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OPTIMIZING RESIDENTIAL FORCED-AIR HVAC SYSTEMS

Optimizing Residential Forced-Air HVAC Systems

Final Report

Prepared for:

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Abstract

This study examines technical issues of residential forced-air space conditioning systems incorporating heating, ventilation and cooling in the context of increasingly energy efficient new housing. Current technologies and practices are reviewed and analyzed with a view to improvements. Potential existing and emerging technologies and strategies are examined. A comparison of conventional and improved design strategies are presented for a house with a 5 kW heating load. A performance model frame work is presented to enable comparative assessment of installed systems in terms of comfort, indoor air quality, energy environmental impact and life cycle cost.

The report makes numerous recommendations to improve delivery of functions and affordability, such as use of shorter ductwork, duct sealing, flexibility of register location, and variable-flow, high-efficiency fans.

The study also proposes changes to resource and training documents and regulations and identifies future research which would be required to accelerate the move to more optimized forced-air systems.

Residential forced-air heating, ventilation, cooling.
Optimized, improved systems, technology and practice.

Acknowledgments

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Executive Summary

With the steady improvements in house thermal envelopes and mechanical ventilation becoming increasingly mandatory in Canada, the role and performance expectations of forced air systems have changed without a corresponding evolution of designs, technologies and installation practices. Canada Mortgage and Housing Corporation (CMHC) retained Allen Associates to study the need for change in forced air distribution systems and practices and to recommend changes in industry direction as appropriate.

The study reviews the traditional understanding and perceived benefits of forced air systems including relatively low first cost and ease of providing space cooling, air cleaning and more recently ventilation supply distribution. While current systems generally distribute the variety of functions adequately, questions of efficacy exist in regards to:

- energy efficiency of air handling,
- appropriateness of current design guidelines,
- integration of functions with different technical requirements
- conformance of field installation with design
- improvements to building envelope resulting in opportunities to optimize design and installation practices

A previous CMHC Study "Efficient and Effective Air Handling Devices" examined the energy efficiency of furnace fan technologies in some detail. This study focuses on the distribution issues of forced-air systems.

The current status is described in terms of prevalence, technology descriptions, design and installation practices, impact of current construction and industry profile.

A host of forced-air system issues are examined and evaluated as to appropriateness of functions served. In-house technical information and industry awareness was augmented by a literature search. Space conditioning issues include supply outlet locations, ventilation effectiveness, cooling, dehumidification, air cleaning, humidification and zoning. The distribution system section analyses duct design, fittings, layout and installation, distribution effectiveness, air leakage and conduction losses, pressure drop, duct contamination, noise transfer, pressurization of interior spaces and controls. Air handler issues discussed are the impact of oversizing, cooling coils and blower technology on required air flow and energy use. A series of improvements were identified that enhance performance, reduce cost or both.

A review of more innovative technologies, existing and emerging, as well as improved practices was undertaken. Topics include duct sealing techniques, diffuser, fan motor and zoning technology, and non-metal ductwork. To learn from innovative installations, the distribution systems of the Advanced Houses and other low-energy house systems are described.

To enable an assessment of improved strategies a performance model framework for forced air systems was developed. The model consists of four main indicators: comfort, indoor air quality, energy use impact and life-cycle cost. In total, twenty-one parameters are evaluated, either by calculation or by relative rating.

To demonstrate potential improvements a conventional forced air system and three improved options were detailed for a 200 m^2 house with a good thermal envelope as may be typical by 2005. The improved options use lower air flow rates, high efficiency fans and shorter ductwork enabling the heat recovery ventilator to act as the air handler for all HVAC functions.

The example systems were costed and the improved options resulted in 40% to 50% ($1400 to $1900) lower first costs for the distribution system.

By comparing the total mechanical systems, including space and water heater(s), HRV and air handlers, the installed costs were $2250 to $3100 lower. These system improvements resulted in energy costs for Ottawa which were 45% lower, a saving of $300 per year. Estimated 15-year life-cycle costs for the total mechanical systems, including capital, operating and maintenance costs, were reduced by 35% or $7500.

The example systems were evaluated by the above performance model and for individual parameters the improved systems were rated as either comparable or better than the conventional system.

Reasons for not adopting more optimum strategies include regulatory barriers, industry entrenchment and lack of current training and resource documents. Further, the use of new strategies, as well as traditional ones, raises issues of performance of convective and forced air transport which require further research.

To accelerate implementation of more optimum systems, the study recommends near-term, mid-term and longer-term system upgrades and changes in practices, research to answer technical questions, code changes to allow improved systems and practices, and training and information activities.

The main improvements to conventional forced air systems proposed are:

- air flow rates approaching ventilation rates to serve various HVAC functions
- shorter supply and return ductwork
- flexibility of supply and return register locations
- sealing of all ductwork and plenums
- high efficiency air handling

By increasing flexibility of design and installation methods, by motivating suppliers to introduce new products and by educating designers, installers and consumers, significantly more affordable forced-air systems will enter the marketplace.

Résumé

Dans la foulée des améliorations constantes apportées à l'enveloppe thermique des bâtiments et compte tenu du fait que les installations de ventilation sont de plus en plus exigées au Canada, le rôle des installations à air pulsé et les attentes en matière de performance que l'on a à leur endroit ont changé sans qu'il n'y ait d'évolution correspondante au chapitre de la conception, de la technologie et des méthodes de pose. C'est dans ce contexte que la Société canadienne d'hypothèques et de logement (SCHL) a demandé à la firme Allen Associates d'étudier les changements qui s'imposent pour les installations de distribution à air pulsé et les modes d'utilisation et, s'il y a lieu, de suggérer de nouvelles avenues à l'industrie.

L'étude passe en revue l'image traditionnelle que projettent les installations à air pulsé et les avantages qu'on leur attribue, notamment un prix de revient de base relativement faible et la facilité avec laquelle elles permettent de climatiser les locaux, de purifier l'air et, plus récemment, d'assurer la ventilation de l'espace. Quoique les installations actuelles s'acquittent généralement bien de leurs fonctions, certains aspects de leur efficacité soulèvent des interrogations :

- l'efficacité énergétique de la circulation de l'air;
- la pertinence des directives conceptuelles courantes;
- l'intégration de fonctions comportant des exigences techniques différentes;
- la conformité des installations en service par rapport à la conception;
- les améliorations de l'enveloppe du bâtiment qui fournissent des occasions d'optimaliser la conception et la pose

Une étude antérieure commandée par la SCHL et intitulée *Efficient and Effective Residential Air Handling Devices* avait déjà examiné dans le détail l'efficacité énergétique des ventilateurs de générateur de chaleur. C'est pourquoi la présente étude porte plutôt sur l'aspect «distribution» des installations à air pulsé.

La situation actuelle est décrite sur le plan de la prédominance, des types de technologie, des habitudes de conception et de pose, de l'impact des méthodes de construction actuelles et du profil de l'industrie.

Un éventail de questions relatives aux installations à air pulsé sont examinées et évaluées quant à leur pertinence. Les auteurs ont amélioré les données techniques et les connaissances sur l'industrie qu'ils possédaient grâce à une recherche documentaire. Pour le conditionnement des locaux, ils ont examiné l'emplacement des grilles de diffusion, l'efficacité de la ventilation, la climatisation, la déshumidification, la purification de l'air, l'humidification et le zonage. La section portant sur les éléments de distribution analyse la configuration des conduits, les raccords, la disposition, la pose, l'efficacité de la distribution, les fuites d'air et les pertes par conduction, les baisses de

pression, la contamination des conduits, la transmission du bruit, la pressurisation des espaces intérieurs et les commandes. Les appareils de traitement de l'air sont abordés sous l'angle du surdimensionnement, des serpentins de refroidissement et de la technologie des ventilateurs dans la mesure où ces facteurs influent sur le mouvement d'air requis et l'utilisation de l'énergie. Une série d'améliorations sont suggérées dans le but d'améliorer la performance, de réduire les coûts ou les deux.

On a aussi examiné des technologies innovantes, nouvelles comme existantes, ainsi que les méthodes améliorées. Les sujets abordés dans cette section incluent les techniques d'étanchéification des conduits, les diffuseurs, le moteur des ventilateurs, le zonage et les conduits non métalliques. Pour apprendre des installations innovantes, on a décrit les systèmes de distribution des maisons performantes et d'autres types de maison à faible consommation d'énergie.

Pour évaluer les stratégies d'amélioration, on a mis au point un modèle de performance pour installation à air pulsé. Ce modèle comporte quatre indicateurs principaux : confort, qualité de l'air intérieur, impact sur la consommation d'énergie et coût global. En tout, 21 paramètres sont évalués, soit au moyen d'un calcul, soit par l'attribution d'une cote relative.

Pour démontrer les améliorations potentielles, une installation à air pulsé traditionnelle et trois installations bonifiées ont été conçues dans les moindres détails pour une maison de 200 m² dotée d'une bonne enveloppe thermique comme celle qu'auront probablement les maisons neuves en 2005. Les installations bonifiées requièrent un mouvement d'air plus faible, font appel à des ventilateurs à haute efficacité et sont pourvues d'un réseau de conduits plus courts qui permettent d'utiliser le ventilateur-récupérateur de chaleur pour faire circuler l'air et ainsi se charger de toutes les fonctions CVC.

On a déterminé le coût des installations mises à l'essai et constaté que celles qui étaient bonifiées permettaient d'abaisser le prix de revient de base du système de distribution de 40 à 50 % (de 1 400 $ à 1 900 $).

Si l'on compare les installations mécaniques complètes, soit le générateur de chaleur, le(s) chauffe-eau, le VRC et les appareils de traitement de l'air, le prix de revient de base à la pose est de 2 250 $ à 3 100 $ inférieur. Ces améliorations apportées aux installations ont entraîné des économies d'énergie annuelles pour Ottawa de 45 %, soit 300 $ par année. Le coût global estimé, étalé sur 15 ans, des installations mécaniques complètes, incluant le coût en capital, le coût d'exploitation et le coût d'entretien, a pu être réduit de 35 % ou 7 500 $.

Le coût des installations témoins a été estimé par rapport au modèle de performance décrit ci-dessus et, dans le cas des paramètres individuels, les installations améliorées ont reçu une cote les classant aussi efficaces, voire plus efficaces, que les installations traditionnelles.

Les facteurs qui nuisent à l'adoption de stratégies plus efficaces sont les obstacles d'ordre réglementaire, l'immobilisme de l'industrie et l'absence de matériel de formation et de documentation à jour. De plus, l'emploi des nouvelles stratégies, mais aussi des anciennes, soulève le problème de la performance du transport de l'air par convection ou par soufflage, une question qui nécessite de plus amples recherches.

Pour accélérer l'adoption d'installations plus efficaces, l'étude recommande, à court, à moyen et à long terme, des améliorations et des changements aux méthodes relatives à l'utilisation des installations, des recherches destinées à répondre à des questions techniques, des changements aux codes devant permettre la venue d'installations et de méthodes nouvelles et des activités de formation et d'information.

Les principales améliorations que l'on propose d'apporter aux installations traditionnelles à air pulsé sont les suivantes :

- des débits d'air s'apparentant aux taux de ventilation afin d'accomplir les différentes fonctions des systèmes CVC;
- des réseaux de conduits de distribution et de reprise plus courts;
- plus de souplesse pour l'emplacement des registres de distribution et de reprise;
- l'étanchéification de tous les conduits et plénums;
- un débit d'air très efficace.

En assouplissant la conception et les méthodes de pose, en incitant les fournisseurs à mettre au point de nouveaux produits et en formant les concepteurs, les installateurs et les consommateurs, on pourra voir arriver sur le marché des installations à air pulsé beaucoup plus abordables.

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1.0 Background

In Canada, forced-air ducted systems exist in almost half of the existing housing stock and are the mechanical distribution system of choice in 48% of houses constructed since 1983.[1] Clearly this technology has a well developed industry of mechanical suppliers and trades.

Forced-air ducted systems in residential buildings serve to distribute heating, cooling, and ventilation air, and to provide a mechanism for humidifying, dehumidifying, or filtering air. While contemporary forced-air systems typically serve these functions adequately, questions of system efficacy in terms of the following exist:

- energy efficiency of air handling,
- appropriateness of current design guidelines,
- integration of functions with different technical requirements
- adjustability of functions delivered to various spaces in the house
- conformance of field installation with design

Probably the most important factors indicating requirements of industry change are significant changes in residential construction practice and recent innovations in forced-air systems. These relatively rapid changes may obviate the original need for conventional forced-air ducted systems - to provide voluminous movement of air to compensate for a leaky and poorly insulated envelope.

The conventional forced-air system should be re-examined in the context of the airtight, mechanically ventilated, highly insulated homes which are becoming the norm in Canada. In this context, it is possible that ventilation could be separated from the services of heating and cooling distribution, humidification or dehumidification, and air filtration as these services may be delivered more effectively and efficiently through other means than air recirculation. Alternatively, supply air requirements may eventually allow heating and cooling to be delivered via ventilation airflow rates. Traditional locations of supply registers may not be maintained, reducing the extent of ductwork.

CMHC commissioned this study to:

- identify where design strategies and construction practices in conventional residential forced-air systems could be improved;
- identify new and emerging technologies and practices that will address the problem areas identified in conventional systems;
- propose more appropriate design and installation strategies and practices for residential forced-air systems;
- present an optimized design and comparative costs;
- identify the barriers and opportunities that exist for the implementation of optimized forced-air systems.

This report describes the historical context of forced-air systems, the current status of the technology, the problems with conventional forced-air systems, the new and emerging technologies and practices that can address these problems, and discusses the role of current Canadian building codes, industry organizations, manufacturers and trades in addressing or exacerbating these problems.

A previous CMHC Study described in detail the technical issues surrounding small residential blowers including furnace fans.[2] While this report may extend this work as required, it is primarily focused on the distribution issues of forced air ductwork systems.

The fundamental work on the design principles and technology development occurred in the 1940's and 1950's, mainly south of the border. As recent Canadian technical reports are sparse in some areas, American, European and Japanese studies have been cited in this report. This study begins to fill the gap and will no doubt be followed by further Canadian reports and field trials to help advance the industry.

2.0 The Current Status

2.1 Historical Context

Forced-air systems developed from the hand-fired stove, through the pipeless furnace and the gravity warm air furnace. Forced-air central heating did not prevail in Canadian houses until the 1950s. Before then, gravity furnaces and hydronic systems were the norm.

Before the advent of forced-air heating, the advantages of warm air gravity systems over hydronic systems were considered to include: lower initial cost, quicker response time, improved air circulation in the home, less space required for diffusers than radiators, the ability to distribute humidified air via ductwork, and no potential for frozen pipes or leaks.[3]

In the 1920s, forced-air systems were introduced. The advantages of forced-air furnaces over gravity furnaces included:

- Flexibility in furnace location and house design
- Increase in basement head room
- Air cleaning ability
- Smaller floor registers
- Increased efficiency

A more detailed discussion of the historical context is given in Appendix A1.

The low capital cost and flexibility to supply a number of functions has continually increased the popularity of forced-air systems. In recent years, the forced-air system has also become a simple and inexpensive mechanism for delivering ventilation air which is now required by code in Ontario and British Columbia and by the National Building Code.

2.2 Present Situation

The central hot air furnace is the most common type (59%) of principal heating system in Canadian houses[+].[1] Other principal heating systems include electric baseboards (18%), hydronic (5%), wood stoves (11%), heat pumps and other (7%). Of the forced-air systems, 72% use natural gas as the principal energy source. Oil and electric forced-air represent 16% and 5% respectively.

[+]the definition of a house from Reference 1 includes detached houses, attached houses but not mobile homes or low-rise or high-rise apartments.

In new construction (1983 to 1994), forced-air furnaces represent 48% of the principal heating systems. The balance of principal heating systems in new construction are electric baseboards (30%), wood stoves (9%), hydronic heating (3%), and heat pumps and other (11%). Figure 2.1 presents a regional breakdown of primary heating systems as estimated by building departments in 1989.[4]

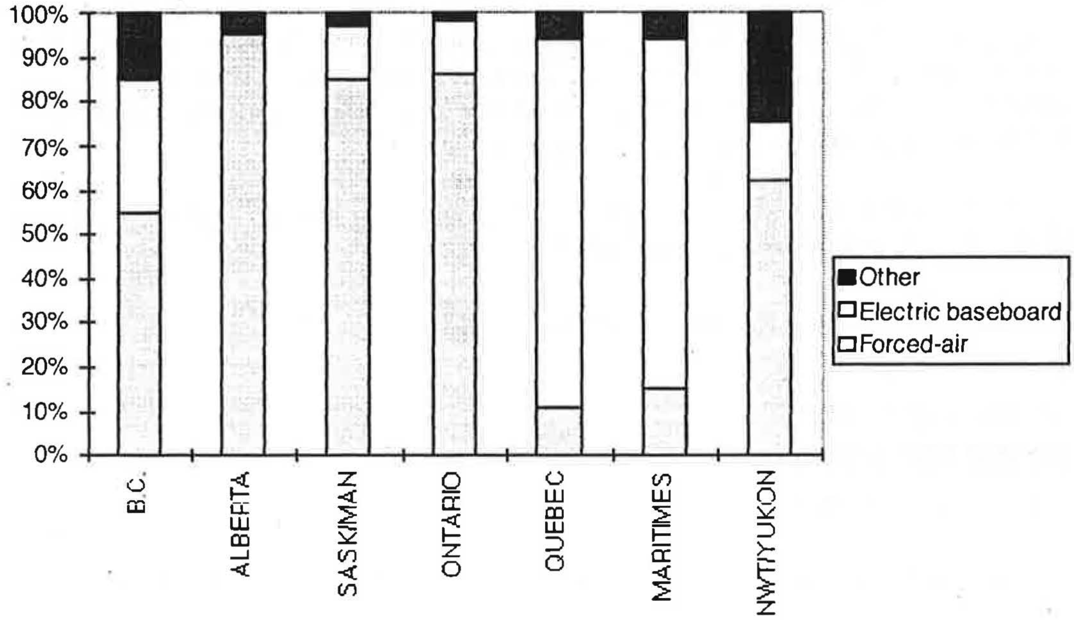

Figure 2.1 Primary Heating Systems by Region

The average costs of principal residential HVAC systems for Canadian houses in 1989 was as per Table 2.1.[4]

Although the hydronics industry promotes their systems as providing superior comfort and quieter operation compared to forced-air systems, their higher capital cost has acted as the main deterrent to more widespread use.

Recently gaining in popularity are integrated water storage heaters providing space heating (via a fan-coil) and domestic water heating from a single heating device. The advantages include reduced capital costs through integration, better match of size of equipment to low energy housing, and improved efficiency of domestic water heating. The required floor area for equipment is reduced and for combustion equipment only one flue vent needs to be installed.

	Heating	Heating & central vent.	Heating w/ HRV	HVAC w/ HRV
Forced-air				
gas/oil	$6,250	$6,750	$8,650	$10,150
electric	$5,275	$5,775	$7,675	$9,175
Hydronic	$9,000	$10,250	$12,200	$14,700
Electric baseboard	$2,375	$3,625	$5,600	$8,100
Heat pump*	$7,300	$7,800	$9,700	$9,700

* heat pumps listed are air-to-air, reversible type (heating & cooling) with electric backup.

Table 2.1 Costs of Principal Residential HVAC Systems

Electric baseboards, although present in only 18% of existing Canadian housing as the principal heating source, represent 30% of new housing systems.[1] Electric baseboards were installed extensively in new construction in the eighties due mainly to their low capital cost. Their main drawback from the consumer's perspective is the high operating cost. With improvements in the tightness of the thermal envelope came the requirement for fully ducted mechanical ventilation. The result is an increased capital cost for the total system close to that of the forced-air system. The improved envelope also reduces, if not eliminates, any zoning benefits of electric baseboards over central systems. Also, to provide cooling by centralized air conditioning, ductwork must be provided to accommodate airflows higher than ventilation rates. In this case, a forced-air furnace with electric heating coil would be selected instead of baseboards.

As indicated by the above statistics, recirculated forced-air is the Canadian system of choice for delivering residential HVAC. Even northern European countries, which have had a long history of hydronic systems, are now starting to introduce forced-air systems into their markets.

2.3 Air Handling

The prime mover in most forced-air systems is the furnace air handler. Furnaces are central heating appliances incorporating a fan or blower which moves air over a heat exchanger. They are heated by a variety of fuels, including natural gas, electricity, oil, propane and wood. The heat is transferred to the air which has to work against the air pressure drop (also known as static pressure loss) of both the heat exchanger furnace cabinet and the attached supply and return ductwork. Furnaces are specified with external static pressure capacity, i.e. the pressure drop imposed by the attached ductwork only.

Heating capacities from 15 to 45 kW (50,000 to 150,000 Btu/h) and airflows from 300 - 750 L/s (600-1500 cfm) are typical. At the design air flow external static pressures for heating-only devices range from 50 to 60 Pa (0.20 to 0.25

in. WG). The "internal" static pressure drop (i.e. across the furnace cabinet) is typically 100 - 175 Pa (0.4 - 0.7 in. WG).

Furnace fan motors are rated on power output, that is, shaft horsepower. This power drives the impeller of the fan. Electrical input power (output divided by motor efficiency) is used to calculate the energy consumption of the fan.

Blower motors for heating-only air handlers range from 1/4 to 1/2 HP shaft power. Motor efficiencies in the 20% to 50% range yield input power requirements of 400 to 1000 W. A residential warm air furnace blower typically requires about 600 watts input power to move 400 L/s of air flow [1.5 W/(L/s)].[2]

Temperature rise (ΔT) from return air to supply air ranges from 40-50°C for gas and oil appliances and up to 40°C for electric forced-air. These result in supply air temperatures of between 60°C and 70°C.

The addition of space cooling (or air conditioning) to a forced-air system tends to be regionally based and at the discretion of the individual homeowner. Almost one third (29%) of Canadian houses use air conditioning during the summer season. In two thirds of these houses a central air conditioning system is employed.[1]

The most common cooling package is the split system, which extracts heat from a direct expansion (DX) coil mounted in the supply air stream and conveys it to an outdoor air-cooled unit via a refrigerant loop. Airflows from 45 to 60 L/s per kW cooling output (350 to 450 cfm/ton) are typical. Blower motors for central heating/cooling air handlers are sized for external static pressures of 125 Pa (0.5 in. WG) and sensible temperature drops of 10 to 12°C across the coil. The average coil temperature is about 12°C.

Conventional mechanical cooling systems provide dehumidification (latent load) along with air temperature control (sensible load). The latent portion accounts for typically 20% to 30% of the total cooling capacity. With high indoor humidity the latent load becomes more significant and the air temperature control capacity becomes reduced. Cooling devices designed specifically for dehumidification use colder coils or condensing surfaces to maximize latent load removal.

Air source and ground source heat pumps are also used for heating and cooling. Heat is delivered to or removed from the supply air via a refrigerant coil or a hydronic coil. Air delivery heat pumps have multi-speed blowers, typically sized to meet the requirements of summer cooling (45 to 60 L/s per kW cooling). Air source heat pumps are provided with 100% backup supplied by electric resistance, gas or propane as their performance and operating characteristics are poor in cold weather. Their winter airflows and supply temperatures are similar to gas or electric furnaces.

With ground source heat pumps, the output temperature is lower than that of furnace systems, typically 40 - 50°C. As a result higher air volumes are required which, unless ducts and fittings are upsized, results in increased air moving loads on the blowers. Design air handling capacities of ground source heat pumps range from 350 to 1000 L/s at 100 Pa external static.

Hydronic fan coil units are often used in conjunction with an integrated storage water heater serving the domestic hot water (DHW) load. To avoid scalding DHW tanks are set to 60°C (140°F) or else require a thermostatic mixing valve. With the tank set to 60°C, the average coil temperature is around 50°C (10°C lower than most furnaces). Due to the lower temperature of DHW systems, higher airflows are required. Flow rates range from 350 to 1,000 L/s. To deliver the same heat as a 400 L/s gas furnace, a fan coil would require an airflow of around 550 L/s. Higher temperature output is available by using boilers rather than storage water heaters. However, the economics of this scenario are less attractive.

2.4 Ventilation

Ventilation in new construction is provided almost exclusively by mechanical means in Ontario and British Columbia due to code requirements and is prevalent in New Brunswick, Prairies and Quebec, where R-2000 construction is popular.

In recent years, the forced-air system has been used increasingly to deliver ventilation air. In forced-air systems, ventilation air is supplied to bedrooms and living rooms via heating supply ductwork and exhausted from washrooms and kitchens via dedicated exhaust ductwork. Mechanical ventilation capacity is provided by either a central exhaust fan combined with an air intake strategy or by a balanced air-to-air heat recovery ventilator (HRV) operated in low-speed with intermittent high-speed. In some cases additional exhaust fans may be part of the ventilation system.

The CAN/CSA F326 Standard and the Ontario Building Code allow ventilation to be distributed via forced-air systems by "soft connecting" the supply side of the HRV to the return duct of the forced-air system (i.e. terminating the ventilation supply ductwork within 300 mm of an opening to the return duct).[5,6]

Even though not mandatory in all cases, HRVs are used extensively in these jurisdictions. In total however, only 10% of Canadian houses have HRVs.[1] They are installed in only about 20% of houses built after 1982. Typical total power consumption values of about 125 watts provide about 60 L/s of both supply and exhaust air flow [2 W/(L/s)]. Sensible (heat) recovery efficiency ranges from 60% to 80% for 0°C outdoor design conditions.

Homes without HRVs typically have kitchen and washroom ceiling-mounted fans exhausting directly to the outdoors with make-up air being supplied by infiltration, by make-up air ducts connected to the return air ductwork, or by passive ducts (e.g. intentional holes in the basement wall).

2.5 Humidity Control

Central humidification is often integrated with forced-air supply. The most commonly used type is the wetted element, a textured wetted media (usually a drum which rotates through a reservoir) through which supply air is blown. Pan type, steam and atomizing humidifiers are also used, although they are less common.

ASHRAE recommends that humidifiers be sized in accordance with ARI Guideline F: Selection, Installation and Servicing of Residential Humidifiers.[7]

Non-ducted (portable) humidifiers are used in houses with non-ducted systems (e.g. hydronic or electric baseboard distribution) or in other non-permanent applications. Portable units are available which provide humidification by any of the previously mentioned means. Some portable humidifiers can be semi-permanently mounted and provided with a dedicated water supply.

Houses with central cooling systems receive summer dehumidification at the cooling coil via latent cooling of supply air. Winter dehumidification, although rare in conventional new housing, is a requirement in low energy housing where infiltration is low. HRVs were originally successfully sold as remediation for existing houses with humidity problems. Portable dehumidifiers are also used (e.g. in damp basements).

2.6 Air Cleaning

Air cleaners in forced-air systems are used to remove specific contaminants from the air. Except for special applications, most residential air cleaners provide some form of particulate removal. Removal of other contaminants, such as odours, chemicals and microorganisms, is not discussed in this study.

Particles of interest for removal range in size as indicated in Table 3.2.

Low efficiency panel filters are typically specified by equipment manufacturers to remove particulates in the 10 to 100 μm range that could otherwise reduce the effectiveness of the blower and heat exchange surfaces. Low efficiency filters are designed for a two-year service life as a safety factor to protect against lack of servicing. Mid-efficiency filters remove smaller particles. However, unless used in conjunction with a low-efficiency filter, they will tend to load in a very short time period (say 1 month). This loading will result in severe lack of flow and could ultimately damage the blower.

Higher efficiency extended surface filters and electronic air cleaners are used to capture even smaller particles. The extended surface provides greater face area resulting in reasonable pressure drop. Maintenance requirements are high unless accompanied by a prefilter. HEPA filters can become quickly loaded and potentially damage the blower if not proceeded by an 80% dust spot efficiency prefilter.

Particulate	Approximate size range (μm)
human hair	20 - 100
viruses	0.001 - 0.1
bacteria	0.05 - 20
skin flakes	0.9 - 10
pollen	10 - 100
plant spores	10 - 100
sneeze droplets	20 - 100
cooking grease	0.08 - 2
tobacco smoke	0.08 - 2
wood smoke	0.08 - 2
household dust	0.001 - 10
insecticide ducts	0.001 - 20
soil dusts	1 - 100
animal dander	0.1 - 10
smog	0.001 - 1

Source: Heil Heating and Cooling Products.
Note that particles smaller than about 50 μm are not visible to the naked eye.

Table 3.2 Sizes of Particulates of Interest for Filtration

Electronic air cleaners also provide higher efficiency particulate removal. However, they will quickly lose their efficiency once their plates become covered in particles. Electronic air cleaners add to the cost of forced-air systems. Because of this, use of these high-end devices is primarily a function of homeowner preference, successful industry marketing or special requirements (e.g. dust allergies).

It should be noted that obtaining effective filtration by special filter types and filtration equipment is not a trivial design exercise and is typically beyond the knowledge level of the homeowner and mechanical contractor. A brief treatise of air cleaner efficiency ratings is presented in Appendix A2.

Air cleaners are located in the return air duct or plenum, upstream of the blower, heat exchanger, and humidifier (if present).

Air cleaners for removal of indoor air contaminants can be added to the system if required. Because different air cleaners have varying efficacy over a range of particle sizes, the type of air cleaner chosen depends on the size range of pollutant to be removed and should be carefully selected. Selecting the correct filter for a various applications would require detailed treatment beyond the scope of this study.

Furnace air cleaners are usually disposable panel filters made of glass fibres with a viscous impingement coating. Electrostatic panel filters made of loose weave of coarse polypropylene fibres are also used. They have similar particle removal efficiency as the viscous impingement type but have a higher initial airflow permeability (22.6 L/s/Pa versus 15.7 L/s/Pa).

High efficiency extended surface filters of the bag and HEPA (high efficiency particulate arrestance) types have initial airflow permeabilities of 7.5 and 2.2 respectively . Bag filters consist of a high packing density of fine spun glass fibres backed with a layer of woven glass fibres. HEPA filters are made of pleated fine-fibre glass paper with aluminum separators between each pleat. Due to their large sizes, high initial and maintenance costs and low airflow permeability, bag and HEPA filters are not common in residential applications.

Flat plate electronic air cleaners have initial airflow permeability around 29 L/s/Pa. They consume in the order of 40W per 500 L/s airflow. Foam pad electrostatic precipitators are designed to fit in the space provided for a 50 mm thick panel filter, however their airflow permeability is only 5.2 L/s/Pa. Electronic air cleaners are capable of producing ozone (toxic to humans) in low concentrations as a by-product of electrostatic precipitation. If levels are sufficiently high an ozone removal device may be required after the air cleaner.

As most filters "load" with particles their efficiency increases, and their airflow permeability decreases. As flat plate electronic air cleaners load, however, their efficiency decreases while the airflow permeability remains unchanged.

2.7 Ductwork Design and Installation

Ductwork design, construction and installation are required to conform to "good engineering practice" by the National Building Code (NBC) and provincial codes.[8] Good practice is referenced as that contained in the manuals from: HRAI (Heating, Refrigerating and Air-Conditioning Institute of Canada and SMACNA (Sheet Metal and Air-Conditioning Contractors National Association, Inc.).[9,10]

HRAI recommends ductwork be sized based on the greater of: heating airflow; cooling airflow; or 1.5 air changes per hour. Air velocity should be in the range of 3.6 to 4.6 m/s (700 - 900 fpm) for supply ducts and 2.6 m/s (500 fpm) for return ducts. HRAI uses the "equal friction" design method in which the total pressure drop measured at each terminal device does not differ by more than 12 Pa (0.05 in. WG). Volume dampers are used in branches of short duct runs to increase the pressure drop .

SMACNA recommend sizing based on the greater of heating or cooling airflow only. They also use the "equal friction" design method, cautioning that, "this method brings satisfactory results provided the user understands its strengths and weaknesses".[10] SMACNA also suggests a modified design method in which the duct sizes are adjusted to equalize the friction in each branch. In applying this method, however, care is required to avoid excess velocities and noise. Regardless of the method, volume dampers are recommended in all branches for balancing purposes.

For insulation, SMACNA recommends 25 mm fibre blanket type for all ductwork within walls, floors and ceiling spaces. A vapour barrier with a perm rating of 0.05 perms is recommended in addition for cooling applications. No insulation or vapour barrier is specified for ductwork in basements. HRAI recommends insulation and vapour barriers only where ducts pass though or next to unconditioned spaces (e.g. garage).

For metal ductwork and fitting fabrication requirements, NBC and OBC had referred to CSA Standard B228.1-1968.[11] This standard had not been updated since 1968 and was recently withdrawn by CSA leaving the SMACNA standard as the referenced document.[9]

Duct systems are laid out with a rectangular sheet metal supply plenum (trunk) at the air handler and with round duct branches (150 - 200 mm dia. in joists and 100 mm dia. in wall cavities) delivering air to the zones. Trunks are typically located in the basement and are seldom insulated. Ductwork in the heated space is usually not insulated even if air-conditioning is used.

Diffusers are conventionally located around the perimeter on the floor below windows. The intent is to bathe the cold glass surfaces to offset radiant heat loss from occupants and cold drafts due to infiltration and convection. With the integration of ventilation, supply air can be below room temperature and high wall supplies are recommended.[5,6] Return air grilles are typically located on each floor of dwellings, as required by provincial building codes. HRAI suggests that installing return air inlets in all principal rooms may result in improved air circulation.[8]

2.8 Effect of Current Construction on Thermal Loads and Air Distribution

While many of the original advantages of warm air heating were valid in the context of the leaky, uninsulated homes of the time, they must be re-evaluated in the context of the advances made in residential construction today. R2000 levels of construction, with better insulation and tested airtightness, can make up a significant portion of new construction. The Ontario Building Code provisions already emulate R-2000 insulation values and construction often approaches R2000 airtightness values. [6,12]

The higher surface temperatures, particularly of windows, and low heat load of the energy efficient home mean that systems can be more centralized. Since experience with Advanced Houses and other low energy homes has shown that with high performance envelopes supply air delivery at windows is unnecessary and required flows are lower, resulting duct runs can be short and of smaller diameter and registers can be smaller. Lowering of material emissions may reduce ventilation rates allowing for further ductwork reductions in cases where heating loads are sufficiently low so that ventilation rates determine the duct sizing

Heating capacities for new houses with advanced envelopes and systems can be 5 kW or lower for which there is a lack of conventional equipment. This is recognized in standard CAN/CSA-F280-M90 (Determining the Required Capacity of Residential Space Heating and Cooling Appliances) which allows the heating system capacity to exceed the total building heat load by 5 kW for buildings with total heat loads under 12.5 kW.[13]

In areas where air conditioning is popular, higher performance glazing and higher efficiency appliances can reduce cooling loads to less than 3.5 kW or 1 ton. CAN/CSA-F280-M90 allows buildings with nominal cooling loads below 7 kW to have an installed cooling capacity which exceeds the load by 1.75 kW.

The quick response time of an air system compared to a hydronic system may have been a significant advantage in the minimally insulated, leaky home whose temperature would change dramatically with a drop in outdoor temperature or with a cold wind. In the tight, well insulated home, on the other hand, thermal comfort conditions change very slowly and do not require such a response.

2.9 Forced-Air Industry

Most forced air systems are designed by mechanical contractors, who typically have taken HRAI's training courses or follow their resource materials. However systems are often designed by rule of thumb. This more likely outside of metropolitan areas, where mechanical permit documentation is more lax. Very few systems are designed by other building professionals: Certified Engineering Technologists (CET's), Certified Architectural Technologists, R2000 evaluators, Professional Engineers or Architects.

There are approximately 20 major furnace manufacturers represented in Canada 10 of which produce equipment in Canada. Of the ground and air source heat pump manufacturers marketing in Canada, six are Canadian, 10 are American and two are Japanese. There are five fan coil manufacturers of distribution units from domestic water heaters, three based in Canada and two in the U.S.

Producers of sheet metal ductwork and fittings are often local businesses due to the high cost of shipping low cost parts. In the major, fittings are typically manufactured by one or two major companies and two to four smaller companies. Unlike the hydronics industry, ductwork and fittings do not require CSA approval labels. As a result of the low risk of damage when ducts leak air, there is a tendency to allow for lower performance of components and practices in residential construction, which is not typically the case in commercial construction or in competing residential systems (e.g. hydronic, electric baseboard).

Diffusers, grilles and registers are manufactured by three major companies and several smaller companies.

In each province, components are distributed to contractors by three to ten major distributors, depending on the region.

Forced-air systems are installed by mechanical contractors. There are approximately 12,000 mechanical contractors in Canada, of whom between 5,000 and 7,000 are active. Most are one- or two-person operations. Licensing is required only for installation of sheet metal and not for design of systems. In Ontario, the Ministry of Education runs apprenticeship programs and grants licenses. The Ministry of Labour enforces licensing.

Mechanical contractors are not fully represented by any one association. However many belong to HRAI, Canadian Mechanical Contractors Association (CMCA), Ontario Electrical League (OEL), Canadian Oil Heat Association, Canadian Geothermal Industry Alliance and other provincial and local associations.

Contractors can receive design training at community colleges, through apprenticeship programs, or informally on the job. Training can be enhanced through courses offered by various trade organizations on specific topic areas.

Competition from hydronic systems do not represent a serious threat to forced-air installers in North America as they can also be installed by mechanical contractors. However, competition exists from electrical contractors who typically install electric systems, except in jurisdictions such as Ontario which have code requirements for dedicated ventilation systems for electrically heated homes.

2.10 Regulatory Environment

Consumer protection in some jurisdictions is provided by provincial codes, the requirement to obtain heating (and sometimes cooling) permits before construction begins, site inspection by municipal and utility inspectors, homeowner warranty (new construction) and product manufacturer's warranty. The rigour of municipal and utility inspections varies widely between municipalities.

3.0 Forced-air System Issues and Potential Improvements

To enable optimization of forced-air systems, the key issues that affect operation and have potential for improvement need to be identified. The issues involved in optimizing forced-air systems can be subdivided into three categories, namely:

- space conditioning
- distribution (ductwork)
- air handling

Potential improvements are discussed in each subsection below. Key improvements are then summarized in Section 4.4.

3.1 Space Conditioning

The central role of the forced-air system to condition the occupied zone+ is often overlooked in light of other issues pertaining to the "physical" aspects of the system (i.e. the ductwork and air handlers).

Forced-air systems are, for the most part, recirculating systems (i.e. air delivered to rooms is returned to the furnace, reconditioned and resupplied to the space with little or no addition of outside air). But there are many other systems capable of producing comfortable conditions which do not require air recirculation. It should also be noted that mechanical ventilation regulations do not presume recirculation to be a necessary condition for adequate ventilation delivery. It is important to recognize that air recirculation serves to address the mechanical requirements and cost-effectiveness of forced-air equipment and systems. While it can serve to even out temperatures from zone to zone, air recirculation does not, simply by its existence, produce more comfortable indoor conditions than other heating strategies.

3.1.1 Performance of Supply Outlets

In traditional forced-air systems, conditioned air is delivered at the floor or the ceiling via diffusers or registers. The discharge volumetric flow, velocity and spread and the location of the diffuser all affect the air distribution pattern and temperature profile.

+The occupied zone is defined in CAN/CSA F326 as: *the region within an occupied space between the floor and 1800 m (6 ft) above the floor and more than 600 mm (2 ft) from the walls.*[5]

Fundamental research performed in the 1950's for high volume systems found the following results:[14]

- Vertically upward spreading supply air from a typical floor diffuser results in a uniform temperature in heating and a small thermal variation (1-2°C) in cooling in the occupied zone.

- With circular ceiling diffusers with horizontal discharge the temperature gradient was 7°C between ankle height (100 mm) and neck height (1.5 m).

- With high sidewall horizontal discharge diffusers uniform temperature in cooling was achieved. In heating, provided the horizontally projected jet can be made to follow the opposite wall to floor level, a temperature variation within 2°C from the ankle to neck height was achieved.

Similar research has not been conducted in low energy houses to quantify air flow characteristics required or achieved.

These results only indicate space air temperature, not the mean radiant temperature, which is the more accurate measure of comfort experienced by the occupants. Mean radiant temperature is dependent on interior surface temperatures and increases with increasing thermal envelope performance.

High air temperatures at the ceiling result in higher ceiling surface temperatures. The radiative effect of this elevated surface temperature warms the occupants and objects in the room. If envelope surface temperatures are close to the room air temperature (e.g. by use of high performance windows) and combine with the elevated temperature of the radiant ceiling, the occupants will experience a mean radiant temperature higher than the air temperature alone would indicate.

In cooling, the lower surface temperature of the ceiling provides a radiant cooling effect, whereby occupants and objects radiate their heat to the cooler ceiling.

Whereas vertical upward floor discharge was considered to be the preferred method for combined heating, cooling and ventilating of conventional housing due to its ability to fairly uniformly heat the air in the occupied zone, high sidewall diffusers have the potential to be the better choice for new construction with improved thermal envelopes for the following reasons.

- The thermal load may be greatly reduced and surface temperatures are close to indoor ambient conditions.

- Comfort of ventilation and cooling supply air is ensured with lower recirculation volumes and delivery outside the occupied zone.

In summary, the optimal locations for diffusers in new construction depend on the function delivered as indicated in Table 3.1.

Function(s)	Optimal diffuser location(s)
Heating only	high sidewall or floor
Heating & ventilation (untempered)	high sidewall
Heating & ventilation (tempered)	high sidewall or floor *
A/C only	high sidewall or ceiling
A/C & ventilation	high sidewall or ceiling
Ventilation only	high sidewall
HVAC (untempered)	high sidewall
HVAC (tempered)	high sidewall or floor *

* floor location adequate if heating design condition, heat recovery, and/or air mixing sufficient to raise supply temperature above 17°C.

Table 3.1. Optimal Location of Diffuser by HVAC Function

Updated research in terms of field studies with detailed monitoring and concurrent modelling tool development is critical to the adequate understanding of the relationships between room heat loads, temperature profiles, air flow rate, room air speed, and diffuser velocity, throw and spread,

3.1.2 Effectiveness of Ventilation

The ventilation function may be inadequately served when thermal comfort conditions become the overriding design parameters in forced-air systems. The Air infiltration and Ventilation Centre (AIVC) defines ventilation as, "the act of supplying clean air to a zone to satisfy the need for such air".[15] According to one Swedish expert, the aim of ventilation is, " the removal of contaminants as quickly as possible from the ventilated space. A side condition is that the ventilation should be arranged in combination with heating or cooling systems such that comfort conditions are met".[16] He further comments that "two decades of experience... has shown that [clients] rarely ask about the performance of a ventilation system as a ventilation system."

The steady state concentration of a pollutant within a space is a function of the ventilation rate when one assumes the ventilation air is perfectly and instantaneously mixed with the general room air. Thus ventilation rates can be established to maintain the concentration of a pollutant at any threshold level. However, as the perfect, instantaneous mixing assumption is often not achieved when using recirculating forced-air systems, ventilation effectiveness also needs to be considered in establishing ventilation rates.

Ventilation effectiveness can be defined as a ratio of air quality, measured as the contaminant level of the air leaving the room to that of the general room air. A ventilation effectiveness of unity indicates that perfect mixing is occurring in the space and that the contaminant concentration in the air leaving the room is the same as the average room air concentration. A ventilation effectiveness less than one indicates that the average room contaminant level is greater than the exhaust. Ventilation effectiveness between one and two means that the air leaving is more contaminated than the room air. This is the most desirable condition. It indicates that the same pollutant threshold level can be achieved with up to 50% less flow than required by a perfectly mixed system. While ventilation effectiveness ratings below unity are likely the norm and their resultant air quality may be considered adequate by many, reduced continuous flow rate requirements can translate into energy savings both thermally and electrically.

While a body of knowledge on ventilation effectiveness exists for commercial buildings, little is published about the effectiveness of ventilation delivered via residential forced-air systems.[17] However, the main issues can be described.

Duct leakage can compromise delivery of intended ventilation air quantities. (Refer to Section 3.2.4.) Ventilation supply "soft-connected" to a forced air distribution system with a continually operating furnace blower is intended to provide adequate room-by-room ventilation air delivery. However, in doing so, any distribution and/or duct leakage problems experienced by the forced-air system may compromise ventilation delivery.

For example, the supply air flow to each room is often determined by whether the thermostat is calling for heating or cooling. When the air handler cycles off (i.e. heating or cooling is not called for) the ability of the ventilation air to reach the intended locations may be compromised.

Unconditioned ventilation air injected into the furnace return can result in increased corrosion and reduce the life expectancy of equipment. Also, excessive cooling of the heat exchanger during the off-period can result in high thermal stress causing premature failure.[4] HRAI recommends a minimum mixed air (return air plus outside air) temperature of 15°C to avoid condensation.[9] CAN/CSA F-326 specifies 12°C unless otherwise recommended by the manufacturer.[5] These minimum temperatures are usually achieved by employing an HRV or a duct heater to preheat the outdoor air or by setting a sufficiently high recirculation to make-up air ratio.

The advantage of coupling ventilation with recirculated forced-air heating may provide capital cost savings over separate individual room supply . Mixing provided by recirculation would tend to approach a ventilation effectiveness of unity but disallows the potentially higher ventilation effectiveness afforded by 100% outdoor air if the displacement ventilation principle is used.

Displacement ventilation systems discharge ventilation air just below room temperatures near floor level at low velocities. Pollutants become entrained in the thermal plumes created by occupants and heat sources and are exhausted at the ceiling exhaust grille. Except where pollutant sources are directly below occupants, displacement ventilation systems employing 100% outside air can achieve much higher ventilation effectiveness (from 1 to 2) thereby improving indoor air quality significantly over recirculating systems. This principle, combined with engineered filtration, was used in the CMHC Hypersensitive House with demonstrated success.[18] In normal occupancy 100% outdoor air ventilation may enable reduced ventilation rates to be used; however, present residential ventilation codes do not consider this.

3.1.3 Cooling and Dehumidification Strategies

In forced-air systems with cooling functions, cool air is supplied to rooms via the same diffusers or registers as used to deliver heating. Yet cooling distribution is often the critical design criteria for diffuser sizing and location. Proper duct sizing and/or the ability to adjust flow is required to avoid uncomfortable drafts.

By allowing a daily air temperature excursion within the ASHRAE comfort zone, from 22°C to 27°C and back to 22°C on the peak cooling day, the required cooling capacity and supply air requirements can be reduced by as much as 50%. This would result in mechanical cooling requirements of around 0.5 to 1.0 ton, which is small for central air-based systems. When required capacities become this small, less efficient window units are often installed. More feasible are chilled water coils in the supply air stream, which can be served by more passive strategies rather than conventional refrigerant-based systems.

Separating the cooling and ventilating functions could further improve comfort conditions. One example is a multi-residential building near Toronto which uses ceiling convectors with drain pans for cooling and dehumidification and individual in-suite HRVs for ventilation.[19]

The low infiltration rate of an improved thermal envelope results in the outdoor air cooling load to be restricted largely to the ventilation supply stream. Dehumidification of the controlled supply air can remove a significant portion of the latent cooling loads at the source. This makes it feasible for a radiant cooling system to avoid condensation on its cool surfaces while supplying to a reduced sensible cooling load afforded by the improved envelope. This approach has been demonstrated in commercial applications in Scandinavia.[20]

Examples of these approaches in low-rise residential buildings are given in Section 5.

3.1.4 Air Cleaning

Air cleaning is not a code requirement for residential HVAC systems. It is typically specified by the air handler manufacturer to protect their equipment. Otherwise, filters are used for special applications and at the discretion of the homeowner. While forced-air systems afford the opportunity to provide high efficiency particulate removal, it is possible that forced-air systems have inherently higher airborne particulates than non-forced-air systems. It is questionable whether a net reduction in airborne contaminants is achieved when room air is mixed, filtered, and diluted with a small proportion of outdoor air. Further research is required to determine whether forced-air systems incur higher airborne particulate in the occupied zone than do non-forced-air systems.

Air cleaner efficiency ratings are based on the type of particles desired to be removed (e.g. Dust Spot Efficiency is based on a 0.5 to 1.0 μm particle size, Weight Arrestance uses 10 μm, DOP uses 0.3 μm, ERC uses 0.45 μm.) and are indicative only of the initial efficiency for that particle size. (Refer to Appendix A2.) There is currently no standard for determining the efficiency of air cleaners as a function of particle size over time. A standard needs to be developed to inform consumers how the filter removes a range of particle sizes over time. Air permeability curves (airflow divided by static pressure versus loading) should also be provided.

Where the filter housing is loose or filters are allowed to load beyond the recommended servicing level, bypass of air around the filter can occur and air cleaning effectiveness can be reduced. Filter housings which ensure a good seal (e.g. gasketed) would significantly reduce the former. Better adherence to the recommended service schedule by way of a service indicator light (say at the thermostat) could improve the latter.

The choice of air cleaning device will have different effects on the static pressure experienced by the blower. For example, a system with 450 L/s nominal airflow (with a standard disposable fibre glass viscous impingement panel filter) will experience reductions in flow due to static pressure of additional air cleaning devices as indicated in Table 3.2.

Air Cleaner	**Initial Static (Pa)**	**Initial Flow (L/s)**	**Final Static (Pa)**	**Final Flow (L/s)**
Fibre glass panel	190	450	205	427
Electrostatic	183	460	195	443
Electronic	188	453	188	453
HEPA	253	353	335	227

Note: The electrostatic filter replaces the fibre glass filter, whereas the others are in addition to a fibre glass filter.

Table 3.2. Effect of Air Cleaner Loading on Flow Rate

Low efficiency panel filters provide, at best, modest filtration while adding up to 125 Pa (0.5" WG.) static pressure which, in turn, increases fan power requirements. Note that this could be as much as a 50 % increase in static pressure or reduction in flow depending upon the characteristics of the air handler.[4]

Insufficient flow can also cause furnaces to short cycle on the high limit switch. A poorly maintained, loaded filter can also be a source of odour, e.g. due to a build up of mold, particularly in the presence of moisture.

The desire for year round air filtration, along with continuous ventilation has been responsible to increase fan energy consumption to the largest single electric load in houses without electric heating.

Local, non-ducted air cleaners can control specific, local contaminants or create local clean rooms. For this application, the local strategy is a far more effective air cleaning strategy than high velocity, continuous central recirculation. For example, one local HEPA filter air cleaner consumes 320 W to deliver 210 L/s [1.5 W/(L/s)]. A central blower (10% efficient) pushing through a HEPA filter would consume approximately 800 W to deliver the same air flow [3.8 W/(L/s)]. and would not have the filtration effectiveness in the room in question.

In non-recirculating systems, with mechanical ventilation supply, filtration can be used to eliminate contaminants in outdoor air from reaching the heat exchanger surface, the supply ductwork or the occupied spaces. Contaminants from indoors are exhausted at source directly to outside. By employing alternative ventilation strategies such as 100% outdoor air ventilation, expensive electronic air cleaners and high efficiency filter packages could be downsized or else avoided altogether.

3.1.5 Humidification

Humidification is predominantly required in existing housing stock due to the high infiltration rate of dry winter air. Moisture generating activities of the household also need to be considered. The problem can typically be remediated by either adding a humidifer or tightening the envelope.

In-duct humidifiers of forced air systems often become breeding grounds for various micro-organisms that can contribute to indoor air quality problems and can cause rusting and premature cracking of furnace heat exchangers. Furthermore, condensation may occur in ducts running through unheated spaces, causing rust as well as mold growth. Distribution ineffectiveness and duct leakage also suggest that the central system may not be the most effective means of distributing humidified air to the house since humid air in warm concealed cavities can lead to mold growth as well as loss of moisture to unconditioned spaces.

The need for humidification in today's housing is decreasing due to improved attention to air sealing construction techniques. Household activities can often maintain relative humidity above 30% throughout the winter. New housing with tight envelopes are often unnecessarily equipped with humidifiers. In fact, there often exist a need for dehumidification in winter in tight existing houses due to the amount of internally generated moisture retained in the house and lack of adequate ventilation.

Exceptions may be a single occupant in a large house, improperly adjusted ventilation system (overventilating) or deficient airtightness. A quick moisture balance calculation during design could convince homeowners that the need is not significant.

For example, in a house with a volume of 700 m^3, an infiltration rate of 0.05 changes per hour and a ventilation rate of 30 L/s, 10 L of moisture are required per day to maintain 30% RH @ 20°C when the average daily outdoor conditions are -10°C @ 100% RH. If a four-person household typically generates 12.4 L of moisture per day, the resulting relative humidity would be 33%.

If humidification is desired as part of the forced-air system, the best method to supply it is by atomizing type humidifiers or enthalpy wheel HRVs.

3.1.6 Zoning

Typically zoning is not required in new construction since temperature homogeneity is readily achieved. With a reasonably well insulated, tight envelope, zoning has not been shown to produce energy savings to justify the additional capital expenditure required compared to single thermostat systems. Further, the forced air system has enjoyed continued success due its relatively low cost and distribution simplicity (single speed fan, single thermostat). Adding to cost and complexity may not be desirable for the homeowner or the industry.

If zoning is desired in the house, special measures are required. Ductwork must be separated close to the heating plant, motorized dampers may be required, and the heating plant itself requires special attention.

A constant volume, single zone system can be converted into a multi-zone, variable air volume (VAV) system by adding modulating dampers, temperature sensors and a central microprocessor. Manufacturers recommend that flow across the heat exchanger not be reduced to more than 70% of the rated capacity. Modeling and field testing demonstrated that variable flow to each zone can be achieved while maintaining 70% flow if a minimum damper position of 35% open is set. [21]

A better approach is to use a variable capacity furnace matched with a variable speed fan. This approach saves heating energy compared to the modified constant volume system by allowing the minimum damper position to be fully closed if no heat is required in a zone. By employing a variable speed fan with controls that maintain efficiency, electricity is also saved.

Another approach is to use a fan coil for each zone which draws from a common return plenum. This method avoids the need for motorized dampers in each zone and allows zoning. Modulating valves would typically be used for hydronic coils to control heat delivered. Alternatively, variable speed fans could be used to modulate the heat.

The bulk of new Canadian houses have relatively low heating costs, therefore zoning may not be economically attractive. However, a number of special conditions, such as large custom houses, remote rooms and mixed occupancy (home/office) can benefit from zoning features.

3.2 Distribution System Issues

Conditioned air leaving from and returning to the air handler is conducted to and from the conditioned space through rectangular and circular ductwork, typically made of galvanized metal. Along the way air and heat can be lost, fan energy requirements can be increased (due to static pressure increases), and indoor air quality problems can take root.

3.2.1 Duct Design, Layout and Installation

The most readily available and used document for duct design is available from HRAI and building codes recognize it as "good practice".[9] It uses a relatively simple equal friction method for sizing duct work and furnace fans, as discussed in Section 2.7. The method is prescriptive and not performance based. For example, it does not address energy performance of the furnace fan. For distribution it advocates perimeter floor locations, as typically do codes. It is not known how many installed systems are designed based upon this approximate method and how many based on "rules of thumb".

The forced-air ductwork in houses is rarely considered in the design of houses at the outset and often has to conform to the site conditions after the fact. The result is poorly configured mechanical systems. A recent survey of Canadian houses found that excessive bends and long duct lengths were common, often as a result of trying to avoid framing in exposed basements, or as a result of thoughtless installations.[22]

Duct chases or drop ceilings are often installed as an afterthought, sometimes compromising the aesthetics of indoor spaces. The mechanical system is often unfairly burdened with the blame for such intrusions. House designers, architects and structural engineers need to coordinate with mechanical designers so that "cleaner" duct runs can be accommodated earlier in the design process. Further, architectural elements such as floor plenums, masonry wood stoves or hollow mass walls should be utilized to obviate the need for additional chases. Note that use of these cavities can have the added benefit of reducing system static pressure requirements.

Building departments should require design certification and consistently demand proper documentation for duct layout. This would empower the site inspector to verify that the installation matches the design.

While forced air system design and duct work installation has been traditionally viewed as a "low-tech" discipline, often depending on rules-of-thumb and replication, this is not applicable in the current context of mechanical system complexities and energy and environmental costs.

A review of duct design methods should be undertaken and an upgraded, engineering-based method appropriate for low-rise residential construction be developed. It should be performance oriented rather than prescriptive, so as not to limit well-designed, innovative systems.

Perhaps through the Provincial Building Code process, a requirement for duct design submission based upon the new design procedure could be created for approval by municipal building departments, as is already required for heat loads and heating distribution.

3.2.2 Duct Fittings

A recent survey of Canadian housing[22] observed the following about duct fittings:

- Boots are roughly installed, forced into position and bent. Many boots were cut too close to the wall, and blocked by the register, especially in older houses.
- In some cases a single house would have more than ten different varieties of boots and registers.
- Some heating ducts were noticed to be tied directly into the main vertical plenum of the furnace, as opposed to the trunk take-offs.
- Very few feeder ducts were taped at the joints.

Duct fittings account for 75% to 85% of the ductwork static pressure in the example buildings in the HRAI design manual.[9] Ductwork static typically represents 60 Pa of pressure on the blower; fittings then represent about 50 Pa. For a typical system with a total static pressure of 175 Pa, fittings represent close to 30%.

Fitting pressure drop could be reduced by oversizing, reshaping, adding turning vanes, and adding inlet scoops at plenum takeoffs. Reducing fitting pressure drop by 50% would reduce total static pressure by 15%, which would allow designers to select smaller blowers. Assuming a 20% overall blower efficiency, a blower with input power of 340 W could be installed in place of a 400 W blower to deliver 450 L/s. In terms of motor shaft power a 1/4 Hp motor would replace the more conventional 1/3 Hp unit. The assumed motor efficiency is 55%.

3.2.3 Distribution Effectiveness

The foremost function of ductwork is to distribute heating or cooling throughout the house. In new construction, ductwork is typically used to distribute ventilation air as well. Two issues should be addressed in regard to forced-air distribution:

1) how effective is the distribution and circulation in forced-air systems, i.e. how much of the air serves its intended function; and

2) how important is forced air distribution and circulation in the context of energy efficient homes.

Conduction losses and duct leakage prevent a significant amount of heating and/or cooling effect from reaching the intended location.[22] Ventilation delivery is further compromised by duct leakage which reduces the ability to balance flows. Cycling of air handlers on heating or cooling demand results in variable ventilation flow rates to various rooms. Usually the ventilation system is not designed for variable flows and critical zones can be starved of ventilation air as required by Canadian ventilation codes. If variable flow is used then the method presented in ASHRAE Standard 62, Appendix H should be used to ensure adequate ventilation reaches the critical zone.[23]

It is also important to examine the appropriateness of traditional heating distribution in air-tight, well-insulated houses. In order to maintain comfort in a poorly-insulated, leaky house heat has traditionally been distributed to the exterior walls and windows to counteract the radiative heat loss from the occupant to these cold surfaces. Similarly, the high heat loss via conduction and air exchange requires that significant heat must be distributed to each area of the house to maintain comfort.

In the well insulated airtight house, distribution to exterior walls and windows is not necessary since their inside surface temperatures will not be significantly lower than the room air temperature. For example, on a -21°C day with the indoor temperature at 21°C, the inside surface temperature of a conventional double-glazed window will be only 7°C while the inside surface temperature of a triple glazed, double low-e, argon gas-filled window will be 17°C. (While these windows of this calibre are not yet the norm, they are readily available and represent where window practices are headed.) Increasing in popularity for new construction are double glazed, low-e, argon gas-filled windows which have an inside surface temperature of 13.2°C under similar conditions.

Similarly, the low heat loss of such houses suggests that it is not crucial to deliver heat to all areas of the house, but that the heat delivered by natural convection from a central distribution point or by solar or internal gains may suffice. For example, where a leaky uninsulated house often requires distribution to kitchen and washrooms, the internal gains in those areas and convective air coupling to neighbouring heated areas by openings can provide sufficient heat to those spaces in an energy efficient home. If there is continuous exhaust, this will further contribute to thermal coupling of the room.

Many low energy homes are successfully heated using a central wood-fired heater with only radiative or convective coupling to the rest of the house. Some wood-fired or gas-fired central heaters have recirculation capacity for air distribution with short duct runs.

3.2.4 Duct Air Leakage

Duct leakage has been found to be, on average, in the 49% range for existing Canadian housing.[24] Duct leakage as high as 70% has been reported while good installations are in the 10% to 15% range.[25] Unless the house has a superior thermal envelope, this duct leakage can have deleterious effects on energy use.

A study of 800 homes in the northwest US indicated that the forced-air "control" house sample had an average of 70% higher air infiltration rates compared to the electric baseboard control house sample. The difference was surmised to be due to blower-induced duct leakage.[26] Ducts located outside the building envelope, such as in uninsulated crawl spaces and garages, have the greatest potential for increasing house infiltration. This practice is much more common in houses in the United States than in Canada.

Duct leakage into enclosed wall and ceiling cavities creates higher pressures which can result in increased exfiltration rates where the cavities contact the exterior envelope. Since the supply air temperature is above the room air temperature in winter and below the room air temperature in summer, the temperature difference at the envelope is increased, thereby increasing conductive losses. For example, for a house with 200 m^2 of RSI 5 walls, on a -20°C day air leaking into wall cavities at 60°C could result in 7 m^2 of exterior wall area associated with an elevated cavity temperature of 40°C. This would result in a 2% increase in wall heat loss or a 0.6% increase in total building heat loss, before additional exfiltration losses are considered.

Similarly, air that leaks into return ducts (typically 5 to 25% of the total return air) can be far colder than the house return air if it comes from an exterior wall cavity.

Duct leakage does not only occur at the fittings. Longitudinal joints typically account for 15% of total duct leakage. Sealing duct joints (including longitudinal ones) can realistically reduce duct leakage by 90%.[27]

Ventilation standards assume that specific and known quantities of supply air are delivered to various rooms. With forced-air supply the quantities are delivered as a proportion of the total air flow. To safeguard requirements to a ventilated room a minimum air flow must be maintained. If the design requirement is 20 L/s, a 50% loss by duct leakage would result in only 10 L/s being delivered to the room, significantly compromising the intent of the ventilation standard. The failure of the ventilation standards to address duct leakage is a serious shortcoming.

Air quality can also be affected by duct leakage. Return leaks can draw contaminated air from attics, wall cavities, crawl spaces, and basements into the system. For example, in many existing houses, basement return plenums made by simply attaching metal panning to the bottom of floor joists are often extremely leaky. As basement air can be contaminated with mold, soil gases, or stored household products such as laundry detergents or paints, the desired indoor air quality may not be achieved. If, however, the basement is conditioned with the forced-air system, some recirculation of basement air will occur anyway. In this case it is therefore important to ensure that basement walls and floors are well insulated and airtight (i.e. soil gas proof).

A recent study of Canadian residential duct systems found that the average total air flow to supply registers for 205 houses sampled across the country was 258.4 L/s.[22] With standard furnace blowers in the 400 to 500 L/s range, the results indicate that only 52% to 65% of the supply air reached its intended location. This is not only important in meeting design values of heating and cooling delivery, but outside air delivery as well.

HRAI prescribes that airflows be increased by 10% for branches with over 15 m actual length to account for duct leakage. Building codes typically recommend only that special attention be given to duct sealing for ducts passing through unconditioned spaces.

In order to ensure supply air is delivered to its intended location duct sealing techniques should be employed or alternative duct materials should be used (refer to Section 4). The most common duct sealing material is pressure sensitive tape, preferably the aluminum adhesive type. Duct sealing by conventional mastic application requires a time-consuming three-coat method. With water-based, fibre-reinforced mastic coating formulations duct sealing is limited to just one application. There is some question of longevity of sealing materials and methods. Only pressure sensitive tapes have test standards to evaluate performance.[35]

Leakage from supply register boots could be reduced by caulking the boot-floor or -wall interface. This would also help to ensure adequate velocity and throw in to rooms, resulting in improved circulation.

3.2.5 Duct Conduction Losses

As described in the section on distribution effectiveness, conduction losses play a significant role in the inability of ductwork to distribute 40 to 45% of its heat to the intended location.

A recent study found that in a Chicago research house (one story with full basement, poorly insulated), about 1/3 of the energy output of the heating system was conducted from the ductwork before it reached its destination. In a more energy efficient house in Washington, DC., with fully insulated ductwork, only about one-fifth of the heat was conducted away from the ductwork before it reached its destination.[26] A Canadian study showed that the combination of duct leakage and conduction losses resulted in an average of only 39.2% of the heat being delivered to the forced-air system reaching the registers.[22]

These losses are problematic in less efficient or poorly constructed housing. In both new and existing housing, heat lost before reaching its intended location can result in overheating of some spaces and underheating of others, especially those at the ends of long duct runs. In a house with a tight, efficient envelope this may be of less concern.

Where ductwork is uninsulated, delivery of cooling effect is also compromised. As well, condensation on the exterior of the ductwork resulting from supply air temperatures below the room dewpoint (usually around 14°C) may result in moisture damage.

The duct heat loss factor increases with increases in air velocity in the duct.[28] By increasing the airspeed from 2 m/s to 18 m/s, the heat loss factor can increase 15% (uninsulated) to 100% with some permeable interior insulation types. However, for the same flow volume in a round duct, a nine fold increase in air velocity would reduce the diameter and surface area by a factor of three. Therefore, an increase in air velocity may reduce duct losses significantly by reduction of surface area. However, static pressure and noise considerations need to be addressed.

Ductwork should be insulated for long runs as the objective of the forced air system is to deliver heating and cooling to a desired destination.

Insulation is applied to metal ducts or ducts can be made of rigid fibre glass insulation. The latter option is dealt with under section 4.1.6 Ductwork Alternatives. Insulation options for metal ducts are semi-rigid boards and flexible blanket types composed of organic and inorganic materials in fibrous, cellular, or bonded particle forms. These can be applied to the outside surface of the duct or to the interior of the duct as a liner.

For insulations applied to duct exterior, vapour barriers or facings may be attached or they may be applied separately. Exterior applied duct insulation can be attached with adhesive, pressure sensitive tape, pre-attached pins and clips, or wiring or banding. Interior duct insulation can be attached with adhesive or pins and clips.

The most common residential duct insulation is the foil backed fibre glass blanket type fastened with aluminum tape.

3.2.6 Duct Pressure Drop

Typical forced-air systems are designed to accommodate external static pressure drops of 60 Pa (0.25" WG.) for heating-only systems and 125 Pa (0.5" WG.) for heating and cooling systems.[9] The cooling coil is assumed to account for the additional 60 Pa (0.25 in. WG). The ductwork beyond the heat exchange devices is assumed to have a combined supply/return pressure drop of 60 Pa (0.25 in. WG). The ductwork system pressure drop is determined by the length of runs and the equivalent lengths of the fittings. Use of high pressure drop fittings, excessive number of fittings and poor installation practices result in higher static pressure drop requirements (and ultimately higher power requirements) for air handling equipment.

High pressure systems with small diameter (50 mm) ducts are occasionally used in housing where large diameter ducts would be problematic. A major disadvantage of the small diameter ducts is the high pressure drop. Cutting the duct diameter in half, while maintaining the same flow rate, increases the power required to drive the air flow by a factor of 32. (Refer to Appendix A3.2)

Small diameter systems (e.g. the Space Pak air conditioning system) have a static pressure drop of about 375 Pa, while conventional systems have pressure drops of about 33% of that amount. The air velocities are about 10 m/s in the small diameter ducts, about four times faster than those in the conventional residential systems. By providing a higher temperature difference across the coil, these systems are able to reduce the required flow rate by 60%, thereby limiting the increase in power to a 2.5 fold increase.

Because of this very strong dependence of power consumption on duct diameter, small diameter systems should be employed when measures are taken to keep velocities and flows low. This would apply to large temperature rise systems or low capacity systems due to high performance envelope.

Techniques used in commercial application which are not typically used in residential applications to reduce pressure drop could be applied at the design stage. These include turning vanes, long-radius elbows, extra-smooth transition pieces, low pressure drop grilles or oversized duct fittings. By using flow-through furnaces at the ceiling, elbows in the supply and return trunks are avoided.

3.2.7 Duct Contamination and IAQ

Ductwork itself has been implicated as a source of poor indoor air quality. Dust and moisture can accumulate in the ductwork, providing a breeding ground for micro-organisms that are ejected throughout the house whenever the blower operates.

Drain pans under cooling coils of air conditioning systems often do not have sufficient slope to fully drain and are difficult to clean. As a result, fungi and bacteria can grow and contaminate the air passing over. Humidifiers also serve to add moisture to the duct environment causing potential micro-organism growth. Dirty filters are potential microbial growth areas. Spills into floor registers can also contaminate ductwork, especially in the kitchen and washroom. Blower motors in the airstream, especially low efficiency types, generate high temperatures in their windings, resulting in off-gassing of volatile organic compounds (VOCs).

Duct cleaning only offers a small improvement. A CMHC study of residential duct cleaning efficiency found that duct cleaning provided no significant improvement in flows, fan power requirements, duct and house airborne dust, or supply duct dust levels.[29] The dust concentration in return ducts and the airborne micro-organisms were significantly reduced, although the reductions in airborne micro-organisms could not be attributed to the duct cleaning operations.

More significant improvements can be made by using systems employed for hypersensitive housing. For example, the CMHC House for the Hypersensitive employs 100% outdoor air supply, an ultra-violet lamp at the cooling coil to control micro-organisms, high efficiency (near-HEPA) filters after the HVAC system and ducts accessible for cleaning.[18] Other houses designed for the chemically hypersensitive have fan motors outside of the supply airstream and good filters on the supply airstream.

3.2.8 Noise Transfer

Noise problems with ductwork are often associated with air movement due to high velocities or abrupt changes in the transition fittings. Other noise sources include the combustion process and fan motor vibration carried from the furnace or fan housing to the ductwork. The use of flexible connections on the ductwork to minimize transmitted vibration and interior plenum sound insulation is good practice. Extensive use of flexible metal ducts can increase noise problems.

Forced-air blower and mechanical system noise is often transferred throughout the house via ductwork. The airflow through ductwork itself also can be a source of significant noise. Ductwork also provides a mechanism for transfer of noise from one room to another in a house.

In higher velocity systems (e.g. Space Pak), noise problems are dealt with using special sound attenuating sections placed at each outlet.

Improvements in noise levels can be achieved with:

- flexible, reinforced plastic connections between the furnace and ductwork
- sound absorbing insulation in plenums
- smooth ductwork and fittings smooth ductwork and fittings

- avoidance of metal flexible ductwork, 90° elbows or any sharp rerouting of air
- lower-flow, higher-efficiency systems
- duct sealing to prevent potential whistling at joints

Lower energy systems are likely to have inherently lower noise levels by virtue of there being less energy to generate noise, e.g. an efficient, low power fan has little waste energy available to generate noise.

3.2.9 Room and House Pressurization

House or room pressurization resulting from forced-air systems has been found to produce significant increases in house infiltration and exfiltration. In homes with central returns, closing tightly fitting interior doors can cause a significant increase in room pressure which results in increased exfiltration from that room, poor supply air to that room, and increased infiltration into the rest of the house.[31] Room pressurization and the ensuing exfiltration has also been implicated in moisture damage. Return leaks in a basement may depressurize the basement and thus increase the transfer of radon, soil gases, and other contaminants into the house, and potentially cause any naturally aspirating combustion appliance to backdraft, distributing the combustion products around the house.

Building codes address the first issue by requiring that doors be undercut or transfer grilles be provided. Return leaks can be addressed by duct sealing.

3.2.10 Controls

Forced-air systems can be controlled by one or more thermostats located in the zones of the house. Most houses are single zone and have only one thermostat. This device is usually located in the centre of the house on the main floor. In a poorly insulated and leaky older home, where heating and cooling was primarily supplied at the perimeter and significant differences in temperature between the core of the house and perimeter rooms was more likely, there could be a delayed response for both the activation of the thermostat and the deactivation.

For low energy new construction, the centrally-located, single-zone thermostat typically provides adequately uniform temperature control. In these houses the practice of setting back the thermostat at night to save energy will have little or no effect with low energy housing due to the long thermal time constant. The thermal time constant refers to the time that would be required for the air temperature to exponentially decay by 37% of a reference temperature difference, e.g. between indoor and outdoor, in hours. It is an expression of the relationship of heat loss and mass effects. Long time constants occur with relatively low heat loss or relatively high mass.

For periods where the temperature is allowed to slip (say during a long weekend or extended vacation) it may be desirable to have enough excess capacity in the system to recover the temperature in a short period. This capacity, however, need not be part of the main heating plant, and could be an ancillary device such as a high efficiency wood stove or natural gas fireplace.

Supply of ventilation in a forced-air system is typically at the mercy of the heating and cooling controller. Unless the furnace fan is set for continuous operation, when heating or cooling are not called for, the circulating fan will stop and only the ventilation supply fan (if present) will continue to push air through the ductwork. The ability of the ventilation supply fan to effectively deliver the required ventilation to the desired locations is compromised. Unless extravagant measures are taken to balance the system, buoyancy effects will dominate in the oversized ductwork. Commercial variable air volume (VAV) systems are designed to provide minimum ventilation requirements to the critical zone when heating and cooling functions are dormant.

For ventilation supply, mechanical ventilation is typically provided in low speed with occupant-switched intermittent high speed. A more desirable ventilation control strategy is demand control where ventilation rates are controlled automatically (e.g. by either a dehumidistat or carbon dioxide (CO_2) sensor in the occupied space). The ventilation system is then controlled to supply high speed ventilation only when required based on the surrogate humidity or CO_2 level.

The intent of ventilation standards, such as the national standard <u>F326 Residential Mechanical Ventilation Systems</u>, the Ontario Building Code (OBC), and the British Columbia Building Code (BCBC), is to have continuous ventilation supply but that the furnace fan operating continuously can provide the distribution. The OBC is specific that switches for the ventilation system and the furnace fan must be installed side-by-side and marked as to function. However, typically the fan is switched into continuous mode at the furnace or contractors install a heating/cooling style thermostat with a continuous (i.e. "automatic") fan setting. The capacity for continuous operation for the ventilation system is mandated in the above codes, but switching is at the discretion of the occupant.

3.3 Air Handler Issues

Furnaces, heat pumps and fan coils are the "prime-movers" of forced-air systems; they are the energy supply side of the system. Their role as air handler requires them to meet an increasing number of end-uses, including ventilation, heating, cooling and dehumidification, filtration and humidification. Their ability to do so is complicated by a number of issues.

3.3.1 Oversizing

Central forced-air heating equipment for new construction are typically oversized by 20 to 40% heating capacity. For low energy housing, oversizing may be even greater due to limited availability of product sizes. Oversizing equipment in low energy housing can result in temporary overheating of the occupied zone from short uncomfortable bursts of hot air or in equipment prematurely shutting down before providing the required heat to the house. (When the anticipator in the thermostat experiences a rapid rise in air temperature, it will shut-off the furnace prematurely resulting in gradual degradation of indoor temperature.)

Oversizing is often justified as an allowance for fast temperature recovery. The reality is that there are a limited range of heating capacities available from manufacturers. Further, as thermal envelopes improve, fast temperature recovery becomes less of an issue due to the increase in thermal time constants. (Refer to Section 3.2.10.)

Interestingly, excess capacity, may already exist in 1.4 million Canadian homes in the form of wood burning appliances such as wood stoves. Also, internal gains from people, lights and appliances can add to the recovery capacity.

Oversizing can result from inaccurate load analyses by contractors and designers based on outdated rules-of-thumb for inefficient, leaky envelope buildings. Also, even when a furnace is chosen for heating only, a model which will permit addition of a cooling coil in the future is often chosen. These models have larger fans capable of moving more air than required in the absence of the cooling coil, causing an unnecessary increase in electricity consumption compared to an accurately sized fan.

Sizing could be based on a longer time-averaged outdoor temperature than the 97.5% outdoor design temperature, taking into account internal and solar gains, and allowing for acceptable temperature excursions. This would significantly reduce the sizing (by 10% - 40%) and ultimately the capital cost for new construction.

3.3.2 Cooling Coils

The addition of cooling to the forced air system has resulted in the installation of larger capacity devices (to accommodate the higher static pressure required to deliver cooling capacity) with longer fan run-times. As a result, the system may be optimally sized for cooling, but inefficient for other uses.

SMACNA recommends sizing the cooling plant slightly below the cooling load to save not only capital and operating costs but to improve comfort by avoiding unnecessary cycling; the longer run-times provide better humidity control.[10] "Grossly oversized equipment can cause discomfort due to short on-times and wide indoor temperature swings. It can also contribute to high energy usage due to an increase in starting and stopping transient thermal losses and off-cycle losses."

The typical residential cooling package consists of a direct expansion (DX)or refrigerant coil in the furnace and an outdoor heat rejection device. The issues related to this technology include ozone depletion from refrigerant leakage (typically R-22, an HCFC), fan and compressor energy consumption, noise from the outdoor unit and potentially dishealthful microbial growth in drain pans in contact with the airstream. Also, when condensate drains in the ductwork are untrapped, air can escape degrading the cooling system performance.

Cooling coils should be designed which exert lower static pressure on the air stream, both during the cooling season and heating season. This may mean oversizing coils to reduce the velocity of the air across the fins. Removing the cooling coil from the airstream by using a bypass strategy would reduce blower energy consumption, e.g.. Waterloo Green Home.

3.3.3 Blowers

Most of the benefits of forced-air systems over gravity systems described in Section 2.0 of this report relate to duct pressure drop. The forced-air system allowed the designer to make ducts smaller and longer, add turns and bends, reduce register size, and add filters. While this flexibility has some advantage, disregard of pressure drop combined with grossly inefficient furnace blower systems leads to significant electricity use. Typical conventional furnace blower systems, with power draws of 500 to 1000 W, are in the order of 10 to 20% efficient, resulting in fan energy use from 1000 kWh to 9000 kWh per year depending on furnace runtime.[2,33] The cost to operate these blowers would be $100 to $900 per year at $0.10/kWh. By prudent choice of best current blower technology, it is feasible that overall blower system efficiencies as high as 50% are possible in the near term.

The CMHC fan study focused on a typical air moving load of 600L/s and 250 Pa for a furnace blower.[2] The 250 Pa was assumed to be split between the furnace cabinet (150 Pa) and the external ductwork including cooling coil (100 Pa). This is equivalent to an air moving load of 150 W. With a 20% efficient blower this requires a 750 W electrical input or costs $525 in annual energy charges if run continuously.

If a number of improvements discussed above were implemented such as improved furnace design, shorter and optimized ductwork including fittings and lower air flow requirements due reduced peak demand, the air moving requirements might reduce to 200 L/s and 150 Pa or an air moving load of 30 W (see examples in Section 6). With a 50% efficient fan-motor assembly, the electrical input would be 60 W or $40 per year of continuous operation.

3.3.4 Other Parasitic Loads

Further electrical consumption by ventilation fans, induced draft blowers, heat rejection blowers (for air conditioners) increase the operating costs of the forced air system. Typical annual costs (at $0.010/kWh) for the above devices are given below.

Ventilation fans	$ 20 - 200
Induced draft blowers	$ 10 - 50
A/C heat rejection fan	$ 7 - 40

Other parasitic loads include motorized dampers. Control systems for defrosting HRVs sometimes use motorized dampers for defrost. The motors on the dampers are typically continuously energized, except during defrost. A continuous power consumption of 11 watts was measured in one air-to-air heat exchanger with the fans turned off.[34]

3.4 Summary of Potential Improvements

The following is a summary of potential forced air system improvements arising out of the issues raised above. The improvements are available for immediate application but some require additional design or technologies that are less easily available.

Reduced loads
- new construction has improved thermal envelope
- the ventilation air heating/cooling load is removed at source (e.g. via HRV) resulting in reduced thermal loads by central system
- system airflow requirements are lowered due to reduced loads

Energy efficiency of recirculation fan
- reduced heating/cooling air flows results in lower fan capacity
- reduced static is achieved by optimum design of duct size, fittings, diffusers and filters
- high efficiency motors with variable speed control maintain efficiency despite variable field conditions (flow, static)
- fan is operated with variable speeds to match loads
- fan is operated on thermal loads only by separating ventilation

Ventilation effectiveness
- supplies and returns are located for maximum ventilation effectiveness
- 100% outdoor air approach (used for non-recirculation systems), properly designed, increases ventilation effectiveness

Space conditioning
- air is supplied at low flow and at low temperature difference with indoor air outside the "occupied zone"

- improved windows remove the need to place heating registers under the windows or at the perimeter and high wall registers with most convenient, shortest duct runs are appropriate
- one return register is sufficient if no impediment to flow exists
- for most new houses humidification is not required
- heat recovery ventilation or similar efficient preheat strategy is used for flexibility and comfort of supplying ventilation air

Design and Installation Practice of Distribution

- all transverse and longitudinal joints are to be sealed
- all ductwork in spaces not consistently conditioned are to be insulated
- low temperature (below 12°C) cooling supply ducts must be insulated

4.0 Innovative Existing And Emerging Technologies

As described in Section 3.0 of this report, forced-air ducted systems have been found to be susceptible to several problems that result in increased energy use or that make their defined function less effective than desired. In this section innovative products and systems are described which reduce energy loss and increase efficacy.

4.1 Innovative Existing Products and Sample Practices

4.1.1 Metal Ductwork Coatings

Biocide and biostat coatings are now available to combat microbial growth in ductwork. These coatings could minimize the contribution of ductwork to indoor air quality problems. Biocides kill microbes while biostats present an environment which does not support microbial growth. Coatings are applied in acrylic primer/finish coatings which are specifically formulated for use on HVAC system components, including lined and unlined ductwork, air intakes, fan assemblies, baffles, dampers, etc. The efficacy of these coatings likely decreases over time as dust collects on the surface.

There are anti-static coatings available to reduce negative ion removal. Again, efficacy over time is not known.

Given the life span of ductwork of 50 years or more, benefit over the long term would need to be proven to warrant the cost of application.

4.1.2 Rationalizing Ductwork Design

The conventional residential duct design method of equal friction is an expedient procedure which does not address optimization. To achieve optimum design of air duct systems, recognition of design alternatives such as short ductwork, new materials, different flow/velocity characteristics need to be introduced.

Fans must operate at optimum system pressure, the ratio between velocities in all sections of a duct system must be optimal, and pressure balancing must be attained by changing duct sizes, not by using balancing devices. The equal friction, static regain, velocity reduction, and constant velocity design methods do not meet the first and second requirement for system optimization whereas the T-Method does meet all such requirements.[35]

It is recognized that for residential systems with HVAC installed costs in the order of $10,000, there is little latitude for inclusion of complicated design tools. A simplified design tool based on the T-method would aid the design community and the forced-air industry.

4.1.3 Diffusers

Significant innovations have been made in commercial air outlet design. These have been driven by a desire to encourage more thorough mixing of supply and room air and increase ventilation effectiveness, while eliminating stratification, noise, uncomfortable drafts, stagnant air at room corners and the need for additional fans or motors.

The low cost floor heating registers commonly used in residential construction have not changed in several decades. With the advent of integrated ventilation, commercial engineered linear diffusers are being employed in residential applications as high sidewall registers with tested throw performance.

The residential ventilation industry, being relatively new and having to grapple with cold air supply issues, has shown more innovation, mainly in Canada and Europe.

In certain applications conditioned air is delivered at high velocity through small 50 mm outlets installed on ceilings, walls or floors (e.g. and Jet-Eye). Manufacturers claim that by using the aspirating effect, gentle mixing of the high-velocity airstream with the room air can be achieved with draft-free circulation and the elimination of stratification.

On the other hand, McGill Jet uses a narrow high velocity jet to deliver conditioned air to the floor of the room with minimal mixing to allow for displacement ventilation supply. This strategy avoids the need to duct supply air to the floor.

Self-regulating diffusers are also available which operate based on an indoor temperature control. As room temperature rises, wax in the unit expands, driving a piston out and reducing the orifice size. When the room temperature drops, the wax contracts and a spring retracts the piston. The movement of the piston positions the dampers in a proportional manner. The requirement to maintain adequate ventilation air supply under the various thermal conditions needs to be considered when designing such devices.

For residential applications the engineered linear diffusers with designed throw patterns are a significant improvement over the stamped metal variety. In the absence of performance requirements or specifications from a designer, the higher cost, though modest, typically precludes their use by residential installers.

4.1.4 Fittings

There are limited improvements for residential metal fittings and dampers available.

Better selection and specification of fittings at the design stage has the opportunity to result in a better installed system. A duct fitting database, developed by ASHRAE, which includes 228 round and rectangular fittings (and soon to include oval fittings) is available from ASHRAE in electronic form. Designers can link the data directly to their duct design programs.

Round duct is the most efficient and economical shape. Where space is restricted, however, oval duct provides most of the performance advantages of round duct while remaining cost competitive with rectangular duct, which does not perform as well.

For residential ventilation, 100 mm (4") round ducts can be fitted with plastic round-to-oval elbows for installation in 89 mm (3 1/2") interior stud walls.

Conventional blade dampers divert flow by increasing static pressure. Flow splitting dampers can be used to proportion flow with minimal static pressure increase. Located in a splitter box or at the plenum the damper can vary the relative face area for a given flow. However, this strategy would require custom design and fabrication for residential applications.

4.1.5 Ductwork Alternatives

Some non-metallic ductwork alternatives have the promise of lower cost, higher flexibility for installation, improved acoustics, better cleanability, lower dust accumulation and possibly lower negative ion removal. While extensively used in ventilation distribution systems, use in heating applications has been limited.

NBC and OBC require that ductwork be of non-combustible material. Limited amounts of non-combustible materials can be used if air temperatures stay below 120°C. As residential forced-air systems typically supply air at 60 to 70°C, a certain amount of combustible material is allowed by Code. Codes are unclear as to what constitutes a limited amount of combustible material except to say that it cannot be used in vertical runs serving more than two storeys and in horizontal runs less than 4 m in length between air ducts and diffusers. A further requirement is that the sealant used to join the ductwork must have a flame spread rating of not more than 25 and a smoke developed classification of not more than 50.

It is interesting to note that in the United States metal duct is used in less than 50% of installations; however, this includes cooling dominant systems.[32]

1. Plastic and Fibre Glass

Plastics are used in an increasing number of liquid and air moving applications in the commercial, industrial and residential sectors. Plastic plumbing has begun to compete with copper for residential hydronic and domestic hot water plumbing applications. Plastics are used in commercial and industrial HVAC ductwork. Plastics are used for residential clothes dryer venting and are allowed for conveyance of ventilation air.

Plastic ducts are available as cylindrical sections made from PVC, CPVC, fibre glass, or polybutylene. Rectangular sections are also available, but at a significant cost premium. Benefits from using plastics include: light weight, easier to field cut, easier to connect, airtight connections (solvent cement), and corrosion resistance. A drawback of plastic ducts is static build-up. As such, plastic ducts should not be used where particulate-laden air is being conveyed or where residents are sensitive to negative ion removal unless anti-static coatings are applied.

2. Rigid Fibre Glass Boards

Rigid fibreglass board, commonly used as insulative sheathing, can also be assembled into ductwork. Manufacturers such as Knauf, Owens Corning, Certainteed Manson and Schuller (Manville) produce air duct board in standard sheets which can be manually tooled in factory or at the site into the desired rectangular or segmental shape. Such tooling is regulated by NAIMA's "Fibrous Glass Duct Construction Standard." Boards have an outer skin of foil which acts as vapour barrier, an inner thickness of glass fibre which insulates, and a resin coating sprayed on to the inner surface to ensure that glass fibres do not break off and enter the air stream. For round residential duct, a product much like fibre glass piping insulation can be envisaged. Such a product should be cost competitive where insulated ductwork is specified.

Benefits which accrue from the use of air duct board include: improved air tightness, vapour impermeability, and thermal resistance; no expansion or contraction (and associated knocking noise as is common with sheet-metal ducting), excellent sound absorption, and ease of fabrication without the need for expensive forming equipment. Such boards meet Class 1 flame spread rating and smoke developed classification for use as duct work which makes it applicable for most low-rise residential construction with systems below a temperature of 120°C.

This type of product affords insulation and sound absorption benefits over standard metal ductwork. It can be expected to be more expensive to install, unless insulated duct is required, and small diameter product is not readily available. It would likely be used in larger high-end custom homes until the manufacturers target the general residential market.

3. Flexible Duct

Corrugated flexible duct is most familiarly used as vacuum cleaner hose. Metal corrugated flexible duct of larger diameters are often used in forced air systems.

Flexible duct is available in stainless steel, aluminum, plastic and rubber. Benefits which accrue from its use are minimal space required for on site storage, ease of installation, allows for connection between misaligned system components, obstacles can be avoided. Drawbacks of rigid corrugated duct are high pressure drop, noise and dust build-up due to high surface area. As such, this product should be used only where spatial constraints warrant its use.

On short runs to the exterior walls, ventilation installations commonly use preinsulated plastic film or foil flexible ductwork reinforced with metal spirals.

4.1.6 Innovations In Motor Technologies

High efficiency induction motors, now normally used in furnaces, are available in the 1/4 and 1/3 hp range that have full-load efficiencies of 71%, but the efficiency falls dramatically at part load.

Electronically commutated motors (ECM) use DC to enable electronic switching of the rotor at any speed or loading with little loss in efficiency which can be as high as 90%. Similar controllers, known as adjustable speed drives, are available for AC induction motors resulting in somewhat lower efficiencies. Variable speed motors are now available from a number of manufacturers of heat pumps, furnaces, fan coils and air handlers. Where motors are belt-driven the ECM technology can be easily employed. One barrier to its installation in current product lines now outfitted with 50% efficient permanent split capacitor (PSC) motors is the cost attributed to receiving CSA approvals. Where the technology is employed in furnaces or heat pumps a slight cost premium must be paid.

Manufacturers with products currently outfitted with ECM technology include some heat pumps from Chinook Phi-Beta, Water Furnace, Canadian Geo-Solar and some furnaces from Carrier and Lennox.

4.1.7 Innovations In Control Technology

1. Zoning for Space Conditioning

With the development of residential scale variable air volume heating and cooling systems, zoned delivery of forced air has become possible. One such product is the Harmony™ II furnace system by Lennox Industries Inc. The system is designed to provide four separate heating/cooling zones utilizing a single indoor unit and a single outdoor unit. The system consists of Harmony controls, a master thermostat and duct mounted zone dampers with a thermostat in each zone. The zone dampers are automatically controlled to supply air flow only to zones with a thermostat demand. At the same time the variable speed motor (VSM) in the furnace automatically adjusts the air volume to the zones as required.

Manufacturers of zone control strategies state that energy can be saved by allowing temperature setback in unoccupied areas while maintaining comfort in occupied areas. This is more appropriate for existing or poorly insulated or large houses where relatively high heating/cooling loads are expected.

Setback and variable-air-volume systems must consider not only energy issues but also the impact on the ventilation air supply and indoor air quality. Simplicity in controls coupled with improved building envelopes will result in comfortable, cost-effective systems for the large majority of new construction.

2. Central Exhaust With Zone Control

Residential exhaust equipment must deal with the generation of odour, moisture and CO_2 of general occupancy while also dealing with larger moisture and odour point loads generated by cooking and bathroom use. Typically, these requirements are fulfilled by either a whole house central exhaust (e.g. HRV) in continuous low-speed with intermittent high speed operation, or, by a smaller capacity central exhaust with separate fans for kitchen and bathroom operated intermittently.

A third approach is one offered by David Hill of Eneready Products Ltd. of Burnaby B.C. It employs central exhaust with zone control. Each exhaust port is fitted with a damper with normal position set at partially open. When a damper is fully opened and high speed is engaged the airflow through that particular grille can be boosted approximately eight times its continuous rate. By this method, the common problem of lack of adequate local flow in high speed is overcome without the inclusion of more fan power and potential pressure imbalancing.

4.2 Advanced Houses Mechanical Systems Designs

The advanced houses discussed below have pushed envelope insulation and airtightness significantly beyond conventional practice and have severely reduced the heating demand. As a result of this and for other reasons described below, the mechanical systems have numerous innovative features. The lessons learned from these installations help to define viable improved technologies and practices.

4.2.1 Advanced House Descriptions

The Brampton Advanced House in Ontario was the first innovative house built under the advanced house concept promoted by EMR (now NRCan) in cooperation with the Canadian Home Builders' Association (CHBA). Completed in 1990, the Brampton Advanced House employs a fully integrated HVAC system supplying space heating, space cooling, ventilation with heat recovery, domestic water heating with greywater heat recovery and ice-based thermal storage.[36] The energy target was to use less than 30% of the energy of conventional construction or 40% of R-2000 housing. Ventilation supply air is preheated in a sunspace prior to being mixed in the return plenum. Supply registers are high on interior walls. With an open staircase to the basement the return is located at the recirculation fan. Ductwork was taped and insulated.

The Advanced Houses Program (1992-1993), sponsored by CANMET (NRCan) and the Canadian Home Builders' Association, was developed to accelerate the development of appropriate technologies by challenging the residential construction industry to build a number of innovative low energy, "green" houses across Canada. The energy target for these houses was to use less than one-half the energy per square metre of floor area of the R-2000 program houses. The following Advanced Houses were constructed:

B.C. Advanced House, Vancouver
Saskatchewan Advanced House, Saskatoon
Manitoba Advanced House, Winnipeg
Waterloo Green Home, Ontario
Hamilton NEAT Home, Ontario
Innova House, Ottawa
Maison Novtec, Montreal
Maison Performant, Longeuil, Quebec
P.E.I. Advanced House, Charlottetown
Nova Scotia Advanced House, Bedford

Advanced House technical requirements relating to forced air systems were limited to fan power:

- the heat recovery ventilator fans shall have an electrical power consumption not exceeding 1.2 W/ L/s of air flow capacity.
- the combination of the warm-air heating and heat recovery ventilator shall have an electrical power consumption not exceeding 0.75 watts per L/s of combined air flow.

Of the 10 Advanced Houses, 9 used forced air systems for providing the bulk of the space heating distribution.[34] Three of the houses heated parts of the house with either hydronic radiant floor heating (B.C., Montreal Maison Novtec) or baseboard hydronic convectors (Manitoba) in addition to forced air heating.

4.2.2 Fan Energy

The most popular motor for forced air fans used in the Advanced Houses was the General Electric ECM Brushless Direct Current motor. The motors come standard with 2 speeds, although the motor incorporates a microprocessor that can be programmed for multiple or variable speeds. The motor has a full load efficiency of 68%. Its advantage is that its efficiency remains high over a very wide speed or load range.

The power consumption of the forced air fans were measured in a number of the Advanced Houses. The power consumption values ranged from 0.3 W/(L/s)in the Brampton House to 0.55 W(L/s) in the Waterloo House. Generally these houses had design heat losses in the range of 1/3 to 1/4 that of conventional houses, and yet the air flows were not proportionately lower. Some systems provided air conditioning which would not allow the airflow to be dropped below 200 L/s for a 1-ton unit. Nevertheless, due the reduced airflows and significantly higher efficiency motors, the power consumption values were between 100 W and 225 W which is considerably lower than the input power of approximately 400 watts commonly found in new residential systems.

4.2.3 Distribution Issues

A number of the Advanced House systems used high side-wall forced air registers with horizontal throws. Generally the registers were positioned on interior walls.

Only three of the Advanced House systems used insulated supply ducts. On the Ottawa Innova House, the Space-Pak Ducts on the branch lines are insulated, partly for sound control reasons.

A number of systems used higher efficiency bag and pleated filters on the space heating and ventilation systems.

The B.C. Advanced House uses a four-zone temperature control system on the air handler.

4.2.4 Ventilation Systems

All but three of the Advanced Houses incorporated air-to-air heat exchangers to provide ventilation air. Generally the air-to-air heat exchangers were connected to the forced air heating system. The Novtec and Brampton houses used an exhaust air heat pump to recover heat from the exhaust air. The Waterloo Green Home used a prototype regenerative rockbed heat recovery ventilator which recovers additional heat from the furnace flue.

To improve motor efficiencies, the AC fan motors were replaced with brushless DC motors. However, no improvements were made to the fans, or the internal geometries of the heat exchangers.

4.2.5 Possible Improvements to the Advanced House Duct and Fan Systems

The following are some steps for improving the systems:

- Greater simplicity in the designs could have been used.
- A more careful analysis of design air flows could have been undertaken.
- Superior fan design, beyond motor technology, could have been chosen.

A more detailed report on the Advanced Houses is given in Appendix A4.1

4.3 Other Non-Conventional Designs

This section discusses the innovative design features found in Code, R2000 and low-energy new construction.

4.3.1 Innovations In Code Housing

The use of a boiler and fan coil combination to integrate space and domestic hot water heating constitutes a significant innovation within conventional housing. Low heating and cooling loads can be matched more accurately. The use of two or more fan coils makes zoned delivery of space conditioning possible as may be desirable for reasons of mixed occupancy (e.g. a home/office).

4.3.2 Innovations In R2000 Housing

The virtue of the R2000 program has been the use of higher insulation values for windows and walls, the requirement of tested airtightness and the development of an educational infrastructure to allow for the training of qualified ventilation system installers, particularly for heat recovery ventilators. With the latest version of R2000 technical requirements energy budget credits are prescribed for non-continuous furnace fans or non-recirculating systems by direct distribution of ventilation air to rooms and for high-efficiency (ECM) motors.

4.3.3 Innovations In Low Energy Housing

Appendix A4.2 describes a number of innovative strategies for forced air systems in low energy houses. A summary of features is given here.

- Heating and cooling delivered via a combination of ventilation supply air stream and radiant floors and ceilings, without recirculation.
- Short ductwork with use of floor cavity as distribution plenum and convenient, non-perimeter distribution.
- Integration of mechanical systems.
- Use of water-based coils in ducts allows zoning.

- Use of potable water in coils directly from hot water tank reduces equipment cost.
- Displacement ventilation strategy for high ventilation effectiveness.
- Use of high efficiency fan-motor set.
- Thermal mass, typically in terms of a masonry wood heater, for reducing temperature swings and improving comfort.
- Use of low powered and/or passive (non-ozone depleting) cooling systems
- Use of low toxicity materials for construction.
- Engineered filtration for supply air in housing for the hypersensitive

5.0 Performance of Forced Air Systems

Forced-air systems serve two fundamental requirements: provide comfortable conditions for occupants, and ensure adequate indoor air quality is maintained. In doing so they consume energy (and produce their associated environmental impacts), and incur capital and operating costs.

It is necessary to have available performance modeling techniques to address the fundamental operating and cost characteristics of a system. In Appendix A5 an attempt has been made to develop a performance model. This model framework is used in Section 6 to compare example systems.

The first step in applying the model is to ensure the basic requirements are met, including heat load, cooling load and ventilation capacity as required by the building code and applicable standards or by alternative sizing methods (see Appendix 5).

The key performance indicators can then be evaluated. They include:

- comfort
- indoor air quality (IAQ)
- energy use and environmental impact
- life cycle costs

Each of these indicators can be established through a number of parameters as listed below (and described in detail in Appendix A5]):

Comfort
- Room temperature profile
- Air speed (draft)
- Temperature drifts or ramps
- Humidity
- Effective temperature
- Supply air temperature (at register)
- Zonability
- Noise Level

Indoor Air Quality (IAQ)
- Contaminant removal by extraction at source
- Contaminant removal by dilution
- Contaminant removal by filtration
- Ventilation effectiveness
- Distribution "evenness"
- Duct cleanability

Energy Use and Environmental Impact

- Site energy consumption
- Primary energy consumption
- Environmental impact

Life Cycle Cost

- First costs
- Annual energy costs
- Annual maintenance costs
- Life cycle cost
- Adaptability

For the examples described in Section 6 and Appendix A6, some of the parameters can be quantified using the equations given in Appendix 5. Others, due to either their subjective nature, a lack of available research, or modeling requirements beyond the scope of this study are only ranked relative to one another, that is, qualitatively. Depending on the parameter, rankings include: unacceptable, acceptable, improved, low, high.

The methodology employed for modeling for each parameter for the purpose of the examples in this study is given in Table 5.1 below.

The application of the performance model is given in Section 6.2 Performance Assessment of Example Systems.

Table 5.1 Performance Model Evaluation Methodology

Basic Requirements	
Heat load	computer model
Cooling load	computer model
Ventilation load	by calculation
Comfort	
Room temperature profile	qualitative
Temperature recovery rate	qualitative
Air speed	qualitative
Temperature drifts or ramps	qualitative
Humidity	modeled
Effective temperature	by calculation
Zonability	qualitative
Acoustics	qualitative
Indoor Air Quality (IAQ)	
Contaminant removal by extraction	qualitative
Contaminant removal by dilution	by calculation
Contaminant removal by filtration	by calculation
Ventilation effectiveness	qualitative
Distribution "evenness"	qualitative
Duct cleanability	qualitative
Energy Use and Impact	
Site energy consumption	by calculation
Primary energy consumption	by calculation
Environmental impact	by calculation
Life Cycle Costs	
First costs	by calculation
Annual energy costs	by calculation
Annual maintenance costs	by calculation
Life cycle cost	by calculation
Adaptability	qualitative

6.0 An Example: Conventional System and Improved Systems

6.1 Example Systems

To demonstrate the different paths residential HVAC could pursue to the year 2005, a future conventional forced-air system and two improved system cases were developed. The future conventional system demonstrates an installation assuming little change in technology and practices were to take place. The improved systems are indicative of strategies such as increased energy efficiency, integration of functions and shorter ductwork with the results of greater cost effectiveness and efficacy of functions. Detailed house and system descriptions, drawings and component lists are given in Appendix A6.

6.1.1 Future Typical House

The systems were sized for a 200 m^2 house in Ottawa with a 4.9 kW heat load and a 4.6 kW cooling load. With four occupants the continuous ventilation requirement was set at 30 L/s (equivalent to the OBC "principal exhaust capacity"[6] and the number of rooms dictated a 60 L/s ventilation capacity as required by the F326 ventilation standard[5]. A heat recovery ventilator with 80% apparent (sensible) recovery effectiveness was used for all systems.

6.1.2 Future Conventional System

The conventional system was designed using HRAI's current design procedure.[9] It includes a current top-of-the-line, 80% efficient HRV and today's smallest available high-efficiency furnace (10.8 kW, 465 L/s @ 125 Pa external static, 375 W blower). The cooling package is a 5.3 kW (1-1/2 ton) split system with a refrigerant coil in the supply airstream. Supply registers are floor mounted at the building perimeter (below windows) in each room. There is one return grille on each floor.

The HRV blower consumes 80 W in low speed and 180 W in high speed. High speed can be engaged intermittently from manual pushbuttons in washrooms or the dehumidistat located in the exhaust air stream. The HRV supply is soft connected to the forced-air system return plenum.

The ventilation effectiveness (VE) of this system was normalized (i.e. VE = 1) in order to facilitate comparison between systems. The actual value may vary from unity, but determining it would require further research beyond the scope of this study.

6.1.3 Improved Systems

The improved systems were developed to demonstrate energy cost savings (and associated environmental impact reduction), capital cost savings and increased ventilation effectiveness. In Improved System 1, duct runs are minimized to reduce capital costs. In Improved System 2, displacement ventilation is employed to provide increased ventilation effectiveness.

Both of the improved systems use the HRV blowers to deliver heating and cooling without the use of typical furnace air flow rates. The furnace is avoided by employing a 5 kW hydronic heating coil on the supply air side after the HRV. The 5 kW includes the ventilation load. The coil is sized based upon air entering at the "design" supply air temperature of the HRV (11°C in Ottawa) rather than 20°C. Cooling is supplied with the same coil utilizing chilled water.

Improved System 1 (Options 1a and 1b) delivers ventilation air via high sidewall diffusers located as close to the HRV as possible, typically at interior walls. Air is exhausted from the kitchen and washrooms.

Improved System 2 delivers air via interstitial floor cavities, with diffusers located on the floor or ceiling of each room. Diffusers are located on the floor for the first and second storey rooms and on the ceiling in the basement rooms. Air is exhausted from the kitchen and washrooms and a corridor exhaust in the basement. On the second floor, high wall (acoustically treated) transfer grilles cascade exhaust air from bedrooms to the corridor ceiling and then into the washroom.

By having floor supplies and high wall or ceiling exhausts on the upper floors, a plug flow or displacement ventilation distribution pattern is established. This is intended to demonstrate increased ventilation effectiveness to the primary living areas when the heating coil is inactive (about two thirds of the heating season and all of the cooling season). When the heating coil is active, the supply air temperature is above room temperature and the supply air will tend to rise more rapidly to the ceiling similar to a conventional floor register system.

The following improved forced air option were chosen for evaluation:

Improved System 1a: 100% outdoor at 30 L/s low speed, 100 L/s high speed
Improved System 1b: 30% outdoor air, 70% recirculation at constant 100 L/s
Improved System 2: 100% outdoor at 30 L/s low speed, 100 L/s high speed

In Options 1a and 2, the HRV supplies 100% outside air to the registers at low speed (30 L/s) continuously. In winter, two-stage heating is provided. The blowers remain in low speed and the heating coil is activated when the first stage of heating is required (~1.5 kW output). High speed (100 L/s) is engaged when the second stage of heating is required (5 kW output). In summer, high speed is engaged when the cooling coil is activated. Intermittent high speed is available at all times for exhausting the washrooms and kitchen.

In Option 1b, the 100 L/s flow rate is maintained at all times. During normal operation 30% of the supply air is from outside and 70% is recirculated from the exhaust. When washroom or kitchen use requires 100 L/s outside air, the system adjusts its dampers accordingly, thereby exhausting "polluted" air directly outdoors.

Options 1a and 1b are assumed to have a ventilation effectiveness (VE) of 0.7 relative to the future conventional case (VE = 1) due to their low flow rates and location of their diffusers high on the walls in the centre of the building.

Option 2 is assumed to have a relative ventilation effectiveness averaging 1.5 on the first and second floor from the displacement ventilation configuration and 0.7 in the basement due to the low flow ceiling registers.

The improved systems use the same HRV as the conventional system, in terms of thermal performance, but with high efficiency (50%) blowers consuming 3.6 W and 60 W in low and high speed respectively for Options 1a and 2 and 60 W continuous for Option 1b. By comparison, the conventional HRV and furnace fans consume 455 W continuous.

6.2 Performance Assessment of Example Systems

The example systems were assessed using the performance model frame work outlined in Section 5 and Appendix A5.

Thermal modeling was performed using the ENERPASS hour-by-hour computer simulation tool with climatic data for Ottawa. Electrical energy consumption for air handling and economic calculations were performed on MS Excel spreadsheets.

The duct layouts and parts lists were sent to a contractor in Toronto for pricing. Where prices where not available for specific components, industry experience and engineering judgment was employed.

The following detailed results were determined.

6.2.1 Comfort

Room temperature profile, temperature recovery rate, temperature drifts or ramps, humidity and effective temperature were assumed to be similar and acceptable for all four cases as a result of the high performance thermal envelope used in all cases.

In terms of air speed, the improved options offer reduced air speed and reduced risk of draft.

For zonability, the conventional case and the improved cases can be zoned by room. However, the improved cases can also be easily modified to create separate zones for each floor due to the riser configuration of the ductwork. In the improved cases multiple coils can also be used for zoned supply more easily than a central furnace.

Sound levels are reduced in the improved cases since fan power and air flow rates are decreased dramatically.

6.2.2 Indoor Air Quality

Contaminant removal for all cases was provided by extraction from bathrooms and kitchen and dilution with outdoor air in accordance with minimum requirements set by ventilation standards. Improved Options 1a and 2 provided 100% outside air and exceed the requirements when the HRV runs at high speed during the cooling season and a significant portion of the heating season.

Although Option 1b employs continuous recirculation, it recirculates only 70 L/s of stale house air rather than 435 L/s as in the conventional case.

Distribution "evenness" was considered acceptable in the recirculated cases (Conventional and Option 1b). Options 1a and 2, however, may produce uneven distribution when operating in low speeds, although further study is required to determine this conclusively.

The shorter ducts of Options 1a and 1b offer improved duct cleanability over the conventional and plenum options.

6.2.3 Energy Use and Impact

Detailed results for energy use and environmental impact are presented in Appendix A6. Annual energy consumptions for the conventional and improved systems are listed in Table 6.1. Domestic hot water (DHW) energy is included to track the effect of the integrated high-efficiency gas appliance.

	Conventional kWh	Improved 1a,2 100% OA kWh	Improved 1b Recirc. kWh
Gas			
Space Htg.	4,065	6,723	5,877
DHW	5,882	5,319	5,319
Total Gas	9,947	12,043	11,196
Electricity			
Fan(s)	4,006	205	526
Cooling	722	657	657
Pump	0	250	250
Total Elec.	4,728	1,113	1,403
Total Energy	14,675	13,156	12,599

Table 6.1 Energy Consumption for Conventional and Improved Systems

Note that the improved cases employing 100% outside air (Options 1a and 2) have identical energy use and impact since only their distribution systems differed. Gas consumption for Option 1b (continuous 100 L/s recirculation, 30% outside air) decreased that of Options 1a & 2 since less outside air was being heated and fans operated in high speed continuously (effectively displacing gas heating with electrical resistance heating). Electricity consumption rose accordingly due to the latter.

Gas energy consumed on-site increased by 2,100 kWh (21%) for Options 1a & 2 and 1,250 kWh (13%) for Option 1b compared to the future conventional case. Electrical energy, however, decreased by 3,615 kWh (76%) and 3,325 kWh (70%) respectively.

Converting site energy into primary energy (by multiplying electricity consumption by a factor of three to account for generation efficiency and transmission losses) revealed a 36% reduction of Options 1a, 1b & 2 compared to the future conventional case.

Environmental impact, measured in terms of annual CO_2 emissions, was reduced by 43% for Options 1a & 2 and by 42% for Option 1b compared to the future conventional case.

Using installed costs as a surrogate parameter revealed that embodied energy reduced about 25% for Options 1a & 1b and by 42% for Option 2 over the future conventional case.

Gas energy cost increased by $50 for Options 1a & 2 and $30 for Option 1b compared to the future conventional case. Electrical energy costs, however, decreased by $362 and $333 respectively. In total, energy costs decreased by $311 (44%) for Options 1a & 2 and $303 (42%) for Option 1b compared to the future conventional case.

6.2.4 Life Cycle Costs

A listing of costs for the various systems are given in Table A6.4 in Appendix A6. Capital costs for the distribution system reduced from the conventional case at $3650 by $1350 (37%) for Options 1a and 1b, and by $1980 (54%) for Option 2. Total HVAC first costs decreased by $3,250, $3000 and $3900 for Options 1a, 1b & 2 respectively from the base case of $12,340. Annual maintenance costs were assumed to decrease $105 from the base case of $175 for all three improved cases. Energy costs decreased as described above.

The life cycle costs were then calculated over a 15-year term with a discount rate of 8%, an electrical escalation rate of 6%, a gas escalation rate of 3% and a maintenance escalation rate of 2%. The result was a savings of $8450 (37%), $8050 (35%), and $9100 (40%) for Options 1a, 1b & 2 respectively compared to the base case life cycle cost of $22,700.

The recirculation case (Option 1b) actually incurs a life cycle cost premium of $400 (3%) compared to the 100% outside air case (Option 1b), despite the energy savings of heating less outdoor air. This is due to increased costs for the recirculating system components and assumed electric rate escalation. It should be noted that the constant flow feature avoids potential distribution problems.

The displacement ventilation case (Option 2) incurs a life cycle cost reduction of $600 (4.5%) compared to Option 1a because of the shorter ductwork required. Option 2 also may offer the benefit of improved IAQ or the potential to reduce outdoor air requirements while maintaining equivalent IAQ to Option 1a.

In summary, the financial benefits of the improved systems are as follows:

- Installed system capital costs are reduced by about $3500
- operating costs reduce by over $400 per year
- system capital and operating savings for 15 years are approximately $10,000 or an average of $650 per year.
- 15-year savings from more detailed life cycle cost considerations are between $8000 and $9000 or an average of $530 to $600 per year.

6.2.5 Summary of Performance Assessment

The above analysis of the various assessment parameters is summarized in Table 6.2 below. This table also appears in Appendix A6 as Table A6.2.

	Conventional	Improved 1a & 1b	Improved 2
Comfort			
Room temperature profile	acceptable	acceptable	acceptable
Temperature recovery rate	acceptable	improved	improved
Air speed	acceptable	acceptable	acceptable
Temperature drifts or ramps	acceptable	acceptable	acceptable
Humidity	30%	30%	30%
Effective temperature	20.5°C	20.5°C	20.5°C
Zonability	low	improved	improved
Acoustics	acceptable	improved	improved
Indoor Air Quality			
Contaminant removal by dilution	acceptable	acceptable	acceptable
Contaminant removal by dilution	acceptable	acceptable	acceptable
Contaminant removal by filtration	N/A	N/A	N/A
Ventilation effectiveness	acceptable	acceptable	improved
Distribution "evenness"	acceptable	a. maybe uneven at low speed b. acceptable	
Duct cleanability	acceptable	improved	acceptable
Energy Use and Impact			
Site energy consumption (gas)	9,947 kWh	a. 12,043 kWh b. 11,196 kWh	12,043 kWh
Site energy consumption (elec)	4,728 kWh	a. 1,113 kWh b. 1,403 kWh	1,113 kWh
Primary energy consumption	24,132 kWh	a. 15,381 kWh b. 15406 kWh	15,381 kWh
CO2 impact	6,588 kg	a. 3,733 kg b. 3,810 kg	3,733 kg
Embodied energy reduction	base	a. 27% b. 25%	32%
Life Cycle Costs			
First costs	$12,340	a. $9,065 b. $9,315	$8,435
Annual energy costs	$712	a. $401 b. $409	$401
Annual maintenance costs	$175	$55	$55
Life cycle cost	$22,687	a. $14,227 b. $14,640	$13,597
Adaptablility	low	high	high

Note: For the purposes of the model, average rates of $0.10/kWh for electricity and $0.024/kWh ($0.250 /m^3) for natural gas were used.

Table 6.2 Summary of Performance Assessment Results

7.0 Advancing the Art

To move towards more optimum solutions of forced air distribution systems an assessment of the context in which the industry operates is required. This section describes relevant clauses of building codes and standards, the barriers within the industry to improvements to forced-air ductwork systems and the major documents used for training and establishing good practice.

7.1 Ductwork in the Building Codes

Often building code clauses seek to solve one problem while impeding progress to wards more optimum systems, in essence a lack of a systems approach. In other cases the reason for a regulation may lie in historic, rather than current, construction practices.

The few clauses of the National Building Code[8] that relate to ductwork systems are described below:

1) NBC Section 6.2.1.1 defines good engineering practice which references a variety of documents utilizing conventional design methods. This discourages more innovative and cost effective systems.

2) NBC Section 6.2.3.2 notes that ductwork must be non-combustible, typically metal. A limited amount of combustible material is allowed for ducts, fittings and plenums, but “limited” is not defined. This limits the use of alternate duct materials for temperatures not exceeding 70°C.

3) NBC Section 6.2.4.3 (4) states that "All round duct joints shall be tight-fitting and lapped not less then 25 mm". While this may be an attempt to address duct leakage, only sealing the ducts with aluminum tape or mastic will truly alleviate this problem. Lack of duct sealing provisions will compromise ventilation and thermal delivery.

4) NBC Section 6.2.4.5 (2) states that supply air outlets in rooms located adjacent to exterior walls must be located to bathe the exterior wall or window with warm air. An appendix provision allows highwall and ceiling diffusers if also used as ventilation air supplies. The emphasis given is not conducive to changes in industry practice.

5) NBC Section 6.2.4.8 traditionally required a return on each floor. While this requirement has been removed from the 1995 NBC version, provincial codes would still require floor-by-floor return locations.

Provincial building codes may have additional clauses that affect duct systems. For example, ventilation requirements of the Ontario Building Code also include clauses that affect the performance of ductwork.[6]

Section 9.32.3.6 describes how ventilation systems may be coupled with forced-air heating systems. Houses that contain direct vent or induced draft furnaces and do not contain a solid fuel combustion appliance (e.g. fireplace) must exhaust from the house but do not require a balanced supply or dedicated air intake.

The mechanical ventilation system must include an HRV in electric houses, for reasons of energy cost affordability, or those with a solid fuel combustion appliance, to avoid backdrafting.

In the most common configuration the supply air is drawn or blown into the return plenum of the forced-air heating system whose blower is used to circulate the ventilation air. The code also allows for continuous central exhaust through the return plenum. In this case, contaminants from kitchens and washrooms are not always directly exhausted but mixed with return air and then diluted by replacing some of the mixed air with supply air. (Switched exhaust fans are assumed to remove contaminants at source at the discretion of the resident.)

The CAN/CSA Standard F280-M90 "Determining the Required Capacity of Residential Space Heating and Cooling Appliances" sets the standards for equipment sizing.[13]

In clause 5.3 heating equipment can be oversized by no more than 40%, unless the building heat loss is below 12.5 kW for gas and propane and below 15 kW for oil. This to allow use of existing equipment to be used for low energy houses and can result in oversizing of greater than 100%, as demonstrated in the conventional example in Section 5. The related air flow rates results in being the critical design criterion for duct sizing.

In clause 6.3 cooling equipment is required to be sized between 80% and 125% of the cooling load but in homes with cooling loads below 7 kW (2 tons) allows exceeding the 125% limit.

When a cooling coil is added to an existing furnace it need not exceed 18 W of cooling per L/s of air-handling capacity of the heating system. This has the intent of avoiding the need for upsizing an existing furnace fan. Nevertheless, this would serve to change the pressure-airflow relationship of the fan, possibly increasing load and reducing efficiency.

7.2 Barriers to Changing Standard Practice

The following industry barriers prevent an easy transition to "optimum" systems:

- forced-air is a popular system; the industry does not perceive a big need to change
- designs are chosen for first cost not life-cycle cost which includes operating cost

- engrained practices are replicated without design
- design training and certification is typically not required
- unclear understanding by installers as to the performance characteristics of forced-air systems
- lack of answers from the research community on required performance characteristics of forced-air systems
- lack of familiarity and information of alternative strategies
- industry mechanism set up to maintain product loyalty, e.g. with incentives, discouraging alternatives
- lack of readily available products for "optimum" solutions
- inflexibility of the municipal permit and inspection process towards less familiar installations

7.3 Review of Resource and Training Documents

The following design, installation and training documents were identified as being commonly available and utilized by the forced-air industry and housing sector.

HRAI Residential Air System Design Manual

This is the most commonly used document in Canada for sizing minimum airflow and related recirculation ductwork systems for heating and cooling delivery.[9] The design procedure chosen is the equal friction method. It does not deal with ventilation issues and the integration with forced air systems beyond air mixing temperature requirements at the return plenum.

Distribution strategies presented are perimeter floor supply with no alternatives recommended. Preinsulated flexduct is mentioned for special or limited applications, such as horizontal branches.

SMACNA Standards

The Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) manuals out of the U.S. are referenced by Canadian codes as standards of good practice.[10] A SMACNA standard is now the only reference in Canadian codes for duct materials and fittings since the CSA standard from 1968, CSA B228.1-1968 Pipes, Ducts and Fittings for Residential Type Air Conditioning Systems, has been retired.

The SMACNA Installation standards for Residential Heating and Air Conditioning Systems is a similar document to the HRAI manual but broader in scope and not as focused on detail design. In some areas, such as acoustic separation, it recommends specific measures as good practice, which exceeds current practice, but does not call for sealing of ducts. Compared to the HRAI document and Canadian codes, it recognizes more potential solutions for ductwork systems, for example, in terms of duct materials and diffuser locations.

However, recommended practice is typically in line with the HRAI document. No reference is made to mechanical ventilation.

R2000 Builders' Manual

Canada's R2000 program has for many years required compliance for airtightness and mechanical ventilation.[12] The manual has sections on space heating, space cooling and ventilation. which make conceptual recommendations on duct layouts of forced air systems integrated with mechanical ventilation. It has for many years noted the advantages of high wall supply registers. General information is also given for installation practices.

CEEA Engineering Manual

The Canadian Earth Energy Association (CEEA) publishes a design manual which includes principles of delivery for air-supply heat pumps.[37] Descriptions are brief and focus on floor or ceiling distribution. However, with integration of ventilation, highwall registers on inside walls are recommended. The benefit of shorter ductwork is noted.

The document emphasizes the importance of return locations. The "ideal" scenario described is the use of high and low returns with seasonal dampers.

CSA F326 Ventilation Standard

Canada's comprehensive national ventilation standard includes design rules, installation requirements for ventilation and compliance verification.[5] It establishes rules for integration with forced air recirculation systems and for diffuser location based upon supply temperature.

ASHRAE HVAC Systems Handbook
Chapter 9 Air Distribution Design for Small Heating and Cooling Systems

ASHRAE handbooks are referenced by Canadian codes as good practice in Part 6. This reference outlines principles of duct system design and diffuser placement and performance.[38] It lists guidelines of good practice some of which exceed current practice. For example, it calls for "tight and sealed ducts to limit air loss". As is typical for engineering references, the guidelines are general and relate to design principles rather than installation practice. Further, the chapter is brief and presents limited design strategies, based upon traditional concepts. Mechanical ventilation integration is not addressed.

Training Courses for Certification of Sheetmetal Work

The regulations for training towards a certificate of sheetmetal work is quite comprehensive and consists of an in-school component and a work experience component. The in-school training emphasizes basic math and physics, drafting, shop practices and job-site assembly. The work experience utilizes the above skills in the shop and job-site setting. It does not deal explicitly with residential ductwork design. Since certification is for all types of sheetmetal work including, for example, metal roofing, residential ductwork is at best a subcomponent of general ductwork practices, dominated by commercial and industrial applications. Though there is no formal requirement for residential ductwork design, mechanical contractors are often in the position of detailing the system in the field. Departure from conventional practice is resisted due to lack of a good grounding in design principles.

Most of the above documents should be revised to:

- expand the strategies for distribution by including alternative duct materials and non-ducted plenums and chases as appropriate
- encourage flexibility of diffuser and return locations in certain circumstances (such as high performance envelopes and unimpeded flow to return)
- stress duct sealing as good practice
- detail the integration of mechanical ventilation

Mandatory trades training should include residential ductwork design, however, the present design method could be simplified.

8.0 Recommendations

This study reviews numerous system issues, existing and emerging products, current and improved practice and existing training materials. Further, knowledge is lacking for a variety of technical issues. The recommendations arising out of these considerations are divided into the following categories:

- near-term, mid-term and longer-term system upgrades and changes in practices
- required research to answer technical questions
- code changes required to implement changes in systems and practices
- training and information activities

8.1 Changes in Systems and Practices

In the context of downsizing of heating equipment due to improved envelopes, the expected national adoption of mechanical ventilation and the increase in air conditioned households, the following staged improvements should be pursued. It is assumed that regulatory barriers will be removed to allow adoption of these measures.

<u>Level 1</u>: Near Term

8.1.1 Encourage flexibility of register locations, such as high on interior walls. This would allow for a larger variety of design strategies and more optimal, shorter ductwork.

8.1.2 Do not require to supply air for rooms with exhausts or small thermal loads as long as total heating load satisfied.

8.1.3 Expand openness concept, which exists for design of ventilation delivery, to heating and cooling. This would allow rooms that are thermally well coupled to be supplied indirectly, resulting in shorter, combined supply.

8.1.4 Allow for one return per dwelling unit as long as free flow throughout the house is ensured, e.g. by undercut doors, open stairwell.

8.1.5 Tape/seal ducts to ensure maximum flow to register, primarily for ventilation compliance.

8.1.6 Simplify duct design to a table sizing format similar to that in use for ventilation duct sizing. Complex systems with large equivalent lengths would revert back to current conventional method.

8.1.7 Insulate air conditioning ductwork unless supply temperature is sufficiently high so as not to cause condensation.

8.1.8 Install an acoustic separator between the air handler and ductwork.

Level 2: Medium Term

8.1.10 Relax restriction on non-metallic ductwork by classifying ductwork for low temperature air delivery (below 120°C)

8.1.11 Encourage a move towards a single air handler supplying heating, cooling, ventilation and, if necessary, recirculation.

8.1.12 Encourage variable speed air handling for staged heating and cooling to lower energy costs..

8.1.13 Enact regulation of air distribution energy performance in terms of normalized annual energy consumption per unit of airflow or energy cost per unit of airflow. This may be part of the comprehensive energy rating for furnaces.

8.1.14 Maintain duct cleanliness so that the distribution system is a minimal contaminant source. This can be achieved by designing in cleanablility and/or by use of high performance filters.

8.1.15 Develop strategies and products for zoning heating, cooling and ventilation functions. Zoneability for different space conditioning requirements will find increasing applicability in residences with home offices and finished basements.

8.1.16 Develop components that incorporate many of the improvements above, such as variable speed blowers, improvement of fittings, filters at registers and non-metallic duct systems. Product development should follow along the lines of space conditioning equipment already in existence for the automobile and aircraft industry.

Level 3: Longer Term

8.1.17 By fundamental understanding of convective and forced air transport in residences (not now available), desired functions of air movement and thermal requirements encourage future residential system strategies. The result may be discrete rather than central air handlers, convective or radiative heating and cooling, or hybrid systems that provide ventilation and a portion of the heating by forced air supplemented with other thermal devices (e.g. radiant) with automatic or non-automatic control (e.g. wood heat).

8.2 Research Activities

The following research initiatives are suggested to fill information gaps encountered in the study.

8.2.1 Proceed with a major fundamental research task investigating natural convective and forced convective mass transport of air within current and future residences. Parameters should include ventilation air flows and temperatures, convective and radiative thermal inputs, supply locations, envelope characteristics. An example output would be the appropriate conditions corresponding to alternative register locations.

8.2.2 Develop clearer definitions of optimum residential comfort and indoor air quality.

8.2.3 Determine the conditions under which more than one return is required, such as high volume flow systems or where spaces are effectively separated.

8.2.4 Pursue an examination to establish adequacy of air distribution at low flows in ducts sized for higher flows

8.2.5 Assess the indoor air quality of current mechanically ventilated forced-air and non-forced-air houses addressing the issues of envelope thermal performance, register location, recirculation rate, low flow air distribution and displacement ventilation.

8.2.6 Evaluate alternatives to metal ducts as appropriate for low temperature supply ductwork by investigating issues of combustability, durability workability and affordability.

8.2.7 Investigate ductwork as a source of contaminants, establish impact on required ventilation rates and develop recommended mitigation practices.

8.2.8 Investigate cooling system alternatives, such as thermal flywheel strategies, radiant cooling and passive cooling strategies, in terms of impact of on duct system sizing.

8.2.9 Investigate air distribution effectiveness of space conditioning in variable flow and zoned systems.

8.2.10 Examine the improvement on indoor air quality by residential air cleaning devices used with forced air systems.

8.3 Code Changes

8.3.1 Remove any reference restricting diffuser locations, except as to disallow floor supply if temperature is too low.

8.3.2 For air systems below 120°C, allow nonmetallic duct materials to be used if noncombustability is demonstrated by testing.

8.3.3 Require only one mandatory return per dwelling unit, provided there is no impediment to air flow.

8.3.4 Disallow heating oversizing by more than 40% since solutions are available for low capacity.

8.3.4 Other provisions arising from research above, e.g. efficacy of distribution with low flows.

8.4 Training and Information Initiatives

8.4.1 A builder's note should be produced outlining changes in design strategies and installation practices that can be implemented given present understanding and regulation. Emphasis will be on low cost improvements with demonstrable benefits, such as duct sealing, or system cost reduction, such as shorter ductwork.

8.4.2 All training resource documents relating to forced air system design and practices should be made consistent, addressing the host of technical issues raised in this study. Specifically they should:

- incorporate Canadian ventilation standards and practices
- clarify the use of non-metallic ducts for low-temperature, low-capacity ductwork
- call for sealing of supply ductwork
- clarify diffuser location, in light of combined heating, cooling and ventilation functions and higher performance envelopes.

8.4.3 Examples of Canadian resource documents that are used by the industry are The HRAI Residential Air System Design Manual, R2000 Builders' Manual and the Canadian Earth Energy (CEEA) Engineering Manual. American documents, such as SMACNA standards and ASHRAE handbooks, are also commonly used by virtue of being reference documents in Canadian codes as well as containing useful information. Efforts should be made to work with the appropriate U.S. committees and associations to upgrade the documents so that they can be continued to be used as code references.

8.4.4 Training initiatives ideally would wait until revised resource documents exist; However, a subcomponent on improvement on current practices could be developed independently, e.g. as the basis for workshops, for eventual incorporation in the traditional documents.

8.4.5 Efforts should be made that the upgraded resource material is added to the curriculum of sheetmetal work certification training.

8.4.6 This study notes that in the search for higher indoor air quality, contractors are promoting and homeowners are buying a variety of air cleaners or filters for forced air systems. However, consistent, comparative information on the air cleaning efficacy, effect on forced air system performance and maintenance requirements, is not readily available. If the benefit is unknown then cost effectiveness can not be determined. A good document for the homeowner and installer should be produced. Much of the information is available as engineering and technical information, but some fundamental research is also warranted.

9.0 Conclusions

Significant opportunity exists to improve forced air distribution systems to yield cost savings. The example distribution systems presented in this study suggest that savings could be as high as 50% or $1900.

A systems approach of improved distribution systems coupled to high efficiency air handlers and integrated heating appliances can result in lower capital costs and lower energy costs. 15-year life cycle cost considerations can yield savings in the $5,000 to $10,000 range.

Removal of barriers such as industry entrenchment, unnecessarily restrictive code provisions and lack of current resource documents, will allow more innovative and affordable designs to be developed and installed.

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APPENDICES

Appendix A1. Current Technology

A1.1 Historical Context

Forced-air systems developed from the hand-fired stove, through the pipeless furnace and the gravity warm air furnace (see Figure A1.1). Forced-air central heating did not prevail in Canadian houses until the 1950s. Before then, gravity furnaces and hydronic systems were the norm.

Before the advent of forced-air heating, the advantages of warm air gravity systems over hydronic systems were considered to include: lower initial cost, quicker response time, improved air circulation in the home, less space required for diffusers than radiators, the ability to distribute humidified air via ductwork, and no potential for frozen pipes or leaks.[3]

In the 1920s, forced-air systems were introduced. The advantages of forced-air furnaces over gravity furnaces included:

- Flexibility in furnace location and house design: reliance on gravity forces dictated that duct pressure drop be minimized by using large diameter ducts. Convention suggested that duct runs be a maximum of 4.5m (15 ft), often limiting the house to one story and about 12m by 15m (40 ft by 50 ft) in plan, and that the furnace had to be located in the center of the basement.

- Increase in basement head room: ductwork for gravity furnaces tended to obstruct much of the basement since the ducts had to be large and have minimum bends and turns. Forced-air ducts, on the other hand, could be smaller and turned to fit along the ceiling and in joist spaces.

- Air cleaning: air filters could be used with forced-air systems but not with gravity systems because of their high pressure drop.

- Smaller floor registers: forced-air systems could accommodate the pressure drop of smaller registers than those used in gravity systems.

- Increased efficiency: the bonnet efficiency was increased with the higher air flow over the furnace heat exchanger in the forced-air system.

As residential air conditioning became more popular, the forced-air system gained more proponents since it could be easily retrofitted to deliver space cooling.

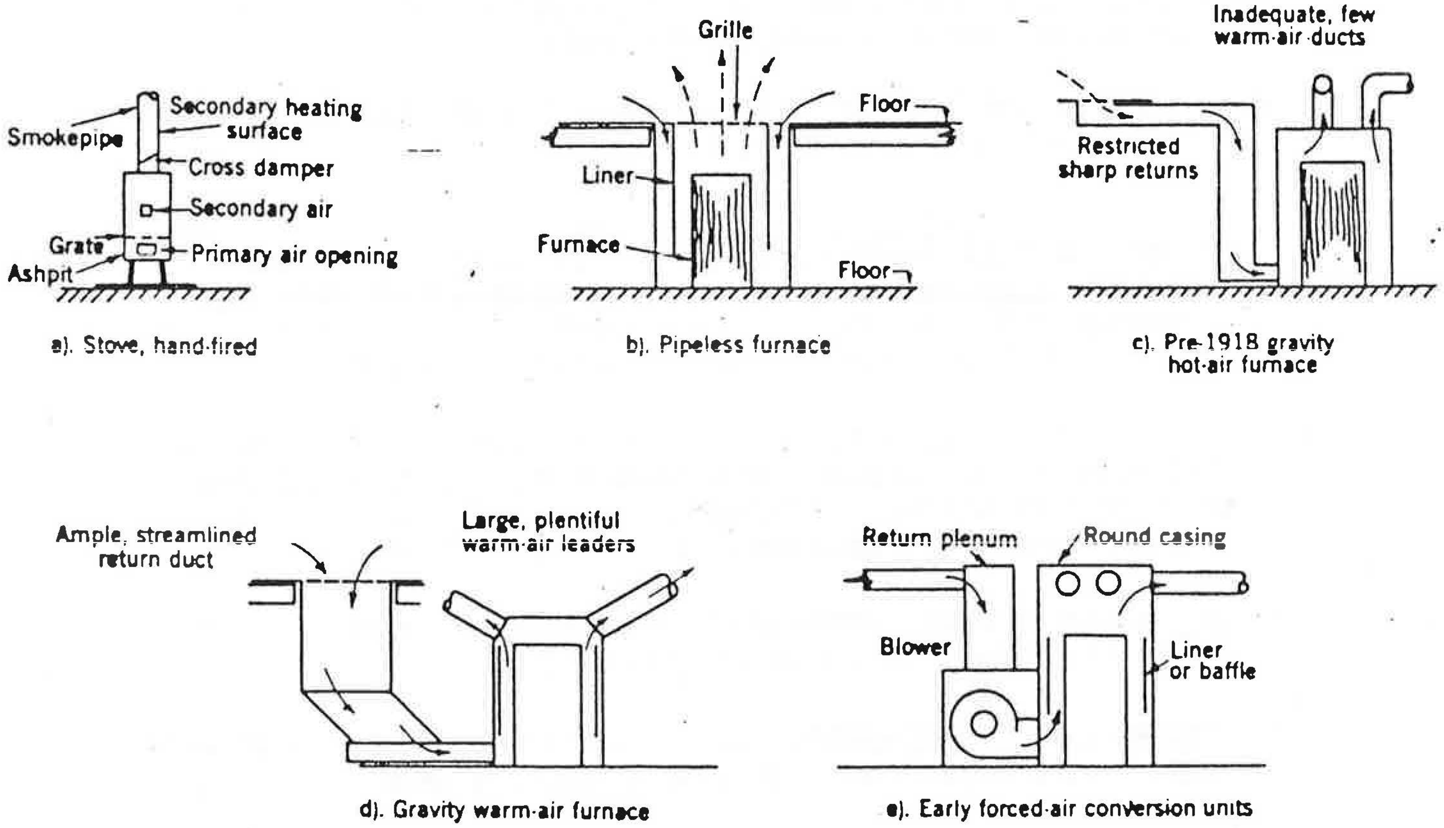


Figure A1.1. Historical Development of Forced-air Systems

A1.2 Types of Forced-air Furnaces

Furnace configurations take on a variety of forms (see Figure A1.2). The most common arrangement is the "high boy" upward discharge.

Gas and oil furnace are typically rated for seasonal efficiency or Annual Fuel Utilization Efficiency or AFUE. Common types range are mid-efficiency (~80%) to high-efficiency (85%-90% plus). Mid-efficiency units are typically of the induced draft type with a high pressure fan expelling combustion products via the flue. While discouraged in new housing by energy-efficiency and back-drafting regulations, many existing houses have naturally aspirating furnaces. For these furnaces, as well as the mid-efficiency furnaces, combustion air is usually provided by infiltration into the mechanical room.

High-efficiency furnaces are typically of the condensing type. The flue has gases that are expelled by a induced draft blower. Combustion air is drawn from the room or, in sealed combustion units, directly from outdoors. Their increased efficiency is due to extended or improved heat exchanger surface area and reduced standby losses. Condensing furnaces recover more energy by condensing water vapour from the exhaust gas. The low temperature exhaust can be direct vented without the need for a chimney.

Heating capacities from 11 to 45 kW (50,000 to 150,000 Btu/h) and airflows from 300 - 750 L/s (600-1500 cfm) are typical . At the design air flow external static pressures for heating-only devices range from 50 to 60 Pa (0.20 to 0.25 in. WG). The "internal" static pressure drop (i.e. across the furnace cabinet) is typically 100 - 175 Pa (0.4 - 0.7 in. WG).

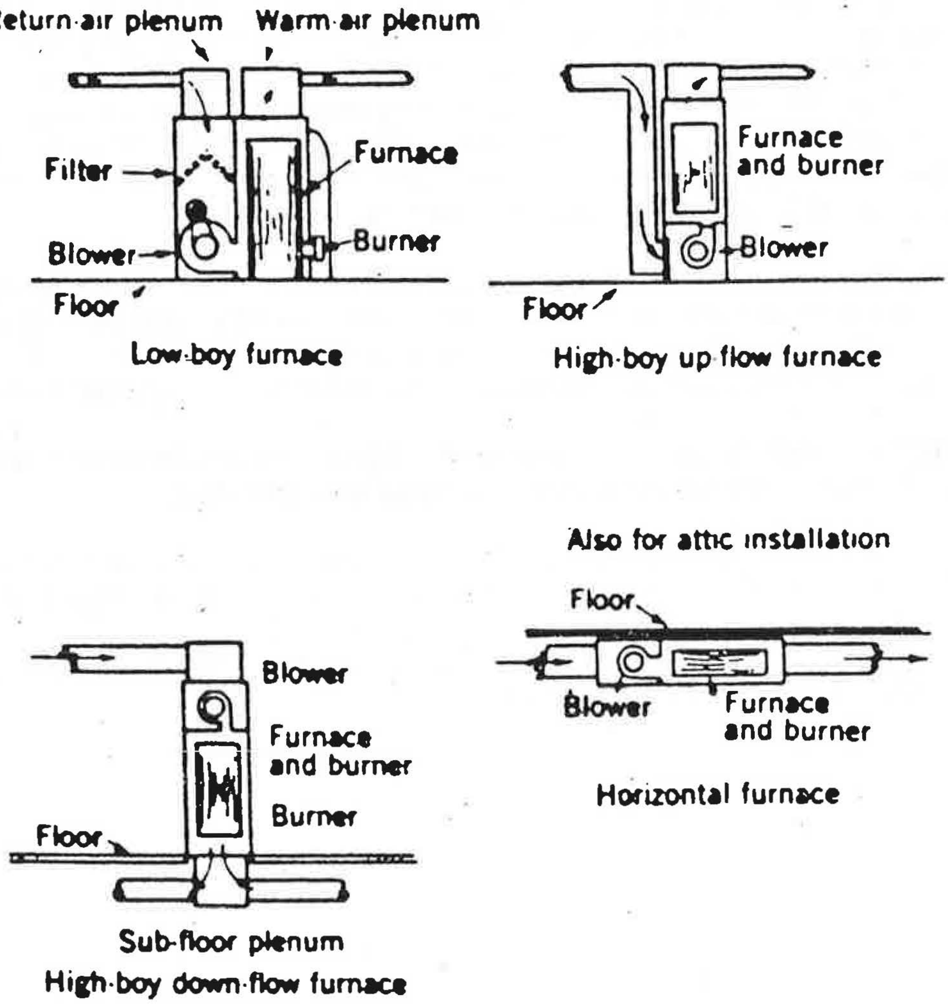


Figure A1.2. Configurations of Forced-air Furnaces

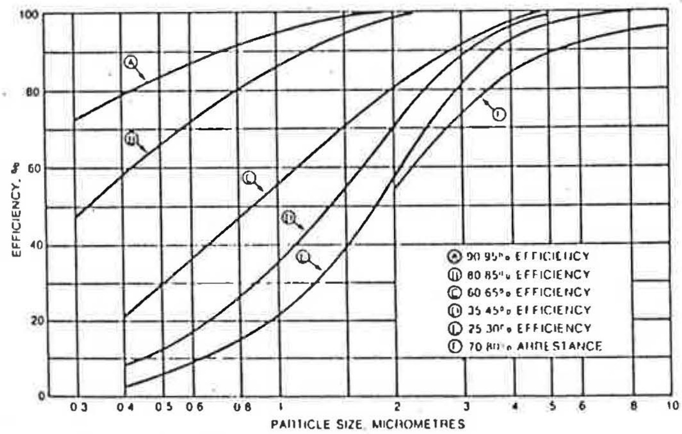
Appendix A2. Filtration

There is currently no standard for determining the efficiency of filters as a function of particle size.

Filters are commonly rated by dust spot efficiency and weight arrestance in accordance with ARI Standard 680, *Residential Air Filter Equipment*, and based on ASHRAE 52, *Method of Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter.* HEPA filters are rated by the DOP (dioctyl phthalate) test in accordance with US Military Standard 282.

Dust spot efficiency is a measure of the ability of the filter to remove finer airborne particles that could visually soil surfaces. Dust spot efficiency tests use atmospheric dust with a surface median particle size between 0.5 and 1.0 μm diameter, depending on local atmospheric conditions.

Weight arrestance reflects a filter's ability to remove large non-respirable particles. Arrestance tests are performed using a coarse synthetic dust with a mass median diameter of 10 μm. Figure A2.1 shows how air cleaning efficiency varies with particle sizes for various air cleaners.



Curves are approximations compiled from manufacturers' recent data and are for general guidance only. Efficiency and arrestance per ASHRAE *Standard* 52.1 test methods. See also Bauer *et al.* (1973)

Figure A2.1 Filter Efficiency Variation with Particle Size

HEPA filters are rated by US Military Standard 282 DOP (dioctyl phthalate) test which measures the removal efficiency for 0.3 μm diameter dioctyl phthalate particles.

Research by Offermann et al. led to the development of effective cleaning rate (ECR).[41] ECR is calculated as the difference in particle decay rates observed with and without an air cleaner operating, multiplied by the room volume. The test is based on the capture of 0.45 μm particles, which the authors claim is representative of the mass median size of particles found in residences. System efficiency is then calculated as the ECR divided by the air flow rate. The system efficiency includes the combined effects of the filter efficiency and the air leakage around the filter.

A summary of air cleaner performance is given in Table A2.1:

Air cleaner	size (mm)	Efficiency (%, test*)	(%, ECR)	Air Permeability (L/s@25Pa)
Panel filters				
visc. impinge.	400x625x25	75 WA	3±1	392
electrostatic	400x500x25	92 DSE, 78 WA	2±1	564
Extended surface filters				
bag	600x600x750	99 DSE, 100 WA	71±8	188
HEPA	600x600x300	99.97 DOP	73±15	55
Electronic air cleaners				
flat plate	625x400x175	95 DSE	69±9	731
foam pad	400x500x50	73 >0.15μm	4±1	130

Primary source: Performance of Air Cleaners in a Residential Forced-air System, Offermann et al., ASHRAE Journal V34#7, July 1992.
* particle removal efficiency based on tests: WA=weight arrestance; DSE=dust spot efficiency; DOP=dioctyl phthalate efficiency

Table A2.1: Summary of Air Cleaner Performance

Due to the range of air permeability ratings, each filtration device affects the system static pressure uniquely.

As an example, a typical system with only a disposable fibre glass filter that has an initial flow rate of 450 L/s @ 190 Pa total static pressure (made up of 30 Pa from the filter, 95 Pa from the furnace and 65 Pa from the duct). As the filter loads (say doubling to 60 Pa) the static pressure increases, decreasing the flow. Lower flow results in lower static in the rest of the system. Assuming a quadratic function between pressure and flow for the furnace and duct, and a linear relation for the fan between 450 L/s @ 190 Pa and 350 L/s @ 255 Pa, the resulting system static pressure is 205 Pa, reducing the flow rate to 427 L/s. When other filter packages are substituted, results as indicated in Table A2.2 are obtained:

Air cleaner type	Initial total static (Pa) cabinet	prefilter	filter	duct	Total	Flow (L/s)
fibreglass	95	30	0	65	190	450
electrostatic	99	0	16	68	183	460
HEPA	58	30	125	40	253	353
electronic - flat plate	87	30	25	60	202	432

Air cleaner type	Final static pressure (Pa) cabinet	prefilter	filter	duct	Total	Flow (L/s)
fibreglass	86	60	0	59	205	427
electrostatic	97	0	32	66	195	443
HEPA	15	60	250	10	335	227
electronic - flat plate	75	60	25	51	212	417

Table A2.2. Effect of Air Cleaners on System Total Static Pressure and Flow

An electrostatic filter having a lower static than the fibre glass filter will allow 460 L/s air flow initially, reducing to 443 L/s when loaded (static doubled). A HEPA filter (with a prefilter) will reduce the initial airflow by 22% and the final airflow by 47%. Unless the fan is upsized, the flow reduction from a HEPA filter will compromise the ability of the system to deliver heating cooling and ventilation air. Electronic air cleaners (flat plate type) do not incur additional static by loading, however their particulate removal efficiency does drop.

Assuming an average filter condition, a 20% efficient single speed blower (assuming the efficiency of the fan and motor combination drops to 10% when static increase causes flow to be cut in half) running continuously (8760 hours/year) would have energy consumption as listed in Table A2.3.

Air cleaner type	Fan energy (kWh) clean	loaded	average	Other (kWh)	Total (kWh)
fibre glass	3,745	3,834	3,790	0	3,790
electrostatic	3,687	3,784	3,735	0	3,735
HEPA	3,912	6,662	5,287	0	5,287
electronic	-	-	3,730	350	4,080

Table A2.3. Air Cleaner Energy Impacts

Appendix A3. Other Technical Issues

A3.1 Diffusers

Fundamental research performed in the 1950's for high volume systems found the following results:(13)

- Increasing flowrates or supply velocities decreases the size of the stagnant zone (i.e. area of little or no air mixing) and the temperature gradient in the room.

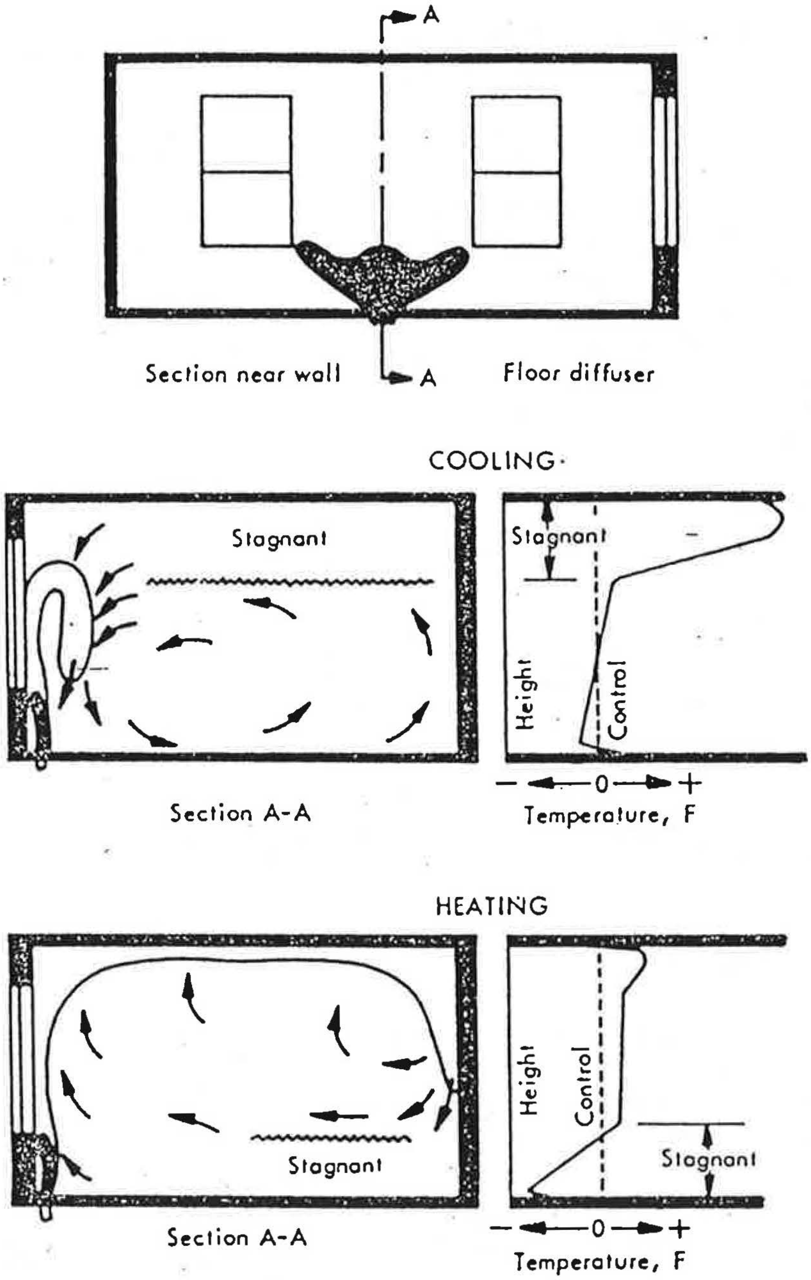
- Spreading the primary air (i.e. dispersing it over a wider area) reduces the thickness of the airstream which permits induced room air to enter and mix with the primary air more easily.

- In heating, vertically upward spreading supply air from a typical floor diffuser results in a uniform temperature about 1°C above the setpoint within the occupied zone above 500 mm. The air is stagnant below 500 mm, with the temperature dropping significantly below the setpoint at floor level. In cooling, however, the stagnant zone is largely above 1.8 m resulting in only a small thermal variation (1-2°C) in the occupied zone. (See Figure A3.1)

- Circular ceiling diffusers with horizontal discharge can produce severe temperature stratification; the stagnant zone engulfs the entire occupied zone. The temperature difference between floor and ceiling is roughly 10°C with the floor being 3°C below the setpoint and the ceiling 7°C above. Between ankle height (100 mm) and neck height (1.5 m), the temperature gradient was 7°C

- Use of manually adjustable ceiling diffusers which are more aerodynamically profiled (e.g. Techgrille by Nutech Energy Systems Inc.) allows for improved throw while allowing for flexibility in terms of air flow rate and velocity. If, however, the system has variable flowrates, automatic adjustment of diffusers would be desired.

- High sidewall horizontal discharge diffusers throw air across the ceiling plane above the occupied zone. In cooling, this has the desirable effect of uniform temperature at the setpoint in the occupied zone with a stagnant zone above. In heating, provided the horizontally projected jet can be made to follow the opposite wall to floor level, a temperature variation within 2°C from the ankle to neck height is achievable.



Spreading upward projection from a floor diffuser. Note that relatively large variations of room temperature occur in the stagnant zone.

Figure A3.1 Circulation Pattern and Thermal Gradients for a Floor Diffuser

High sidewall diffusers are the better choice for new construction with improved thermal envelopes for the following reasons.

1. Interior Surface Temperatures

The requirement for high volume flow, high velocity and wide spread is less critical in buildings with improved envelopes since the thermal load is greatly reduced and surface temperatures are close to indoor ambient conditions. Interior surface temperatures for windows and walls with different R-values for 20°C indoor and -25°C outdoor temperatures are shown below.

	Insulation Value	Surface Temp. °C
Window	RSI 0.35	6.0
	RSI 1.4	16.5
Walls	RSI 0.5	10.5
	RSI 2.0	17.5
	RSI 5.0	19.0

Diffusers need not be located at outside walls or near windows. However, care should be taken to judiciously locate them so as not to produce any uncomfortable drafts.

2. Comfort of Supply Air

Forced-air furnace systems which continue to supply ventilation when the heating element cycles off, can create cool drafty conditions for occupants. Even if a high ratio of return air to outside air is employed, cool drafty conditions with intermittent hot periods can result.

For example, -20°C outside air mixed with 6 times as much 20°C return air would result in a supply temperature of 14°C. This is below the F326 standard required heating supply temperature of 17°C for floor discharge.[5] The industry recommends ceiling or high sidewall discharge for supply air as low as 13°C which may be the case for air conditioning and ventilation supply.[4] Alternatively, a 75% effective HRV would raise the supply temperature to 19°C allowing the air to be introduced from floor diffusers without loss of comfort in a heating-only application.

For comfort cooling, ceiling diffusers can be designed with sufficient throw to blanket the occupied zone with cool air. However they are typically not a feature common in residential practice. High wall registers with engineered throw patterns would work almost as well and are consistent with ventilation delivery.

Separate space cooling packages often used in retrofit situations where forced air systems do not exist use high velocity small (50 mm) diameter ceiling discharge. Because the high velocity stream of air could cause discomfort if projected over a seating area, the outlets are usually located in the corners of rooms, discharging vertically downward.

In finished basements, floor registers are sometimes mounted on the ceiling to act as ceiling diffusers. As they are not designed to give the appropriate throw to blanket the room in cool air, instead the air falls to the floor directly below the diffuser and is not spread over the room).

Since the system flows to each room are sized and usually balanced for heating the cooling delivery will likely be out of balance. Some rectification of balance may be performed by the homeowner, such as closing basement registers in summer.

Diffusers for cooling systems are best located at the ceiling or high sidewall with horizontal discharge so as to blanket the occupied zone.

A3.2 Power Required to Move Air in a Round Duct

The following formula shows the power required to drive an air flow in a cylindrical duct.

$$P = 8\, f\, L\, \rho\, Q^3/(\pi\, D^5)$$

where:

P = power (watts)
f = friction factor (dimensionless)
L = length of duct
Q = volume flow (m^3/s)
D = duct diameter (m)
ρ = fluid density
π = 3.14159

Thus the power required varies as the inverse of the duct diameter raised to the fifth power, assuming constant friction factor, air flow, and duct length. Cutting the duct diameter in half, while maintaining the same flow rate, increases the power required to drive the air flow by a factor of 32. As the friction factor normally increases with decreasing duct diameter, the effect of reducing duct diameter is even greater.

A3.3 Negative Ion Removal

A lack of negative ions or an excess of positive ions in the air can have harmful effects on human health, causing tension, anxiety, migraine headaches, and reduced breathing capacity. It has been suggested that forcing air through metal ductwork creates friction that results in the loss of negative ions and an excess of positive ions.[39]

Selection of duct material, use of anti static coatings, and inclusion of negative ion generators for metal ductwork systems are potential improvements to potential problem.

The phenomenon of negative ions affecting human health is somewhat controversial in that some researchers believe the effect is negligible.[40]

Appendix A4. Innovative System Design

A4.1 Advanced House Systems

A4.1.1 Advanced House Descriptions

BRAMPTON ADVANCED HOUSE 1990

This was the first innovative house built under the advanced house concept promoted by EMR (now NRCan) in cooperation with the Canadian Home Builders' Association (CHBA). Completed in 1990, the Brampton Advanced House employs a fully integrated HVAC system supplying space heating, space cooling, ventilation with heat recovery, domestic water heating with greywater heat recovery and ice-based thermal storage.[36] A two-storey passive solar sunspace preheats ventilation air which is drawn in by negative pressure by virtue of being ducted to the return plenum. Fresh air enters high in the sunspace where it mixes with the warm stratified air. The air is then drawn through a shaft adjacent to the thermal mass of a contra-flow fireplace and finally by contact with the mass of a hollow core slab on the floor of the sun space. Ventilation is provided by an exhaust-only strategy resulting in negative pressure of the sunspace but maintaining balanced regime in the house itself.

The system utilizes a 300 L/s fan coil supplied by a heat pump which produces both hot and chilled water. In heating the fan coil receives hot water via the domestic hot water tank. The house had a circular staircase from second floor to finished basement and the return register was located directly at the fan coil and was not ducted floor-by-floor. Engineered supply registers were located high on interior walls. All ductwork was taped and insulated.

The central 100 W recirculation fan runs continuously so as to redistribute solar and internal gains near the ceiling. This creates a radiant ceiling effect and eliminates discomfort usually associated with forced-air furnaces.

ADVANCED HOUSES PROGRAM 1992-93

The Advanced Houses Program, sponsored by CANMET (NRCan) and the Canadian Home Builders' Association, was developed to accelerate the development of appropriate technologies by challenging the residential construction industry to build a number of innovative low energy, environmentally "green" houses across Canada. The energy target for these houses was to use less than one-half the energy per square metre of floor area of the R-2000 program houses. The following Advanced Houses were constructed:

B.C. Advanced House, Vancouver
Saskatchewan Advanced House, Saskatoon
Manitoba Advanced House, Winnipeg
Waterloo Green Home, Ontario

Hamilton NEAT Home, Ontario
Innova House, Ottawa
Maison Novtec, Montreal
Maison Performant, Longeuil, Quebec
P.E.I. Advanced House, Charlottetown
Nova Scotia Advanced House, Bedford

Advanced House technical requirements relating to forced air systems were limited to fan power :

- the heat recovery ventilator fans shall have an electrical power consumption not exceeding 1.2 W/ L/s of air flow capacity.
- the combination of the warm-air heating and heat recovery ventilator shall have an electrical power consumption not exceeding 0.75 watts per L/s of combined air flow.

The following sections describe the features of duct and fan systems used in the 10 Advanced Houses Program.

A4.1.2 Space Heating and Cooling Systems

Of the 10 Advanced Houses, 9 used forced air systems for providing the bulk of the space heating distribution. Only one house, the Saskatchewan Advanced House, used a hydronic system (radiant floor heating) as its sole heating distribution system. Three of the houses heated parts of the house with either hydronic radiant floor heating (B.C., Montreal Maison Novtec) or baseboard hydronic convectors (Manitoba) in addition to the forced air heating.

A4.1.3 Fan Motors

The most popular motor for forced air fans used in the Advanced Houses was the General Electric ECM Brushless Direct Current motor. The motor is a nominal 1/2 horsepower capacity, direct drive belly-band style that can be energized with either 115 or 230 volts. The motors come standard with 2 speeds, although the DC nature of the motor would allow for multiple speeds. The motor incorporates a microprocessor that can be programmed. In a fan application, the motor can be programmed for constant speed, constant torque, or constant flow if the characteristics of the fan are known. The motor must be programmed at the factory, or with a computer that has specialized software and an EPROM burner. The motor has a full load efficiency of 68%. Its advantage is that its efficiency remains high over a very wide speed or load range.

The power consumption of the forced air fans were measured in a number of the Advanced Houses. The power consumption values are given in the table below. The Brampton Advanced House circulation fan, using a PSC motor, is included for comparison.

	MOTOR INPUT Watts	AIR FLOW L/s	RATIO W/(L/s)
B.C.	150	400	0.375
Manitoba	225	N/A	
Hamilton	149	400	0.37
Waterloo	155	283	0.55
Montreal Novtec	203	470	0.43
Brampton	100	300	0.3

As can be seen from the above table, the air flows used were relatively generous considering the low space heat requirement of the houses. Generally these houses had design heat losses in the range of 1/3 to 1/4 that of conventional houses, and yet the air flows were not proportionately lower. Some systems provided air conditioning which would not allow the airflow dropped below 200L/s for a 1-ton unit.

A number of the houses used water heaters (B.C., Manitoba, and Hamilton) or ground source heat pumps (Novtec) for space heating, and with these units a lower water temperature is used to ensure higher efficiency of the water heater or ground source heat pump. It is not known if any of the teams performed an optimization of the air flow rates in relation to the space heating source temperature.

As can be seen, the power consumption values are considerably lower than the approximately 400 watts commonly found in residential systems.

A4.1.4 Ventilation Systems

All but two of the Advanced Houses incorporated air-to-air heat exchangers to provide ventilation air. Generally the air-to-air heat exchangers were connected to the forced air heating system, with the exception of the Saskatchewan Advanced House, which used only a hydronic radiant floor heating system. The Novtec House used an exhaust air heat pump to recover heat from the exhaust air. The Waterloo Green Home used a prototype regenerative rockbed heat recovery ventilator.

The air-to-air heat exchangers used were all of a standard configuration (plate types or rotary wheels). To improve motor efficiencies, the AC fan motors were replaced with brushless DC motors. However, no improvements were made to the fans, or the internal geometries of the heat exchangers. The Fasco Motor Company supplied the DC motors for most of the air-to-air heat exchangers.

A4.1.5 Possible Improvements to the Advanced House Duct and Fan Systems

The following are some steps for improving the systems:

1. Greater simplicity in the designs could have been used. As can be seen from Table 1, a number of the teams used 2, 3, 4 or 5 space heating zones with separately controlled thermostats. Because the Advanced Houses have high insulation values, the use of zoning to save energy is not warranted. Internal temperature differences of any magnitude are difficult to achieve in very low energy houses, as natural convection and conduction will act to balance temperatures in the houses. The separate zones add substantially to capital costs while making almost no impact on operating costs.

2. A more careful analysis of design air flows needed could have been undertaken. Given the relatively low space heating needs of the houses smaller air flows are sufficient for these types of houses. In those houses using water heaters and a fan-coil, an optimization could have been performed on the water temperature, coil heat transfer capacity, coil air side pressure drop, and air flows that would provide the appropriate amount of space heating capacity while minimizing the air flow requirement and power consumption. The Waterloo Green Home team provided one of the most detailed designs, including a slide-out cooling coil that allows for a smaller pressure drop on the air system during the heating season.

3. Superior fans could have been chosen. The GE ECM motors were the state-of-the-art at the time, and most of the teams used these motors. However, almost all the teams used forward-curved centrifugal fans, which are less expensive but inherently less efficient than backward-curved fans. The AEROVENT Company markets a backward-curved fan with an efficiency of 64% excluding drive losses (See also Reference 2).

A4.2 Other Innovative Systems

ARMOUR/CRAINFORD RESIDENCE

The Armour/Crainford residence in Toronto employs a system with three zones to accommodate disparate occupancies:

- Office heating and cooling
- Above grade residence heating and cooling
- Below grade residence heating only

No recirculation is employed as 100% fresh, filtered and tempered air is delivered via two HRV's (outfitted with heating and cooling coils and carbon filters) to short ductwork terminating in an intermediate floor plenum with floor and ceiling grilles as necessary. Ventilation air is thus coupled with thermal space conditioning and is accomplished by both radiant and convective means.

In the heating season the coils are supplied with hot water from a hot water storage tank which receives solar and wood heat prior to incurring natural gas heating.

Water for the cooling coils is provided by cistern water chilled by night-sky radiation cooling. Water runs over a metal roof at night which loses heat to deep sky which is below the ambient air temperature.

COUCHICHING HOUSES

This CMHC award-winning mechanical system design for 20 houses for the Couchiching Native Band at Fort Frances, Ontario, employs an intermediate floor plenum containing hydronic finned-tube convectors. Ventilation supply air from an HRV is blown into this plenum. Floor registers to upstairs and ceiling registers supply tempered ventilation air. The ventilation air provides part of the space heating while the floor and ceiling act as radiant surfaces. During operation of dryer exhaust, make-up air is provided by conveying cold outside air to the floor of an air sealed and thermally isolated basement cold cellar.

WALKER RESIDENCE

In the Walker residence near Ottawa passive gains from a south-facing sunspace and the radiant heat from a contraflow masonry wood heater migrate to the second floor via cross-over ducts in the second floor cavity. A blower circulates these gains through an electric sauna on the second floor which is the back-up heater. The air then circulates down to an insulated concrete crawl space plenum, which acts as coupled thermal mass, and back to the living space through standard floor grills. The result is that stratification and associated discomfort are minimized. Ventilation air is delivered via a HRV to the crawl space for mixing and circulation to the house. Air conditioning consisted of a hot water heat pump located in and drawing from the crawl space. By extracting heat from the crawl space during hot water demand cooling delivery capability was stored in the mass for even supply temperatures.

KANI RESIDENCE

The Kani residence in Toronto was a major retrofit of an existing bungalow into low energy two-storey house. Many of the principles of the Brampton Advanced house were "tested " in this project. This included sunspace preheat and the same integrated mechanical system and engineered high wall supply registers on interior walls. To minimize duct runs, the mechanical room is located in the closet of a second floor bedroom. The closet is airsealed and acts as a plenum for the forced air supply. Fresh air is drawn by negative pressure from the sunspace to a sealed drop plenum at the second floor ceiling and is mixed with return air, from a single register at the top of the stairs, for re-delivery to space. Taking advantage of the high performance envelope, conditioned supply air is delivered high at the centre walls of the house through taped and insulated ducts set in the return air drop plenum with good comfort results.

CMHC HOUSE FOR THE CHEMICALLY HYPERSENSITIVE

This house located at on CMHC property in Ottawa was designed for chemically hypersensitive occupancy. Numerous strategies were used to minimize outgassing, avoid envelope condensation and provide superior control of indoor air quality.[18]

Displacement ventilation and high performance particulate and activated charcoal filtration provide high ventilation effectiveness. A custom HRV maintains ventilation supply air at 18°C which is supplied at low flow near floor level to occupied spaces. The balance of the 3 kW heating load is supplied by hydronic radiant floor heating. A negative pressure plenum is used to exhaust from kitchens and washrooms as well as from in the exterior wall to avoid contamination to the occupied space.

If the outdoor air is deemed to be temporarily polluted, e.g. due the neighbour's garden pesticides, the HRV can operate in full recirculation mode.

The cooling system design does not require recirculation. The cooling package of two-thirds of a ton dehumidifies the ventilation supply air and chills the water in the radiant floor. The heat is rejected via the exhaust air stream whose rejection capacity is increased by humidifying.

DUMONT RESIDENCE

The Dumont Residence in Saskatoon, Saskatchewan has design heat loss of 5 kW at -34°C (15.3 W/m^2 floor area). For heating, the house uses a 6 kW hydronic fan coil supplied with 30°C water generated by solar thermal panels. The blower incorporates a General Electric brushless DC motor and a Delhi forward curved fan. In high speed, the blower uses 110 W to move 363 L/s of supply air (0.3 W/L/s). To minimize frictional losses, ductwork was carefully sealed at joints, air velocity in the system was kept low and transition fittings were carefully designed and installed. Pleated paper filters (25 mm thick) were employed for air cleaning. Judicious material selection and strict construction practices were employed to avoid pollutant sources in the house. A dual core HRV with two brushless DC motors was originally used to supply ventilation air (currently on loan to Saskatchewan Advanced House project).

The owner is considering upgrading the system to include: an economizer type retrofit of the HRV that bypasses the core in summer thereby reducing static pressure on the fans; relocating the coil at the same height as the solar hot water storage tank to allow the thermo-siphoning effect to eliminate the 6 W DC pump; replacing the fan with a backward curved air foil design.

PEAWANUK/WINISK RESIDENCES

After the town of Winisk, Ontario, on the south shore of Hudson Bay, was flooded out, these houses across the Winisk River in the new town of Peawanuk, replaced some of the housing of the old village. They have two finished levels with a wood stove on the lower level. The heat convects via ceiling and floor grilles to upstairs. The upstairs entry steps up so as to trap cold air which would otherwise cascade into the basement. The architect preferred to use intermittent exhaust fans with fresh air and combustion air preheated by finned ducts run parallel to the flue pipe.

Appendix A5. Performance Modeling

Forced-air systems serve two fundamental requirements: provide comfortable conditions for occupants, and ensure adequate indoor air quality is maintained. In doing so they consume energy (and produce its associated environmental impacts), and incur capital and operating costs. In order to compare how well systems meet the fundamental requirements, a model is required which defines their performance characteristics. This section provides a performance model framework which outlines methodologies for assessing characteristics of forced air systems. The methodologies range from computer models to equations to technical descriptions to enable qualitative comparisons.

A5.1 Heating, Cooling and Ventilation Requirements

All systems must first demonstrate that they are capable of supplying the heat load, cooling load and ventilation capacity as required by the building code and applicable standards or by alternative sizing methods as listed below:

Requirement	Conventional method	Alternative method
Heat load	CSA F280	peak hour detailed energy model
Cooling load	CSA F280	thermal flywheel model
Ventilation	CSA F326, NBC, OBC, BCBC	adjusted for ventilation effectiveness

1. Peak Hour Detailed Energy Model

CSA F280[13] uses outdoor design temperatures in the absence of solar and internal gains for calculating heat load. Peak heating demands for non-Part 9 buildings are often determined using a hour-by-hour computer model similar to those used for commercial buildings which accounts for solar and internal gains stored in the building mass. Using such a computer analysis for houses (e.g. ENERPASS) may result in a downsized heating plant. The reduction can be expected to be about 10%.

2. Thermal Flywheel Model

CSA F280 and ASHRAE use a fixed indoor design temperature of 24°C for cooling with low tolerance for temperature swings.[13,41] (ASHRAE allows for a 1.5°C swing from this setpoint.) However, the ASHRAE residential summer comfort zone allows indoor temperature to swing between 22°C and 27°C.[42] An hour-by-hour computer model which demonstrates that space temperatures remain within the comfort zone during the cooling season may allow significantly lower capacity cooling plants (in the order of 50% of conventional capacity) to be used.

3. Ventilation Effectiveness

Systems which demonstrate improved ventilation effectiveness beyond the requirements of CSA F326[5] or Provincial Building Codes could be credited with decreased ventilation capacity requirements. Similarly, low ventilation effectiveness would require increased ventilation capacity. (See discussion on ventilation effectiveness below.)

Indicators which are useful in comparing forced-air systems can be grouped into the following major categories, each of which is described below:

- comfort
- IAQ
- energy use and impact
- life cycle costs

A5.2 Comfort

It is important to recognize that comfort is a highly subjective and relative term which varies with the times, culture, season, occupant age and sex, and a complex host of other influences.

The steady-state condition is not necessarily optimal for comfort control. Not only do people have varying thermal regimes, but they themselves have time-varying preferences. In an effort to minimize complaint, the engineer has sought the neutral response condition. This is, however, of limited value since stimulation of the senses (e.g. sunshine warming you through a window on a cold winter day) can be deeply satisfying and ultimately produce more comfortable conditions.

The following indicators are an attempt to objectively determine comfort, primarily from a thermal perspective. However, despite years of research in this area, they do not ensure well-being. Instead, they represent a method to minimize complaints.

1. Room Temperature Profile

Air temperature normally increases with height above the floor. If the gradient is sufficiently large, local warm discomfort can occur at the head, and/or cold discomfort can occur at the feet, although the body on average is thermally neutral. The gradient in room temperature in the occupied zone, measured at the 0.1 m and 1.7 m levels is required to be no greater than 3°C to provide adequate comfort for 90% of the occupants.[42]

To minimize foot discomfort, floor surface temperatures should be between 18°C and 29°C.[42]

2. Air Speed

There is no minimum air speed necessary for thermal comfort within the thermally acceptable temperature ranges.[42] It is, however, essential that air speed be controlled so as to avoid drafts (unwanted local cooling of the body) for sedentary occupants.

The local air speed in the occupied zone is required to be less than 0.1 m/s to avoid discomfort from drafts for 95% of the occupants.[43] One study noted that hydronic convectors resulted in air speeds of 0.1 m/s during heating system operation, while a forced-air system produced air speeds up to 0.23 m/s.[44] Little data was found to establish if air speed is adequate to produce the desired "perfect" mixing condition assumed for conventional forced-air systems. Although the study results would indicate uncomfortable conditions resulting from forced-air system, more testing is required to determine how widespread are the results. Further research is required to compare air speed in non-forced air systems to those in conventional and innovative forced-air systems. As house loads decrease, forced-air flows are significantly reduced.

Air movement across the skin can produce a desirable cooling effect in summer. A flow of 1 m/s is equal to 2.5°C of cooling setpoint temperature. An airflow of 0.15 m/s produces negligible cooling effect.[42]

3. Temperature Drifts or Ramps

The rate of temperature change can also influence comfort. During steady state heating and cooling the thermal device normally cycles on and off in periods of 15 minutes or less. According to ASHRAE, if the peak cyclic temperature variation (i.e. setpoint differential) exceeds 1.1°C, the rate of temperature change shall not exceed 2.2°C/h.[42] There are no restrictions on the rate of temperature change if the cyclic variation is less than 1.1°C.

Temperature drifts refer to passive temperature changes in the space (e.g. solar gains) while ramps refers to actively controlled temperature changes (e.g. resetting setpoint after setback). The maximum allowable drift or ramp condition from a steady state starting temperature of between 21°C and 23.3°C is a rate of 0.5°C/h. The drift or ramp change should not extend above the upper operative temperature limit by more than 0.5°C for any more than one hour.[42]

4. Mean Radiant Temperature

The mean radiant temperature (MRT) is a measure of the area weighted surface temperatures that the body "sees". It relates to the thermal loss by the body to those surfaces. In a poorly insulated house, the MRT may be significantly lower than the air temperature resulting in the requirement to raise the thermostat setting to achieve comfortable conditions.

Alternately, when a heating system uses radiant surfaces to deliver heat to the space, air temperature can be lowered while equivalent comfort conditions are maintained.

The MRT of a space can be established from the average temperature of all surfaces in the space.

$$MRT = (\sum T_n \times A_n) / \sum A_n$$

where: MRT = mean radiant temperature (°C)

T_n = temperature of nth surface (°C)

A_n = area of nth surface (m^2)

Operative temperature

The operative temperature combines sensible temperature and MRT into one "equivalent" temperature by weighting them according to their heat transfer coefficients.

$$T_o = (h_c \times T_a + h_r \times MRT) / (h_c + h_r)$$

where: T_o = operative temperature (°C)

h_c = convective heat transfer coefficient ($W/m^2 \cdot K$)

T_a = ambient sensible room temperature (°C)

h_r = radiative heat transfer coefficient ($W/m^2 \cdot K$)

MRT = mean radiant temperature (°C)

Using typical values from ASHRAE Fundamentals for h_r and h_c of 6.0 and 4.7 $W/m^2 \cdot K$ respectively, the equation can be simplified to:

$$T_o = 0.56 \times T_a + 0.44 \times MRT$$

Operative temperature can then be combined with relative humidity into a single index known as Effective Temperature (ET*).

5. Humidity

The upper and lower limits of humidity in ASHRAE Standard 22-1992 are based on considerations of dry skin, eye irritation, respiratory health, microbial growth and other moisture related problems at a 10% dissatisfaction criterion. The minimum humidity ratio shall be maintained at 4.5 g/kg air, which ranges from 30% RH @ 20°C to 20% RH @ 27°C. The maximum relative humidity is 60%.[42]

Temperatures of interior building surfaces and materials (e.g. windows, ductwork) must be maintained above the dewpoint to avoid condensation.

6. Effective Temperature

Effective temperature combines operative temperature (which includes mean radiant and sensible effects) and humidity into a single index. It is defined as the temperature of an environment at 50% RH that results in the same total heat loss from the skin as in the actual environment. For a seated person in relatively still air the equation can be expressed as:

$$ET^* = T_o + 0.66 \times (p_a - 0.5\, p_{ET^*,s})$$

where:

ET^*	= effective temperature (°C)
T_o	= operative temperature (°C) (use t_{sub})
p_a	= water vapour pressure in ambient air (kPa)
$p_{ET^*,s}$	= saturated vapour pressure at ET* (kPa)

ET* can be calculated using the equation above, or it can be found using the ASHRAE comfort chart given in ASHRAE Standard 55-1992. According to the Standard, acceptable ranges for operative temperature (with 10% dissatisfaction criterion) are:

winter	(heavy slacks, long sleeve shirt, sweater)	20 - 23.5°C
summer	(light slacks, short sleeve shirt)	23 - 26°C
	(shorts, T-shirt)	26 - 29°C

Alternatively, in winter, clothing levels could be increased to reduce the minimum acceptable ET* below 20°C.

ET* considerations assume a general air speed that is no greater than 0.2 m/s. Over this range differences in comfort are not significant. For typical heating indoor temperatures the general air speed should not exceed 0.2 m/s. In summer higher temperatures combined with higher air speeds can provide equivalent comfort. For more discussion, see Section 2: Air Speed, above. For the purposes of ET* calculation it is assumed that typical forced air systems do not produce general air speeds significantly greater than 0.2 m/s.

To demonstrate how MRT, T_o and ET* would be applied, consider the following examples (at -20°C outdoor design condition):

Example 1. A room 3m x 3m x 2.5m high in a superior envelope house with two exterior walls (RSI 5.3), two 1.2 m^2 windows (RSI 0.88), two interior walls next to conditioned space, floor over conditioned space, and ceiling with attic above (RSI 8.8).

With a conventional forced-air delivery system, where:

$T_a = 21°C$

all exterior walls are 20.1°C

all interior walls are 21°C

window surfaces are 16.5°C

MRT = 20.6°C

$T_o = 0.56 \times 21 + 0.44 \times 20.6$

$= 20.8°C$

If RH is 30%, then $p_a = 0.747$ kPa

solving iteratively:

assume ET* ~ 20.5°C, then $p_{ET^*,s} = 2.414$ kPa

$ET^* = 20.8 + 0.66 \times (0.747 - 0.5 \times 2.414)$

$= 20.5°C$

This is within the ASHRAE comfort envelope.

Example 2. Consider the same house with ET* = 20°C and 50% RH. Solve for T_a:

by iteration, $T_a = 20.1°C$

Thus, the temperature could be lowered from 21°C to 20.1°C and still remain within the ASHRAE comfort envelope.

Example 3. Considering a house with more conventional insulation levels (walls RSI 2.64, windows RSI 0.35), ET* = 20°C and 30% RH. Solve for T_a:

by iteration, $T_a = 20.6°C$

Thus, the effect of cooler surface temperatures in a conventional house is a 0.5°C higher temperature setpoint requirement than in a well insulated house. Note that this has space heating energy implications not usually considered in energy calculations.

Example 4. Considering the conventional house above with ET* = 20°C and a ceiling radiant panel (9 m^2) creating a 50°C surface temperature (T_p), solve for T_a:

average unheated surface temperature (AUST) = 14.1°C

panel output $q_r = 4.96\ (((Tp + 273)/100)^4 - ((AUST + 273)/100)^4)$

$= 188\ W/m^2$

by iteration, $T_a = 18.1°C$

Thus, by adding a radiant input of 188 W/m^2 to the room acceptable operative temperature levels can be maintained with an air temperature of 18.1°C

7. Supply Air Temperatures

Air entering the furnace heat exchanger is required to be at least 15.5°C to avoid damage. If a fan coil or heat pump is employed, the entering air temperatures can be lowered, although generally not below 1°C unless special precautions are taken (e.g. 30% or greater glycol solution).

For uninsulated ductwork, the air temperature should not be below the dew point temperature to avoid condensation on the duct surface. CSA F326 suggests 14°C as the minimum uninsulated duct temperature.

The temperature of unheated supply air entering the space establishes the proper location of diffusers to avoid uncomfortable conditions.

Supply temperature from ventilation device:

$T_v = (T_i - T_o) \times eff_{HRV} + q_{ex}/(Q_v \times 1.2) + T_o$

$Q_t = Q_v + Q_r$

Supply temperature from air handler:

$T_s = (Q_v \times T_v + Q_r \times T_i)/Q_t + q_{motor}/(Q_t \times 1.2)$

Supply temperature at register:

$T_r = T_s + (T_i - T_s) \times UA_{duct}/(Q_t \times 1.2)$

where: T_v = ventilation supply temperature (°C)

T_i = indoor air temperature (°C)

T_o = outdoor air temperature (°C)

eff_{HRV} = apparent effectiveness of HRV (%)

T_s = supply air temperature leaving air handler (°C)

Q_t = total supply air flow (L/s)

Q_v = ventilation air flow (L/s)

Q_r = recirculated air flow (L/s)

q_{motor} = motor heat gain to system (W)

q_{ex} = duct heater output (W)

T_r = supply air temperature at register (°C)

UA_{duct} = duct conduction gain factor (W/°C)

8. Zonability

Zonability refers to the degree of individual room temperature control of which the system is capable. Rather than being a basic requirement for comfort, it is more an added benefit to occupants as it allows them to set room temperatures preferentially.

9. Noise Level

The level of noise generated by the HVAC system can affect occupant's aural comfort. People respond differently to fan noise. Some consider any fan noise disturbing while others consider a continuous fan sound as a positive background ("white noise") to mask other household noises. Intermittant fan noise is usually more noticeable and irritating than continuous fan operation. Generally, lower airflows and lower fan power will result in lower noise generation.

Direct duct connections between rooms will transfer sound generated outside the room. Ducts brought back to the main plenum would have lower sound crossover than branches splitting close to rooms. Short duct runs may require special sound attentuation.

A5.3 Indoor Air Quality (IAQ)

1. Contaminant Removal By Extraction

Contaminant removal at source by exhaust ports in kitchens and bathrooms is routinely practiced in newer Canadian housing. However, the effectiveness of the removal and its impact on indoor air quality is difficult to quantify rigorously. Quantities for ventilation rates used in codes are rooted in the dilution principle operating with ideal air mixing, rather than crediting the at-source removal principle.

2. Contaminant Removal by Dilution

Steady state concentration of pollutants are achieved by balancing the contaminant emission rate with dilution via outside air. The dilution rate for the critical contaminant is used (i.e. the contaminant requiring the largest outdoor air rate).

Outdoor air requirement:

OAR = N/(Cex - Ca)

where: OAR = outdoor air requirement (L/s)

OAR = outdoor air requirement for critical pollutant (L/s)

N = emission rate of critical pollutant (L/s)

Ce = concentration of critical pollutant at exhaust (ppm)

Ca = ambient concentration of critical pollutant outdoors (ppm)

Where it is assumed that carbon dioxide produced from human respiration is the critical contaminant, it can be used as a surrogate for acceptable indoor air quality.

Assuming the emission rate of CO_2 is 0.0052 L/s/person, the concentration of CO_2 at the exhaust is 1000 ppm and outdoors is 350 ppm:

OAR = 0.0052 L/s/pers / (0.001 - 0.00035)
= 8 L/s/pers

A value of roughly 8 L/s/person is used as the minimum outdoor air requirement by several residential ventilation standards.

3. Contaminant removal by filtration

Specific pollutants can also be removed by filters or air cleaners. Filters are designed to give specific removal efficiencies for particulates, odours, chemicals, micro-organisms, etc. Refer to Appendix A2: Filtration.

4. Ventilation Effectiveness

The outdoor air requirement (e.g. 8 L/s/person) assumes perfect mixing occurs in achieving contaminant removal. In reality, systems may have a ventilation effectiveness below unity (i.e. not perfectly mixed) or greater than unity (i.e. the concentration of pollutants at the exhaust exceeds the room average). The outdoor air requirement could therefore be adjusted to account for these differences. In the case of a poorly-mixed system a ventilation effectiveness of 0.6 could increase OAR by 67%. A displacement ventilation system with a ventilation effectiveness of 1.5 could decrease OAR by 33%.

$$OAR_{adj} = OAR \;/ VE$$

where: OAR_{adj} = outdoor air requirement adjusted for ventilation effectiveness (L/s)

VE = ventilation effectiveness of modeled system

5. Distribution "Evenness"

Distribution evenness refers to the ability of the system to maintain its distribution pattern through different operating conditions. For example, a system may be designed to deliver specific ventilation flow to each room in high speed operation, but may not achieve such a distribution when in low speed.

6. Duct Cleanability

Cleanability refers to the ability to access ductwork for routine inspection and cleaning. Length of duct runs, number of fittings, and choice of duct material all affect cleanability.

A5.4 Energy Use and Environmental Impact

1. Site Energy Consumption

Energy consumed at the site is used by utilities to charge customers. energy consumed by the HVAC system depends on the component efficiencies of the systems and the imposed thermal and electrical loads.

$$Elec = \sum(elec_i)$$

$$Fuel = \sum(fuel_i / eff_i)$$

where: Elec = annual electricity consumption (kWh/y)

$elec_i$ = annual electricity consumption of ith device (kWh/y)

Fuel = annual fuel consumption (kWh/y)

$fuel_i$ = annual output of ith device (kWh/y)

eff_i = average fuel efficiency of ith device (%)

2. Primary Energy Consumption

Site electricity consumption does not account for the efficiency of electricity production at the power plant and transmission losses. As used by the C-2000 program, primary energy for new projects or energy savings is a measure of the equivalent energy consumed at the margin by the power plant to deliver electricity to the site (i.e. house) at 33% net efficiency. Nuclear and hydraulic power primarily serve base load demand while the rapidly varying highest few percent of demand, i.e. on the margin, are typically supplied by coal combustion. Net efficiency may range from 25% to 50% depending on age and technology of fossil plants and distribution efficiency. It is assumed that electrical load reduction, such as from energy efficiency, primarily displaces marginal fossil combustion.

$$PE = Elec \times 3 + Fuel$$

where: PE = annual primary energy consumption (kWh/y)

Elec = annual electricity consumption (kWh/y)

Fuel = annual fuel consumption at site (kWh/y)

3. CO_2 Impact

The environmental impact of energy consumption can be quantified as the sum of direct and indirect emissions for each pollutant (e.g. CO_2, NO_x, SO_x, particulates, radionuclides). Direct emissions result from fuel consumed on site. Indirect emissions result from fuel burned at the power plant to produce electricity for the site.

For the purposes of this study, CO_2 emissions alone will be tracked. (Note that the equations could be used for any of the pollutants by substituting the appropriate emission factors.)

$$Em = Elec \times eef + Fuel \times fef$$

where: Em = annual emission of CO_2 (kg/y)
Elec = annual electricity consumption at site (kWh/y)
eef = electricity emission factor of CO_2 (kg/kWh)
Fuel = annual fuel consumption at site (kWh/y)
fef = fuel emission factor for CO_2 (kg/kWh)

The electrical emission factor for CO_2 (and other pollutants) are dependent upon the marginal mix of power generation sources making up the supply. For the purposes of the model, which is based in Ottawa, it is assumed that 90% of the marginal power is generated using coal-fired thermal generating stations (33% efficient including transmission losses) burning coal with an energy content of 8.134 kWh/kg and a carbon content equal to 2.74 kg CO_2/kg coal. The balance of power is from hydraulic and nuclear sources which are assumed to have no greenhouse gas emissions (e.g. CO_2, CH_4, chloro-fluorocarbons). Others may use a lower proportion of coal generation on the margin, but exact numbers are hard to source. However, given the recent outage of the Pickering nuclear station, it can be argued that the large majority of the marginal energy production is coal-based. The effect of a lower coal-based would reduce the total quantities proportionately but percentage savings remain the same.

The emission factor is then:

eef = (0.9 x 2.74 kg CO2/kg coal) / (8.134 kWh/kg x 0.33)
= 0.92 kg/kWh of electricity consumed on site

The natural gas emission factor is based on 51.1g CO_2/MJ of fuel heating value. Assuming a 22% transmission emission increase (for methane and CO_2 from losses and combustion at the well, line losses and combustion for compressors) and the emission factor is:

fef = 51.1g CO_2/MJ x 3.6 MJ/kWh x 1.1 / 0.9
= 0.225 kg/kWh of gas consumed on site

Note that the value for Fuel is obtained by dividing the fuel heating load by the AFUE (Annual Fuel Use Efficiency).

4. Embodied Energy

Detailed examination of embodied energy has not been included since measurement tools are not readily available. However, a rough first cut can be made by assuming that the cost of equipment and ductwork is proportional to embodied energy and relative savings can be approximated.

A5.5 Life Cycle Cost

1. First Costs

First costs include labour and capital costs of all materials and components associated with the HVAC system.

$$F = \sum(\text{labour}_i + \text{material}_i)$$

where: F = first cost ($)

labour_i = cost of labour for ith component ($)

material_i = cost of ith component ($)

2. Annual Energy Costs

Energy costs include annual electricity and fuel costs for all devices related to the HVAC system.

$$E = \text{Elec} \times \text{rate}_{elec} + \text{Fuel} \times \text{rate}_{fuel}$$

where: E = annual energy cost ($/y)

Elec = annual electricity consumption (kWh/y)

rate_{elec} = average electricity rate ($/kWh)

Fuel = annual fuel consumption (kWh/y)

rate_{fuel} = average fuel rate ($/kWh)

For the purposes of the model, average rates of $0.10 /kWh for electricity and $0.024 /kWh ($0.250 /m^3) for natural gas were used.

3. Annual maintenance costs

System maintenance costs include: mechanical repairs, annual tune-ups, filter cleaning/replacement, and duct cleaning.

$$M = \sum(M_i)$$

where: M = annual maintenance cost (\$/y)

M_i = annual cost of maintenance for ith component (\$/y)

4. Life cycle cost

The present worth of a system is the sum of the first costs and the present worth of the annual operating costs over the study period.

$$a_x = (i - e_x)/(1 + e_x)$$

$$P_x = [1 - (1 + a_x)^{-n}]/\,a_x$$

$$L = F + \sum(E_x \times P_x)$$

where: a_x = effective interest rate of future cost x

i = discount rate or cost of money (% per annum)

e_x = escalation rate of future cost x (% per annum)

P_x = present worth multiplier of future cost x

L = life cycle cost (\$)

F = first cost (\$)

E = annual energy cost (\$/y)

n = term (years)

For the purposes of applying the model, the discount rate was set at 8% and the escalation rates were as follows: electricity 6%, gas 3%, maintenance 2%. A term of 15 years was used.

5. Adaptability

The ability to adapt to the myriad of possible demands of future users is a key aspect of good system design to maintain future retrofit costs lower . For example, an adaptable design would anticipate future changes in fuel type by employing a hydronic coil in the air handler and a heat exchanger in the DHW storage tank so that only the water heating device would need replacing.

The HVAC systems should be flexible and adaptable so as to accommodate as many possible space utilization scenarios as possible. Attic and basement renovations and other additions will require HVAC services and will alter the heating and cooling load of the house. Subdividing the house into apartments or wanting to close off part of the house may require a zoned distribution system.

Appendix A6. Example Systems

To demonstrate the different paths residential HVAC could pursue to the year 2005, a future conventional forced-air system and two improved system cases were developed. This appendix outlines the characteristics of a future typical house and the system characteristics for each option. Detailed floor plans with duct layouts are attached.

A6.1 Future Typical House

All systems were modeled in a 200 m^2 house in Ottawa. It has the following assumed characteristics (which may be common by the year 2005):

Interior design temperatures:	summer	27°C
	winter	21°C

Floor area (w/ finished bsmnt):	196 m^2 (3 floors)
Volume:	489 m^3

	RSI (m^2·K/W)
Above grade walls	4.94
Basement walls - above grade	3.5
Basement walls - below grade	2.11
Slab	0.7
Roof	7.0
Windows	0.88

Infiltration rate:	0.05 ACH
Heat load:	4.9 kW
Cooling load:	4.6 kW
Occupants:	4 persons (3 bedrooms)
Min. outdoor air requirement:	30 L/s
Ventilation capacity requirement:	60 L/s

Ventilation:
- by heat recovery ventilator (HRV)
- 80% sensible recovery effectiveness
- 30 L/s low speed, 100 L/s high speed
- balanced flow (2 blowers)
- core defrosted by recirculated air
- exhaust air taken from kitchen and washrooms
- ventilation effectiveness (VE) = 1

All three systems modeled employ HRV's. The HRV blower performance differs from the conventional to the improved systems. The conventional system uses today's best available "off-the-shelf" HRV. Its blowers have air moving efficiencies of 8% and 17% for low- and high-speed, respectively. The improved systems use the same HRV in terms of thermal performance, but with

50% efficient blowers (low and high speed), to reflect the use of improved impellers and drive technologies.

A6.2 Future Conventional System

The conventional system uses HRAI's current design procedure, the current top-of-the- line HRV, and current smallest available condensing furnace (10.8 kW). (Note that it is oversized by 120%). The cooling package is a 5.3 kW (1-1/2 ton) split system with a refrigerant coil in the airstream. The air delivery rate was 465 L/s due to the oversized furnace, exceeding the minimum HRAI requirement of 1.5 ACH or 205 L/s for "comfort" air circulation (heating and cooling air flows were not critical). Registers were located in each room so as to "air-wash" the windows. Ductwork joints are not taped.

The ventilation effectiveness of this system had been normalized (i.e. VE = 1) to facilitate comparison between systems. The actual value may vary from unity, but further research is required to determine it.

The system specifications are as follows:

Heating device:	10 kW gas furnace (94% AFUE)
Blower:	375 W input, constant speed, continuous
Flow:	465 L/s @ 125 Pa external static
Location/config:	basement near outside wall, high-boy
DHW:	190 L gas fired direct vent water heater (85% AFUE)
HRV:	- blower low speed (80 W total input, 8% efficiency) - blower high speed (180 W total input, 17% efficiency) - intermittent high speed - manual & dehumidistat - soft connected to return plenum
Cooling:	5.3 kW split unit w/evaporator coil in supply airstream
Supply registers: room	floor mounted at perimeter (below windows) in each
Return grilles:	one on each floor
Distribution:	per HRAI (see attached drawings)

A6.3 Improved Systems

The two improved system options share the common feature of utilizing the HRV blowers to deliver heating and cooling via ventilation air flowrates. Space heating is provided by a hydronic coil in the supply air stream connected to a high efficiency storage gas hot water heater. The coil has sufficient capacity for supplying cooling. Based upon thermal flywheel considerations described in Appendix 5, the cooling package providing chilled water is sized at 2.3 kW.

Two ventilation modes are presented for Option 1, 100% outside air and recirculation with 30% outdoor air.

Although, duct runs are kept to a minimum in both cases, the improved systems differ primarily in how the air is delivered to the occupied space. The first improved system delivers ventilation air via high sidewall diffusers located as close to the HRV as possible. Air is exhausted from the kitchen and washrooms.

The second improved system delivers air via interstitial floor cavities, with diffusers located on the floor or ceiling of each room. Diffusers are located on the floor for the first and second storey rooms and on the ceiling in the basement rooms. Air is exhausted from the kitchen and washrooms and a corridor exhaust in the basement. On the second floor, high wall (acoustically treated) transfer grilles cascade exhaust air from bedrooms to the corridor ceiling and then into the washroom.

By having floor supplies and high wall or ceiling exhausts on the upper floors, a plug flow or displacement ventilation distribution pattern is established. This is intended to demonstrate increased ventilation effectiveness to the primary living areas when the heating coil is inactive (about two thirds of the heating season and all of the cooling season). When the heating coil is active, the supply air temperature is above room temperature and the supply air will rise rapidly to the ceiling similar to a conventional floor register system.

In options 1a and 2, the HRV supplies 100% outside air to the registers at low speed (30 L/s) continuously. In winter, two stage heating is provided. The blowers remain in low speed and the heating coil is activated when the first stage of heating is required (~1.5 kW output). High speed (100 L/s) is engaged when the second stage of heating is required (5 kW output). In summer, high speed is engaged when the cooling coil is activated. Intermittent high speed is available at all times for exhausting the washrooms and kitchen.

In option 1b, the 100 L/s flowrate is maintained at all times. During normal operation 30% of the supply air is from outside and 70% is recirculated from the exhaust. When washroom or kitchen use requires 100% outside air, the system adjusts its dampers accordingly, thereby exhausting "polluted" air directly outdoors.

Options 1a and 1b are assumed to have a ventilation effectiveness (VE) of 0.7 relative to the future conventional case (VE = 1) due to their low flowrates and location of their diffusers high on the walls in the centre of the building.

Option 2 is assumed to have a relative ventilation effectiveness averaging 1.5 on the first and second floor from the displacement ventilation configuration, and 0.7 in the basement due to the low flow ceiling registers.

Options 1a & 1b Improved system - high sidewall registers

Air is delivered via high sidewall diffusers located as close to the HRV as possible.

The system specifications are as follows:

Heating device:	5 kW hydronic coil (sized for cooling) 94% AFUE storage water heater (integrated w/ DHW)
Pump:	50% eff motor, 125 W input on-demand for heating/cooling
Blower:	see HRV
Flow:	100 L/s @ 40 Pa external static 1a. 100% outside air 1b. 30% outside air, 100% on call for high speed exhaust
Location/config:	1st floor, central, in ceiling
DHW:	integrated w/ space heating
HRV:	- blower low speed (3.6 W total input, 50% efficiency) - blower high speed (60 W total input, 50% efficiency) - intermittent high speed - 2nd stage heating, cooling, manual & dehumidistat
Cooling:	2.3 kW water cooler single heating/cooling hydronic coil
Supply registers:	high sidewall in each room, centrally located
Exhaust grilles:	at air handler, washrooms and kitchen
Distribution:	minimal supply and exhaust duct runs (see attached)
Ventilation:	VE = 0.7

Option 2 Improved system - short ductwork / radiant plenum

Air is delivered via interstitial floor cavities, with diffusers located on the floor or ceiling in each room. During heating, the air temperature in the plenum is between 25 to 30°C. Heat is transferred radiantly to the space via the ceiling and floor surfaces and convectively via the ventilation air flow. When heating coil is inactive, air is distributed to upper floors in displacement ventilation mode.

This system is similar to 1a, with the following modifications:

Supply registers:	floor of 1st and 2nd floor rooms, ceiling of basement
Exhaust grilles:	ceiling of washroom and kitchen and lower floor corridor
	above-door transfer grilles from bedrooms to corridor above-door transfer grille from corridor to washroom

Distribution:	interstitial floor cavities are supply plenums radiant floors/ceiling for sensible heating/cooling (see attached)
Ventilation:	displacement ventilation to upper floors (VE = 1.5), basement VE = 0.7

A6.4 Summary of Example Comparison Results

The example systems were evaluated using the performance assessment model framework presented in Appendix A5. The results are summarized in Table A6.2 below.

The detailed energy consumptions, environmental impacts in terms of CO_2 and energy costs are given in Table A6.3 The detailed costing and life cycle summary is given in Table 6.4.

Life cycle cost analysis of options requires capital or first cost, energy costs and maintenance costs. Cost estimates for system first costs were made for the ductwork, HVAC appliances and ancillaries. Since the focus of the study is the distribution system, costs for ductwork installations for the different options was solicited from a contractor in Toronto. The material and labour costs, including taxes, for ductwork only for the conventional and improved options are given in Table A6.1.

The costs for the distribution systems from Table A6.1 were used in Table A6.4

	Toronto
Conventional System	
Material	$1150
Labour	$2550
Total	$3700
Improved System 1 (high wall)	
Material	$ 850
Labour	$1450
Total	$2300
Improved System 2 (plenum)	
Material	$ 800
Labour	$ 900
Total	$1700

Table A6.1 Forced Air Distribution Capital Costs for Toronto.

	Conventional	Improved 1a & 1b	Improved 2
Comfort			
Room temperature profile	acceptable	acceptable	acceptable
Temperature recovery rate	acceptable	improved	improved
Air speed	acceptable	acceptable	acceptable
Temperature drifts or ramps	acceptable	acceptable	acceptable
Humidity	30%	30%	30%
Effective temperature	20.5°C	20.5°C	20.5°C
Zonability	low	improved	improved
Acoustics	acceptable	improved	improved
Indoor Air Quality			
Contaminant removal by dilution	acceptable	acceptable	acceptable
Contaminant removal by dilution	acceptable	acceptable	acceptable
Contaminant removal by filtration	N/A	N/A	N/A
Ventilation effectiveness	acceptable	acceptable	improved
Distribution "evenness"	acceptable	a. maybe uneven at low speed b. acceptable	
Duct cleanability	acceptable	improved	acceptable
Energy Use and Impact			
Site energy consumption (gas)	9,947 kWh	a. 12,043 kWh b. 11,196 kWh	12,043 kWh
Site energy consumption (elec)	4,728 kWh	a. 1,113 kWh b. 1,403 kWh	1,113 kWh
Primary energy consumption	24,132 kWh	a. 15,381 kWh b. 15406 kWh	15,381 kWh
CO2 impact	6,588 kg	a. 3,733 kg b. 3,810 kg	3,733 kg
Embodied energy reduction	base	a. 27% b. 25%	32%
Life Cycle Costs			
First costs	$12,340	a. $9,065 b. $9,315	$8,435
Annual energy costs	$712	a. $401 b. $409	$401
Annual maintenance costs	$175	$55	$55
Life cycle cost	$22,687	a. $14,227 b. $14,640	$13,597
Adaptablility	low	high	high

Note: For the purposes of the model, average rates of $0.10/kWh for electricity and $0.024/kWh ($0.250 /m^3) for natural gas were used.

Table A6.2 Summary of Performance Model Results

	Conventional	Improved 1a,2 100% OA	Improved 1b Recirc
Site energy consumption			
Gas	(kWh)	(kWh)	(kWh)
Heating	4,065	6,723	5,877
DHW	5,882	5,319	5,319
Total	9,947	12,043	11,196
Electricity			
Fan(s)	4,006	205	526
Cooling	722	657	627
Pump	0	250	250
Total	4,728	1,113	1,403
Primary energy consumption			
ekWh			
Gas	9,947	12,043	11,196
Elec.	14,185	3,338	4,210
Total	24,132	15,381	15,406
Reduction		36%	36%
Environmental Impact			
CO_2 (kg/yr)			
Gas	2,238	2,710	2,519
Elec.	4,350	1,024	1,291
Total	6,588	3,733	3,810
Reduction		43%	42%
Annual energy cost			
electricty @	$ 0.100 /kWh		
gas @	$ 0.024 /kWh		
	$ 0.250 /m3		
Gas			
Heating	$ 98	$ 162	$ 141
DHW	$ 141	$ 128	$ 128
Total	$ 239	$ 289	$ 269
Electricity			
Fan(s)	$ 401	$ 21	$ 53
Cooling	$ 72	$ 66	$ 63
Pump	$ -	$ 25	$ 25
Total	$ 473	$ 111	$ 140
Annual cost	$ 712	$ 401	$ 409
Savings		44%	42%

Table A6.3 Energy Use and Impact for Example Systems

CMHC Residential Forced-air Study
MODELED EXAMPLES

LIFE CYCLE COST

FIRST COSTS	Conventional	Improved 1a (Highwall, 100% OA)	Improved 1b (Highwall, recirc)	Improved 2 (Displ. ventil.)
Materials				
ductwork	$1,150	$800	$800	$800
HRV	$1,500	$2,000	$2,200	$2,000
furnace	$2,700	$0	$0	$0
DHW heater	$1,200	$1,800	$1,800	$1,800
pump	$0	$150	$150	$150
heating coil	$0	$400	$400	$400
cooling system	$2,500	$1,800	$1,800	$1,800
TOTAL materials	$9,050	$6,950	$7,150	$6,950
Labour				
ductwork	$2,500	$1,500	$1,500	$870
HRV	$150	$200	$250	$200
furnace	$270	$0	$0	$0
DHW heater	$120	$180	$180	$180
pump	$0	$15	$15	$15
heat/cool coil	$0	$40	$40	$40
cooling system	$250	$180	$180	$180
TOTAL labour	$3,290	$2,115	$2,165	$1,485
TOTAL first cost	$12,340	$9,065	$9,315	$8,435
ENERGY COSTS				
electricity	$473	$111	$140	$111
gas	$239	$289	$269	$289
TOTAL	$712	$401	$409	$401
MAINTENANCE COSTS				
ductwork	$30	$10	$10	$10
HRV	$25	$25	$25	$25
furnace	$100	$0	$0	$0
DHW heater	$10	$25	$25	$25
cooling system	$10	$10	$10	$10
TOTAL	$175	$70	$70	$70

LIFE CYCLE COST

discount rate	8%	term (years)	15		
escalation rate (elec)	6%	eff. interest rate (elec)	2%	PW multiplier (elec)	12.96
escalation rate (gas)	3%	eff. interest rate (gas)	5%	PW multiplier (gas)	10.48
escalation rate (maint)	2%	eff. interest rate (maint)	6%	PW multiplier (maint)	9.79

	Conventional	Improved 1a	Improved 1b	Improved 2
First cost	$12,340	$9,065	$9,315	$8,435
PW elec costs	$6,127	$1,442	$1,819	$1,442
PW gas costs	$2,507	$3,035	$2,821	$3,035
PW maint. costs	$1,713	$685	$685	$685
LIFE CYCLE COST	$22,687	$14,227	$14,640	$13,597
Savings		37%	35%	40%

Table A6.4 Life Cycle Costs for Example Systems