return air is transported via the common corridor.

The blower door tests were performed using two adjacent offices on the west facade of the building as test facilities. Both corridor doors were replaced by a blower door. Therefore, the blower doors were in a parallel arrangement. This setup makes it possible either to determine the permeability of all walls of each of the zones, or to separate the dividing wall from the other walls. In order to reduce the wind influence, the windows and corridor doors of the rooms next to the two considered offices were kept open. The supply ducts were taped to eliminate the influence of the duct work on the permeability measurements.

The results of the blower door tests are shown in Table 4. As seen before, only the deduction method produced consistent results. The agreement between the two calculation methods for the deduction technique obtaining the permeability coefficients and the pressure exponent for the outside walls is remarkable. Especially the small deviation of the correlation coefficient for the "ΔQ method" from its optimum is worth mentioning. This is probably a result of the measures taken to reduce the influence of the wind.

On the other hand, the results for the guarded zone method were again less satisfactory. Both calculation methods produced pressure exponents below $n = 0.5$ for the dividing wall. The correlation coefficient for the "ΔQ method" is less than $r = 0.9$.

Table 4: Pressurization Measurements; Results for JCR-Building 26a; Inside/Outside Temperature = 24/25°C.

CASE/ Technique	Method	D [$m^3/h\ Pa^n$]	n [-]	Corr. Coeff. [-]
all walls				
single zone	direct	166.9	0.54	0.9996
outside walls				
guarded zone	direct	119.0	0.56	0.9950
deduction method	ΔQ	129.6	0.55	0.9988
deduction method	D & n	132.2	0.54	1.0000
dividing wall				
guarded zone	ΔQ	57.5	0.41	0.8965
guarded zone	D & n	49.5	0.45	0.9999
deduction method	direct	34.7	0.54	0.9893

3.4.3 Comparison

Both multizone blower door methods have one thing in common: Due to the limited accuracy of the equipment, neither method gives reasonable results for building components with relatively small permeability. In the case of the guarded zone method this can be explained by the accuracy of the two blower door measurements (in the case of the very tight building components = repeatability), which have to be performed to obtain the permeability characteristics. The influence of air flows caused by pressure differences between the guarded zone and the guarding zone might be negligible in this case.

For the deduction method, the differences of air flow necessary to obtain a constant pressure for the constant pressure zone, while changing pressures in the floating pressure zone, might cause static pressure differences between the nozzle and the undisturbed environment, which are below the accuracy of the pressure gauge:

$$Q = C\ (\Delta p_{nozzle})^{m} \tag{11}$$

$$Q = D_{out}(\Delta p_{out})^{n_{out}} + D_{in}(\Delta p_{in})^{n_{in}} \tag{12}$$

$$\Delta p_{nozzle} = (\frac{1}{C})^{1/m} \left\{ \left[D_{out}\ (\Delta p_{out})^{n_{out}} \right] + \left[D_{in}\ (\Delta p_{in})^{n_{in}} \right] \right\}^{1/m} \tag{13}$$

and with C and $\Delta p_{out} = const.$

$$\Delta p_{nozzle} = [C_1\ (C_2 + D_{in}\ (\Delta p_{in})^{n_{in}}]^{1/m} \tag{14}$$

As C_2 is determined by the permeability of the outside walls of the constant pressure zone and the pressure difference between the zone and the outside, reducing the pressure level of the constant pressure zone can improve the accuracy of the measurement. This is especially the case, if the flow rate can be reduced so much, that a different flow measurement regime (e.g. using a flow plate) can be reached. This, as a consequence, reduces the value of C_1. The disadvantage, however, is, that the measurements become more wind dependent. The larger the permeability of the considered building component, the better the accuracy of the deduction method (see Table 2). Better results can be obtained by reducing the C_2-value (e.g. by taping visible openings in the outside wall).

The major difference between the two methods is, that for the deduction method, the pressure differences between the constant pressure zone and the floating pressure zone are deliberately kept relatively high. Therefore, small variations in pressure differences due to wind, fluctuation of the fan flow, or the limited accuracy of the pressure gauge, cause only relatively small errors in the measured air flows.

The error associated with the guarded zone method is governed by the pressure difference between the guarded and the guarding zone. The air flow for an internal wall obtained by two blower door tests is the consequence of:

$$Q_{in} = D_{tot}\ (\Delta p_{tot})^{n_{tot}} - [D_{out}\ (\Delta p_{out})^{n_{out}} \pm (D_{in}(\Delta p_{in})^{n_{in}})] \tag{15}$$

Eq. 15 shows, that this technique is least precise, when Δp_{out} is very small. The error introduced is biggest, when openings between the guarded zone and the guarding zone are present, which cause turbulent flows already at very low pressure differences.

4. DISCUSSION

From the results of the tests in the three buildings we learned that by using standard blower door equipment, the guarded zone method does not give consistent results. Especially the pressure exponent varies from test to test. With the same equipment, the deduction method gives more consistent results.

The other disadvantage of the guarded zone method is, that both zones have to be exactly at the same pressure level. As the pressures in both zones influence each other, the tests are very time-consuming. It can be expected, that the time necessary to perform the tests will increase even more when using very sensitive pressure measurement devices.

The deduction method needs only one zone to be kept at a certain pressure level. For the floating pressure zone, the observance of an exact pressure level is not important for the test. Therefore, if the floor-plan of the considered structure allows access to the controls of the two fans from a single zone, the deduction method could be performed by a single person.

The tests performed at the JRC show that the best results are provided by the deduction method, if the permeability characteristics can be obtained by the "direct method". If this is not possible, subtracting the two curves gives more reasonable numbers, than a curve fitted to the subtracted values from the two measurements.

5. CONCLUSIONS

Two multizone blower door techniques used to determine inter-zonal leakage were tested on three buildings in the premises of the Joint Research Centre of the European Communities in Ispra, Italy.

The tests did show significant differences in the consistency of the results. Furthermore, as these measurement techniques are very sensitive to distortion due to wind, very high uncertainties can be expected at higher wind speeds [27]. However, the real flow characteristics of the considered walls are not known. Therefore, both techniques ought to be tested in multizone test cells, which eliminate the influences of the weather conditions, with known flow characteristics for all of the walls. These tests have to be done before considering one or both methods to be recommended for a measurement standard.

6. ACKNOWLEDGEMENTS

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Fig 1): Use of Blower Doors to obtain the Flow Characteristics for the Wall separating Zone A and B using two blower doors [21].

a) Guarded Zone Method:
Pressure of adjacent zones is increased by increments of 10 Pa; keeping the two zones (A and B) at the same pressure level. This eliminates flows between the two considered zones.

b) Guarded Zone Method:
Zone C is kept at outside pressure while the pressure in zones A and B is increased in increments of 10 Pa (see Fig. 2a).

c) Deduction Method:
Pressure in Zone A is kept at constant level (e.g. 50 Pa). Pressure in zone B has to be changed to obtain pressure differences between the two zones $0 \leq \Delta p_{A,B} \leq 50Pa$. The flow rate at equal pressure between the considered zones is deducted from the flow rate at each of the pressure differentials. The residual determines the permeability characteristics of the wall A/B (see Fig. 2b).

Fig. 2a): Air Flow versus Pressure Difference for Guarded Zone Method

Fig. 2b): Air Flow versus Pressure Difference for Deduction Method

Fig. 2c): Air Flow versus Pressure Difference for Guarded Zone Method for different Wall Configurations and different Data Analyses.

Fig. 3a): ENEA Building

Fig. 3b): View of the ENEA Building

Fig. 3c): Floor Plan of Corpo B of the ENEA Building

Fig. 4a): Casa Solare

Fig. 4b): Floor Plan of the Casa Solare

Fig. 5a): Building 26A

Fig. 5b): Floor Plan of Building 26A

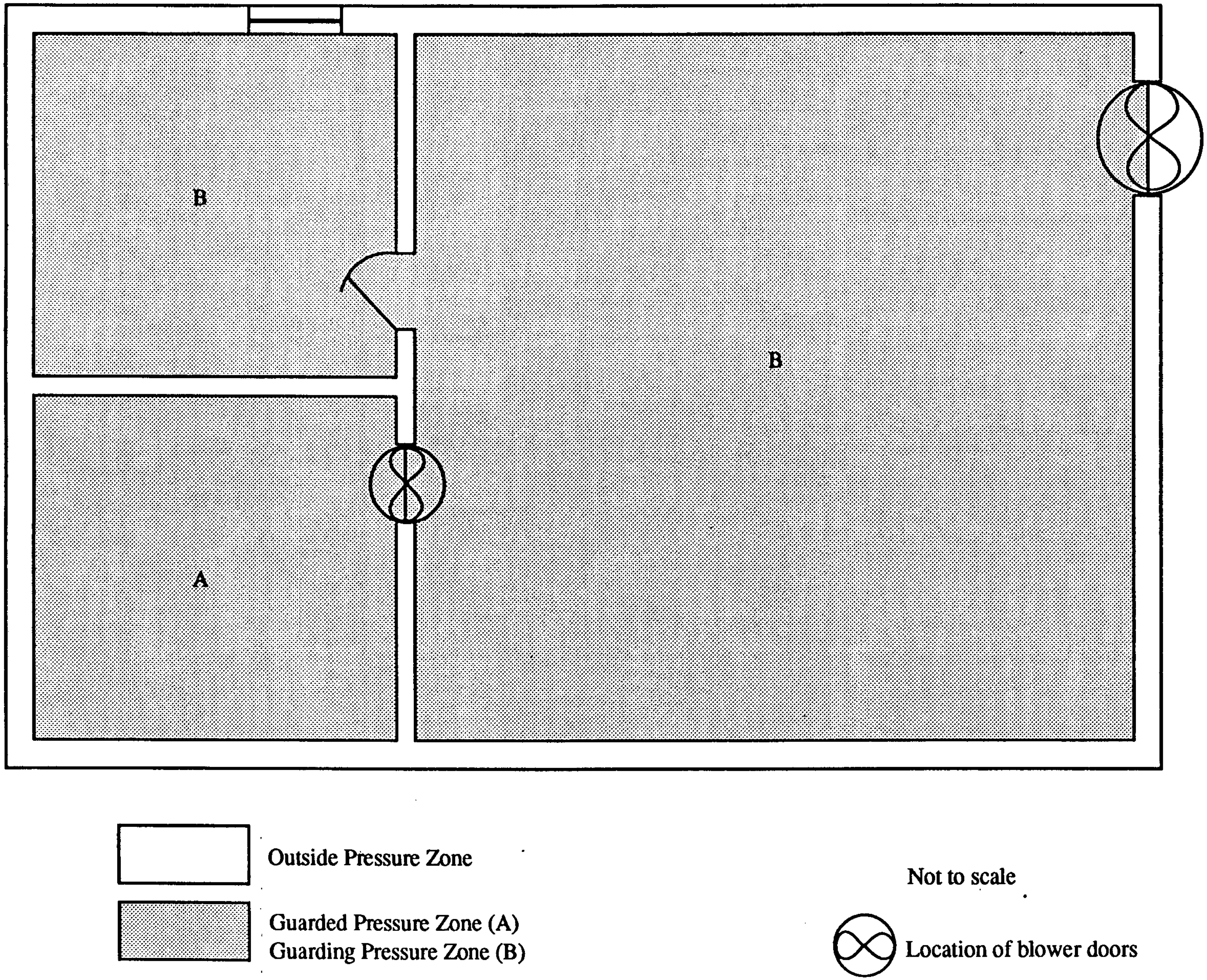

Fig. 1a

XBL 899-3539

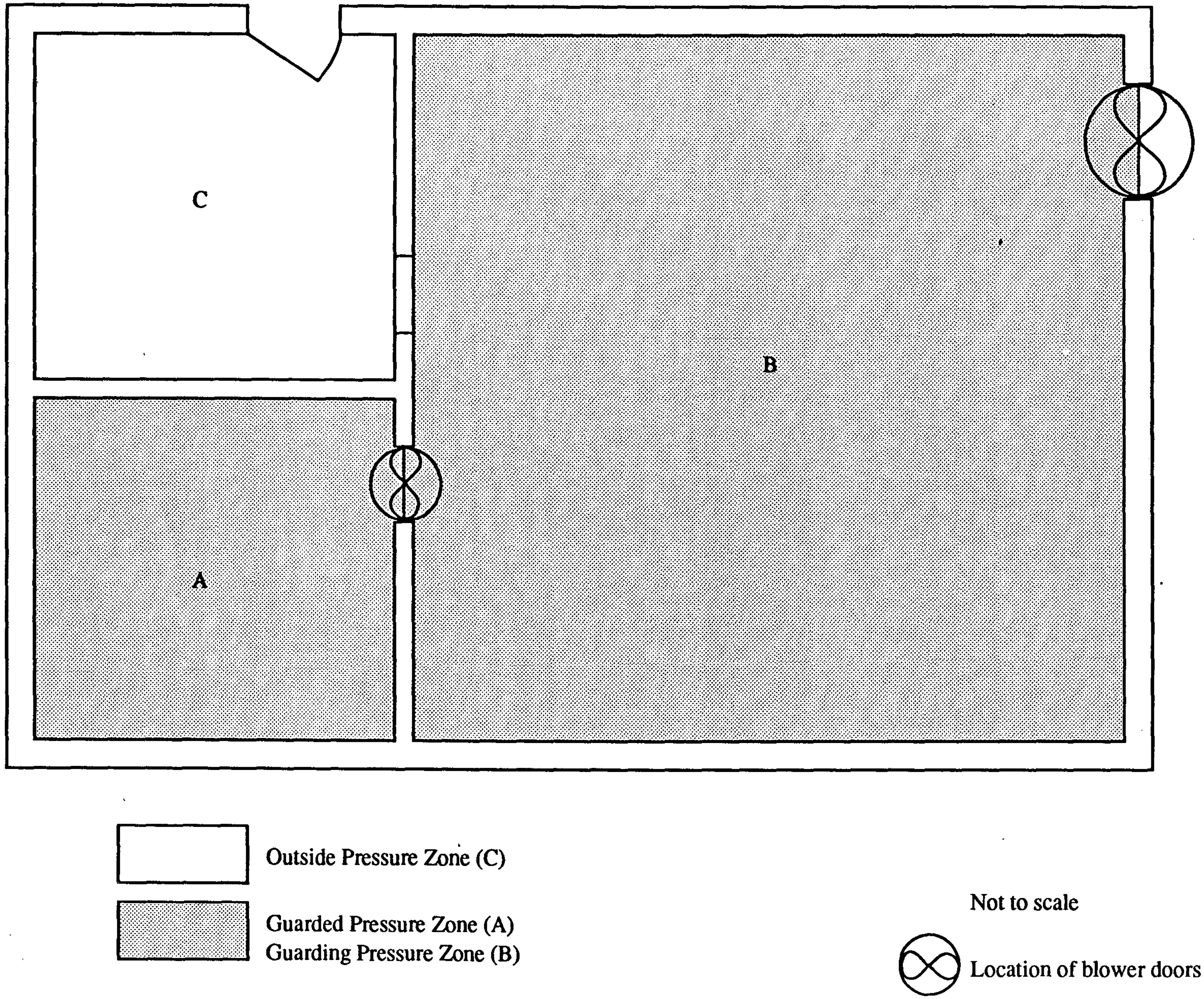

Fig. 1b

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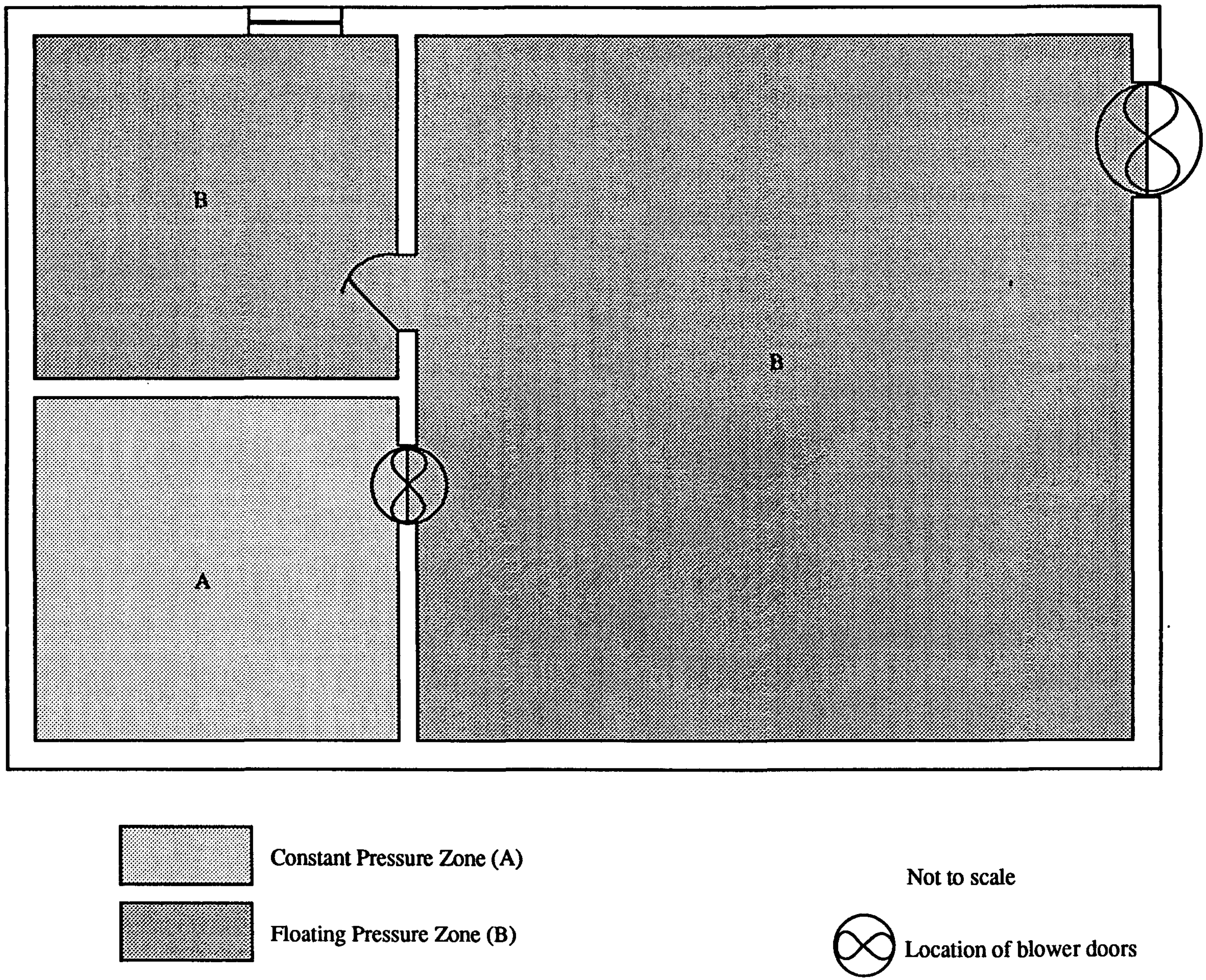

Fig. 1c

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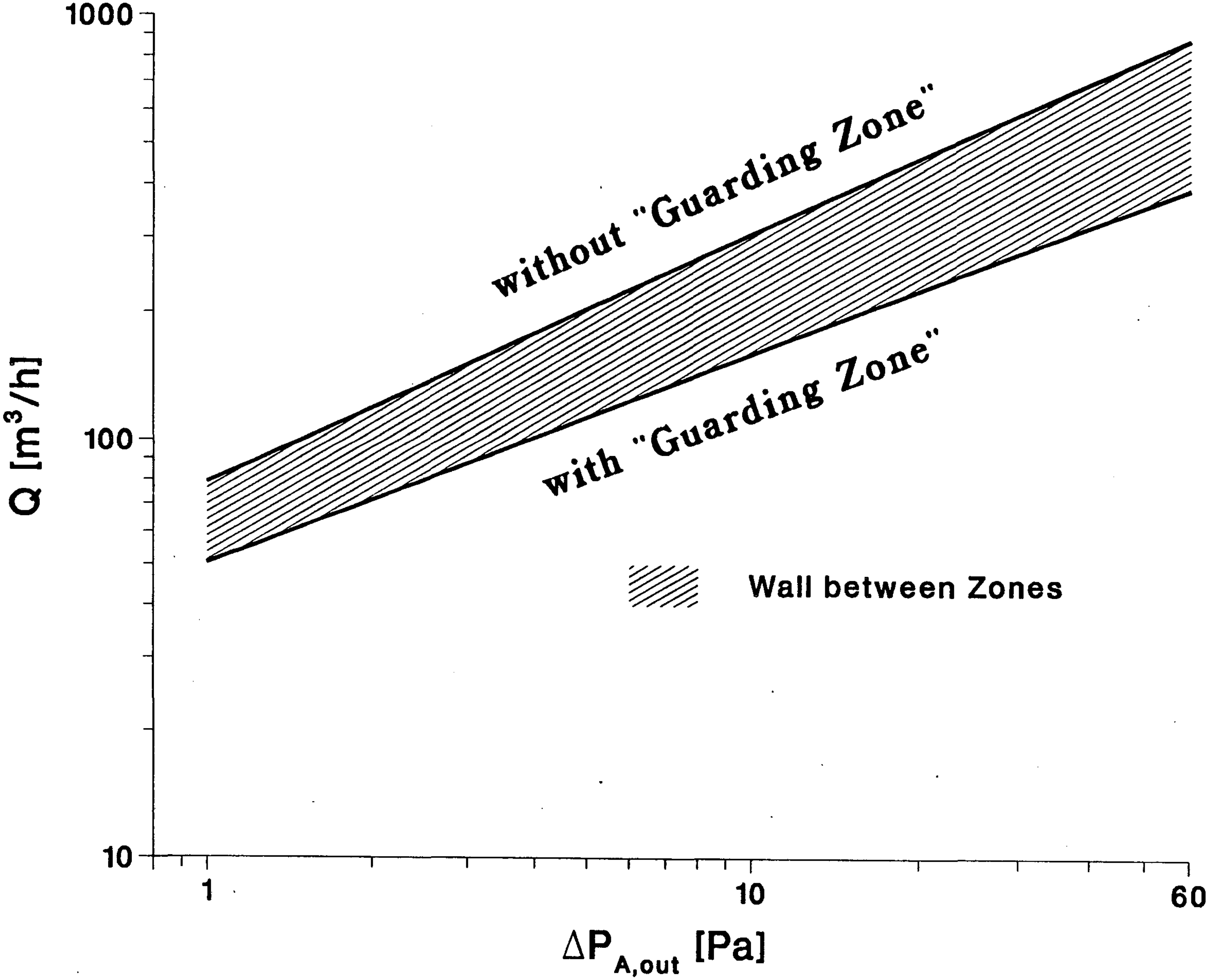
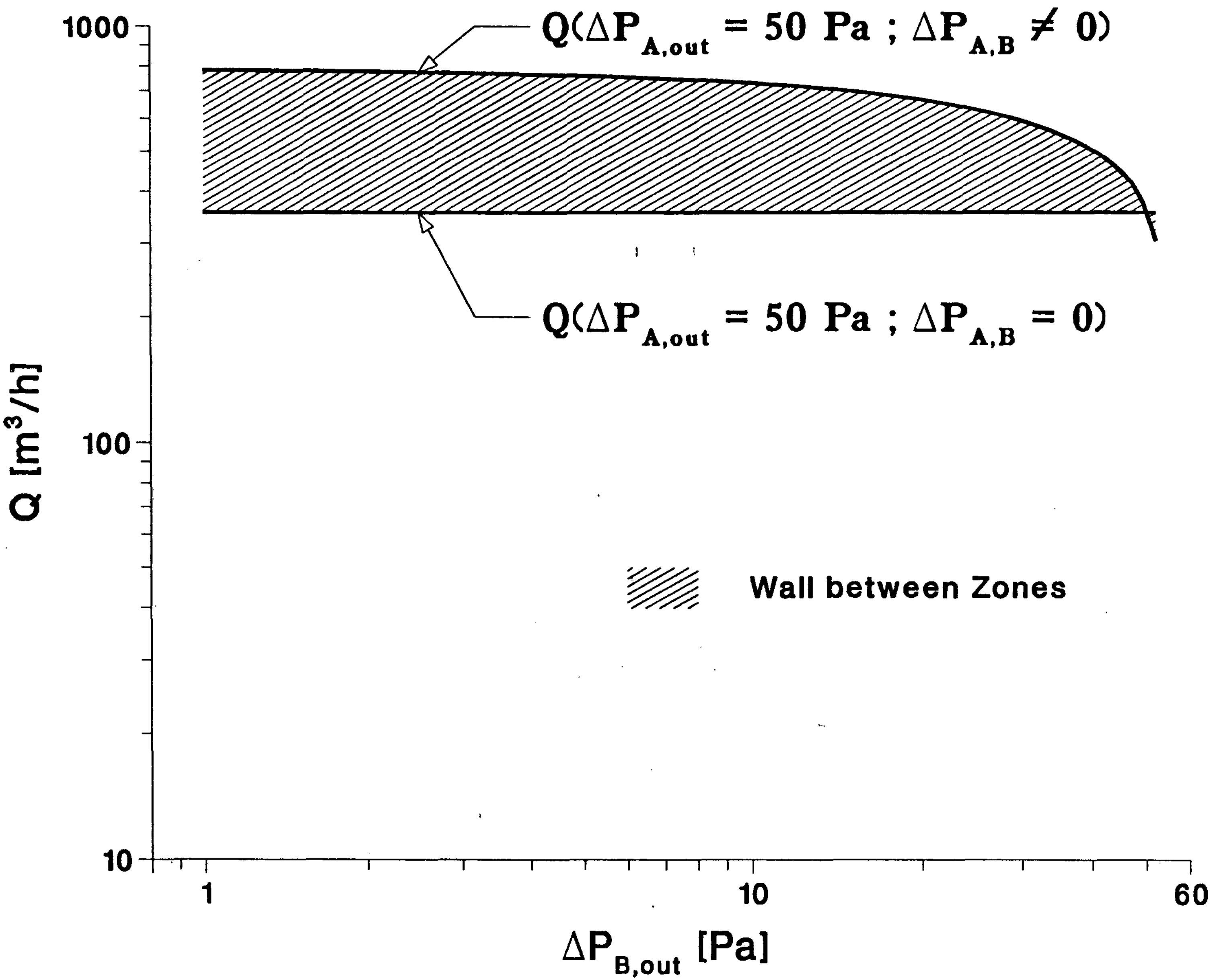


Guarded Zone Method

Fig. 2a

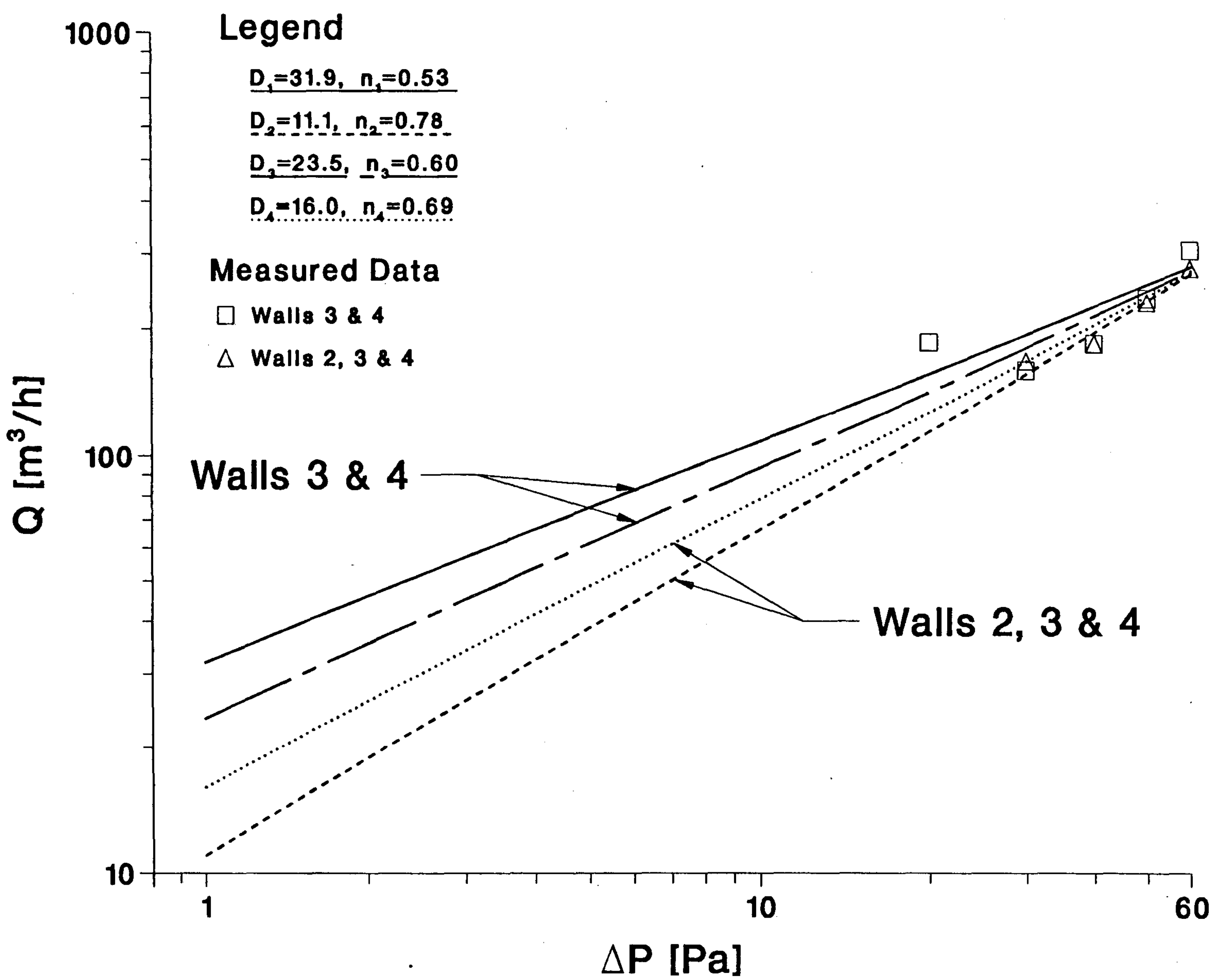
XBL 899-3545



Deduction Method

Fig. 2b

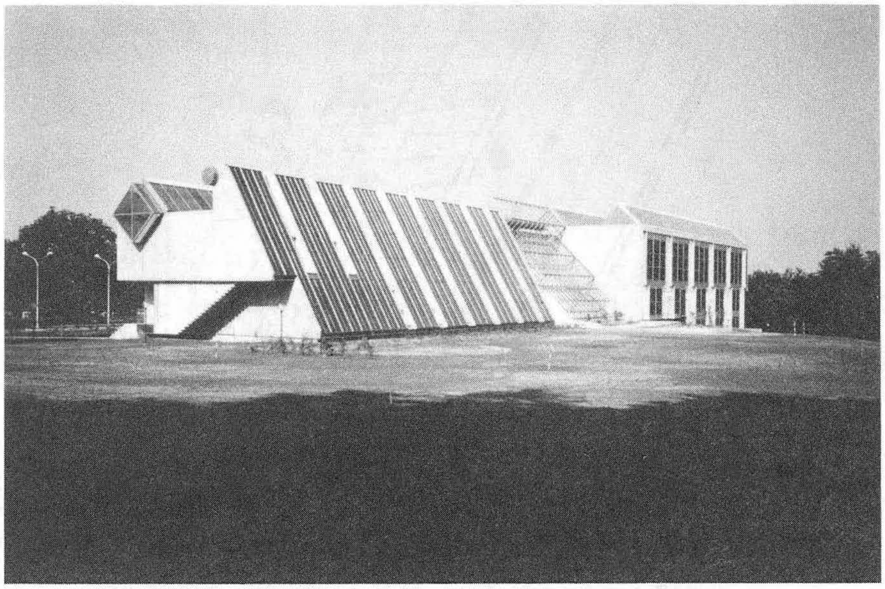
XBL 899-3546



Guarded Zone Method

Fig. 2c

XBL 899-3547



CBB 880-11382

Fig. 3a

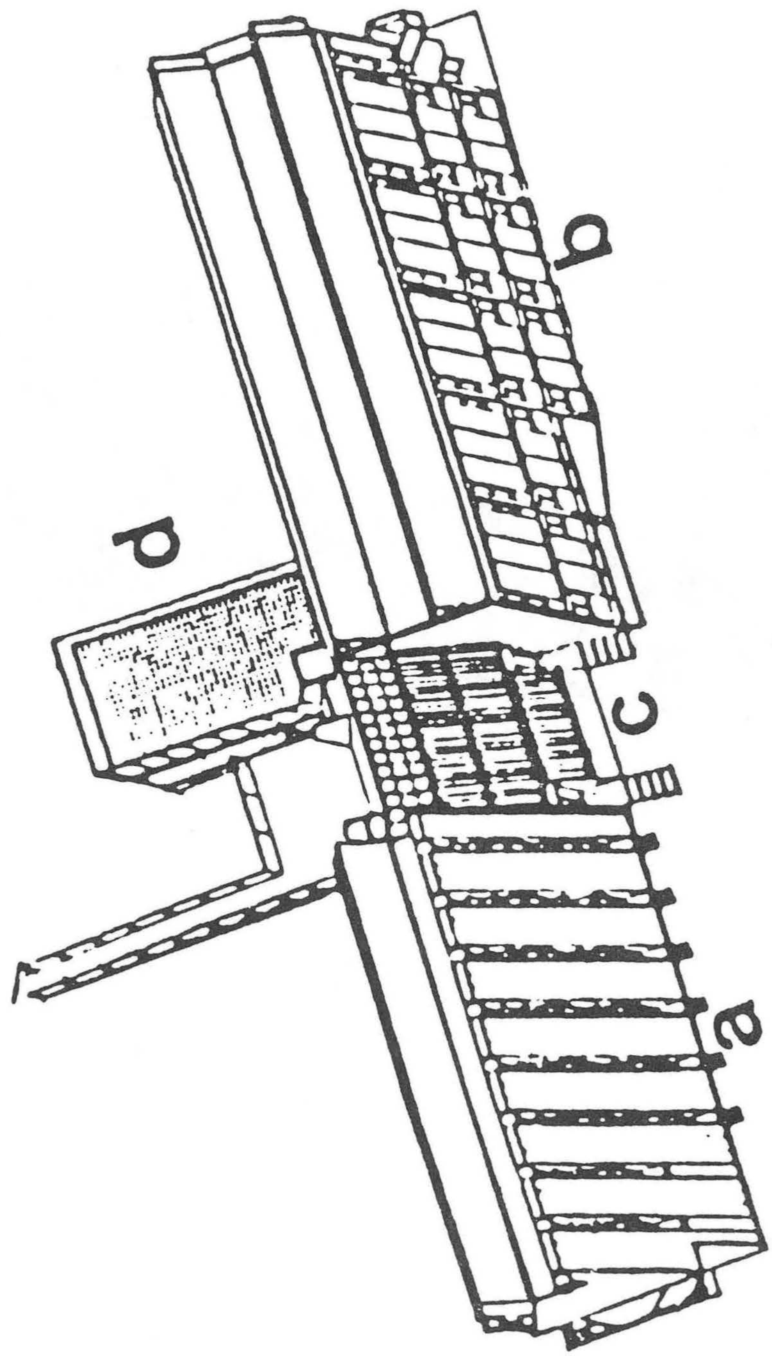


Fig. 3b

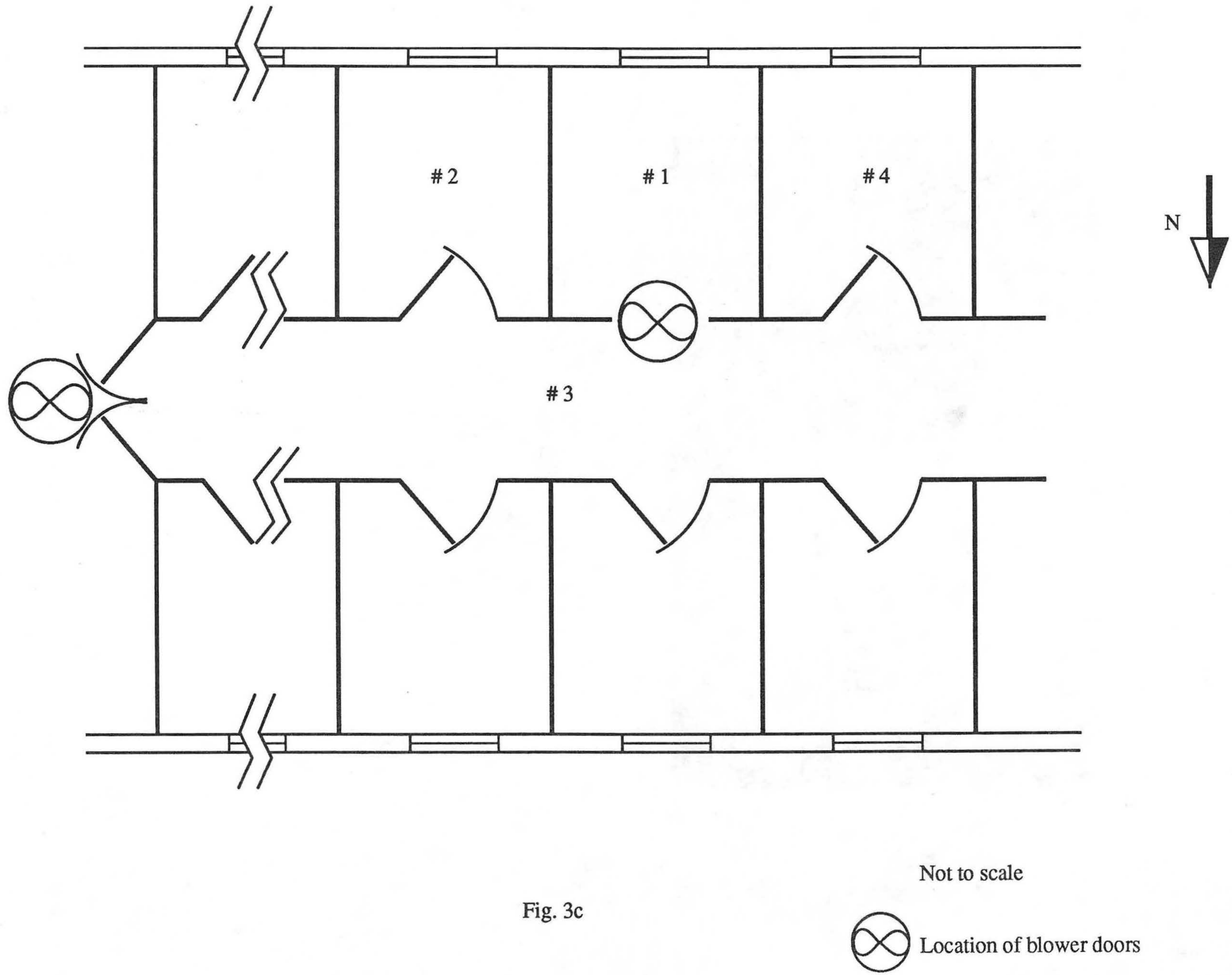


Fig. 3c

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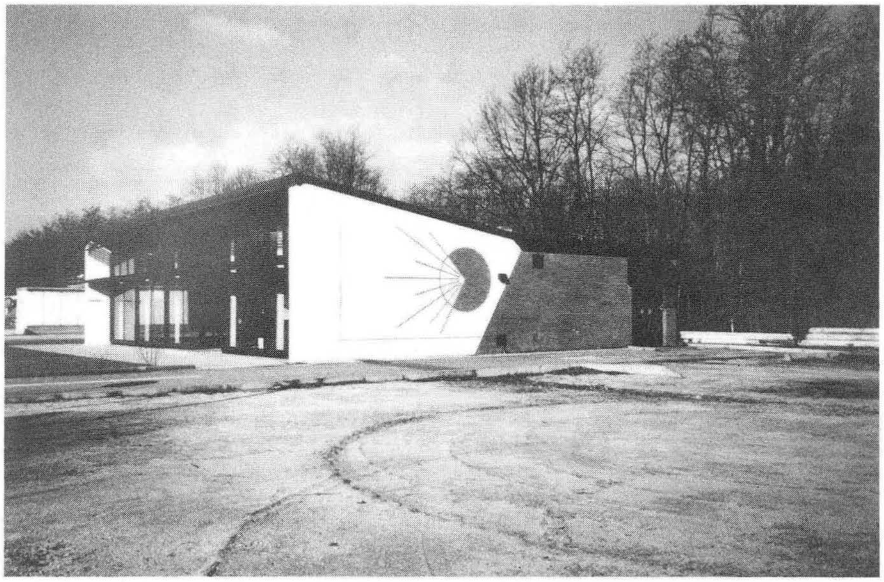
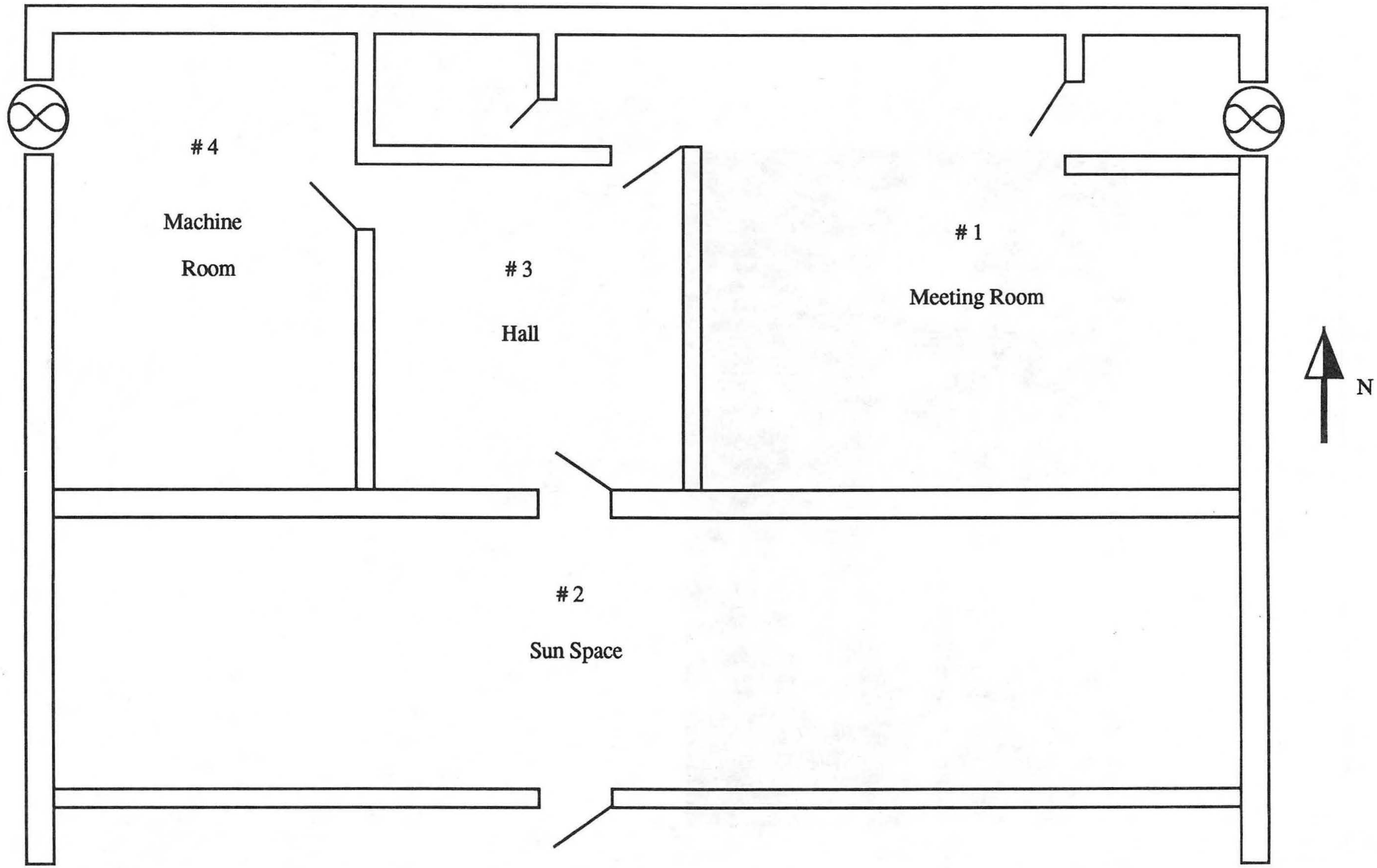


CBB 880-11384

Fig. 4a

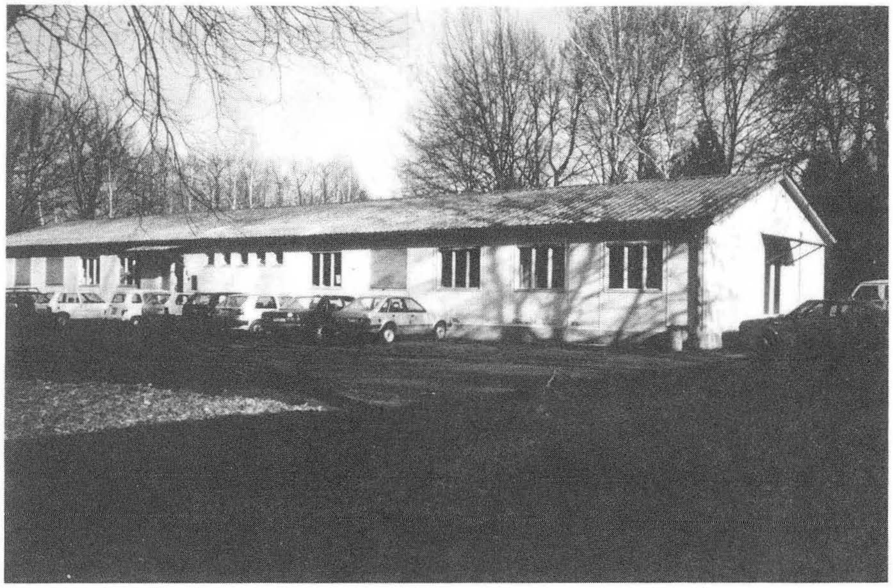


Not to scale

Fig. 4b

Location of blower doors

XBL 899-3543



CBB 880-11386

Fig. 5a

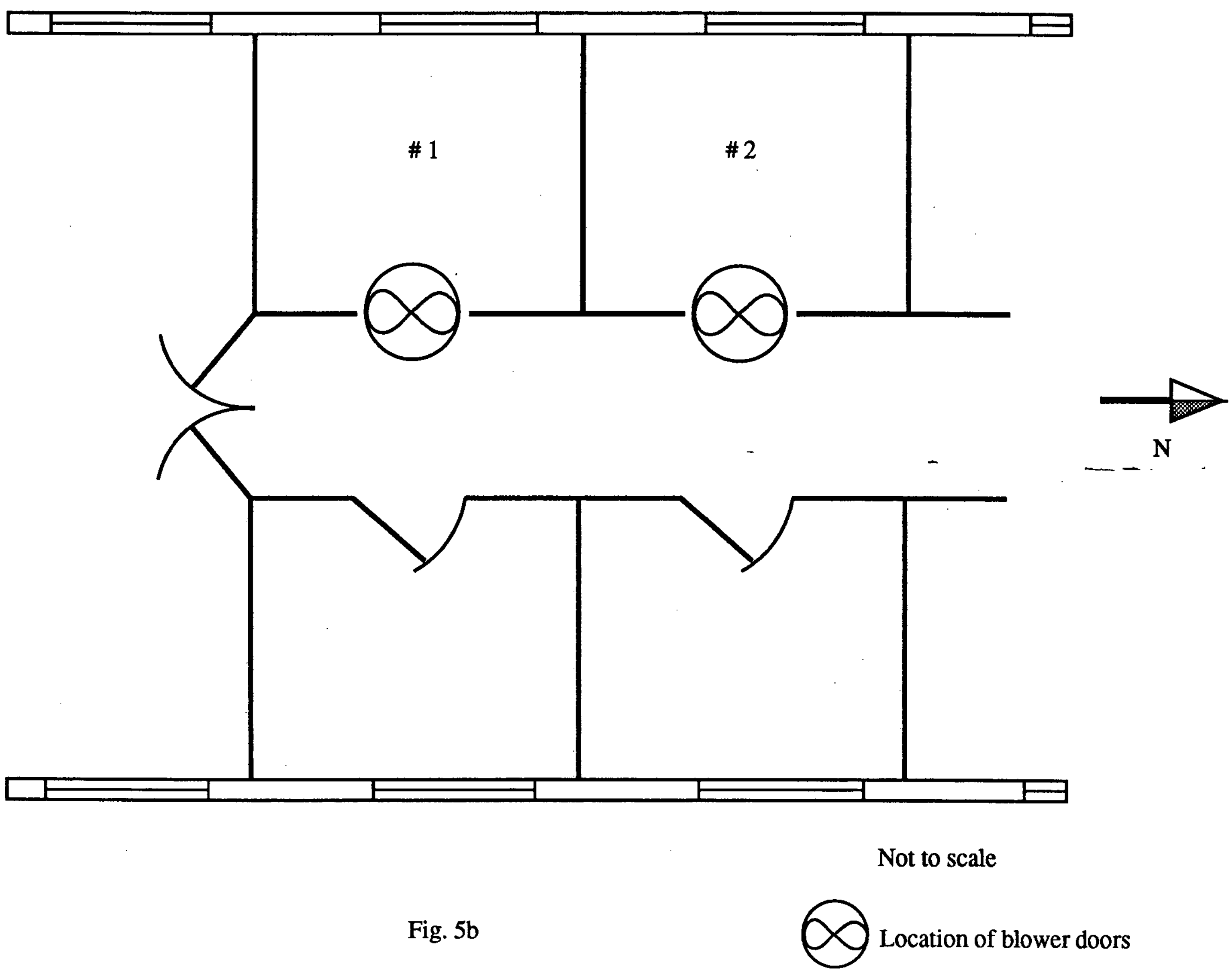


Fig. 5b

XBL 899-3544