Air Infiltration in Warehousing and Light Industrial Buildings

A RESEARCH REPORT

Infiltration Considerations and Their Application to the Warehousing and Light Industrial Building Category: A State-of-Practice Review

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The Buildings Energy Technology Transfer Program (BETT) of EMR has been created to assist building owners, users and practitioners active in the design, construction and operation of buildings in identifying technical obstacles to energy conservation. Through a nationwide network of research agencies and private sector consultants, BETT carries out research and development projects and provides the audiences mentioned above with technical reports, how-to manuals, training manuals, audio-visual aids and data bases to help them overcome these obstacles.

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ABSTRACT

A state-of-practice review of air leakage considerations in buildings is presented, with particular emphasis on buildings in the warehousing and light industrial building classification. Aspects addressed include the significance of infiltration/exfiltration, air leakage sites, and methods used to measure and estimate infiltration.

The main conclusions from this review are as follows:

1. Virtually no research work has addressed air leakage in buildings within the warehousing and light industrial building category. Therefore, only limited leakage data for components prevalent in light industrial buildings are available.

2. No estimation method has been developed specifically for use in warehousing and light industrial buildings. However, one of the numerous models previously developed for residential application could possibly be adapted.

Recommendations for further work include:

1. Generation of an air tightness/infiltration data base from fan pressurization and tracer gas tests for a cross-section of light industrial buildings.

2. Generation of component air leakage data using on-site tests.

3. Development (or adaptation) and validation of an infiltration estimation method.

RÉSUMÉ

Un examen des techniques propres à l'étude des aspects de l'infiltration et des fuites d'air dans les bâtiments, en particulier les bâtiments d'entreposage et les bâtiments industriels à structure légère, est exposé dans le présent rapport. Parmi les aspects traités, notons l'importance de l'infiltration et des fuites d'air, les points de fuite ainsi que les méthodes servant à mesurer et à évaluer cette infiltration.

Voici les principales conclusions qui se dégagent de cet examen:

1. Les fuites d'air dans le bâtiments de la catégories de l'entreposage et des bâtiments industriels à structure légère n'ont pratiquement fait l'objet d'aucune recherche. Il s'ensuit que l'on ne connaît qu'un nombre limité de données en la matière relativement aux éléments propres aux bâtiments industriels à structures légère.

2. Aucune méthode d'estimation spécialement conçue pour les bâtiments d'entreposage et les bâtiments industriels à structure légère n'a été élaborée. Toutefois, il serait possible d'adapter à cette fin l'un des nombreux modèles déjà conçus pour le secteur résidentiel.

Parmi les travaux de recherche qu'il est recommandé d'approfondir, il faut mentionner.

1. La préparation d'une base de données sur l'étanchéité et l'infiltration, à partir d'essais de pressurisation par ventilateur et d'essais au gaz traceur portant sur un échantillonnage de bâtiments industriels à structure légère.

2. La production de données sur les fuites d'air, au moyen d'essair effectuées sur place.

3. L'élaboration (ou l'adaptation) et la validation d'une méthode d'estimation de l'infiltration.

Le lecteur trouvera un sommaire en français de ce rapport à la page iii.

TABLE OF CONTENTS

The Buildings Energy Technology Transfer (BETT) was initiated by the Department of Energy, Mines and Resources (EMR) of the Government of Canada in late 1981. The principal objectives of this program are:

- to identify the potential for energy conservation in both new and existing building
- to determine R, D and D requirements and their priority in order to exploit this potential
- to perform and/or expedite the necessary R, D and D
- To effectively transfer the necessary technology to the appropriate individuals, groups or agencies
- to provide technological support to EMR in the development of policy and programs

The Building Engineering Group (BEG) was selected* by EMR to develop and execute a comprehensive R, D and D program for energy conservation in the warehousing and light industrial building sector. BEG is a semi-autonomous, non-profit agency associated, through the Waterloo Research Institute (WRI), with the University of Waterloo. This multi-disciplinary group attempts to provide a comprehensive range of R and D services to the building industry.

The warehouse and light industrial building sector is particularly important because:

- the square footage of building space encompassed by this category is second only to that of the residential building category
- to date very little R and D, energy-related or otherwise, has been directed towards this building category
- the nature of these buildings, both new and existing, makes them particularly amenable to some degree of energy conservation

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* DSS Number 02SQ.23380-1-6665-4 Serial OSQ81-00137 and Proposal Number WRI 109-01, September 20, 1981

In the initial phase of the R, D and D program developed by BEG, the priorities were to:

- establish a statistical profile of the building category
- develop a comprehensive review of the current state-of-practice
- initiate the development of a portfolio of representative case histories

Ten related studies are being undertaken in this initial phase, Seven of these studies provide either supporting documentation or input for a comprehensive state-of-practice report.

This report entitled "Air Infiltration in Warehousing and Light Industrial Buildings" by John Ferguson of Spider Engineering Associates (Waterloo) Inc. While the report provides an excellent stand-alone review of the topic it should be read in conjunction with the other six reports, especially the report entitled "Ventilation, Air Distribution and Air Quality: The State of Practice".

This report is an early product of what is intended to be a concerted multi-year program of research, development, demonstration, dissemination and evaluation. Feedback with regard to the report or related issues is welcomed and should be directed to the undersigned.

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Un examen des techniques actuelles propres à l'étude des fuites d'air dans les bâtiments, en prticulier dans les bâtiments d'entreposage et les bâtiments industriels à structure légère, a été effectué. La définition de "fuite d'air" comprend tout passage d'air imprévu de l'extérieur à l'intérieur (infiltration), et dans le sens inverse (fuite d'air), de l'enveloppe du bâtiment. Aux fins de l'étude, la catégorie des bâtiments d'entreposage et des bâtiments industriels à structure légère englobe les bâtiments de faible hauteur dont l'atmosphère est sensible aux variations climatiques et exempte des variations dues à la présence d'êtres humains ou à l'exécution d'un traitement industriel.

L'étude a porté sur les aspects suivants des fuites d'air:

i) l'importance que revêtent les fuites d'air,
ii) les endroits où se produisent des fuites d'air dans l'enveloppe du bâtiment,
iii) les moyens pris pour réduire les fuites d'air,
iv) les méthodes employées pour mesurer l'infiltration d'air et le degré d'étanchéité, et
v) les méthodes employées pour estimer et modéliser l'infiltration d'air.

Les fuites d'air dans les bâtiments revêtent de l'importance en raison des trois facteurs suivants:

La consommation d'énergie - une part importante des besoins en climatisation peut être due à l'infiltration;
La hausse du taux d'humidité - les fuites d'air sont la principale cause d'infiltration d'eau, source de problème pour les matériaux et les éléments structurels des bâtiments;
La ventilation - l'infiltration d'air peut être la principale source de ventilation des bâtiments dont la structure est surtout constituée d'une enveloppe (comme dans le cas des bâtiments d'entreposage ou des bâtiments industriels à structure légère).

Les point de fuite d'air comprennent toutes les fissures de l'enveloppe du bâtiment par lesquelles l'air peut s'échapper, notamment dans

les murs (en particulier à l'emplacement des joints) et à l'emplacement des fenêtres (au châssis et au cadre des fenêtres), des points extérieures de pénétration et des portes. Les moyens pris pour réduire les fuites d'air consistent en général à obturer le plus possible les points de fuite (grâce au calfeutrage des fissures et à l'installation de pare-vapeur et de coupe-bise) ou à réduire la différence de pression de manière à affaiblir la force de pénétration ou d'évacuation de l'air par les orifices (grâce à l'utilisation de vestibules et de cours intérieures).

On utilise surout deux méthodes pour mesurer l'infiltration et les fuites d'air caractéristiques d'un bâtiment: la méthode du gaz traceur et la méthode de pressurisation par ventilateur. La méthode du gaz traceur sert à mesurer l'infiltration, elle nécessite l'injection d'une mélange gazeux temoin que l'on peut déceler à l'intérieur du bâtiment. C'est en vérifiant l'évolution de la concentration du gaz traceur au cours d'une certaine période que l'on peut déterminer le taux d'infiltration.

Les essais de pressurisation par ventilateur servent à déterminer le degré d'étanchéité de l'enveloppe du bâtiment (par exemple une entrée de porte) permet d'obtenir un écart de pression uniforme dans l'immeuble. La circulation d'air qui en résulte permet d'obtenir une mesure relative de son étanchéité. Il importe de noter qu'un tel essai de pressurisation par ventilateur ne permet pas de mesurer explicitement l'infiltration.

Une vaste gamme de types d'immeubles a été soumise à des essais au gaz traceur et à des essais de pressurisation par ventilateur. Des deux méthodes, la seconde est la plus facile à exécuter, en général.

Le taux d'infiltratiuon doit être mesuré de façon précise en fonction de la taille des appareils de chauffage, de ventilation et de climatisation et ensuite en vue de déterminer le rapport coût-efficacité des moyens envisagés pour réduire cette infiltration. Cette tâche s'est révélée ardue, mais de nombreuses méthodes ont été élaborées à cette fin. Des techniques comportant l'étude des changements d'air et des fissures, ainsi que des modèles empiriques et des modèles informatisés détaillés sont décrits dans le présent rapport.

De cet examen se dégagent diverses conclusions, dont voici les principales:

1. Les fuites d'air constituent un aspect important du rendement du bâtiment. Toutefois, très peu de travaux de recherches ont été consacrés aux fuites d'air dans les bâtiments de la catégorie de l'entreposage et des bâtiments industriels à structure légère. Il s'ensuite que l'on ne connaît qu'un nombre limité de données sur celles qui se produisent dans les éléments propres aux bâtiments industriels à structures légère.

2. L'estimation précise des fuites d'air d'un élément de bâtiment ne saurait se faire sans l'établissement de données sur les lieux.

3. Les essais au gaz traceur et les essais de pressurisation par ventilateur constituent les meilleures façons de mesurer l'infiltration d'air et l'étanchéité, d'un bâtiment.

4. Quoique aucune méthode d'estimation d'infiltration n'ait été concçue tout spécialement pour les bâtiments industries à structure légère, il serait possible d'adapter à cette fin l'un des nombreux modèles qui s'appliquent déjà au secteur résidentiel.

Plusieurs recommandations ont été formulées en prévision d'autres recherches sur l'infiltration d'air, entre autres:

1. La création d'un service mobile d'analyse de la consommation d'énergie des bâtiments, installation qui permettrait d'effectuer sur place des essais au gaz traceur et des essais de pressurisation par ventilateur et de mesurer la différence entre les pressions intérieure et extérieure.

2. La préparation d'une base de données sur l'étanchéité et l'infiltration, à partir

d'essais de pressurisation par ventilateur et d'essais au gaz traceur portant sur une gamme témoin de bâtiments d'entreposage et de bâtiments industriels à structure légère.

3. La préparation de données sur les fuites d'air d'éléments de bâtiment, au moyen d'essais de pressurisation effectués sur place.

4. La conception et l'essair en laboratoire de techniques de constructions améliorées.

5. La conception et la validation d'une méthode servant à estimer l'infiltration dans les bâtiments industriels à structure légère.

6. La démonstration, à l'aide d'une structure pleine grandeur construite à cette fin, de nouvelles façons de concevoir des détails structuraux.

1. INTRODUCTION

Recent concern over efficient energy utilization and conservation has led to increased interest in energy-efficient building design. One aspect of building performance which can contribute significantly to building energy requirements is the conditioning of outside air.

The flow of outside air into a building can occur through either intentional or unintentional openings in the building envelope. Intentional openings include fresh air intakes, doors, and openable windows. Unintentional sites include cracks, interstices, holes, or any other inadvertent opening in the building envelope.

This report presents a state-of-practice review of air leakage considerations in buildings, with particular emphasis on buildings in the 'Warehousing and Light Industrial' building category.

For the purposes of this report, the term 'air leakage' will be considered to include all air flow through unintentional holes in the building envelope, whether inward (infiltration) or outward (exfiltration), caused by wind and buoyancy effects, as well as any imbalance between supply and exhaust air. 'Air tightness' will refer to the resistance of the building envelope to air flow, as determined by fan pressurization testing.

The warehousing and light industrial building category is considered to comprise all those buildings which are low-rise, weather-sensitive, and neither people- nor process-dependent (Building Engineering Group (1981)).

The report is organized into eight main sections, the first being this introduction. The second section discusses the significance of air leakage with respect to energy consumption, condensation, and ventilation considerations. The third section describes air leakage sites in the building envelope, and the fourth presents techniques used to reduce air flow through these components. The fifth section reviews the methods used to measure air leakage in existing buildings. The sixth section reviews techniques used to estimate infiltration. The seventh and eighth sections present the conclusions and recommendations.

2.1 Energy Consumption

The uncontrolled flow of outside air into a conditioned space as a result of infiltration can substantially increase the space conditioning load.

The space heating or cooling load can be divided into sensible and latent components. The sensible load represents the energy required to heat (winter) or cool (summer) the outside air to the desired room temperature. If the indoor air is humidified during the heating season, energy is required to evaporate water to replace the water vapour lost through infiltration. This energy is referred to as a latent component. Similarly, if air conditioning is provided during summer operation, latent energy is released when moist indoor air condenses on the evaporator coil. A principal source of this moisture is infiltration, particularly in non-process or people-dependent buildings, such as warehouses and light industrial buildings.

Of these two components, the sensible load dominates light industrial applications for two reasons. A large majority of buildings within this category are neither humidified nor air conditioned. Secondly, for those buildings requiring humidification, latent heating requirements are on the order of 28% of the sensible load for typical winter conditions (Tamura and Shaw (1976)).

A third energy requirement, related to the latent coil load, can be found in refrigerated warehouse applications. Under normal operating conditions, the surface temperature of the evaporator coil is less than 0 C. Therefore, any condensation occurring on the coil will freeze. Various strategies, all requiring energy input in some form, are used to periodically defrost these coils.

Draughts resulting from infiltration can also lead to increased energy consumption. The thermostat may be adjusted upwards to maintain adequate comfort, and airflow through insulation may decrease its effectiveness (Emroth (1978)).

Various estimates have been made of the proportion of the space conditioning load which is attributable to infiltration. Recent literature deals primarily with non-industrial type buildings. Estimates of the percentage of annual heating energy consumed as a result of infiltration are:

- 20-40% for residential buildings (Quirouette (1976), Mattingly et al (1979), Sherman et al (1979), Shaw and Tamura (1980), Eyre and Jennings (1981), Nylund (1980)).
- 29% for schools (Shaw and Jones (1979)).
- 22-46% for high-rise buildings (Tamura and Shaw (1976)).

Limited estimates exist for buildings within the category of interest. Bonnar (1974) reports that infiltration losses in refrigerated warehouses under heavy load conditions may vary between 20-40%. Webber (1979) estimates that coil defrost in refrigerated warehouses requires 0.22 kWh/L of condensate, and that a 6 m long 3 mm crack results in an annual defrost cost of $40.

A consultant is preparing a case study which documents the operating characteristics of actual warehouse buildings. As a part of this study, estimates of heat loss due to infiltration were made by comparing actual energy consumption with estimated conduction heat losses (which can be calculated with a reasonable degree of accuracy). The difference between these two values was assumed to be attributable to infiltration.

Preliminary calculations indicate that infiltration is responsible for 36.7% of the total heat loss in a 7.3 m high, 3718 m2 warehouse, with wall and roof U-values of 0.62 and 0.68 w/m2 K respectively (Steel (1982)).

It should be noted that this value corresponds to an air change rate of 0.33 ac/hr, which is significantly lower than expected. For example, ASHRAE (1981a) recommends the use of 2-3 air changes per hour for commercial buildings. Two factors have been suggested to account for this difference: this relatively new warehouse was particularly well constructed, and the ASHRAE values are primarily for use in sizing HVAC equipment, and are therefore conservative.

In any event, it is readily apparent that infiltration can account for a significant portion of the total space conditioning load.

It should be noted that forced ventilation can also have a significant effect on the heating demand. If, for example, a 3776 L/s (8,000 cfm) exhaust fan were operated in the previously described case study building, and no heat recovery were used for the make-up air, the resulting heating load would be equal to that of 0.5 air changes per hour. Although no specific data exists, Bragg (1982) estimates that ventilation is critical to the operation of roughly 5% of light industrial buildings, and may be required to some degree in up to 50% of the remaining buildings.

2.2 Moisture Within Building Construction

Excessive moisture accumulation within the building envelope can result in a marked deterioration of materials, and subsequent deterioration in the thermal and structural performance of the building shell.

The most common cause of moisture accumulation is the condensation of water vapour on cold surfaces within the envelope (ASHRAE (1981a)). The problem is particularly important in a refrigerated storage facility due to the prevalence of cold surface temperatures. ASHRAE (1978) states that, in refrigerated warehouse applications, "the success or failure of an insulation envelope is due directly and entirely to the ability of the vapour barrier system to prevent water vapour transmission into and through the insulation".

Although vapour will migrate through materials by diffusion (due to a vapour pressure difference), it is recognized that exfiltration is the dominant mechanism for transporting water vapour to the point of condensation. Calculations indicate that, under a specific set of conditions, from 6 to 7 times as much water vapour will be deposited as a result of air leakage as will be deposited due to diffusion (ASHRAE (1981a)).

It is therefore important to minimize air leakage, not only to reduce energy consumption but also to safeguard material performance.

2.3 Ventilation

This report does not address ventilation requirements per se; nevertheless, the contribution of infiltration to ventilation requirements can be substantial. Due to its random nature, infiltration may not be as desirable as forced ventilation. However, infiltration can be the main source of ventilation in envelope-dominated buildings (ASHRAE (1981a)).

An order-of-magnitude calculation indicates that minimum ventilation requirements can be met easily by infiltration. For example, an infiltration rate of 0.5 air changes per hour, in a building with dimensions of 30 m x 61 m, provides sufficient ventilation for a work force of up to 500, under ideal conditions.*

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* Based on ventilation requirement of 5 L/s per person (ASHRAE (1981b)).

Air leakage occurs through a variety of leakage sites, including:

i) Walls/Roofs - leakage cracks in walls and roofs, particularly at intersections of walls, floors and roofs, can contribute significantly to total leakage (ASHRAE (1981a)). Measurements in an apartment building indicate that the floor/wall joints, windows and window sills are the three major leakage sources in outside walls (Shaw (1980)). Other sites include penetrations for electrical and mechanical services.

ii) Windows - leakage occurs around the sash, particularly for operable windows, as well as around the window frame.

iii) HVAC System - the presence of a heating, ventilating and air conditioning (HVAC) system provides potential leakage sites around louvres and through poorly fitting dampers. In addition, conditioned air can escape from the building as combustion air, or through the back draft damper, or by supply air duct leakage into unconditioned spaces.

iv) Exterior Doors - the types of doors used in a industrial building range from swinging doors used for pedestrian traffic, to multi-section overhead doors. The total air leakage is related not only to the size of the leakage openings (which is a function of the fit), but to the frequency of use as well.

It should be noted that air flow through cracks in the structure is usually the dominant source of air leakage. Diffusion accounts for less than 1% of the air flow (ASHRAE (1981a)).

A variety of methods can be used to physically locate leakage sites in a specific building. The building may be artificially pressurized or depressurized (the technique used to create pressure differentials across the building skin is discussed in Section 5.2), and detection devices such as smoke sources, acoustic sensors, manual methods, or infrared thermography (Harrje (1981), Kronvall (1980)) employed.

Various measures can be used to reduce air leakage, at the design stage, during operation, and as a retrofit activity. The following description of possible strategies is by no means exhaustive, but is intended to illustrate the range of available techniques.

Having established that unintentional cracks between building components are a major source of infiltration, the primary focus of any attempt to reduce infiltration would naturally concentrate on reducing these openings. As a first step, all windows and doors should be adjusted to fit tightly, and all joints should be caulked or weather-stripped. Where construction permits, a continuous air/vapour barrier (e.g., polyethylene sheet) applied to the warm side of the insulation is one of the most effective means of reducing air leakage through walls, and around windows and door frames (ASHRAE (1981a)). Several research groups, notably the Saskatchewan Research Council (Eyre and Jennings (1981)) and the Division of Building Research, NRC (Quirouette (1978)) have developed residential construction guidelines and framing details which are aimed at improving the effectiveness of these air/vapour barriers. However, the design recommendations are based on wood frame construction, which is not commonly found in the warehousing and light industrial building category.

Where use of a continuous barrier is not practical, in un-insulated masonry construction for example, several other approaches can be used. Foamed-in-place insulation (e.g., urethane) has a low vapour permeability, effectively seals the majority of leakage cracks, and can be used in low-temperature applications (Lamiman and Nixon (1969)). Prefabricated metal skins may also be used as both vapour and air retarders (Webber (1979)).

In attempting to eliminate leakage openings in the building envelope, attention should be paid to construction details for joints, particularly the wall/roof joint (Webber (1979), ASHRAE (1981a)). Lamiman and Nixon (1969) present a wall/roof detail for masonry construction which uses a butyl rubber gasket to reduce air leakage.

Several measures have been developed to reduce air leakage through exterior doors. Loading docks may by enclosed with a partially conditioned anteroom, or teamway, which permits the closure of exterior doors during loading and unloading. A second benefit of a teamway in a refrigerated warehouse is the opportunity for the air conditioning system of the teamway to remove most of the water vapour entering through the exterior doors. The teamway's evaporator coil generally operates above 0 C, thus avoiding the need for any energy-consuming defrost cycles (Webber (1976)).

Heat and moisture transfer through exterior openings may also be suppressed through the use of an air curtain, which forces air across doorways through a series of nozzles. While air curtains can reduce heat transfer by 60-85% under optimum conditions (Hayes and Stoeker (1969)), their effectiveness is sensitive to wind, and they are felt to have only a limited range of applications in a Canadian climate (Bragg (1982), Kent (1982)).

Other methods used to reduce infiltration include flexible door pads positioned around the perimeter of a loading door which are used to create a seal between truck and door frame, and flexible, clear plastic strip doors, which allow both visibility and access through entrances, while suppressing air movement to a certain degree.

Infiltration through doors can also be reduced by slightly pressurizing the entrance. However, this technique is thought to have limited applicability to industrial buildings for two reasons. Many entrances are not isolated from the building proper. Hence, any pressurization would increase exfiltration through the building envelope, and aggravate any exfiltration-related condensation problems (Latta (1973)). Secondly, the air used to pressurize the space would be conditioned. Tamura and Shaw (1976)) estimate that 3.2 times the normal infiltration rate of air would be required to pressurize a multi-story office building. No equivalent figure was found for light industrial buildings.

Air infiltration through pedestrian doors may also be reduced by installing a vestibule or an exterior wind break, and automatic door closers (Dubin and Long (1978)).

Two primary methods are used to measure the air leakage characteristics of a building: the tracer gas method, and the fan pressurization method. Tracer gas tests are used to measure the actual infiltration of a building. Fan pressurization test results are used to characterize the air tightness of a structure, and have been used to estimate infiltration performance (see Section 6).

The following sections describe these two techniques.

5.1 Tracer Gas Measurements

5.1.1 Procedure

To measure infiltration using the tracer gas technique, an inert and inactive gas is released into the building, where it is allowed to mix uniformly with building air. If this 'tracer' gas is non-reactive, and is not absorbed by building materials, measurement of its concentration over time will provide an accurate accounting of the air exchange (i.e., infiltration) occurring within the building.

Two versions of the tracer gas technique have been developed:the decay method,and the constant concentration method.

To apply the decay method, a quantity of tracer gas is mixed with the air within the building, and its decay in concentration over time is measured. The air change rate can be calculated as follows:

$$I = \frac{1}{t} \ln \left(\frac{Co}{C(t)} \right) \qquad (1)$$

$C(t)$ = concentration of the tracer gas, as a function of time, t

C_o = initial concentration

I = infiltration rate, air changes per hour.

t = measurement time period, 1 hour.

A plot of tracer gas concentration vs time on a semi-log graph results in a straight line if the tracer concentration is uniform and the infiltration rate is constant. The absolute value of the slope of the line is the air change rate.

The constant concentration method requires control of the injection rate of the gas to maintain a constant concentration of tracer gas within the building space. The infiltration rate is equal to the ratio of the tracer gas injection rate and the concentration.

The decay method is the more common of the two techniques, primarily because it requires relatively simpler detection equipment (ASHRAE (1981a)). In addition, the instrumentation does not require absolute calibration, since only concentration ratios are required (Kumar et al (1979)). However, the decay method is more susceptible to measurement errors resulting from inadequate mixing (Harrje et al (1982)). In addition, the measurement intervals could be limited to short time periods in buildings with large air changes by the scale range of the detector (Kumar et al (1979)).

The constant concentration method may be used over long time periods, and is a steady state method which is not affected by factors such as adsorption and absorption. Disadvantages include the requirement for relatively sophisticated measurement/control apparatus, which must be calibrated to measure an absolute concentration (Kumar et al (1979)).

Regardless of the technique used, accurate tracer gas tests require two conditions:
perfect mixing of tracer gas with building air,
and perfect mixing of infiltrating air with building air (Harrje et al (1982)).

This mixing may be achieved through operation of the HVAC air circulation system, or through the use of small circulation fans. Although one circulation fan is usually adequate for residential-sized applications (Harrje et al (1982)), Potter (1979) reports the use of four fans in a residential test. The mixing flow rate is a compromise between a high rate to achieve perfect instantaneous mixing, and a low rate to minimize mixing-induced leakage (Shaw (1980)).

5.1.2 Applications

Most tracer gas testing has been applied to residential applications. However, Harrje et al (1982) state that the method may be applied to the smallest home or the largest building complex. The method can be used in buildings with air circulation-type heating systems, or hydronic or electric systems if circulation fans are used (Blomsterberg and Harrje (1979)). The use of tracer gas testing has also been reported for high rise apartment buildings (Harrje et al (1982)).

5.1.3. Test Apparatus

Increasing interest in infiltration measurement has led to the development of a broad spectrum of tracer gas test apparatus and procedures. Following is a description of two procedures, which can be considered to cover the range of methods, from simple (bottle sampling) to very sophisticated (automatic sampling).

5.1.3.1 Bottle Sampling

Bottle sampling, a recent development reported by Harrje et al (1982), involves injecting a tracer gas into a building and collecting air samples in flexible plastic bottles, or other suitable containers, at specific time intervals. In residential applications, samples from one location should be adequate. In larger buildings, multiple sampling is desirable. For example, a test of a 9-storey apartment building used a total of 75 measurement sites. The contents of the bottles are then analysed in a central laboratory.

The bottle technique has been successfully applied to buildings as large as 140,000 m3. Comparisons between infiltration estimates produced using the technique with estimates from concurrent conventional tracer gas tests indicated differences of less than 6%.

Grot (1979) describes a predecessor of the bottle sampling technique, which uses flexible plastic bags instead of bottles. It is estimated that a relatively unskilled technician can test approximately one house per hour.

5.1.3.2 Automated Sampling

The desire to perform continuous, automatic measurements of infiltration, weather parameters, pressure differentials, and building systems operation on a large building led to the development of a micro-computer based 'intelligent' monitoring system (Grot et al (1980)). The micro is programmed to make decisions concerning the injection of tracer gas from as many as five sources, and the concentration sampling from a 10-port manifold. The tracer gas detection system utilizes a gas chromatograph and an electron capture detection system. The system has been successfully used to study infiltration in a 4-story, 68,000 m3 university building, and a 26-story office building.

5.1.4 Tracer Gas

A variety of compounds can be used as a tracer gas, including sulpher hexafluoride (SF6), nitrous oxide (N20), methane (CH4), carbon dioxide (CO2), and ethane (C2H6) (Harrje et al (1982)). In North America, SF6 is most commonly used (Kronvall

(1980)). It is inert, relatively non-toxic, not normally found in air, relatively inexpensive, and detectable at low concentrations (Kumar et al (1979), Grot et al (1980)). The last factor is particularly significant in the analysis of large buildings. For example, a test using N2O would require 1,000 times as much tracer gas as would a comparable test using SF6 (Grot et al (1980)). A comprehensive study of 3 compounds, SF6, N2O and CH4 (Grimsrud et al (1980)), concluded that although SF6 consistently over-predicted infiltration, the error was small compared to the uncertainty associated with a single tracer gas measurement.

Detection equipment for the various tracer gases uses principles such as gas chromatography, thermal conductivity, flame ionization, and infrared detection, and are of comparable complexity and cost (Harrje et al (1982)). Detection equipment for SF6, comprised of a gas chromatograph and electron capture detection system, costs in the order of $5,000 (Harrje et al (1982)).

Quirouette (1982) describes a relatively inexpensive technique whereby water vapour (produced by a humidifier) is used as the tracer gas in a residential test. This method is not thought to be practical, particularly for industrial application, because of the inaccuracies resulting from secondary sources of water vapour.

5.1.5 Secondary Applications

Tracer gas test results may not be limited simply to infiltration studies. It has been suggested (Bragg (1982)) that tracer gas tests may also be used to investigate air motion within buildings, which would be useful when analysing ventilation requirements.

5.2 Fan Pressurization

As previously noted, air leakage through building components is caused by pressure differentials across the building envelope. Naturally occurring pressure differentials, caused by wind and buoyancy (or stack) effects, are generally not uniform over the entire building shell, and wind induced pressure differentials can fluctuate rapidly (Hill and Kusada (1975)). (Relations used to quantify these natural pressure effects are discussed in Section 6.) To characterize the leakage of a building for a known uniform pressure differential, the fan pressurization test procedure was developed.

5.2.1 Procedure

In a fan pressurization test, a uniform pressure differential is maintained across the entire building envelope using a fan that is temporarily mounted in a exterior opening, usually a door. The air flow drawn through the fan is equal to the air leakage through the building envelope.

The pressure differential across the building envelope can be measured in several locations. A relatively uniform pressure differential can be approached if the effects of wind and buoyancy are minimized. Wind-induced pressures can be reduced by conducting tests during periods of calm winds. Minimizing the stack effect is not as critical, since it is relatively stable, and usually small compared to the fan-induced pressure (Sherman et al (1979)).

Care should also be taken to isolate the effects of dampers. During pressurization tests of schools, Shaw and Jones (1979) found that 15-43% of air leakage was attributable to intake and exhaust openings.

The induced pressure differential generally ranges between 10-75 Pa. By way of comparison, the pressure differential induced by wind and stack action generally ranges from 0 to 10 pa.

The results of fan pressurization appear to be insensitive to time of year, indicating that the leakage area does not change with temperature (Shaw and Jones (1979)).

Tests can be conducted using both negative and positive interior pressures. It appears that most tests are conducted under negative (suction) pressure conditions. Test results indicate that leakage through walls is unaffected by pressure direction, but that windows leak 12% more on average when subjected to positive pressure compared with negative pressure (Shaw (1980)).

5.2.2 Applications

Pressurization tests have been performed on a variety of buildings, including residences (Blomsterberg and Harrje (1979), Beach (1979), Dumont et al (1981)), schools (Shaw and Jones (1979)), multi-story apartment buildings (Shaw (1980)), and multi-story office buildings (Tamura and Shaw (1976)).

5.2.3 Test Apparatus

The test equipment used for residential-sized applications can be quite simple. However, the air volumes necessary to establish sufficient pressure differentials in larger buildings can require a sizeable fan. For example, a test apparatus used for schools (Shaw and Jones (1979)), shopping malls (Shaw (1981a)) and a 295 m3 apartment building (Shaw (1980a)) incorporates a vane-axial fan with a variable pitch blade that is capable of air flows of up to 23 m3/s (50,000 cfm). The fan intake requires several lengths of .9 m (3 ft) diameter duct for use as a flow straightener. Electrical power used to operate the fan was obtained from a stand-by generator, as the schools' circuits did not have sufficient capacity.

Air flow rates were measured using total pressure averaging tubes for high flow rates, and an orifice plate for low flow rates. The total cost of the test rig (excluding the generator) is approximately $10,000 (Shaw (1982)). To reduce equipment costs, a number of smaller fans may be used in place of one large one. A smaller test apparatus,intended for use in residential application, would probably cost on the order of $2,000.

Tests have also been performed in which the buildings' supply air system was used to pressurize the interior (Shaw et al (1973)).

It is generally acknowledged that a fan pressurization test is simpler to administer than a conventional tracer gas test. Dumont et al (1981) estimate that 2 persons could pressure test about 5 neighboring houses per 8-hour day. Shaw (1982) estimates that 4 persons would require 1 day to test a large building.

5.2.4 Component Testing

As previously noted, fan pressurization tests are used to establish the relative tightness of a particular building. They can also be used to determine the leakage performance of individual building components by selectively sealing various components and monitoring the change in air flow Shaw (1980a), (Shaw and Jones (1979), Tamura and Wilson (1963)).

A modified pressurization test has also been used to determine component leakage in a portion of an apartment wall. Shaw (1980a) found that leakage results from each component could be summed to produce an accurate estimate of the performance of the entire unit.

Components may also be leak-tested in lab-scale experiments. In a review of the ASTM Laboratory Air-Leakage Test Method E283, Sasaki (1973) cautions that the primary purpose of a lab-scale test is to check the quality of design and manufacture. For quantitative air leakage data, Sasaki recommends leakage studies on completed buildings.

Unlike tracer gas tests, fan pressurization test results are not a measure of infiltration, since the pressure distribution imposed by the fan does not model the naturally occurring pressure. However, attempts have been made to correlate fan pressurization results with actual infiltration performance. This work is described in Section 6.3

The accurate prediction of infiltration performance is important at the building design stage to size the HVAC system properly. In addition, estimation of the cost-effectiveness of implementing strategies to reduce infiltration, such as those identified in Section 4, requires an accurate estimate of the potential reduction.

To date, no consistently accurate, generalized estimation technique has been developed for infiltration. Although the fundamentals of air flow through leakage cracks are well understood, accurate estimation of the numerous factors which affect infiltration has proven difficult.

In spite of (or perhaps because of) this difficulty, a variety of estimation techniques have been developed, ranging in complexity from simple handbook methods to comprehensive computer models based on hourly weather data. Some of the more common methods are described in the following sections.

6.1 Air Change Method

The air change method (ASHRAE (1981a)) produces crude estimates of hourly air change rates, as a function of exterior fenestration. The reference air change estimates are based on residential measurements, and average weather conditions and construction. Because of its residential base, the air change method is not recommended for use in commercial buildings (e.g., warehouses and light industrial buildings) (Janssen et al (1980)).

6.2 Crack Method

6.2.1 Fundamentals

Air flow through leakage openings in a building envelope can be modelled using classical orifice theory (Cole et al (1980)),

$$Q = K\,(\Delta P)^n \qquad (2)$$

where Q = flow rate of air
K = flow coefficient
ΔP = pressure differential across the orifice
n = flow exponent

The crack method uses equation 2 to estimate air leakage through each leakage component. The total leakage through all components is then multiplied by a factor less than 1, generally 0.5, to account for the fact that a portion of the calculated air flow would be exfiltration (i.e., air leakage outward along leeward walls).

Although equation 2 is relatively straightforward, calculation of each parameter can prove difficult.

6.2.2 Determination of Leakage Characteristics

The terms K and n characterize the leakage performance of a component, or an entire building envelope. K is a measure of the resistance of the opening to air flow. The value of the flow coefficient n ranges from 0.5 to 1 depending on the relative contribution of kinetic and viscous forces to the energy loss incurred by the flow. Various values have been suggested for n, ranging from:

0.5 - for high-rise buildings (Tamura and Shaw (1976))
0.5 - for residences (Cole et al (1970))

0.65 - for schools (Shaw and Jones (1979))
0.65 - for residences (Cole et al (1979))
0.65 - ASHRAE (1981a)

0.75 - for high-rise buildings (Tamura and Shaw (1976)).

It has been suggested that n may increase slightly as ΔP increases (ASHRAE (1981a)); however, a constant value is generally assumed. The most common value appears to be 0.65.

Values for K and n have been determined experimentally for a variety of building components. Leakage performance may also be specified as a leakage rate over a given range of pressure differentials (see ASHRAE (1981a)). In addition, nomographs have been developed which relate air leakage through windows, and swinging and revolving doors, to factors such as pressure differential, wind speed, design type, use, and weather stripping (ASHRAE (1981a), Dubin and Long (1978)).

6.2.3 Calculation of Pressure Differential

As previously noted, the pressure differential across an element of the building enclosure, ΔP, is primarily caused by three factors: stack effect, wind effect, and any net difference between exhaust and make-up air.

The pressure differential caused by stack effect, resulting from buoyancy due to differences in indoor and outdoor air temperature, can be estimated as (ASHRAE (1981a)):

$$\Delta P_s = 0.342 \; P_{atm} \; h \; \left[\frac{1}{T_o} - \frac{1}{T_i}\right] \qquad (3)$$

ΔP_s = ?

where P = stack effect pressure difference Pa,

P_{atm} = atmospheric pressure, kPa

h = height from neutral level, m
T_i = indoor air temperature, K
T_o = outdoor air temperature, K

The neutral pressure level, h, is that point on the building surface where interior and exterior pressures are equal, and is a function of the vertical distribution and resistance of openings to air flow. Its position can be difficult to locate.

Measurements in tall buildings indicated that h ranged from 0.3 - 0.7 of the building height (ASHRAE (1981a)).

The flow of air around buildings due to wind also exerts pressure on the building surface. The magnitude of this pressure is a function of wind speed, direction, surrounding buildings and the interaction between air flow and the structure. Wind pressure on the exterior surface of the building also affects interior air pressure.

The maximum positive pressure increase that can be caused by wind, known as the stagnation pressure, is (ASHRAE (1981a)):

$$P_v = \frac{1}{2} \rho V^2 \qquad (4)$$

where P_v = stagnation pressure, Pa

ρ = density kg/m^3
V = wind velocity, m/s

The actual distribution of wind pressure exerted over the surface of a building can vary greatly, depending on the building shape, wind direction, and surrounding terrain (Tamura and Shaw (1976)). If the wind velocity of the site is known, this pressure distribution can be expressed using wind pressure coefficients, which are equal to the ratio of the actual wind-induced pressure and the stagnation pressure. Values for wind pressure coefficients have been determined through extensive boundary layer wind tunnel testing for a variety of building shapes (Tamura and Shaw (1976), Sander (1974), Shaw and Tamura (1977). Since buildings in the warehousing and light industrial classification are generally rectangular in shape, calculation of pressure coefficients should be relatively straightforward.

Several difficulties are encountered when estimating local wind velocity. Meteorological wind speeds are generally measured at sites which are distant from the location of interest. Shaw (1981) reports that wind speeds measured at a site within 32 km of the weather station were 85% of the meteorological wind speed. Dalgliesh and Boyd (1962) have attempted to develop conversion factors for transposing meteorological wind speed to site wind speed.

Local terrain and adjacent buildings or vegetation can effect the wind-induced air flow around buildings. Baily and Vincent (1942) estimate that a building will affect the air flow patterns within 8 building widths downwind. At present, physical modelling is the only method available to accurately predict shielding effects. Due to the large variety of possible configurations, however, a systematic study of shielding is not feasible (Shaw (1979)). An empirical shielding model has been developed (Warren (1979)) which determines wind speed profiles for 4 different terrain classifications.

Localized disturbances can cause significant turbulent wind components. Attempts to analyse the effects of such transients have concluded that the resulting infiltration process is extremely complex (Hill and Kusuda (1975)).

The determination of interior pressure effects is more difficult (Guy and Stathopolous (1982)), and is a function of the ratio of windward and leeward opening areas. Stathopolous et al (1979) have experimentally determined internal pressure coefficients for various building types. Some analytical work has also been carried out for the prediction of internal pressures based on external pressure distribution (Stathopolous and Homma (1980)).

The pressure effect caused by the operation of the HVAC system in an existing building is fairly easy to determine; it is simply the difference between the building enclosure pressure differentials with the system operating and turned off. This measurement technique was used by Shaw and Jones (1979) during an infiltration study of schools.

During a review of infiltration literature, no analytic technique for use in calculating this pressure differential was found.

The pressure components from stack, wind, and HVAC system effects can simply be added to calculate the total pressure differential:

$$\Delta P \text{ total} = \Delta P \text{ stack} + \Delta P \text{ wind} + \Delta P \text{ HVAC} \qquad (5)$$

Although stack action tends to dominate wind effects for multi-story buildings in cold conditions (Tamura and Shaw (1976)), calculations and measurements indicate that both stack and wind effect can be equally significant for low level buildings (Shaw and Jones (1979), ASHRAE (1981a)), of which warehouses and light industrial buildings could be considered a subset.

6.2.4 Accuracy

Although the crack method is based on sound principles, its accuracy is restricted for two reasons. Limited data exist on the air leakage performance of building components, particularly for components prevalent in commercial construction (Tamura and Shaw (1976), Shaw et al (1973)). The majority of data available relate to residential window and wood frame wall designs. ASHRAE (1981a) presents very limited leakage data for curtain wall construction, and one type of masonry construction. A review of additional sources yielded only performance data for two masonry wall designs (Funkhouser (1979)). In particular, little or no information was found regarding the performance of the reduction strategies discussed in Section 4.

The second, and perhaps most significant (ASHRAE (1981a)), limitation of the crack method relates to the difficulty in accurately estimating the correct pressure differential.

6.3 Empirical Methods

Considerable effort has been directed towards developing empirical infiltration models, because of the inability of the crack method to accurately predict infiltration, as well as the need to estimate hourly infiltration rates in building energy computer programs.

Empirical models generally take the form of functional relationships which relate infiltration as a function of wind velocity and temperature difference. The coefficients of the various weather parameters may account for factors such as building geometry, orientation and construction, as well as terrain effects. Various assumptions are usually necessary to maintain reasonable simplicity.

6.3.1 Regression Models

The simplest group of empirical methods is classified as regression models. The weighting coefficients of the weather parameters are determined using regression analysis on measured infiltration results. The most common form of the relation is (ASHRAE (1981a)):

$$Q_{inf} = K_1 + K_2 \Delta T + K_3 V \qquad (6)$$

where Q_{inf} = infiltration rate

$K_1, K_2, K_3,$ = regression coefficients

Several other relations with various combination of temperature and velocity terms have also been proposed (Sherman et al (1979), Achenbach and Coblentz (1963), ASHRAE (1981a)).

6.3.2 Quasi-Empirical Models

Regression models cannot be considered to be predictive models, since prior knowledge of infiltration of at least a similar structure is required. Recent research efforts have produced more sophisticated models, which have been termed 'quasi-empirical' models, since to some extent their development has a theoretical basis.

Although the algorithms developed for the various models can be quite diverse, the steps used in their development are usually similar. Pressure components due to wind and stack effect are estimated. The calculation of stack effect is straightforward, and is usually estimated using equation 3. Wind-induced pressure difference coefficients may be estimated based on building-specific, or generalized wind tunnel test results, or on actual measured field data. Factors such as terrain effects, building shape and orientation, and wind direction, may or may not be accounted for. The pressures are then combined to produce an estimate of the total effective pressure differential across each building surface. Calculation of the resulting infiltration is based on an equation similar to equation 2:

$$Q_{inf} = \sum_{i=1}^{n} A_i \quad K \quad (\Delta P_{ei})^n \qquad (9)$$

where A = total surface area
K = leakage coefficient per unit of surface area
ΔP_e = effective pressure difference and
$_i$ = denotes surface i

Since the pressure differential at a particular location is related to its distance from the neutral pressure level (NPL), and since the location of the NPL is governed by the fact that infiltration must equal exfiltration, a simultaneous solution may be required.

The value of K and n is generally determined using fan pressurization test results. The distribution of the leakage sites is generally considered to be uniform over the vertical surface of the building.

Residential models have been developed by Tamura (1979) and Reeves et al (1979). A limited comparison of predicted and measured infiltration results indicated reasonable agreement for each model.

Shaw has developed procedures to calculate infiltration in schools (Shaw 1980b) and tall buildings (Shaw and Tamura (1977)). The tall building procedure is further modified to account for shielding effects of surrounding buildings of uniform height (Shaw (1979)).

Grimsrud et al (1982) have developed a particularly rigorous model to predict infiltration in a residential structure. Infiltration is estimated as a function of the leakage area of the building and weighted temperature difference and wind velocity terms. The building leakage characteristic may be determined using fan pressurization testing. The wind velocity weighting factor is a function of terrain, localized shielding, distribution of leakage sites, and building height. The temperature difference weighting factor is a function of building height, height of the neutral layer under no wind conditions, and distribution of the leakage sites. While the model is suitably rigorous, the resulting algorithm is relatively straightforward. Several parameters, notably crack distribution and the height of the Neutral Pressure Plane under no wind conditions, may be difficult to establish. However, it was found that the model was relatively insensitive to varying the estimates of crack distribution.

Comparison of long-term model predictions with measurements for 3 test houses indicated an agreement within 20% . Comparisons of short-term results were not as favourable. Grimsrud et al (1982) feel that a significant element of uncertainty in the model (as well as any other model that uses estimated wind pressures) is the effects of localized wind shielding.

However, it may be relatively straightforward to account for shielding effects in light industrial buildings due to the general similarity in surroundings (e.g., low rise buildings, no trees, fairly open terrain). In addition, as previously mentioned, the simple rectangular geometry dominant in industrial buildings would simplify the accurate calculation of wind pressure coefficients.

6.3.3 Direct Fan-Pressurization Correlation

In the previous quasi-empirical models, fan pressurization test results represented only a portion of the total information required to estimate infiltration. In the past, efforts to estimate infiltration directly from fan pressurization rates have been unsuccessful. Recently, however, several researchers have achieved a certain degree of success with direct correlations.

Kronwell (1978) found that simply plotting fan pressurization test results for a test pressure of 50 Pa (expressed as air leakage per area of building envelope, m3/m2.h) against infiltration performance for a number of Swedish residences yielded a fairly distinct trend. It should be noted, however, that Sweden has adopted residential air leakage performance standards, which would tend to result in housing stock with similar infiltration characteristics. The fact that no similar standard currently exists for Canadian warehouse and light industrial buildings, combined with the diversity of design and construction techniques, strongly suggests that this direct correlation technique would not prove suitably accurate enough for this classification of buildings.

Shaw (1981b) has developed an infiltration/fan pressurization correlation for houses in a suburban area. Using tracer gas and fan pressurization test results from two houses of similar design but different construction, equations were developed for three weather regimes: temperature dominated, wind dominated, and mixed. Infiltration data obtained from 25 Canadian and Swedish homes were used to evaluate the proposed correlation. Most of the measured infiltration rates were within 25% of the predicted rates.

For simplicity, factors such as furnace operation, height of neutral pressure level, house shape, and distribution of leakage openings were neglected in the analysis. This simplicity, combined with the fact that infiltration is estimated directly from fan pressurization results, result in a modelling tool which could be very effective in energy analysis, particularly in light of the ever-expanding fan-pressurization data base. However, the inherent simplicity may also restrict the applicability of the method to other buildings. In the absence of any relevant experimental results, it is difficult to speculate whether the approach could be used to accurately analyse buildings within the warehousing and light industrial building category.

6.4 Detailed Computer Models

The category Detailed Computer Models is defined to include those comprehensive infiltration models which account for the location and interaction of all leakage sites, whose complexity requires the use of computer modelling. It excludes those empirical models which have simply been programmed for computer application.

Two detailed models have been recently developed by the National Research Council. Sander (1974) has developed a computer model which calculates air flows and pressure differentials resulting from wind and stack effects and HVAC system operation. It was developed primarily for modelling multi-story buildings, but it could be used for virtually any building provided air leakage and wind pressure coefficients for each surface are known. The model is based on the iterative solution of various internal and exterior mass balance equations.

Konrad et al (1978a) has developed a very detailed residential model, which is used in a residential energy analysis program called ENCORE (Konrad et al (1978b)). Openings in each leakage component are modelled as a series of holes at the component height. The number of holes and their flow resistance are automatically calculated based on a 'tightness factor' which is specified by the user. Wind-induced pressures are calculated based on building shape and the surrounding terrain.

A detailed model of the operation of an oil fired furnace is also incorporated. Hourly infiltration rates are calculated using iterative solutions to the mass balance equation.

A detailed computer model to predict infiltration specifically for light industrial buildings is not available. However, a detailed model, such as either of the two previously described, could be adapted for application to light industrial buildings provided flow coefficients and exponents were known. In fact, light industrial buildings may prove to be relatively straightforward to model for two reasons: their interiors are usually open, with very few internal flow restrictions, and as mentioned previously, their simple shapes and usual location may simplify the accurate estimation of shape factors and terrain effects.

It is anticipated that the complexity of any suitably rigorous computer program, with the attendant lengthy input requirements, would preclude its use as a general predictive tool. However, such a program could be useful as a research tool to simulate new design approaches, create a data base, or aid in the development of an empirical model.

7. CONCLUSIONS

The preceding sections of this report present a state-of-practice review of air leakage considerations in buildings, with particular emphasis on buildings in the 'warehousing and light industrial' building category.

Based upon this review, the following conclusions may be drawn:

7.1 Importance

Infiltration can contribute significantly to the space conditioning load. It can also be used to satisfy ventilation requirements, particularly in warehousing and light industrial buildings which do not require selective or large-scale exhaust.

Exfiltration is also a primary cause of moisture accumulation within the building envelope.

7.2 Air Leakage Sites

The dominant sites for air leakage are unintentional cracks in the building envelope, and doorways. Reduction of air leakage therefore requires the reduction or elimination of these leakage openings, and the reduction of the pressure differential across them.

7.3 Measurement Techniques

The measurement of both infiltration and air tightness is important. Infiltration measurements provide an absolute estimate of the building's infiltration performance. They are also essential to the development of predictive models. Air tightness measurements can be used to estimate infiltration performance, through various correlations, to establish the leakage characteristics of a particular component, or to estimate the effectiveness of an air leakage reduction technique.

Tracer gas testing is the best method available for measuring infiltration. Test procedures and equipment have been developed to the point where consistent and accurate results may be obtained for a large variety of building types. Although tests of buildings in the warehousing light industrial category have not been reported, buildings in this category are likely to be particularly well suited to tracer gas testing (few interior partitions, simple HVAC systems).

Of the tracer gas tests available, bottle sampling may be the most suitable. It is relatively simple, does not require an elaborate set up, can use a centrally located detection system for consistent and inexpensive analysis, and could easily be incorporated as a test performed by a mobile energy analysis laboratory.

An automated test procedure is probably not warranted, due to the nature and use of light industrial buildings.

Fan pressurization tests represent the best method to determine air tightness of buildings or of building components. The test procedure is relatively straightforward. However, the equipment required for large-building applications can be expensive.

The use of HVAC systems to induce pressurization is limited to those buildings whose exhaust or make-up air fans are large enough to create a measurable pressure differential across the building enclosure. The method would therefore be limited to a subset of the buildings which required forced ventilation.

Pressurization testing of components in a laboratory may be valuable during the development stage of new construction techniques. However, accurate estimation of installed leakage performance requires site measurements on actual buildings.

7.4. Estimation Techniques

One of the most common estimation techniques, the air change method, is not suitable for use in predicting infiltration in warehousing and light industrial buildings. The accuracy of the crack method is also restricted because of difficulties in estimating pressure differentials, and the lack of data concerning the leakage characteristics of industrial building components.

The most suitable model to estimate infiltration may be an empirical model. A variety of models have been developed. However, no model has been developed for, or even applied to, a building that would fall within the warehousing and light industrial classification. One model, developed by Grimsrud et al (1982), may be particularly suited for application to a variety of building types, since it appears that the development of its algorithm was generally not limited to residential design characteristics.

Shaw (1981b) has developed a very simple direct-correlation method for residences. Further work is required to evaluate its applicability to warehousing and light industrial buildings.

The development of a detailed computer model for use in warehousing and light industrial buildings could be based on an adaptation from one of several existing programs.

7.5 Future Work

Significant research effort has been directed towards understanding, estimating, and reducing air leakage. However, virtually none of this work has addressed building types within the warehousing and light industrial building category. Although it is recognized that much of the work can, to some degree, be applied to buildings in this category, several areas require building-specific efforts.

The most important area requiring further work concerns component leakage. Air leakage data is vital to estimating infiltration and determining the cost-effectiveness of alternative designs. Virtually no air leakage data are available for many components or building constructions found in warehousing and light industrial buildings.

8. RECOMMENDATIONS FOR FUTURE WORK

This state-of-practice review was undertaken as part of a large, multi-year research project. One of the objectives of this project is the implementation of an R, D and D program for the energy-efficient design, operation and retrofit of buildings in the warehousing and light industrial building category (Building Engineering Group (1981)).

Based on the above objectives, and this state-of-practice review, the following tasks are recommended for adoption in the overall research plan:

1. Development of a mobile energy analysis facility capable of conducting on-site infiltration and fan pressurization tests, as well as pressure differential measurements across the building envelope. The facility should also be capable of monitoring and recording local weather parameters and building operation. This mobile facility could be used to generate an extensive air leakage/infiltration data base for a cross-section of typical industrial building types. The data would be necessary in accurately establishing infiltration-related space heating loads, the development and validation of an infiltration estimation model, and identification of specific designs or operational procedures which are particularly important in minimizing and controlling air leakage.

2. Determination of air leakage characteristics of components prevalent in industrial building constriction, using on-site component pressurization tests. The tests should include (but not be limited to):

- walls	- masonry
	- metal siding
- windows	- fixed
	- FRP glazing
- doors	- overhead
	- pedestrian doors, with and without vestibule

- teamways
- flexible loading seals
- flexible strip doors

3. Development and laboratory-scale testing of improved component designs and building systems. The results of tasks 1 and 2 will be used to assess which components require improvement.

4. Development of a method specifically designed to estimate infiltration in light industrial-type buildings. Potential models to consider include direct correlation, linear regression, and quasi-empirical (e.g., Grimsrud et al (1982)). Results from task 1 can be used to develop and validate the model.

5. Demonstration of the new design techniques in an actual building, or buildings.

It should be recognized that the contributions of these tasks are not limited to infiltration considerations alone. For example, an infiltration estimation model is vital to the development of an overall building energy analysis computer program. Infiltration-related measurements are only one aspect of building operation and energy consumption which could be measured by a mobile test unit. A full-scale demonstration building could also be used to demonstrate other energy-related building technology (insulation, HVAC system design, operational controls).

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