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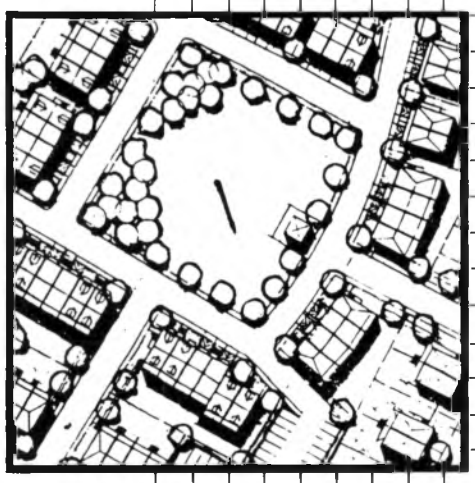
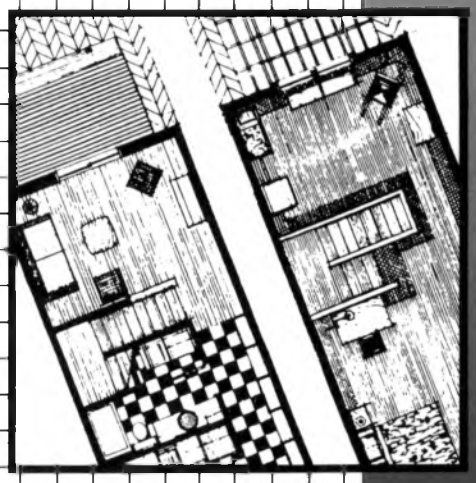
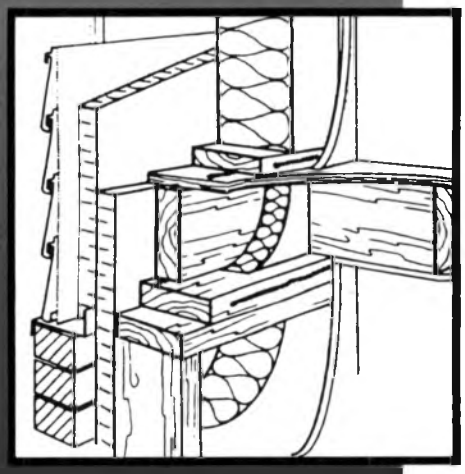
Sustainable Residential Developments

Planning, Design and Construction Principles







"Greening" the Grow Home

Canada

McGill University
School of Architecture
Affordable Homes Program

NHA 6781

Sustainable Residential Developments:
Planning, Design and Construction Principles
("Greening" the Grow Home)

Affordable Homes Program
School of Architecture
McGill University

Avi Friedman
Vince Cammalleri
Jim Nicell
Francois Dufaux
Joanne Green

Research Assistants:

Susan Fisher - *Xeriscapes*
Aud Koht - *Environmental Comfort*
Kevin Lee - *Water Efficiency*
Aryan Lirange - *Water Efficiency*
Denis Palin - *Mechanical Systems*
Mark Somers - *Waste Disposal*

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Abstract

The notion of sustainable development has become an important issue in housing. Generally, the term has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In addition to seeking a compromise between conservation of the natural environment and pursuit of economic growth, the development of sustainable housing projects includes structural, social and cultural dimensions. While many of the issues involved in the assessment of sustainability are difficult to quantify, various planning, design and construction approaches which are consistent with the principles of sustainable development can be identified.

The narrow-front rowhouse, for instance, is one housing type that facilitates the implementation of sustainable principles. The Grow Home is an example of a narrow-front rowhouse which has been successfully implemented. It was developed in 1990 at the Affordable Homes Program of McGill University as an affordable and adaptable alternative for an urban dwelling. The design was for a townhouse of 93 square meters, measuring only 4.3 meters wide.

The design of the Grow Home addresses both the functional requirements and financial limitations of the changing North American household. Simple and effective design strategies ensure that resources are used efficiently in the development, construction and operation of housing, reducing both cost and environmental impact. The narrow-front rowhouse configuration allows significant reductions in the use of land and infrastructure as well as energy consumption, since the heat losses are restricted to two exposed walls and a small roof area. The house's small size and simple layout make efficient use of construction materials. By eliminating irregular contours and staggers, reductions in material wastage and cost can be expected at every stage of the construction process, from foundation to roofing. Both labour and material requirements are reduced by simplifying the construction task and standardizing the basic unit design.

The inherent qualities of the Grow Home make it an appropriate housing form in any discussion on sustainable development. This study investigates a broad range of issues related to planning, design and construction of sustainable residential developments, using the Grow Home as a case study. Social, economic and environmental concerns are analyzed at the unit, site and community level. The report is divided into three parts.

The first part addresses several aspects of the housing unit, ranging from general planning approaches through design and detailing of the building envelope. Water-efficient landscapes and plumbing fixtures, responsible domestic waste disposal and good indoor air quality are among the topics covered. The effect of specific building systems, components and materials on the environment throughout their life cycle is also examined, including basic construction materials, window units, mechanical systems and prefabricated wall alternatives. For each subject, the discussion focuses on strategies for minimizing the environmental impact of design solutions. This includes conserving energy and other natural resources, minimizing land, water and air pollution, and providing for healthy indoor environments. Where possible, the economic and environmental impact of proposed solutions are evaluated.

While the first part of the report evaluates the impact of technical improvements at the unit level, the second part examines some more general environmental, social and economic issues as they apply to lot subdivision and site planning. Here, the study concentrates on the creation of sustainable communities. Strategies for building housing developments are proposed which are not only resource-efficient and ecologically-sound, but which provide pleasant, comfortable and functional living environments. Topics include site planning, vehicular circulation and parking, outdoor spaces, environmental comfort and housing identity. Alternative approaches to these are illustrated in the third part of the report through three examples of urban developments with varying densities, housing types and planning approaches.

The report is formatted such that each principle of sustainable development is discussed as an independent subject, comprising a separate section of the report. This facilitates rapid retrieval of specific information, and allows for convenient upgrading and expansion. Each section is summarized with a set of concise guidelines, references and suggestions for further reading, making it practical for architects, planners and builders to access information at various levels of detail.

General Introduction

Background

Sustainable development has become one of the key issues debated in the field of housing. The term sustainable development can be defined in various ways. Globally, it is seen as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). In the industrial world, sustainable development refers to forms of economic development which stress the importance of environmental quality and the conservation of nature's assets (Pearce, 1991). In addition to seeking a compromise between the natural environment and the pursuit of economic growth, the parameters of sustainable development include structural, social and cultural dimensions.

Although it is possible to describe the general direction in which residential development must proceed in order to promote sustainability, the precise conditions for sustainability vary according to individual projects and sites. The general principles of sustainability must be adapted, tailored and refined to satisfy local circumstances.

Narrow-front row-housing represents a concrete and realistic approach to adhere to the demand for more affordable housing, as well as to uphold the general principles of sustainable development.

In June 1990, the McGill Affordable Homes program unveiled a prototype of a narrow-front town house with a construction cost of $40,000. Several objectives underlined the design principles of this project. The first and foremost was to demonstrate that affordability can be achieved by reducing unit size, while maintaining high quality construction and materials. A second objective was to demonstrate that the socio-economic changes in North America over the past few decades have created a demand for different house forms. These new forms better address the spatial needs and lifestyle concerns of clients that, in the past, were considered marginal. Today's housing must be designed to accommodate a variety of users: singles, couples, single-parent families, and the traditional family unit. The Grow Home has been modified by builders to meet these demands and as a result, has been successful in the marketplace with 1000 units built in approximately one year (Figure 1).

The higher density housing type offered an alternative to low density planning solutions. By virtue of the Grow Home's inherent characteristics, both the user and society benefitted from major financial savings. Land and infrastructure costs per unit are significantly reduced compared with traditional detached housing. Less building materials are used during construction, and the energy performance of the house is by far superior when compared to a conventional detached home.

During the design phase, the inherent environmental benefits of the Grow Home were not investigated. The purpose of this research project is to conduct this investigation. A selected number of technical and design topics relating to both micro and macro aspects of the house are studied. The study is not restricted to technical environmental issues (e.g. energy and resource efficiency). The social and economic benefits of the Grow Home are also discussed. Both builders (the decision makers) and owners (the end users) focus on economics and well-designed places. Sustainable communities will be successful only if economic and social factors are understood and integrated into design solutions, in addition to environmental considerations. All three factors, economy, society and environment must be integrated into community design in an effort to encourage sustainable living practices.

It is essential to further identify the economic, environmental and social variables which contribute to sustainable housing alternatives.

Economy

The restructuring of the Canadian economy away from resource-based activities and heavy manufacturing industries means that there will be a greater population concentration around urban centres whose economies are primarily service and information-based (Pearce, 1991). With land and infrastructure costs having increased to 24% of the total cost of a new home in 1982 from 11% in 1949 (U.S. League of Savings, 1983) it will be necessary to re-evaluate the current housing market in order to make it affordable for people who want to live near the city, especially low- to moderate-income families and first-time home buyers. In addition, the increased cost of construction and the decline in median income relative to median housing prices have further contributed to the affordability gap.

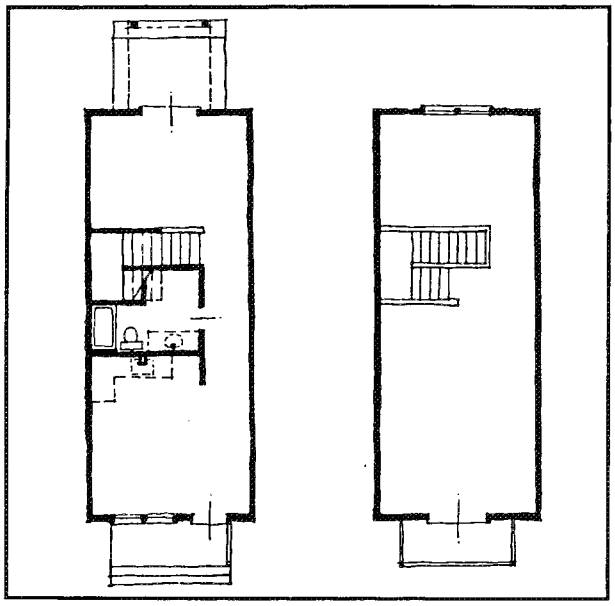
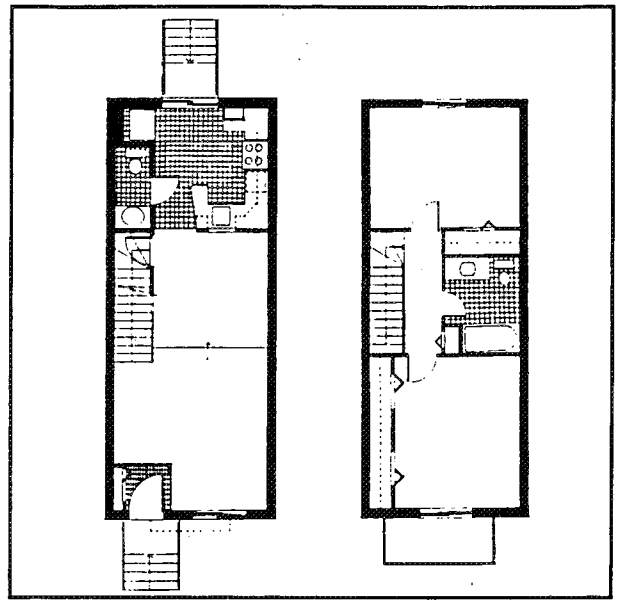


Figure 1: Plans of a Grow Home Unit, Conceptual



Plans of a Modified Grow Home Unit, Built

At present, over 60 percent of Canada's housing stock is made up of single-family, detached dwelling units, the least dense of housing options and the most consumptive in terms of land, energy and water (CMHC, 1991). However, home buyers have very high expectations from their housing and still consider the single family detached home the preferred dwelling type (Friedman and Cammalleri, 1992). Unfortunately, the single-family detached home is the least economical of all housing: detached houses consume anywhere from 15 to 67 percent more energy than other common ground-oriented housing options and they accommodate some 60 percent less people per net hectare than row-houses (CMHC, 1991). By increasing density, land and infrastructure is used more efficiently, the cost of building materials is reduced, and heating energy costs are lowered. These economic advantages of high-density developments will make housing more accessible to low and medium-income families and to many first-time home buyers, particularly if smaller, more efficiently-planned units are provided.

The home building industry should also be convinced of the economic advantages of increasing development density. The builder is the final decision-maker in the home building industry and is ultimately responsible for the implementation of new ideas in housing development. A builder's decisions are based on market-driven forces and on a return on investment. The organizational structure of the building industry must be understood in order to initiate change: the majority of house construction is done by small companies who build 25-100 units per year making it very convenient to build simple, low-cost units (CMHC, 1988). Considering the generally conservative nature of the industry, the introduction of innovative design and building technologies can only be successful if it integrates well with this established practice. The only way to succeed with new ideas is to make them appealing to builders. Novel housing practices must be demonstrated to illustrate the relative ease of implementation, the potential for market acceptance and economic viability. Also, a certain range of buyers interested in affordable housing must be targeted to exploit the existing demand for this new type of housing.

Society

A knowledge of relevant demographic trends is necessary for builders to respond to changing market conditions. Today's housing must be able to adapt to life-cycle and lifestyle changes and must provide all the necessary amenities at both the unit and community level.

Several significant changes in the demographic make-up of society have contributed to the need for change in the type of housing currently available. The traditional image of the family consisting of a married couple with the father working and the wife at home with the children represented only 17% of families in

1989, a drop from 27% in 1980. Average household sizes have decreased to 3.18 persons with 42% of households having only one or two people. Lone-parent families, due to the increase of divorce and separation, have risen from 11 % in 1980 to 13 % of all families with children in 1989. Deferral of marriage, the tendency for divorced or separated people to remain as separate households and a steady increase in the number of elderly people remaining in their own homes has increased the proportion of single-person households to 31% (CMHC, 1990). In a survey of recently built, narrow-front row-house home buyers, it was found that these statistics directly correspond to the socio-economic cross-section of the purchasers (Friedman and Cammalleri, 1992). Builders will have to respond to these changes in the marketplace and provide a wider range of housing types to suit the rapidly changing demographic profile of North American society.

Another large buyer group is the two income family with children which now represents 50% of all households, an increase from 43% in 1980 (CMHC, 1990). The increased time pressures and reduced maintenance time facing these homeowners are giving rise to the need for multiple-use spaces such as kitchen/activity centres and offices located within the home. Also, an increased demand for smaller, easily-maintained houses and "smart" house systems is expected and builders will have to respond accordingly.

Diversity in the housing stock within the same development can be a good solution to accommodate a variety of family types. Different families will require design strategies which can provide for several functional and spatial needs within the same structure. Homes need to be designed for growth and adaptability in response to changing life-cycle and lifestyle needs. Considering that the life-span of a house is between 60 and 80 years and due to the mobility patterns of North Americans, a house will, on the average, accommodate between 6-8 users during its "lifetime." Thus, in addition to being flexible, houses must be designed to be able to adapt to the changing needs of its original users as well as those of subsequent occupants.

Environment

The natural and built environments can often be incompatible but they can also be mutually reinforcing. Integrated decisions have to be made at the beginning of the development cycle when social goals and policies are being set. Considering social, economic and environmental issues near the end of a project proposal makes it difficult to act responsibly and respect the principles of sustainable development. A transition to more sustainable forms of development does not mean returning the planet to a hypothetical "natural" state in which human activities have no impact; people cannot live on the earth without altering the environment (MacNeill, 1991). Sensitizing the public to the benefits of sustainable development is the key to achieving these benefits, as a demand will be created to which the industry will undoubtedly respond.

Society is aware of the extent to which the earth's natural resources are being depleted. With this recognition, changing attitudes, behaviour and lifestyles are emerging. Would-be homeowners are beginning to demand houses that use less resources both to build and operate. Responding to these changing values, builders are starting to use resource saving strategies as marketing tools. Builders have started to respond to basic design principles, thereby facilitating environmentally-sound living spaces.

In addition, a more efficient utilization of the existing infrastructure such as sewers, roads and community facilities is necessary. A reduction in the quantity of required material, as well as energy consumption in the occupancy phase would not only benefit the environment, but also reduce construction and operating costs.

The success of sustainable developments relies on the integration of economic, social and environmental considerations. These factors must be recognized and addressed in the initial design stages to ensure appropriate implementation and attainment of potential sustainable developments. Increasing development density, in the form of the narrow-front row house, is recognized as a viable solution to respond to today's social, economic and environmental challenges.

Objective of the Study

The objective of this paper is to demonstrate how sustainable developments can be implemented if planners, developers and builders familiarize themselves with the principles and practices that encourage sustainability.

In the past three years, the Grow Home has progressed from a concept and demonstration unit on campus to a reality in the marketplace. The post-occupancy evaluations conducted at recent projects provided the opportunity to interview both builders and home owners. Efficient construction and affordable selling prices were found to be the key motivators for both builders and buyers. Communication of innovative ideas and principles need to consider the homebuilding industry if implementation is to be achieved. In an attempt to reach an audience of builders, architects and planners, this report has several practical features:

- The reader should be able to select from the available information that which is relevant material.
- Numerical data and graphic illustration were used to supplement the written text.
- The study of technical and planning issues vital to the design of sustainable units and communities was undertaken in separate sections.
- Three design alternatives, each of a different density, were used to illustrate the possibilities for a particular site and provide basic guidelines for sustainable design.

Structure and Outline of the Report

The study consists of three parts. The **first part** provides information on the products, methods and practices currently used to conserve energy, land, water and other natural resources, such as building materials. The issues are analyzed at both the unit and the community levels. The main areas of research in this section include building materials, energy efficiency, water efficiency, and waste disposal.

In the **second part**, principles related to the creation of more comfortable and livable Grow Home housing environments are studied. Site planning principles for sustainable communities, vehicular circulation and parking, outdoor spaces, the creation of community and house identity, and environmental comfort are the five areas of research.

Part three demonstrates the ideas that were developed in the previous sections for an existing site located in Aylmer, Quebec. The site was selected for a number of reasons: a Grow Home housing project is currently being built on this site, the integration of a new community into an existing urban fabric is a favourable site condition in terms of sustainable planning practice and the topography is interesting as a river sits to the east and the town of Aylmer to the west.

Three specific designs at the community level are presented. Each proposal attempts to confront different physical, environmental and social features that were studied in previous sections. The designs are sufficiently detailed to enable quantitative and qualitative comparisons to be made.

This document is intended to assist builders, architects, planners and housing authorities in their efforts to promote more sustainable living environments.

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The Grow Home

Background

In June, 1990, a team of researchers from the Affordable Homes Program at McGill University, sponsored by Dow Canada, developed the Grow Home--an affordable and adaptable alternative for an urban dwelling. The design was for a townhouse of 93 square meters, measuring only 4.3 meters wide. It had a kitchen, bathroom and living room on the ground floor. An unpartitioned second floor, which could later be modified to include two bedrooms and a second bathroom, was proposed in an effort to reduce costs and enable the owners to complete the unit at their own discretion (figure 1). A full-scale prototype of the house was erected on the university campus and opened to the public for one month (figure 2).

The Grow Home was intended to demonstrate that affordable living accommodation could be built for under $40000 without sacrificing quality or occupant living comfort. It was designed under the belief that housing prices could be reduced by focusing on the product itself and reducing construction costs, an element that has been considered to play an insignificant role in the affordability equation. It was aimed at sensitizing the public to an alternative form of housing, more suited to the changing demographic profile of the North American household and more attainable to the average young, first-time buyer.

The design of the Grow Home was based on seven principles, as follows (Rybczynski et al., 1990).

The Narrow-Front Rowhouse

The house that shares its side walls with its neighbors is described variously as a rowhouse, townhouse, or terraced house, and is a traditional urban solution that dates back to at least medieval times. During the Industrial Revolution, the rowhouse became the chief housing form in cities, both in Britain, and in America. Its chief advantages were that it could be built on a fairly narrow plot, typically between twenty and twenty-four feet wide, which allowed relatively high densities, but which also incorporated most of the advantages of the individual, single-family home: a private front-door, easy access to the ground, and a clear definition of a public, street side, and a private, rear garden.

The chief constraint on the rowhouse is the width between the shared walls on either side. Since the rowhouse has only two facades available for windows, its width governs its depth, and also the number of rooms that can be placed against the exterior, windowed wall. In nineteenth-century London, houses, that is to say rowhouses, were classified according to width: Class I were twenty feet wide and four floors high; Class II were eighteen feet wide, shallower and three floors high; Class III were sixteen feet wide, two stories high, with a basement; Class IV were fifteen feet wide, two stories high, without a basement (Muthesius, 1982). The important distinction was between the first two,

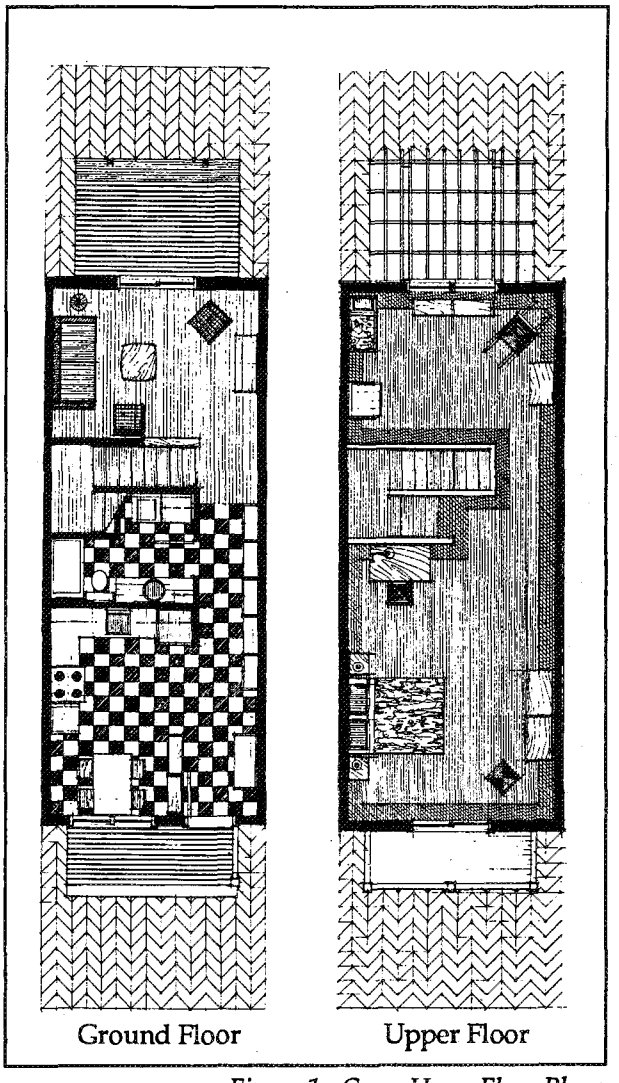

Figure 1: Grow Home Floor Plans

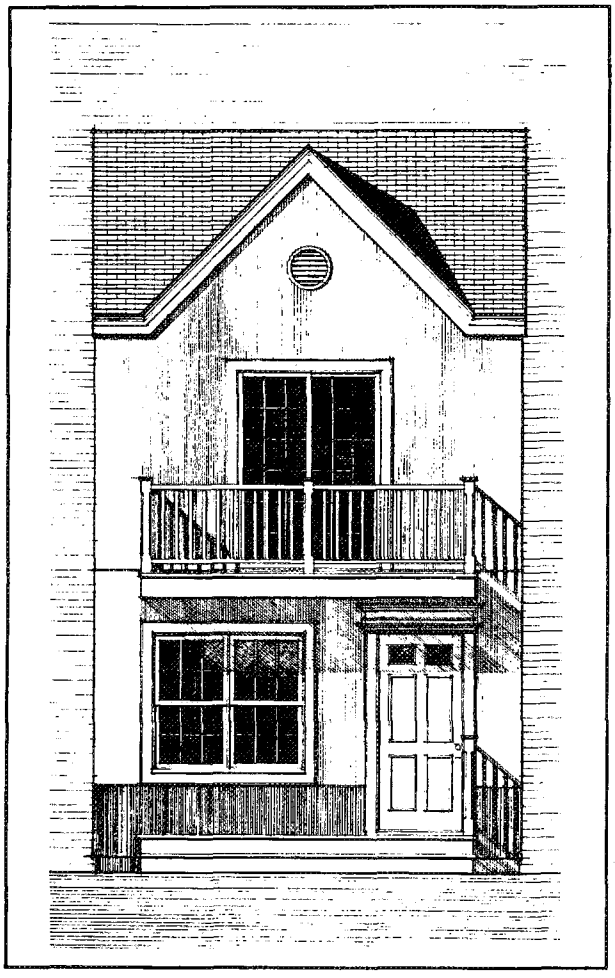

Figure 2: Grow Home Elevation

which were wide enough to be subdivided into two rooms, and the last two, which were not.

The narrow rowhouse has been the object of study of many modern architects interested in reducing construction cost. An early example was designed by J.J.P. Oud for the 1927 Weissenhof Exhibition in Stuttgart. The width was eighteen feet, which permitted the bay to be subdivided into a narrow and a wide bedroom. The "Roq" and "Rob" housing, designed (though unbuilt) by Le Corbusier for Cap Martin in 1949, proposed a fifteen-foot wide rowhouse, a dimension which allowed two extremely narrow bedrooms, side by side. The settlement of Siedlung Halen, a version of this project, designed by Atelier 5, was built on the outskirts of Bern in 1961; the bay width was sixteen feet (Sherwood, 1978).

The narrow-front rowhouse, which can be as narrow as fourteen feet, can successfully accommodate a small family. On the ground floor, fourteen feet is wide enough for a living room, or a kitchen-dining room; on the upper floor it provides two generous bedrooms--a third bedroom could be added in the basement. The small structural span reduces construction cost, and allows flexibility in internal partitions.

The narrow-front rowhouse has important implications on land-use. A one-story bungalow on a sixty by a hundred-foot lot results in a gross density of about five homes/acre; a two-story, fourteen-foot wide rowhouse on a fourteen by a hundred-foot lot gives a gross density of twenty-four homes/acre. Put another way, an acre of land can accommodate about twenty persons living in bungalows; the same amount of land, and the same amount of roads, sewers, water-lines, and storm-drains, can accommodate more than four times as many people living in narrow-front rowhouses. Crudely put, such housing is about four times cheaper.

The effect on the environment of denser neighborhoods is considerable: less automobile travel, less roadways, hence less run-off, and less energy invested in community infrastructure. Rowhouses, which share walls with their neighbors, provide significant savings in building materials and energy consumption. A two-story, narrow-front rowhouse has only about one third the area of exterior walls compared to a similar bungalow, and one half the roof area; heating and air-conditioning costs are reduced accordingly.

The Small House

The easiest way to reduce construction cost is to build smaller houses--less than 1,000 square-feet of finished space. As has been pointed out, since families are smaller today that in the past, this does not mean any real lowering of living standards. Money can be spent on quality rather than quantity. Nor does it imply a reduction in comfort, since all the amenities of a modern home are included, particularly the wide range of electric appliances and electronic devices that more and more define modern domestic life. Much of the savings in area can be accomplished by eliminating waste space, and by rethinking conventional standards.

A smaller house has other advantages. It is cheaper to heat, and cheaper and easier to maintain. In families where both adults work outside the home (among young families who are buying a home for the first time, this is now the "typical" household), a more compact home means less housework. The same applies for single-parent families.

Unpartitioned Space

The housing market today is characterized by an unprecedented heterogeneity. The nuclear family of the 1950s still exists, of course, but it now represents a minority of all households. The first-time homebuyer may also be a childless couple, a single-parent (usually female) with children, two unrelated adults pooling their money to share the cost of a home, empty-nesters, single adults, parents with returned grown children, and so on. These different groups have different space needs, different resources, and different priorities. People who work at home need offices, people with small children need nurseries, people with elderly parents need a guest room, childless couples may prefer large, open spaces.

Different priorities have added significance in a small, inexpensive house since they lead to very different trade-offs. One way to accommodate these trade-offs is to leave part of the house unpartitioned--in effect, a loft space. Provision can be left for service hook-up for a future bathroom. The homeowner could choose to use the loft as a single open space, or build (or have built) partitions as required.

An unpartitioned second floor is an idea that worked when William J. Levitt introduced it in the form of an unfinished attic in the late 1940s, and it remains a useful device to reduce the initial construction cost of the house. Moreover, it also provides an adaptable and responsive home which can be completed according to the wishes, needs, and financial resources of the user.

Most Canadian and American males (and increasingly females as well) grow up learning rudimentary carpentry skills as a matter of course. The explosive growth in the number of neighborhood so-called renovation or home-improvement centers attests to the popularity of the do-it-yourself movement. These stores sell a variety of tools and building materials as well as electrical and plumbing supplies, and often provide information, plans, step-by-step manuals, and handbooks on construction. Traditionally, the basement has served as the chief locale for do-it-yourself additions and modifications to the home, and in that sense, the provision of unpartitioned space has a long and well-tried history.

Do-It-Yourself Components

It has long been the European custom to provide homes without built-in kitchens and closets, leaving these components to be provided later by the homeowner. This strategy has several advantages. First, the quality of these elements--which can vary considerably--is left up to the discretion of the homeowner. He or she can choose a less expensive kitchen, for example, and replace it later. Or, he may install a minimum amount of more expensive cabinetry, temporarily, and complete it when he has additional funds. Conversely, the handyman might decide to do the carpentry himself, or with the help of friends. There is an additional advantage to leaving the exact location of clothes closets to the discretion of the homeowner, since it makes it possible to use space more efficiently by placing storage elements only where required.

Finally, there is a cost benefit to removing the cost of such finished carpentry from the construction cost of the home, and hence from the mortgage. Every dollar included in the house mortgage means two or three dollars expended by the mortgage holder. Home improvements made out of personal savings avoid this penalty.

The provision of kitchens and closets by the homeowner is facilitated by a variety of furniture stores that now sell unfinished, knocked-down, and partially assembled furniture. There are several national chains, the best known of which is probably IKEA, a Swedish corporation with branches in all the major Canadian cities, and an expansion plan for the United States that is underway. Stores such as IKEA sell not only domestic furniture, but also sectional closets, cupboards, bathroom cabinets (and fixtures), and modular kitchen cabinets and counters. The growing popularity of such stores attests, again, to the attraction of the do-it-yourself movement.

Traditional Appearance

The cardinal rules for the designer of more-affordable homes are "Keep it Small," and "Avoid Complexity." A simple box is almost always the least expensive solution, that is why vernacular buildings such as farmer's cottages have always been rudimentary, compact volumes, with little irregularity of contour or variation in shape. These are not the ingredients that lead to exciting or spectacular architecture, that is why popular housing has always tended to the modest and banal, but there is no reason why it should be unattractive. Decorating simple boxes is precisely what Georgian architects did so well, and a well-placed molding around the entrance door, or a carefully proportioned window, made all the difference.

The traditional language of architecture is a rich one, and using vernacular domestic elements such as porches, balconies, bay windows, gables, dormers, and so on, continues to be a useful way to give a sense of identity to individual homes, while maintaining a cohesive street facade (Rybczynski, 1989). Of equal importance is the fact that this language is comprehensible to the public.

Cost-Effective Materials

The building materials industry offers a wide range of choices to the home designer. Careful research is required to identify and select materials and components that are environmentally sound, energy efficient, and perform efficiently over the life of the building. Using poor quality windows, or reducing insulation values, for example, is, in the long run, a poor strategy for saving, since the cost of future upgrading will be high.

Finish materials account for a large percentage of construction cost, and here one could take a different approach. It is possible to achieve significant savings through the use of less-expensive materials in cases where these can be easily and practically replaced with better quality in the future. Vinyl tile, for example, is the least-expensive flooring, and can later be replaced with carpeting, wood parquet, or ceramic tile. The same applies to hollow-core doors, light fixtures, and interior paint.

Prefabrication

Industrialized materials (plywood, gypsum wallboard, asphalt shingles, polyethylene vapor barriers, wall-cladding systems, board and batt insulation) continue to revolutionize the building industry. Prefabrication in housing construction already accounts for a large portion of the house: roof trusses, space joists, windows, pre-hung doors, and kitchen cabinets, are all manufactured in the factory. The large-scale prefabrication of entire building components such as walls, floors, or even houses, is less common. Panelized building, in which all walls are manufactured in a factory (and floors, roof, and interiors are finished on the building site), is the most common prefabrication technology in North America; the manufacture of houses as two or more completely pre-finished boxes--or modules--is in second place. Thus far, neither method has managed to make a significant breakthrough in reducing construction costs (Weidemann et al., 1989).

Nevertheless, the success of large-scale house prefabrication in Japan (steel, wood, plastic) and Sweden (wood) suggests that such breakthroughs are likely to occur in the coming decade. The Japanese experience suggests that prefabrication has the greatest chance for success when it is part of a comprehensive approach to housing delivery that integrates marketing, customer relations, design, manufacturing, erection, and post-occupancy servicing in one organization. House construction is a trade, and hence local in character. House manufacturing is an industry, and in a period where international trade takes on greater importance, the export of manufactured houses introduces a new and important factor (Sweden currently exports prefabricated single-family homes to both coasts of the United States). The manufactured housing industry has always experienced difficulties with unstable local markets; developing export markets might help in overcoming this obstacle.

Implementation

Six months after the erection of a full-scale prototype on the university campus, Mr. Leo Marcotte, a local developer, started the first housing project based on the Grow Home concept. During that same period,

the provincial and municipal governments implemented programs aimed at promoting housing starts for first-time buyers through interest and tax reduction incentives. With the aid of these incentives, all of the 87 units in the project were sold within the first four weeks - before any ground was broken. Following Mr. Marcotte's lead, 12 other builders started Grow Home-type projects in and around Montreal. Over 660 units were built within the first 10 months in 19 projects, ranging in price from $69 000 to $95 000, and several new projects have since been started.

The built projects revealed some interesting interpretations of the Grow Home concept. While the 4.3-meter width was retained in all cases, the builders modified the design to suit the tastes and budgets of their own particular market. The original plan, which subdivided the space with a central plumbing/stair core, was altered in most cases to accentuate the full depth of the space. The second floor was partitioned and finished in all but one project, some with "luxurious" bathrooms with separate showers and whirlpool baths. Eleven of the builders provided brick veneer on the exterior to increase quality and project an image of permanence, while the remainder used a cement-based aggregate finish. All units were built with basements, adding 46.5 sq. meters to the floor area, and indoor garages were included in 15% of the homes. Vestibules and walk-in closets were added to the units in one of the projects, while separate garages were added to the sides in another. These options, which were proposed as extras in the original design, became standard features.

Affordability

The affordability of the units was enhanced with government programs aimed at reducing the cost of home ownership for the first few years. The federal government makes the purchase possible with as little as 10% down payment through an existing insured mortgage program. In a effort to promote housing starts, the Quebec government offered up to $5 000 to buyers of new homes built by local builders and costing $150 000 or less. Applicants had the option of choosing 8.5% financing for three years, or a subsidy of 4.5% of the total cost of the dwelling. At the same time, the City of Montreal implemented a program aimed at attracting residents back into the city. An annual reduction in property tax of $1 000 for five years was made available to first-time buyers purchasing a newly built or renovated dwelling costing up to $100 000, not including land, infrastructure or sales tax. The reduced development, construction and operating costs of the Grow Home, combined with the government subsidies, enabled the purchase of a $76 000 home on $618 a month (including sales tax). With a down payment of under $8 000, apartment tenants with a gross annual household income of $24 000 would have been able to become homeowners.

The combined effect of the subsidies and reduced construction costs on affordability is illustrated in figure 3. The median household income in Montreal was approximately $41 500. Assuming a 32% gross debt service ratio and a 10% down payment, the maximum affordable home at this income is close to $86 000. This is $24 000 lower than the average price of a resale listing and $40 000 less than the average price of a new house. At these prices, household incomes of $49 500 and $55 300 would be required, falling well into the upper income brackets.

Through lower property taxes and heating costs, the Grow Home shifted the affordability curve towards the left (line 2). Because of the lower development and construction costs, the units were priced at $76 000, making them attainable to households earning slightly more than $33 000 -- just below the middle income bracket. By offering 8.5% financing, the

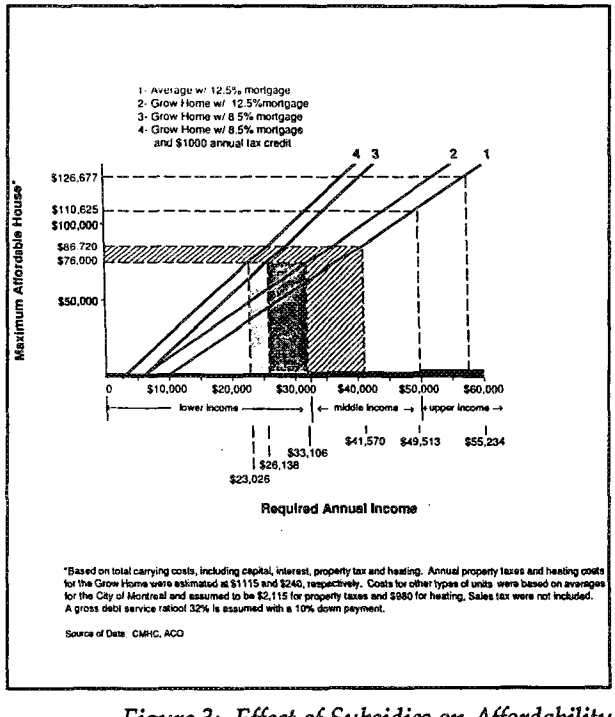

Figure 3: Effect of Subsidies on Affordability

provincial government put the units within the range of households with a $26 000 annual income. The tax credit offered by the city shifted the curve further (line 4) to reduce the required household income to $23 000.

Post-Occupancy Evaluation

The proliferation of projects presented an opportunity to evaluate the sociological, architectural and financial characteristics of the occupied dwellings, and to identify those aspects of the design concept which were most helpful in gaining the acceptance of the buyer and builder alike. Seven projects were selected, and a series of structured interviews were conducted with the builders in order to examine their experiences with the inception, design and implementation of the concept. Questionnaires were then distributed to the occupants of the units to assess their initial reaction to their new surroundings (Friedman and Cammalleri, 1992).

The main purpose of the study was to evaluate the potential of narrow-front rowhousing to respond to Canada's affordability challenge. There are three aspects regarding the inception, design and implementation of the projects that were of interest in evaluating this potential. The first was how successful the product itself was in meeting the functional requirements and financial limitations of the buyers. The second aspect was the role played by the builder in interpreting the concept and marketing the units, and finally, what the effect was of external factors, such as the regulatory environment and government subsidies, on the implementation and sales of the projects.

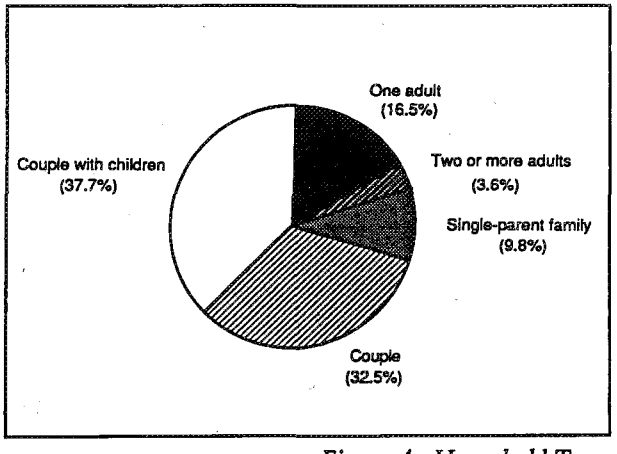

Figure 4: Household Type

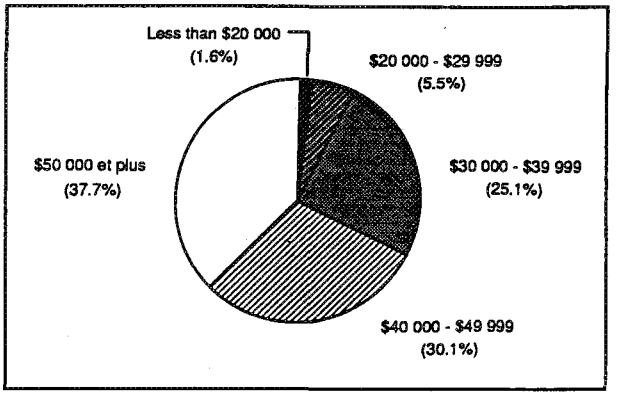

Figure 5: Household Income

Demographic Profile

One of the objectives of the study was to establish a socioeconomic profile of the buyers in order to determine what segment of the population the projects were attracting. The Grow Home has, for the most part, attracted the demographic group for which it was intended. The projects provided starter homes for 89.4% of the respondents. The households were made up mainly of young couples (25-34 years of age) with one child. The single-person household accounted for 16.5 of the cases. The vast majority of respondents (86.6%) were formerly tenants, 92.2% of which lived in apartments.

The household incomes, however, were found to be significantly higher than anticipated. The majority of respondents (67.8%) claimed annual household incomes greater than $40 000, while those of 37.7% were over $50 000. With the municipal and provincial subsidies in effect, the homes would have been affordable to households earning from $24 000 to $27 000. Calculations based on the respondents' total carrying costs revealed that the buyers were allocating from 18.5% to 26.1% of their income on housing. Given that new homes priced 15% to 20% higher than the Grow Home-type units were available in most of the municipalities, it was evident that the tendency to allocate a lower portion of income on accommodation was intentional and not for lack of choice. It is likely that the high income levels are reflective of a change which may be occurring in the spending habits of either the average first-time buyer or the North American household at large, or reflect regional or cultural preferences and aspirations. In either case, it seems that there is a tendency for the buyers to allocate a greater portion of their income to factors other than living accommodation.

Occupants' Shopping and Buying Experience

The rate of sales in the Grow Home-type projects was unusual, especially for a period of economic recession. Consequently, there was an interest in examining the buyers' intentions and expectations at the time of purchase. It was found that the majority of respondents (59.9%) were not actively looking to buy a house at the time of purchase, and seem to have come across the projects by chance. Close to one third (29.4%) of the buyers visited only one project, and 61.3% visited no other project after having seen the one in which they purchased a unit. Furthermore, 39.3% of respondents decided to buy the unit immediately, and another 44.9% decided within one or two weeks of their visit. The vast majority of respondents (77.4%) purchased the house without having seen a model unit.

These buying patterns suggest that the projects represented an exceptional bargain for many of the buyers. Those projects which started earliest had the highest percentage of buyers who were not actively shopping for a house. These buyers also visited the least number of projects and made the quickest buying decisions. The implementation of subsequent projects appears to have filled a market void, enabling the buyers to take more time and do some comparison shopping.

The reasons for purchasing the Grow Home were probed by first asking the occupants to list those features which they thought were most attractive about the projects, and then by listing 6 specific features which the occupants were asked to rate in terms of importance in their decision to purchase. In both instances, the unit's selling price was found to be the most appealing feature by a wide margin.

In the open-ended question, the unit selling price was specified by 40% of the respondents and was the most frequently mentioned attribute in 5 of the projects. It also received the highest importance rating, with 90% of respondents rating it as "extremely important." The second biggest attraction in both questions was the unit's overall layout, which received mention from 22% of the occupants and top rating from 68%.

The majority of respondents (69.8%) also mentioned aspects of the design that they felt uneasy about at the time of purchase. The most frequently mentioned reservations were about the kitchen. Size, layout and storage space in the kitchen designs collectively accounted for 16.7% of all entries. Inadequate parking arrangement and small yard area were also cause for concern, receiving 9.3% and 8.5% of the mention, respectively. The unit's total amount of space was also a concern for 9% of respondents.

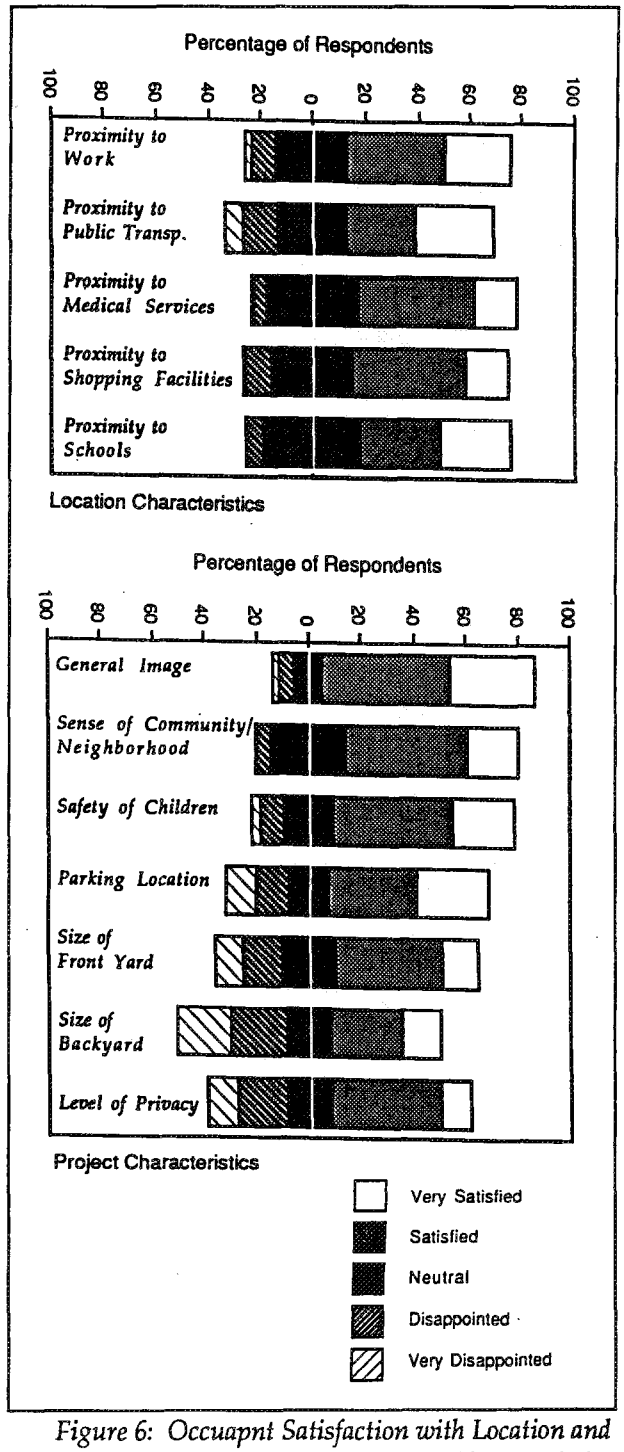

Figure 6: Occuapnt Satisfaction with Location and Project Characteristics

Because the projects were not built with the original second floor "growing" potential that was demonstrated in the prototype, there was an interest in determining whether or not the idea of involving the buyer in the construction process would have been acceptable. The results revealed that 20% of the buyers were willing to accept an unpartitioned second floor, and 33% would have assumed some of the construction work (particularly the finishing operations) in exchange for a reduction in price. Although these percentages represent a minority, there was undoubtedly an interest in participating. The notion of involving the buyer in the construction of his home remains a plausible option for reducing housing costs, and may be worthy of further study.

Buyers' Preferences

As an absolute measure of the buyers' willingness to compromise for the sake of ownership, some of their preferences and aspirations were investigated. The findings reflect a fairly strong desire to live in a suburban setting in a new, single-family detached dwelling. The majority of respondents (51.8%) rated the suburb as their most preferred location (regardless of price), and the single-family detached dwelling received the highest rating from 78% of respondents. Approximately 58% of the buyers were specifically looking for a newly-built house, while 54.6% wanted two bedrooms.

The majority (68.9%) of the respondents also specified the desire for a particular feature in their new home. The items mentioned most frequently were a second and/or large bathroom (15.8% of respondents) and a large and/or private backyard (12.8% of respondents). Sufficient storage, natural lighting and a basement were also considered to be relatively important. While the occupants' desire to have these elements was satisfied in most cases, the acceptance of a townhouse (which was the preferred type of dwelling for only 13% of respondents) represented the first tradeoff that the buyers were willing to make for the purpose of home ownership.

Satisfaction and Improvement

In a second phase of analysis, the occupants were asked to evaluate their level of satisfaction with each of 23 attributes, including 5 which were related to location, 7 to the site plan and 11 to the unit itself, and to indicate how they compared to those of their

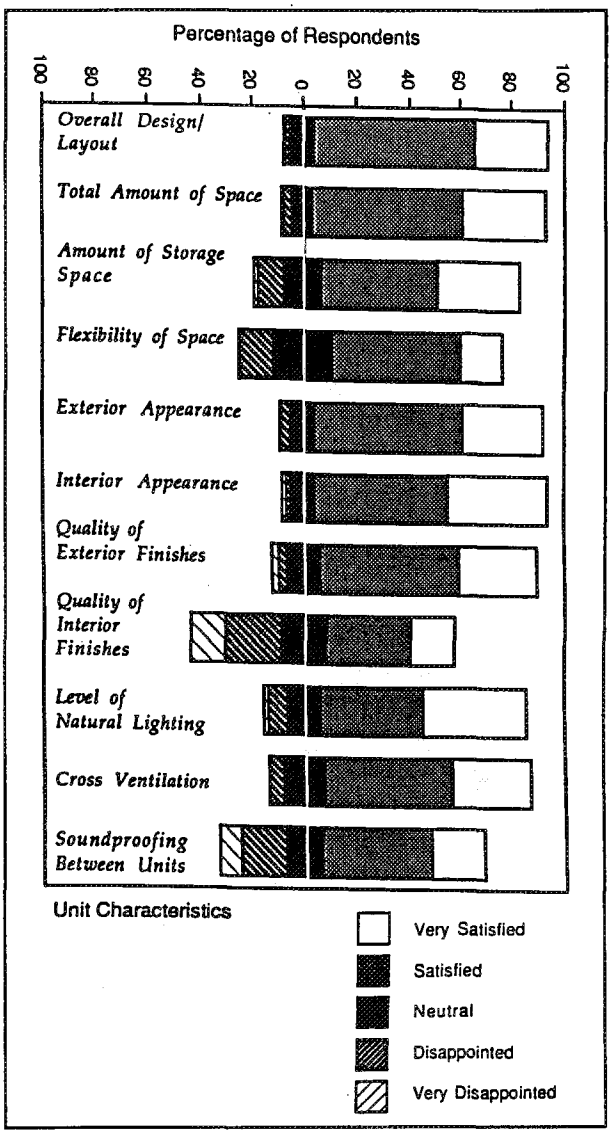

Figure 7: Occupant Satisfaction with Unit Characteristics

former dwelling. They were then asked to do the same for each of 10 interior spaces in the dwelling. The issue of location, privacy and parking was examined in a little more detail, and suggested improvements to the projects were recorded.

The majority of respondents expressed satisfaction with 22 of the 23 attributes that were evaluated, and with all of the 10 interior spaces in their dwelling. About 88% of respondents found that their general experience with their new house was about the same or better than what they expected, and the vast majority of the buyers (92%) reported that they would recommend their purchase to a friend.

Satisfaction levels were generally highest with the units themselves, particularly with the individual rooms and spaces, and the lowest level of satisfaction was reported in the site characteristics. On a scale of 1 to 5 ("very disappointed" to "very satisfied"), the average overall ratings for location, site, unit and room characteristics were found to be 3.697, 3.513, 3.933 and 4.092, respectively. Although there was some variance in satisfaction levels among projects, several aspects of the development were rated fairly consistently across the survey:

• The majority of occupants from all of the projects were satisfied with all of the location characteristics except for their access to public transportation, which was rated as disappointing to most of the occupants in 2 of the projects.

• The project's general image was the highest source of satisfaction among the site attributes in 5 of the projects surveyed, with 32.6% of the respondents reporting being "very satisfied," and another 49.5% "satisfied."

• The majority of the 196 respondents were satisfied with all of the 11 unit features listed, and a significant fraction reported that they were "very satisfied" with 7 aspects in particular: interior appearance (38.5%), exterior appearance (31.2%), quality of exterior finishes (30.3%), total amount of space (32.2%), overall design/layout (28.3%), amount of natural light (40.2%) and amount of cross-ventilation (30.2%). The total percentage of respondents expressing satisfaction with these attributes ranged from 79.9% for amount of natural light to 90.2% for both overall design/layout and total amount of space.

• Occupant satisfaction with the interior spaces in the units was exceptionally high. The most successful rooms were those which are found on the second floor. The master bedroom was the highest source of satisfaction for the majority of the occupants, with 57.7% reporting to be very satisfied and another 37.0% satisfied. The bathroom and second bedroom were satisfactory to 92.1% and 93.5% of the respondents, respectively. There were only 3 instances where substantial disappointment with the unit's interior spaces was expressed. These were the entrance area in two of the projects (34.5% and 47.7% dissatisfaction) and the kitchen in one other project (50.0% dissatisfaction).

• The weakest source of satisfaction with the units was the quality of interior finishes (receiving an average rating of 3.193), and soundproofing between units (3.500), although there was no other evidence of acoustic privacy being a problem.

• The most frequently mentioned changes that were proposed by the respondents dealt with the kitchen, the entrance, and the unit's width (increase to 5 meters), which received mention from 24.0%, 16.8% and 14.3% of the respondents, respectively.

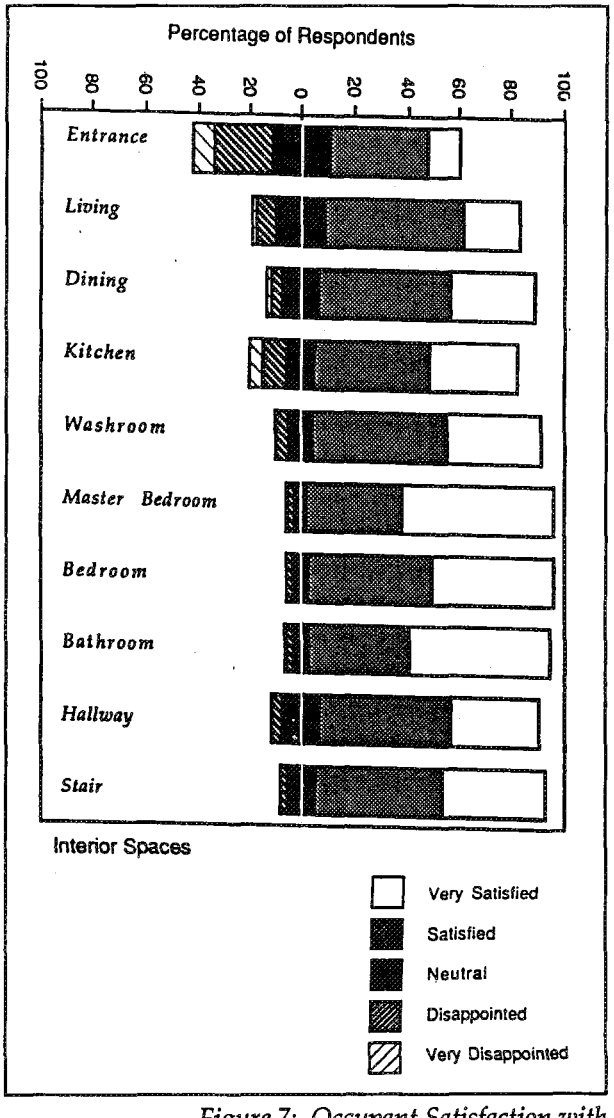

Figure 7: Occupant Satisfaction with Interior Spaces

The only attribute which was found to be a source of considerable disappointment was the size of the backyard areas, where 41.7% to 64.5% of respondents

from 5 of the 7 projects reported being unsatisfied with the results. The projects' inability to provide an adequate backyard area was found to be the single most significant source of failure in the projects.

The study also found that there was a general increase in the occupants' use of a car as a primary mode of transportation, and in their commuting time to and from work. Furthermore, the occupants' distance from their work place received an exceptionally high priority rating when the importance of this aspect was evaluated. Although the purchase of the unit meant having to move further away from work for the majority of respondents in 3 of the projects, these same occupants reported being satisfied with their new situation. This leads to the conclusion that, for the most part, there was a strong willingness from the buyers to give up this particular aspect of location for the purpose of home ownership.

The level of improvement with respect to the occupants' former dwelling was fairly consistent among the site attributes, with the general image of the projects rating highest (3.876) and the level of privacy lowest (3.483). With the exception of the level of soundproofing between the units in one of the projects, all of the unit characteristics in all of the projects represented an improvement for the majority of occupants. Similarly, with the exception of the kitchen in one other project, all of the interior spaces were considered to be an improvement over the occupants' former dwelling.

Unit Modifications and Living Adjustments

The next phase of analysis examined the changes that occurred in the occupants' physical surroundings and living habits. This was not only a way of determining the extent to which the buyers' functional requirements were being satisfied, but also a way of testing the unit's adaptability.

The amount of work done by the occupants on the units was quite significant, considering the short period of residency. The study found that 39% of respondents had already done some work, all of it in the basement, including partitions which were erected by 22.5% of the respondents, implying that there was some kind of room addition. The most-frequently mentioned type of work was drywall installation, presumably to finish the exposed structure ceiling.

The majority of respondents (83.8 %) were planning to do work in their units. The most significant modifications planned are in the basement, where 61.5% of the items mentioned involve major work, such as the addition of a playroom, den, toilet, laundry, or bedroom. The type of modifications that were being planned for the upper floors were consistent with the findings of the previous questions, with the primary intention to upgrade the finishes and re-plan the kitchen.

More than half of the respondents (51.1%) reported that they were able to save either less or much less money than in their previous dwelling, while 31.5% specified that there was no change in this regard. The changes in living/leisure patterns were less pronounced, with 46.8% of respondents reporting a change. The majority of these (60.7%) reported spending more time at home and 29.1% reported that they were entertaining more at home. The majority of respondents (71.4%) reported that the expenses in their new home were either the same as or lower than anticipated.

Builders' Contribution and External Influences

The effect of 3 external factors on the implementation of the projects was examined with the following results:

- The effect of government subsidies was found to be significant in enhancing the affordability of the units. Close to 98% of those surveyed qualified for the subsidies, 34.4% of which felt that they would have bought the house anyway had the subsidies not been available, 38.7% said that they would not have bought, and the remaining 26.9% were not sure. The subsidies were therefore directly responsible for at least 38.7% of the sales.

- The regulatory environment was not considered to be a major obstacle. The long processing periods were reported to be a deterrent for many of the builders who considered applying for narrow-front lot subdivision. There was, however, no evidence of any real incentive or effort to change the existing lots. Concerns about the project's image caused minor delays in some cases, but with no significant effect on either the units or the price.

• The depressed economic climate proved to be somewhat beneficial. With housing production almost at a standstill, builders, who have traditionally been characterized by a reluctance to accept innovation, were given an incentive to look into new markets and become more receptive to new or unfamiliar design alternatives. Furthermore, with the increased competition in a struggling labour market, many of the subcontractors were offering reduced rates.

The small, local builder working independently was found to be an essential source in the production and delivery of affordable housing. The builders' knowledge of the market, coupled with their ability to act quickly and adapt to regulatory restrictions resulted in a successful and efficient interpretation of the Grow Home concept, which proved to be well-suited to most of the buyers' preferences and aspirations.

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Introduction - Part I

Sustainable Development and The Green Grow Home

The Need for Sustainable Development

A sustainable society is able to satisfy its economic and social needs without jeopardizing the prospects of future generations. According to the World Commission of Environment and Development, sustainable growth is based on forms and processes of development that do not undermine the integrity of the environment on which they depend (McNeill, 1989). Any movement toward sustainability that is to succeed must involve existing communities and eventually entire cities, not just a few dedicated environmentalists working on their own.

A *resource* is any material which is needed or used to sustain life and livelihood. Air to breathe; water to drink; land to live, walk, and grow food on; forests for timber, paper, and wood products; ores for iron, aluminum, copper, and other metals; oil, natural gas, and coal for energy are all examples. In short, there is nothing humans do which does not draw upon resources. Many people believe that our present industrialized societies use too many virgin resources and degrade the environment in too many ways, and that such practices cannot continue much longer without some very serious consequences. Resources can be divided up into three general categories:

Renewable resources are those that are replenished through relatively rapid natural cycles. Examples include water, air, and biological products such as food, fibres and timber. In theory, a renewable resource can last forever. However, all renewable resources are sharply limited by the capacity of natural systems to renew them. For example, natural processes which accomplish water purification often do not occur at a sufficiently rapid pace to replenish clean water that is consumed and reintroduced into the environment as waste. Learning to manage and use renewable resources while respecting this limitation is in essence the study and practice of conservation. Management or conservation of renewable resources must include practices that overcome factors leading to overexploitation.

Non-renewable resources that can be recycled include all non-energy, mineral resources which occur in the Earth's crust. Ores of iron, copper, aluminum, mercury, and other metals and minerals are examples. As these materials are mined, they are not replaced, at least not rapidly enough to be relevant within the human timeframe. However it is possible, at least in theory, for people to collect these materials after they are used and recycle them.

Non-renewable resources that cannot be recycled are "mineral" energy resources such as fossil fuels including coal, oil and natural gas, and uranium that is used for nuclear energy (Nebel and Wright, 1993). Human beings around the world expend in one year a quantity of fossil fuels that it took nature approximately 1 million years to create (Buchholz, 1993). There is no way of recycling the energy in fossil fuels - once the energy has been released, it cannot be regained.

The development of a sustainable society involves the development of a more livable environment with less air and water pollution, and less waste to dispose of that can pose a threat to human health and the environment.

The Cost of Sustainable Development

We often hear how much it will cost to clean our air, water and land and to keep it clean. However, we rarely hear about the costs of not cleaning up these resources - costs to health, property, ecosystem stability, quality of life, and human survival. Most of our environmental problems are a result of technology rather than overpopulation. The ratio of pollution generated to population size has increased sharply since the end of World War II. Although population and urbanization have increased in the past several decades, the rates of increase have been small in comparison to the rise in pollution levels (Nebel and Wright, 1993). Unfortunately, this trend is difficult to halt due to the momentum of old practices which holds us to our current path; i.e. it is difficult to break old habits and to develop new healthier ones. It would be unrealistic to expect all environmental problems to have ultimate technical solutions. In fact, it is highly unlikely that there will be strictly technical solutions to any environmental problems.

The Grow Home and Sustainable Development

Many problems of the environment are unsolvable in the absolute sense. They can be minimized, but they cannot be eliminated. Development of the Grow Home within the context of sustainable development requires a minimization of the impact of the Grow Home on natural resources. This necessarily implies:

(1) reduced consumption of renewable resources in order to allow earth's natural cycles to make them available at a sustainable rate;

(2) recycling non-renewable resources to make them available for processing into new products, thereby reducing the need for the exploitation of new sources of raw materials;

(3) making a significant reduction in the energy and raw material content of new products;

(4) improving the efficiency of use of non-renewable non-recyclable resources.

Accordingly, it is the intent of this section of the report to demonstrate many areas in which the design of a "Green", i.e. environmentally friendly, Grow Home can contribute to society in a manner which is consistent with the goals of sustainable development. Opportunities which exist in the design of a Green Grow Home are discussed below.

1. *Minimize the environmental impacts of building materials:* The environmental impact of building materials can be reduced through judicious selection of building materials to minimize embodied energy, resource depletion and ecosystems' effects while maximizing product lifetime/durability. The basic design of a unit can be modified to provide a more economical and environmentally responsible product without compromising the occupants' living comfort and health. Total impact on the environment can be reduced by such strategies as minimizing the total building materials required, selection of alternative materials and reducing construction wastes by minimizing cutoffs.

2. *Improve the energy efficiency of the building envelope:* The consumption of non-renewable energy resources can be minimized through proper design, materials selection and choice of technologies for heating and cooling. Strategies to minimize energy losses include energy-efficient building practices (R-2000 building technology), the use of energy efficient mechanical systems and windows, air-tight construction, and the use of passive solar strategies, among others.

3. *Improve the efficiency of use of renewable resources:* The rate of use of renewable resources can be minimized by implementing systems which require the least amount of resource consumption to accomplish a given task. Common strategies include the minimization of water consumption through application of technologies such as low-flow toilets, shower heads, and faucets. In addition, significant savings can be achieved through xeriscaping, a landscaping technique which minimizes irrigation requirements through use of naturalized gardens, native plants, and drought resistant species. Such "xeriscapes" also require less maintenance and fertilizers, thus reducing the impact on non-renewable energy and mineral resources.

4. *Minimize waste generated:* The efficient use of non-renewable resources and minimization of the environmental impacts associated with the disposal of wastes requires that recyclable non-renewable resources be returned to the manufacturing sector. Grow Home units can be designed which maximize the use of materials which are recyclable and/or which originate from recycled materials. In addition, the design of Grow Home communities and individual units can be made consistent with the current trends toward waste minimization through designs which accommodate efficient recycling and composting. These trends are not passing fads, but are a reality for communities faced with increasing waste management costs.

The sections that follow cannot be directly placed under each of the above categories since each aspect of the Grow Home can have impacts in more than one of these areas. Therefore, each of the sections of the report have been presented as separate units with occasional references to other related sections.

It should be noted that this is not an exhaustive study of all possible improvements that can be made to optimize the design of a Grow Home with respect to the ideals of sustainable development. In many cases, it is very possible that additional improvements can be made in the design to further reduce the impact of the Grow Home on the environment.

However, it is the intent of this report to demonstrate what is not only possible, but practical given current technologies and the cost of implementing them. The Grow Home was designed as affordable housing and should remain consistent with this intent. This practicality is fundamental to the concept of sustainability which requires that development take place which is consistent with the environmental, social and economic needs of society.

Economical Evaluation of the Green Grow Home

In the discussions which follow, many technologies and practices have been evaluated using an economical analysis based on a payback period. The payback period is the length of time necessary to recover the initial investment of a project. The simplest form of payback makes no allowance for the time value of money. That is, it is an expression of how fast an individual can recover their initial investment. It can be expressed as:

$$n = C / S$$

where "C" is the initial cost ($), "S" is the annual savings (in $ per year) and "n" is the number of years it will take for the initial cost to be recovered, also known as the simple payback.

However, the above expression does not account for the fact that if the initial amount of money were invested elsewhere, it would earn interest. In addition, in order to provide an estimate of the true time value of money, it is also necessary to account for inflation. Therefore, true payback is discounted payback expanded to allow for escalation. It can be calculated using the following formula:

$$n = \frac{\log\ [1 + C/S\ (1 - 1/k)]}{\log k}$$

where C/S is the simple payback as discussed above (Brown and Yanuck, 1985). The constant k accounts for the time value of money, and is calculated as follows:

$$k = \frac{(1 + e)}{(1 + i)}$$

where "e" is the escalation rate (inflation rate) and "i" is the discount rate (interest rate on invested money).

In the discussions of the true payback period in the following sections, it has been assumed that the interest rate which can be expected on investments for the coming years is 10% (i = 0.10) and the rate of inflation will be 4% (e = 0.04). These values are conservative estimates that are used in current economic analyses of engineering projects in Canada. In addition, the cost value (C) used in these calculations of true payback is not the total initial investment that is made but rather the difference between the investment made and a traditional investment. For example, in the calculation of the payback of a low-flow toilet which will save on water consumption, the cost used is the cost of a low-flow toilet over and above the cost of a traditional toilet. This strategy has been taken since devices such as toilets, windows, home heating systems, etc. must be bought and installed in a new home, anyway. Therefore, it is the additional cost of choosing environmentally friendly technologies which must be overcome in the design of a Green Grow Home. It should also be noted that the values of the costs and savings associated with each technology have been estimated from existing products and literature. The figures quoted should provide a good estimate of the economic potential of each of the strategies discussed; however, the actual values may change depending on locality and availability of technology and services.

Energy Consumption

In the comparison of alternative building techniques and components, the effect on energy consumption is often evaluated to determine the approximate annual cost savings which are possible for the consumer. All calculations have been conducted using the degree-day method (ASHRAE, 1989). Climatic data and heating costs used for the calculations are for the Montreal area, and are based on the following values:

Interior design temperature: 21 deg. C
Exterior design temperature: -23 deg.C
Degree days (18 deg. C): 4463 deg.C
Wind speeds (avg): 14.4 km/hr (4 m/s)
Cost of fuel (electric): $0.0469/KWh
Assumed correction factor C_D: 0.6

The energy comparisons found in the various sections are based on differences in heat loss, be it through conduction, convection, infiltration or radiation.

Internal and solar heat gains and thermal storage characteristics of materials and furnishings were not calculated separately, as they are highly dependent on unit orientation and are affected by furnishing, decorating and living habits. For purposes of comparison, however, this omission is of little consequence, as all other factors are assumed to remain equal except for the component under investigation. Incremental changes in energy costs represent the extra heating required to compensate for additional heat loss.

It is important to note that the degree of accuracy possible in predicting the energy performance of any building is a debatable issue, even with the most sophisticated computer software. However, regardless of the procedure used, the evaluation of relative differences between alternatives is generally more accurate than absolute values obtained for specific designs. The energy figures presented in the sections which follow are intended to illustrate the potential benefits of using one alternative over another, and should not be taken to represent the actual energy consumption associated with either alternative.

Construction Cost Estimates

Construction costs for alternative building materials and techniques presented in this report are based on an elemental cost estimate which was generated from actual building costs submitted by 7 Grow Home builders in the Montreal area (Friedman and Cammalleri, 1992). All costs include labour and material, and are based on standard construction practices. The cost of building the model unit with conventional construction was estimated at $57,720, including a brick exterior (full front elevation, one floor sides and back), an unfinished basement and a fully finished second floor.

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Unit Planning Characteristics

Introduction

The notion of sustainable housing is often associated with such technical considerations as environmentally-safe materials and energy-efficient envelope design. There are, however, several basic planning decisions made at the preliminary design stage which can significantly affect the economic, environmental and social implications of a housing development. Manipulating the unit's dimensions, configuration, size and grouping, for instance, can reduce the heat loss and amount of construction materials required, leading to cost savings for both builder and buyer without compromising the occupants' living comfort. The discussion which follows will illustrate how significant energy, material and cost savings can be achieved through careful planning.

Background

Energy requirements for countries in cold climates are generally high, partly due to space heating requirements. Energy usage per capita in Canada is one of the highest in the world. Heating, cooling and operating housing accounts for approximately 20% of our total energy consumption. Furthermore, an additional 5-10% is used as indirect or embodied energy from construction, renovation and demolition of housing and its infrastructure (Robinson, 1991).

Construction is also responsible for some 16% of the total solid waste production, and approximately 20% of this is from new homes. Some 80% of this waste ends up in a landfill, much of which can be avoided. A study conducted in the Greater Toronto Area during the a period of high building activity found that construction of an average home produces 2.5 tons of waste, and 20 tons in cases where demolition is required (REIC, 1991). Approximately 25% of the waste is dimensional lumber, and another 15% is attributed to manufactured wood products. The situation is not only wasteful in terms of embodied energy, but also contributes to the problem of waste disposal. Despite Canada's vast terrain, most of its population is concentrated in a small number of urban centers, and waste disposal in landfills has become a serious crisis, with a growing problem of toxic leaching, resulting in contaminated soils and groundwater.

> **Objective**
>
> The objective of this section is to examine how the basic design of a unit can be modified to provide a more economical and environmentally responsible product without compromising the occupant's living comfort.

It is evident that alternatives to current design, construction and operating standards for residential developments can play a major role in reducing our total energy consumption and alleviating the growing problem of waste disposal.

Planning Guidelines

There are several design factors which will help conserve resources by reducing the amount of building materials required and by improving the thermal efficiency of the building envelope. The modifications will also result in a more affordable and marketable product, since both selling price and operating costs will be lowered. There are five basic strategies which can be adopted, none of which will interfere with a builder's traditional working routines.

1. Building Configuration/Plan Simplification One of the simplest ways of reducing material use and heat loss is by simplifying the unit's configuration. A more complex building form requires more corners and perimeter, which in turn requires more skin. This results in higher construction costs and increased heat loss. Generally, the ratio of floor area to perimeter should be maximized.

2. Modular Design/Dimensioning and Efficient Framing Practices. Another simple and effective way of reducing material waste is through careful dimensioning of the building to accommodate the modular configuration of the building materials. At the most basic level, designing within standard dimensions for structural framing members such as studs, joists and plywood could result in substantial savings. It has been estimated that in a typical detached home, the use of general dimensions for stud spacing (ie. 405 mm or 16" module) to eliminate

the need for an extra stud at the end of the wall, placing and dimensioning windows accordingly and locating partitions to line up with the structural studs may altogether save a ton of lumber in an average home. Designing for 2200 mm (4-foot) modules and 610 mm (24") stud spacing alone can reduce lumber use by 8%. Providing for efficient details at corners and intersections of exterior walls and interior partitions doubles these savings.

With more careful planning and material selection, the same principle could be implemented to accommodate interior finishes such as drywall and floor tiles. Cost savings are achieved not only through efficient use of materials, but also through reduced labour requirement, since less cutting and fitting is required.

3. *Area Distribution/Floor Stacking*. While the vertical distribution of a unit's floor area will have the greatest impact on land use efficiency and housing density, it can also have substantial effects on the use of building materials, and, to some extent, energy efficiency. Vertical designs make most efficient use of space, since more stacking results in the need for less construction material. The cost of a two-storey square house, for instance, is less per square foot than a one-story with equivalent area, since it has half the foundation and roof area. Floor to floor heights, which are affected by such factors as the floor thickness and the presence of suspended ceilings, will also have an impact on the amount of raw materials that go into construction, especially in the building envelope.

Generally, buildings with a smaller ratio of surface area to volume make the most efficient use of materials and require less energy to heat. Bungalows, which have an average surface to volume ratio of .38, are considered to be wasteful. Split-level-type plans, which accommodate the same floor area on 1.5 storeys, have a lower ratio, usually in the area of 0.25.

4. *Grouping/Joining Units*. One of the most effective ways of reducing energy consumption is by joining units into semi-detached or rowhouse configurations, since heat losses are limited to two walls (or three, for a semi-detached unit) and a small roof area. Grouping units is also an effective way of improving construction efficiency. The repetition of design in a set of rowhouses usually results in a shorter construction period per unit. The reduction in perimeter area can have a significant impact on the delivery time, since construction of the envelope is a labour-intensive operation.

5. *Size Reduction/Efficient planning*. Efficient planning of the unit's interior layout can be instrumental in reducing both construction costs and energy consumption. By increasing the ratio of usable to gross floor area, the quantity of construction materials is reduced, as are the space heating requirements. The design objective would be to "trim the fat", and provide a smaller house with the same usable floor area so as not to disrupt the occupants' living comfort. This can be achieved in several ways.

One possibility is to reclaim the attic, especially for small houses. Most types of prefabricated trusses can be wasteful where small spans are involved, particularly since they render the space unusable for living purposes. Using knee-type trusses or stick-build framing methods in the roof could increase the floor space without necessarily increasing construction costs. For a 4.3 x 11 meter (14' x 36') area, for instance, a 2.4 meter (8') clearance could be achieved with a roof slope of 6:12. Assuming that 40% of this space is usable for occupancy, an additional 19 square meters (200 sq.ft.) of floor space could be added to a house like the Grow Home.

Eliminating the basement could also be beneficial where there is sufficient living space on the main and upper floors of a unit, or where accessible dwellings are desired. Slabs on grade, crawl spaces and pier foundations use less concrete, are less expensive to build and use less energy to heat. Where a basement is deemed necessary, the use of preserved wood foundations, particularly in the form of prefabricated panels, can provide dry, energy-efficient basements that are relatively easy to finish. The use of wood rather than concrete reduces the amount of embodied energy by about 30%. It also enables the buyer to participate in the construction process, since wood is easier to work with than most other alternatives. Interior finishes, for instance, are relatively labour intensive and can account for about 33% of the total cost of a house. By having the buyer finish the house independently, its selling price can be reduced substantially.

As far as the internal layout and space division are concerned, there are several factors which should be considered. The open interior plan, for instance, is

most flexible, energy efficient and uses less materials. Local heat gains and losses are more easily equalized, and energy demand for mechanical ventilation is reduced, since there are no obstructions to the air flow. Circulation paths and hallways, which receive marginal use, should be reduced to a minimum. Design for concentric or circular movement patterns are generally most efficient.

It should also be kept in mind that the illusion of large spaces can be created without having to increase the size of the room by emphasizing horizontal lines, removing part of the wall between two adjacent spaces, using gently sloping ceilings and interior walls 6.5 feet tall.

Planning efficiency can also be increased by grouping spaces with similar functions and environmental control needs. Pipe, duct and conduit runs can be minimized by planning for close bathroom, kitchen and laundry areas, preferably with back-to-back sinks.

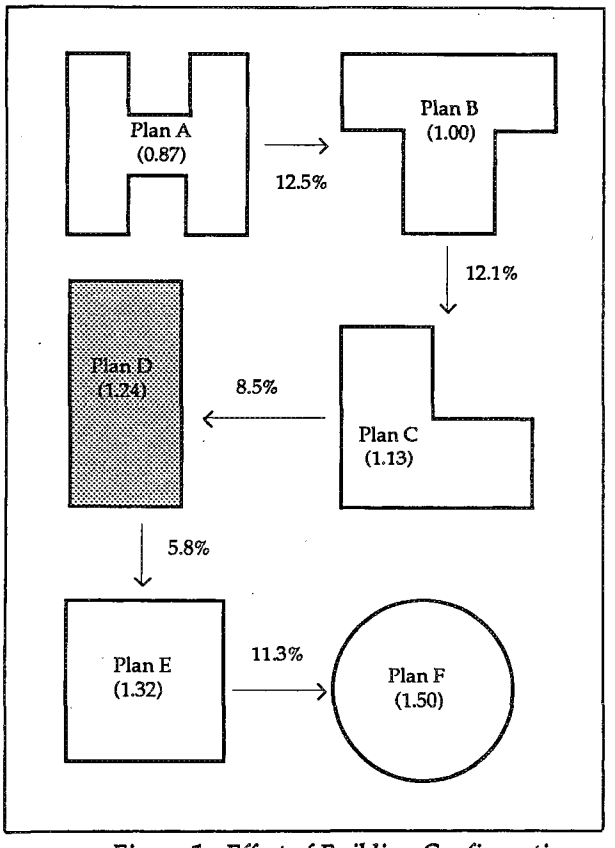

Figure 1: Effect of Building Configuration on Perimeter and Floor Area

Plan Configuration	Wall Area (sq.m.)	Energy Required (KWh)	Associated Heating Cost
Plan A (H)	160	2859	$134
Plan B (T)	140	2501	$117
Plan C (L)	123	2198	$103
Plan D (Rect)	112	2001	$94
Plan E (Square)	106	1894	$89
Plan F (Circle)	94	1679	$79

Table 1: Effect of Building Configuration on Energy Consumption

Analysis

Building Configuration/Plan Simplification

Figure 1 illustrates several possible building configurations having the same floor area. On one extreme, the "H" shaped plan has a ratio of floor area to perimeter of 0.87, requiring 160 sq. m. (1,722 sq.ft.) of exterior wall area for a 93 sq.m. (1000 sq.ft.) house. The required envelope decreases progressively as the plan is simplified to a "T" shape, an "L", a rectangle, square and circle. The latter makes the most efficient use of space, requiring close to 11% less wall than the square for the same floor area.

A simple plan costs less to build since there are fewer corners and, most likely, fewer windows. Envelope costs, from the basement to the roof, are reduced while simple configurations generally require less cutting and fitting of building materials. Consequently, the amount of material wasted is reduced, and the management task is simplified.

Reductions in the exposed wall area are accompanied by a proportional decrease in heat loss. When a plan is simplified from a "T" shape to a square, conductive heat losses from the walls alone can save $28 in heating costs annually for a small (93 sq.m.) house in Montreal (Table 1). These savings could easily be doubled if the additional heat losses from the basement and infiltration are accounted for.

While the circle provides the best area/perimeter ratio, its potential savings can be easily offset by the extra cost of building curved walls, and the interior plan may lead to layouts that are not functional. Similarly, the square provides a more efficient perimeter to floor area ratio when compared to a rectangle. This configuration, however, may be difficult to plan efficiently on the interior. The

rectangle appears to be the most advantageous configuration in this regard. Furthermore, the rectangle would require less land, since it can be built on narrower lots, and can benefit more easily from being grouped into rowhouses, which in turn leads to additional savings in construction and energy costs.

Plan Module	Joists (m)	Studs (m)	Sheathing (sq.m.)
Plan 1 (no module)	378.2	561.1	232.5
Plan 2; 406 mm (16")	384.4	520.1	233.3
Plan 3; 610 mm (24")	299.9	559.2	242.4
Plan 4; 1220 mm (48")	302.4	534.0	237.9

Table 2: Measured Material Requirements

Modular Design/Dimensioning and Efficient Framing Practices

Figure 2 illustrates four simple plans which have approximately the same floor area and configuration, but are dimensioned for different modules. Theoretically, the amount of structural wood required to build these plans should be almost the same, since there is no significant difference in either floor area or perimeter between the alternatives. Table 2 shows the quantity of floor joists, wall studs and sheathing materials (walls and floors) required for a two-storey house as measured from the plans. The sheathing requirement is fairly consistent from one plan to another, with a difference of about 10 sq.m. (108 sq.ft.) between the highest and lowest estimates. This is equivalent to about 3.5 standard sheets of material. Similarly, the total length of wall framing components (including top and bottom plates) changes little between alternative floor plans except for Plan 2, which approaches a square and has less perimeter than the others. More floor joists are needed for the first two plans (Plan 1 and 2), which are wider and require tighter joist spacing (405 mm; 12").

Although the total measured material requirements vary little for plans which use different modules, the amount of waste generated in each design can vary significantly. The amount of waste produced is generally higher in those plans which are based on smaller modules or random dimensions (Table 3). Between 6% and 7% of the material bought for Plan 1 (random dimensions) is wasted on cut-offs that cannot be reused because they are too small. This wastage is reduced gradually as the plans are designed for larger modules. The structural frame based on a 2220 mm (4 ft) module needs very little cutting, and can be built producing little or no waste. Consequently, 5% less sheathing material needs to be purchased.

The amount of wasted material for each plan in Table 3 represents ideal conditions, assuming that all reasonably-sized material cut from a whole sheet or length of lumber is reused. In actual construction, it is probable that some, if not most of the "scrap" will not be recovered or reused. Lumber falling on wet ground, for instance, is not likely to be recovered, nor is that which is cut in a location which is distant from the area where it can be reused.

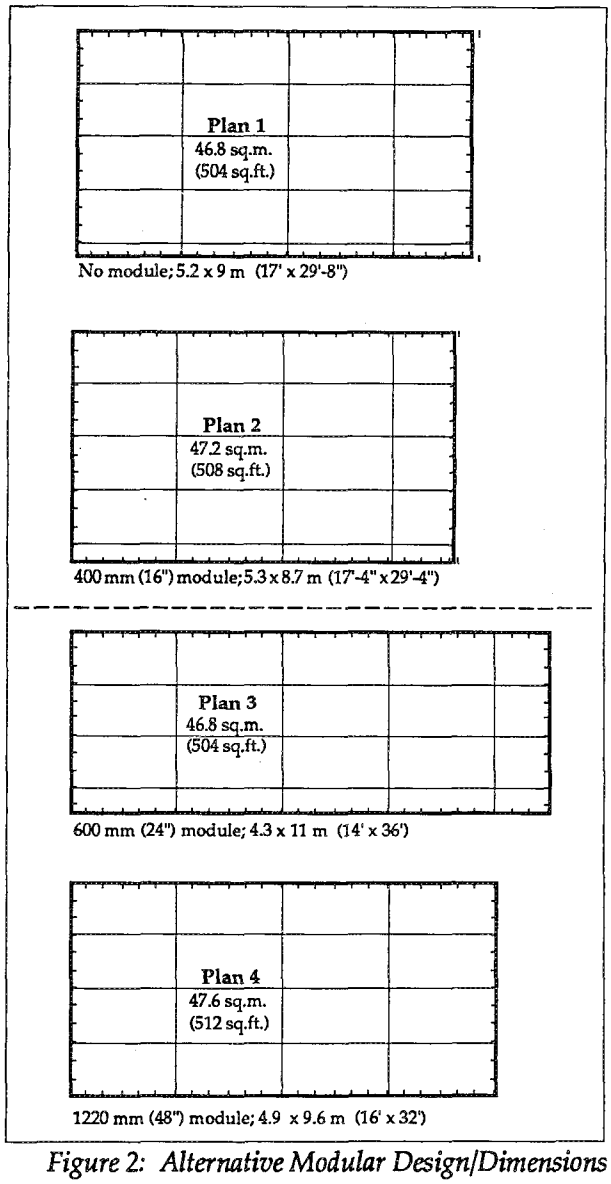

Figure 2: Alternative Modular Design/Dimensions

Plan Module	Joists		Sheathing	
	Ordered (m)	Wasted (m)	Ordered (sq. m.)	Wasted (sq.m.)
Plan 1 (no module)	403.6	25.4	249.7	17.2
Plan 2; 406 mm (16")	408.4	24.0	249.7	16.4
Plan 3; 610 mm (24")	302.4	2.4	249.7	7.3
Plan 4; 1220 mm (48")	302.4	0.0	237.9	0.0

Table 3: Material Usage

Efficient Framing

The amount of lumber required in the building frame can further be reduced in three ways: (1) by using wider spacing between components; (2) by removing any extra lumber whose main purpose is to provide nailing surface for interior finishes; and (3) by lining up the floor joists and wall studs, thereby eliminating the need for a double top plate.

The savings that can be achieved in the Grow Home by applying these principles are shown in Table 4. Lumber used for wall framing can be reduced by over 12% by spacing the studs at 610 mm (24") centers rather than at 405 mm (16"). Similar savings can result from aligning floor joists with wall studs, which eliminates 61 meters (200 ft) of wall studs. Using 2 studs at the corners rather than 3 can save an additional 19.5 meters (64 ft.) of lumber, and the same techniques applied to interior partitions saves 97.5 meters (320 ft.) of interior framing lumber. When all four techniques are applied, lumber savings can add up to 713 kg., with associated construction costs of $539 and an embodied energy content of approximately 5262 MJ, or 1,463 KWh. With every 4 houses built, enough lumber and energy can be saved to frame the walls of a fifth house and heat it for at least one year.

Area Distribution/Floor Stacking

The effect of floor stacking on energy efficiency will depend on several factors, including unit size and grouping (figure 3). In the case of the Grow Home, the energy benefit of moving from a one-story, 93 sq. m. bungalow to a two-story cottage-type model with the same floor area is marginal.

Although the transition increases the total exposed wall area by more than 50%, the extra heat losses are compensated for by a reduction of basement and roof areas. Total heat losses are therefore fairly balanced, resulting in a negligible savings in the order of 1% (Table 5). By reducing the footprint of the house, however, and consequently excavation and foundation requirements, substantial construction cost savings can be achieved.

Framing Alternative	Lumber Savings (m)	Lumber Weight (kg)	Constr. Cost Savings	Embodied Energy [1] (MJ)
Lining up joists w/studs	61.0	204	$139	1502
Stud spacing at 610 mm (24")	68.3	228	$156	1682
Exterior Walls	19.5	65	$44	481
Interior Partitions	97.5	217	$200	1597
	Total	713	$539	5262

[1] Based on energy intensities and conversion factors taken from Sheltair, 1991.

Table 4: Savings From Efficient Framing Practices

For a narrow-front house like the Grow Home, a major advantage of stacking floors is that it allows two or more units to be joined, leading to significant reductions in heat loss and improved land use efficiency.

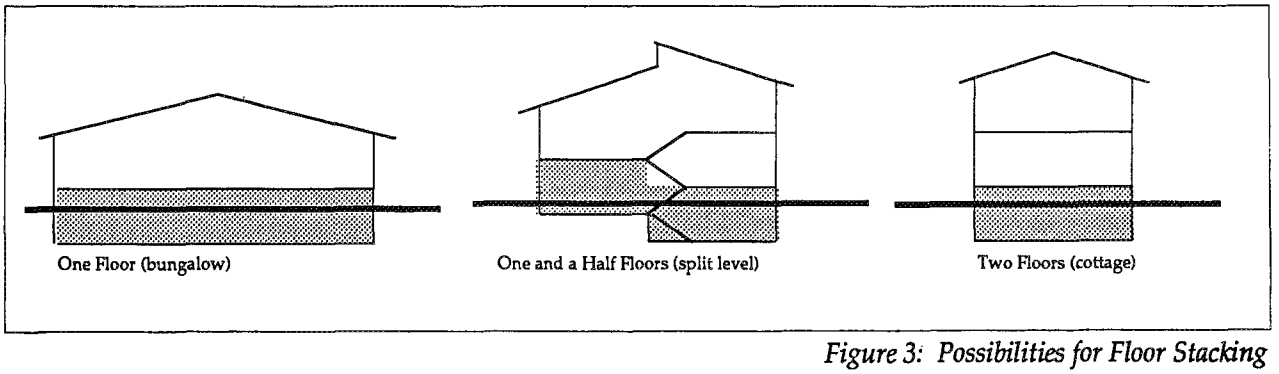

Figure 3: Possibilities for Floor Stacking

Grouping/Joining Units

The joining of units into groups of 2 or more can provide significant savings in both construction and energy. Joining 4 detached units into semi-detached, for instance, reduces the exposed wall area by 36%. Grouping all four units as rowhouses provides an additional 28% savings (Figure 4).

Heat-loss reductions of approximately 21% can be achieved when two dwellings are attached, and a further 26% savings for the middle unit when 3 or more dwellings are joined as rowhouses (Table 5). For Montreal, the transition from a detached unit to a rowhouse results in annual savings of $174. In addition to substantial reductions in energy consumption, the joining of units enables efficient use of land and infrastructure.

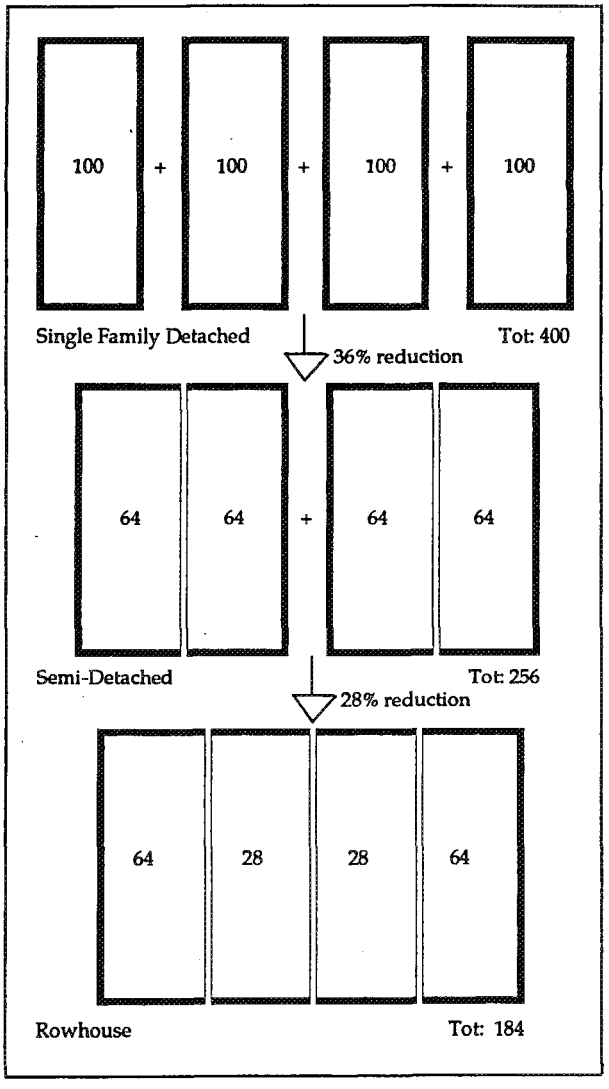

Figure 4: Effect of Unit Grouping onExposed Wall Area

Component	Heat Loss (Watts)			
	1 Storey	2 Storeys		
	(bungalow)	Detached	Semi-det	Rowhouse
Roof	558	279	279	279
Walls	1005	1643	1005	367
Doors and Windows	1598	1598	1598	1598
Basement	1560	1249	780	311
Infiltration	1547	1413	1250	1087
Total	6267	6182	4912	3642
Annual Energy Consumed (KWh)	9154	9029	7174	5320
Associated Heating Costs (Montreal)	$429	$423	$336	$249

Table 5: Combined Effect of Floor Stacking and Unit Grouping on Heat Loss

Summary

Substantial savings in construction and operating costs can be achieved through efficient planning and framing techniques. By simplifying the building configuration, construction costs and heat loss can be significantly reduced, since there are less corners to build and less exposed wall area. Building on two floors and grouping the units into semi-detached or rowhouse configurations saves land and infrastructure, and reduces energy consumption by 42%. Careful dimensioning reduces the amount of waste generated, and simplifies the construction task. Efficient framing practices can reduce lumber requirements by 25% in a small house like the Grow Home. Over a ton of lumber can be saved for every two units built, which translates into $1,200 worth of construction costs. While implementing such basic planning principles can lower operating expenses and make the unit more affordable, the usable floor area remains unchanged, and the occupants' living comfort is not affected.

Further Reading

The Conservation of Energy in Housing. Canada Mortgage and Housing Corporation, Ottawa, 1981.

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Guidelines

Significant savings in material, energy and construction time can be achieved by following some basic planning principles.

- Do not overdesign the structure; stud spacings of 24" on center are usually sufficient for most two-storey houses; corners can be built with 2 studs, and intersections with interior partitions could be supported without using studs.
- Dimension units to accommodate modular dimensions of building materials.
- Dimension and locate openings to accommodate stud spacing.
- Simplify the unit's configuration and plan interiors efficiently.
- Stack floors; two-storey homes use less material and are less expensive to build.
- Group units as semi-detached or rowhouses to save on land, infrastructure, energy and material.

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R-2000 Building Technology

Background

In response to the oil price increases of the mid to late 1970's, the federal government established the Super Energy Efficient Homes (SEEH) program to stimulate the construction of energy-efficient homes. Under this program, Energy, Mines and Resources (EMR) provided builders with training and incentives to build what were called "R-2000" homes, a program whereby a standard for energy efficiency and construction quality was set.

Stated simply, the R-2000 program objectives are to provide technical information for the industry, to provide financial, technical and marketing assistance to participating builders, and to assist industry with further research and development. Participation in the program is voluntary and open to different levels of involvement. Builders wishing to participate fully can register and are offered a complete package of services including training, certification and marketing. Alternatively, builders may wish to simply familiarize themselves with the building technology in order to improve the general quality and energy efficiency of their homes.

Although certain planning options, construction methods and building materials for R-2000 homes are suggested, the program is essentially based on a performance standard. The standard is in the form of an energy budget adjusted for house size and climate, and a set of technical criteria (Figure 1). Builders registered in the R-2000 program may meet the energy budget using designs and materials of their choice, suited to local conditions and market preferences. During construction, the home is inspected and tested to verify that it meets the design criteria, and an identification sticker and certificate are issued to the builder.

How difficult is it to implement R-2000 building technology?

A survey of 244 builders who were involved in the construction of R-2000 demonstration homes revealed that implementing the technology is not a difficult task. Ninety-one percent of R-2000 demonstration builders had no major problems in meeting the R-2000 energy performance standards. It has also been relatively easy for participating builders to reduce envelope losses due to uncontrolled air leakage. Eighty-five percent of R-2000 demonstration builders passed the air-tightness requirement on the first test. The survey demonstrated that with proper attention to technique and choice of materials, builders can construct homes with significantly lower space heating requirements.

Objective

The objective of this section is to review the principles of R-2000 building technology and to examine some of the alternatives for energy-efficient envelope construction. The impact of implementing these principles is evaluated in the context of affordable narrow-front housing.

The construction techniques pioneered by the SEEH/R-2000 program have been recognized as the best techniques for building quality, energy-efficient housing for the North American climate (CHBA, 1989). The Canadian Home Builders' Association (CHBA) assumed responsibility for the program in 1982, and builders participating in the R-2000 program deal directly with CHBA through their provincial associations.

Energy-Efficiency, Durability and Occupant Comfort

One of the most rewarding aspects of the R-2000 program is that it goes beyond the simple testing of building materials; it considers the house as a whole and accounts for how the various building systems, subsystems and components, including the people using it, interact and perform. It acknowledges the close relationship between the external environment, the building's envelope and its mechanical system. It accounts for the effect of the interior finishes, furnishings, lighting and appliances on the house's total energy performance. It includes the migration of heat, moisture, air, sound and radiation between the exterior and interior environment, and provides recommendations for virtually every aspect of house design and construction, from site planning to envelope detailing. By concentrating on performance rather than construction specifications, it ensures

that the home is assembled using quality craftsmanship. By adopting an integrative approach to building construction, it provides a product which is not only more energy efficient, but also more durable, comfortable and healthy for the occupants.

R-2000 Principles

R-2000 technology addresses three general areas of building design and construction. The first deals with planning principles at the site, lot and unit level. The use of proper landscaping and unit orientation helps reduce exposure to wind and snow, while attention to floor layout ensures that the right spaces benefit from solar exposure. Solar heat gain is controlled through size and placement of window units and shading devices to reduce heating costs and prevent heat gains from reaching uncomfortable proportions.

The second area deals with the design, detailing and construction of the building envelope. Higher insulation levels, air-tight construction and high-performance windows ensure that heat losses are minimized and that pollutants are not carried into the house. With proper detailing, water, vapour and air migration are controlled to avoid penetration and condensation, which could rapidly deteriorate the building.

Finally, the use of efficient mechanical systems ensures that space conditioning, ventilation and water heating requirements are fulfilled with minimal amounts of energy. Due to the air-tight envelope, ventilation is given special attention, requiring that a constant and sufficient supply of fresh air is distributed to every room of the house.

Potential for Improvement

R-2000 houses built to performance standards consume 1/2 of the energy of a typical house in the 1980's, and 1/4 of the energy of post-war housing. While the cost of building such homes can vary widely depending on the individual builder and location, significant reductions in heat loss can be achieved with relatively minor investment by simply applying some of the practices recommended by R-2000. With attention paid to frame detailing and stud spacing, for instance, energy consumption related to heat loss can be reduced by as much as 10%. Replacing the exterior sheathing material with rigid board insulation can save an additional 8%, and the use of energy-efficient windows could save 15% of total energy costs.

Although attractive savings can be achieved by addressing individual components of the house, it should be kept in mind that energy efficiency can only be applied successfully through a systems approach, whereby the performance of all building systems, subsystems and components are considered integrally. The high interdependence between heating and ventilating systems and the building envelope's performance requires that all aspects of the building's interior environment and physical

Energy Budget

The total energy budget from an R-2000 home is derived from an equation that provides a specified figure for nonspace heating energy requirements and and for building envelope losses per square meter. The calculation allows for variations in climate (degree days) and house size, expressed in equivalent floor area (the heated volume of the house, including basement, divided by 2.5).

Technical Requirements

- *Air leakage* : 1.5 Air changes per hour at 50 Pa maximum
- *Ventilation*: Continuous ventilation at a rate of 5 litres/second (10 cfm) for each room, plus 10 litres/second (20 cfm) for the master bedroom and the basement. Exhaust capabilities must be supplied in the kitchen and bathroom.
- *Replacement air:* must be provided for all appliances that exhaust air from the home e.g.: clothes dryers, power vented hoods, central vacuum systems, etc.
- *Combustion equipment:* specific requirements for gas or propane, oil-fired and solid fuel-fired appliances
- *Windows*: double glazed with 1/2" air space min.
- *Walls*: 3.5 RSI (R-20) min.
- *Water heaters*: insulated to RSI 1.75 (R-10); "heat trap" or insulation for the first 3 meters of pipe; temperature normallyset at 50 deg. C (120 deg. F) max.
- *Appliances*: within the upper 33% of *Energuide* rating (EMR)

Figure 1: R-2000 Performance Standard

construction be accounted for. Misapplied R2000 buiding technology can otherwise result in problems such as poor indoor air quality and moisture damage.

The evaluation of several individual energy-saving techniques in this report is carried out strictly for comparitive purposes. The environmental impact of various details, window units and mechanical systems is evaluated in other sections. In the discussion which follows, alternatives for energy-efficient building envelopes are examined independently.

Building Envelope Alternatives

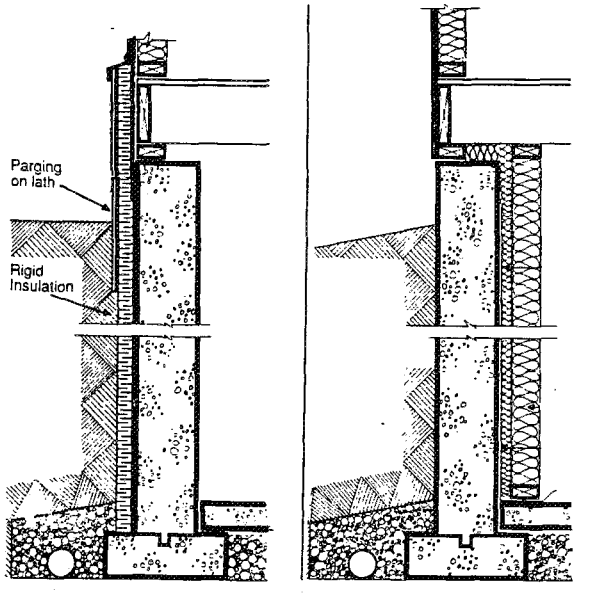
One of the most basic considerations in the design and construction of energy-efficient housing is the amount of heat loss which occurs through the building envelope. While this heat loss could be reduced by simply adding insulation, the design and construction of an energy-efficient envelope involves much more.

In addition to providing structural support for the building, basements, walls and roofs have to perform

Function		Mechanism	Solution	Materials/Processes
Control Heat Flow	Heat Loss	Conduction	Insulate; avoid thermal bridges, particularly at foundation wall, floor/wall junctions, roof/wall junctions and window frames.	Batt, rigid board, blown or sprayed insulation; careful detailing to avoid thermal bridges
		Radiation	Reflective coatings (where air spaces are present); low-emissivity coatings in glazing units	Aluminum-coated papers; proprietary coatings
		Convection	Keep air spaces narrow and/or interrupt convective currents with grid patterns; fill in wide air spaces with insulation.	Use appropriate designs/processes eg. apply adhesives for rigid boards on foundation walls to form squares/rectangles
		Air Leakage	See "Control of Air Flow"	
	Heat Gain	Solar	Control heat gain for summer and winter conditions through appropriate design and window size, location and orientation	Overhangs; solar shading devices; low-emissivity windows
Control Air Flow	Infiltration/ Exfiltration	Diffusion	Provide continuous layer of sheet materials that are impervious to air.	Air barriers: rigid sheet materials (drywall, plywood, etc.) or membranes (polyethylene, aluminum, etc.) or a combination of both
		Leakage	Seal all gaps to form a continuous air-tight building envelope, particularly at windows, electrical boxes and service penetrations	Sealants, caulking beads, tapes and gaskets; polyurethane foams; air-tight boxes and wraps for electrical fixtures
Control Moisture Flow	Water	Gravity	Slope exterior finishes and flashings away from wall at joints; slope grade away from foundation wall; use overhangs with drips (where applicable)	Weather barriers: olefin sheets, building paper, tar coatings, polyethylene, exterior finishes, waterproof paints, etc. Flashing materials: metal, plastic, etc.; gaps sealed with sealants, caulks and gaskets.
		Capillary action	Keep exterior finishes away from soil; interrupt flow of water from soil with a weather/ moisture barrier	
		Momentum	Keep exterior finishes away from soil; use appropriate flashing materials and details; provide roof overhangs	
		Pressure difference	Use rainscreen principle ie. provide a sealed, drained air space between exterior finishes and wall to equalize pressure difference	
	Vapour	Diffusion	Provide a continuous layer of sheet materials that are impervious to vapour; located on the warm side of the insulation to control outgoing vapour.	Vapour diffusion retarders (VDRs) or "vapour barriers": aluminum-coated kraft paper, polyethylene, vapour-resistant paints, extruded polystyrene; multiple layers of building paper and other materials may also act as VDRs
		Air Flow	See "Control of Air Flow"	

Figure 2: Principles of Envelope Design and Construction

several functions at once and be able to resist deterioration. As a basic form of shelter, the envelope must prevent the entry of water, snow and ice which are driven upon it by wind, air and hydrostatic pressures (as is the case with basement walls). Noise and air pollutants from the exterior need to be kept out, while vapour carried in the warm interior air must be kept in. Convective, radiative and conductive heat flow must be minimized in both directions to reduce energy losses through convective currents, air spaces and materials. Last but not least, the building envelope must control the flow of air, both infiltrating and exfiltrating, which carries with it heat, vapour and contaminants.



(adapted from Marbek, 1987)

Exterior Insulation

Advantages:

- Wall is warm; less probability of concealed condensation
- Lower labour requirements; no need to fasten below grade; pressure of soil usually enough
- Lower probability of adfreezing and frost damage
- Airtightness at sill plate can be improved; thermal bridge at header minimized; easy to ensure continuity of air barrier/vapour barrier
- Thermal mass of foundation wall on interior; concrete not exposed to temperature fluctuations; less chance of freeze/thaw damage

Interior Insulation

Advantages:

- Lower material costs
- Provides a finished interior space
- No changes to exterior finishing detail
- Thermal bridge from warm foundation to brick veneer is reduced
- Space provided for mechanical/electrical services
- Protection above grade does not require more complex details, reduces costs
- Does not require special care/supervision during backfilling

Figure 3: Options for Insulating Basement

While it is beyond the scope of this section to study scientific principles of envelope design, a partial summary of the functions of the building envelope is given in Figure 2, along with the normal solution and materials used. The alternatives presented below represent only some of the possibilities for upgrading the thermal performance of the building envelope. Readers interested in a more thorough discussion should consult the *Builders' Manual* from the Canadian Home Builders' Association.

Basement/Foundations

It has become common practice in most urban and suburban municipalities to build homes which include a basement. In cold climates, building codes usually require that foundation walls be constructed to 1.2 meters (4 ft.) or 1.4 meters (4 1/2 ft.) below grade to ensure that the footings rest below the frost line, although this may vary from 0 to 2.4 meters(8 ft.). If this is the case, a basement could be provided, adding from 30% to 50% usable floor area to a house, at a modest incremental cost, since most of the excavation work and construction of the foundation walls is required anyway.

Basements are, however, an important source of heat loss, accounting for 20 to 30% of energy losses through the building envelope. Furthermore, they are often problematic relative to other parts of the building envelope, as they are susceptible to moisture penetration and cracking, resulting in damp, uncomfortable living spaces. In addition to sufficient insulation, attention must be given to draining soil water away from the wall, and keeping it from freezing and causing frost damage.

There are many ways to insulate and waterproof basement walls, depending on the intended use of the basement space and the availability of labour and material. Figure 3 illustrates two basic approaches to insulating foundation walls, along with the advantages of each.

While properly built, well-insulated basements can improve the space needs and flexibility in a home,

there are several other alternatives which are less expensive to build and cost less to heat. Depending on the climate, soil conditions and intended use, these options may be worth considering.

1. *Heated Crawlspace*: One basic variation on the full basement approach is the heated crawlspace, which is designed, built and detailed in the same manner except for a shorter perimeter wall. Space heating requirements are reduced because the surface area for heat loss is decreased. Construction cost savings are achieved because less material is required.

2. *Unheated Crawlspace*: This approach functions in the same way as an unheated, ventilated attic. A framed floor, placed over a perimeter foundation wall, is insulated between the joists. It can be more energy-efficient than the heated crawlspace, since it allows for high levels of insulation, and, more importantly, a high degree of air tightness is more easily achieved. Water and service pipes, however, as well as ductwork must be insulated independently or placed on the warm side of the floor. Since there is no heat loss from below grade, the foundation wall is also more susceptible to frost damage. As is the case with any floor system that forms part of the envelope, care must be taken to minimize thermal bridging. Cold floors can be avoided by building a multi-layer floor, and circulating supply or return air between the subfloor and the finished floor.

3. *Slab on Grade*: This method uses a concrete slab placed at grade level with either perimeter edge reinforcing or a perimeter wall. The slab is insulated either from below or above (in which case rigid insulation rests under a built-up subfloor), and at the edges. When properly insulated, the concrete can provide thermal storage for solar and internal heat gains. Improper insulation, however, could lead to frost damage. Slabs on grade are not suited for expansive soils.

Walls

R-2000 proposes three general ways of thermally upgrading standard wood-frame walls consisting of 38 x 140 mm (2" x 6") studs. The first and most basic method replaces the exterior sheathing with rigid insulation. The second method adds horizontal strapping to the interior of the wall, which is then filled with batt insulation. Finally, the most efficient alternative involves the construction of double-stud walls of variable thicknesses and spacings to achieve whatever thermal resistance is desired. Combinations of these three basic varieties are also possible (figure 4).

1. *Single Stud Walls (SSW) with insulative sheathing*: The most basic way to upgrade a wall's thermal resistance is to replace the exterior sheathing (commonly plywood or waferboard) with rigid or semi-rigid boardstock insulation. Depending on the thickness of insulation selected, this approach can lead to thermal resistance values as high as RSI 4.9 (R-28), which represents an improvement of 40% over the conventional RSI 3.5 (R-20) wall with structural sheathing. The most attractive characteristic of the SSW with insulative sheathing is that it requires only minor changes to conventional

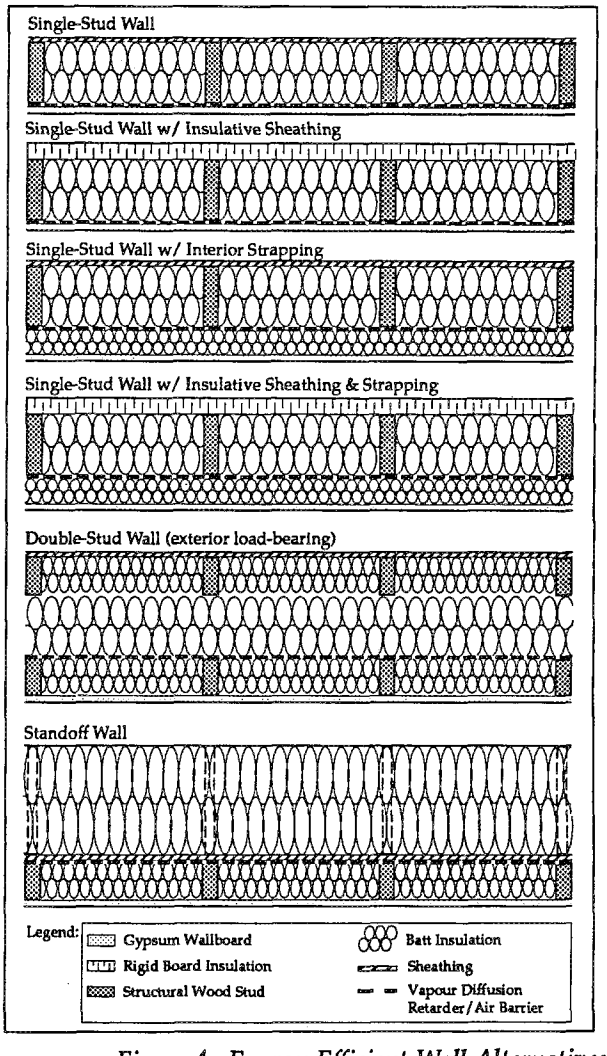


Figure 4: Energy-Efficient Wall Alternatives

construction practices. The type and thickness of insulation can also be varied without major changes to the process. Incremental cost increases over standard building practices are usually limited to the cost of material, and are relatively small ie. the additional labour costs are minimal.

The absence of a structural sheathing material, however, requires that diagonal bracing of wood or preformed metal be installed. The increased wall thickness also requires that window and door openings be built out slightly. The exterior insulation and mechanical fasteners need to be compatible with the exterior finish material.

2. *Single Stud Walls (SSW) with interior strapping*: Another method of improving the energy efficiency of walls is to add horizontal strapping to the interior of the wall, which creates a space for additional insulation. Using 38 x 64 mm (2" x 3") strapping, the thermal resistance of the wall could be increased to RSI 4.9 (R-28). When combined with rigid exterior insulative sheathing, this value increases to RSI 6.3 (R-36), an 80% improvement over a conventional wall, and a 28% improvement over a SSW with insulative sheathing.

In addition to the general reduction of conductive heat loss, the horizontal strapping method reduces thermal bridging across the wall studs, since the insulation between the strapping is perpendicular to the load-bearing studs. One of the biggest advantages of using this method, however, is that electrical and plumbing devices could be installed in the strapping space, thereby minimizing the number of penetrations through the air/vapour barrier. Consequently, air leakage and moisture migration is substantially reduced, making for a more energy-efficient and durable assembly. The labour-intensive operation of sealing openings around electrical boxes and drilling through vertical studs is practically eliminated, making the contractor's work easier.

Spacings between both structural studs and strapping members could be varied to accommodate interior and exterior finishes more efficiently. Some care in the soldering of pipes, however, is required to avoid damage to the polyethylene vapour retarder. The only other drawback to the use of interior strapping is that blocking must be provided to support kitchen cabinets, baseboards, curtain rods and other fixtures. As was the case with the insulative exterior sheathing, the wall also needs to be built out and in to accommodate the extra thickness. Alternatively, vertical strapping staggered with the structural studs could be installed to accommodate whatever interior finishes and/or furnishings are desired. Electrical wiring could still be installed without the need for drilling, as they could be fitted around the staggered studs. In this case, the assembly required approaches that of the double-stud wall.

3. *Double Stud Walls (DSW)*: The most energy-efficient option involves the construction of two practically separate walls, which enables high levels of insulation to be installed (both between the studs and in the spacing between the two walls). This also ensures that the vapour barrier and air barrier are not penetrated by plumbing and electrical services, providing a continuous air seal throughout the building envelope. These expanded wall systems consist of a load-bearing structural wall, which may be located either at the interior or the exterior, and a second, lighter non-bearing wall that supports either the interior drywall or exterior sheathing. Both walls are filled with batt insulation, and are spaced to accommodate a third layer of insulation between them. The latter spacing is usually 89 mm (3.5") or 140 mm (5.5"). Smaller spacings of 64 mm (2.5") are possible, but the extra thermal resistance of RSI 1.4 (R-8) might not justify the added expense of building the extra wall. Larger spacings in the order of 250 mm (10") are also possible, but would consume a significant amount of floor area. Furthermore, the energy savings achieved by adding very large amounts of insulation in the cavity may not be worth the initial investment. A life-cycle cost analysis would be required to determine the point of diminishing returns.

The thermal performance of double stud wall systems can range from RSI 6.3 (R-36) with an 89 mm (3.5") cavity to RSI 7.7 (R-44) when a 140 mm (5.5") cavity is used. These are 80% and 110% more efficient than standard single-stud walls, respectively, not accounting for savings from a virtually air-tight envelope (see section on building details).

While the DSW provide significant improvements in thermal performance, the added labour and material costs are higher than they would be with other systems. Material requirements are increased

substantially, while framing and finishing operations are much more demanding, particularly around openings. The rigidity of the assembly provides an exceptional air barrier, but the associated increase in cost may render these systems unfeasible for smaller, affordable homes. While the increased wall thickness could make for some pleasant detailing on the interior of window openings, they may be difficult to justify where space limitations are critical.

4. *Standoff walls*: A variation of the double-stud wall system involves the attachment of prefabricated or site-fabricated trusses to the exterior of a standard stud wall. The width (spacing) and depth of the trusses could be selected to accommodate a variety of insulation widths and thicknesses. One of the biggest advantages of this method is that a polyethylene vapour barrier can be installed continuously from roof to foundation wall over the exterior sheathing of a conventionally-built wall. The trusses are attached to the studs through the sheathing. The outer member of the trusses can be of small-dimension lumber, since it is not load-bearing.

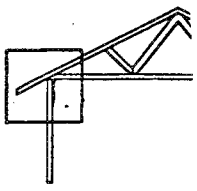
Attics/Roofs

Most builders use prefabricated trusses to frame the roof and ceiling. Many structural roof trusses, however, can limit the amount of insulation that can be installed at the eave above the top plates of the exterior wall. Consequently, the increased heat loss through this area has a tendency to melt the snow directly above the wall. This not only reduces the energy-efficiency of the envelope, but may cause ice dams, water penetration and, eventually, water damage to the wall.

The same situation applies to traditionally-framed roofs and attics, which are usually restrictive in their ability to accommodate sufficient amounts of insulation at the eaves. There are several types of trusses and framing techniques, however, that will allow higher levels of insulation to be installed at a uniform thickness over the entire attic floor, including above the exterior wall's top plates (Figure 5). While some of these require a higher initial purchase price or labour cost, the potential energy savings and prevention of moisture-related problems makes for an attractive investment.

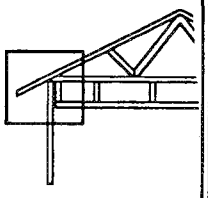
Standard Truss

- Least expensive option
- Insulation compressed at the exterior wall
- May lead to ventilation/condensation problems



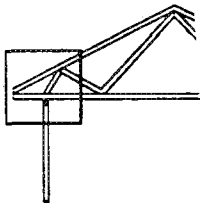
Dropped Chord

- Allows for full-depth insulation up to perimeter walls
- Helps reduce truss uplift
- Price may be higher than standard trusses
- Requires longer studs
- Additional siding required
- Blocking required at ceiling/wall



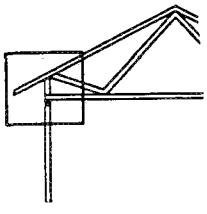
Cantilever

- Allows for uniform thickness of insulation, including above top plates
- Slightly higher price than standard trusses



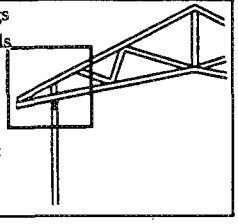
Raised Heel

- Allows for full-depth insulation over entire attic floor
- Higher purchase price than standard trusses
- Additional siding required



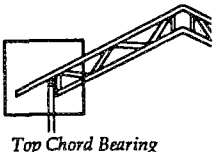
Scissor Truss

- Economical way to provide vaulted ceilings
- Can more easily accommodate higher levels of insulation than conventional ceilings
- Allows for full-depth insulation up to perimeter walls
- Difficult to insulate between chords except with blown material
- Requires insulation baffles

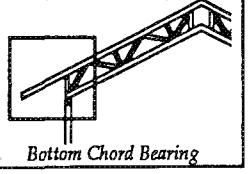


Parallel Chord Trusses

- Allow for large amounts of insulation
- Ventilation can be provided without cross-purlins (when solid web materials are not used)
- Heat losses from thermal bridging may be high with steel webs
- Difficult to insulate between chords, particularly if solid wood is used



Top Chord Bearing



Bottom Chord Bearing

Compiled from CHBA, 1989.

Figure 5: Roof Truss Alternatives

Analysis

As noted earlier, implementing all of the R-2000 principles, including air-tight construction, increased insulation levels, high-performance windows and efficient mechanical systems could reduce total energy consumption to 50% that of a conventionally-built home. Increased insulation levels alone could reduce heat loss by as much as 30%. In the case of the Grow Home, however, these savings are somewhat less pronounced than they would be for larger, more conventional single-family detached units. Due to the narrow front rowhouse configuration, heat losses are restricted to 2 walls and a small roof area, and up to 30% of the wall is taken up by windows and doors.

Figure 6 compares the breakdown of heat losses between a standard Grow Home and a conventional house. The fraction of heat loss through basements, walls and roofs is approximately 27% of the total, compared to 55% for more traditional plans. Only 10% of the total heat loss occurs through the walls in a rowhouse version of the Grow Home.

Foundations: Replacing the basement with a crawlspace or a slab on grade not only reduces construction costs, but heat losses are decreased by up to 11% (Table 1). Since heating costs for attached homes are relatively low, these savings represent a small annual fee, ranging from $46 for a slab on grade to $63 for an unheated crawlspace.

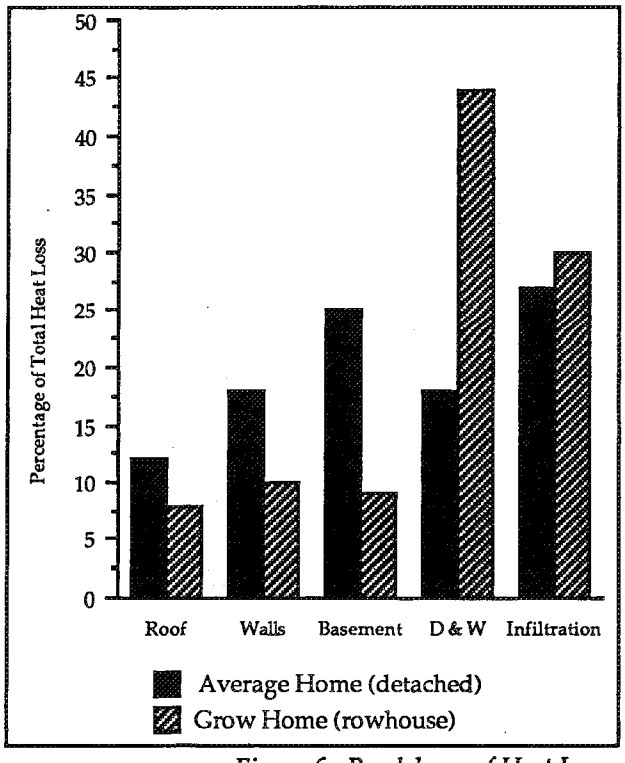


Figure 6: Breakdown of Heat Loss

Annual Performance Characteristics	Foundation Option			
	Full Basement	Heated Crawlspace	Unheated Crawlspace	Slab on Grade
Rowhouse				
Heat Loss (W)	3641	3167	3334	3228
Energy (KWh)	5318	4626	4870	4715
Heating Costs	$249	$217	$228	$221
Constr. Cost	$7191	$5828	$6106	$6002
Energy Savings	———	$32	$21	$28
Cost Savings [1]	———	$104	$83	$91
Total Savings	———	**$137**	**$104**	**$119**
Semi-detached				
Heat Loss (W)	4912	4211	4120	4396
Energy (KWh)	7174	6151	6018	6421
Heating Costs	$336	$288	$282	$301
Constr. Cost	$8523	$6015	$6137	$6205
Energy Savings	———	$48	$54	$35
Cost Savings [1]	———	$192	$183	$178
Total Savings	———	**$240**	**$237**	**$213**

[1] Equivalent annual payments to finance initial contruction cost difference on a 25-year mortgage; assumes 10% disount rate and 4% escalation

Table 1: Characteristics of Basement Alternatives

Construction cost savings from eliminating the basement, however, could be substantial, generally in the area of $1000 for a rowhouse to $2400 for a semi-detached version of the Grow Home. These savings represent present values of uniform annual payments in the range of $85 to $190. Coupled with energy cost savings, the initial construction cost difference translates to annual savings of up to $255 for a semi-detached unit with a heated crawlspace.

Considering that a basement could substantially increase much-needed living and/or storage space in this type of housing, the added expense of adding and heating a basement may be worthwhile from a marketing perspective. If space limitations are not critical, however, eliminating the basement makes for a more affordable and energy-efficient home. If perimeter foundation walls were replaced with edge beams or pier foundations, additional savings could be incurred, while damage to the existing terrain would be minimized.

Walls and Roofs: A similar situation exists with the house's walls and roofs. Table 2 shows energy consumption and heating costs associated with some variations of the single, double and standoff wall

Alternative Wall Type	Estimated Heat Loss (W)	Required Energy (KWh)	Associated Heating Costs
Rowhouse			
SSW (standard)	434	634	$30
SSW w/Insul Shthng (25mm)	329	481	$23
SSW w/Insul Shthng (38mm)	300	439	$21
SSW w/Strppng (38 x 64mm)	300	439	$21
SSW w/SPG + STG (25mm)	250	366	$17
SSW w/SPG + STG (38mm)	235	343	$16
DSW (38 x 89mm cavity)	236	345	$16
DSW (38 x 140mm cavity)	188	274	$13
SOW (254mm truss)	188	274	$13
SOW (305mm truss)	156	228	$11
Semi-detached			
SSW (standard)	1188	1735	$81
SSW w/Insul Shthng (25mm)	902	1317	$62
SSW w/Insul Shthng (38mm)	822	1201	$56
SSW w/Strppng (38 x 64mm)	822	1201	$56
SSW w/SPG + STG (25mm)	685	1001	$47
SSW w/SPG + STG (38mm)	642	938	$44
DSW (38 x 89mm cavity)	646	944	$44
DSW (38 x 140mm cavity)	514	751	$35
SOW (254mm truss)	514	751	$35
SOW (305mm truss)	428	625	$29
Roofs			
Standard (RSI 5.3)	383	559	$26
Upgrade 1 (RSI 7.4)	274	400	$19
Upgrade 2 (RSI 10.6)	192	280	$13

Note: Values apply to wall or roof components ONLY.

Table 2: Energy Performance of Alternative Wall and Roof Components

systems. While the upgrades could reduce energy consumption by up to 65%, the actual cost savings remain limited. For a semi-detached version of the Grow Home, for instance, energy consumption relative to a standard wall could be reduced from 1765 KWh to 625 KWh for the Montreal area. At an assumed energy cost of $0.0469/KWh, this represents annual cost savings of about $53. When compared to the initial investment required to build the wall, these savings are fairly modest.

Table 3 compares annual cost savings with incremental construction costs for some of the options. Generally, the savings generated don't justify the investment at a purely economic level. The cost of building double-stud walls, for example, varies from $1,216 for the rowhouse to $3,241 for a semi-detached unit, while annual savings generated from these are $17 and $46, respectively. Using exterior insulative sheathing appears to be the most effective thermal upgrade. The process is uncomplicated, and incremental costs are only about $170 for the rowhouse. Similarly, upgrading the roof insulation from RSI 5.3 (R-30) to RSI 7.4 (R-40) would cost a marginal $126.

It should be noted that these estimates are restricted to heat loss from conduction, and only evaluate the impact of adding insulation. Losses from thermal bridging, low-performance window units and air leakage due to inadequate detailing, which represent a significant fraction of total heat loss, were not accounted for. Furthermore, the application of energy-efficient technologies results in reduced requirements for the size of the heating system, which provides additional savings. While adding insulation in itself may not have a great impact on energy savings for this type of housing, it reduces thermal bridging and facilitates the construction of an air-tight wall. The effects of these are covered in their respective sections in the remainder of this report.

Summary

There are various ways to improve the energy-efficiency of foundations, walls and roofs which require different levels of complexity and investment. Alternatives for wall assemblies range from the simple replacement of exterior sheathing with rigid boardstock insulation, to the construction of double walls which are separated and filled with high levels of insulation. Energy-efficient assemblies could

Alternative Wall Type	Annual Energy Savings	Initial Cost Difference
Rowhouse		
SSW w/Insul Shthng (25mm)	$7	$170
SSW w/Insul Shthng (38mm)	$9	$246
SSW w/Strppng (38 x 64mm)	$9	$315
SSW w/SPG + STG (25mm)	$13	$486
DSW (38 x 140mm cavity)	$17	$1216
Semi-detached		
SSW w/Insul Shthng (25mm)	$20	$454
SSW w/Insul Shthng (38mm)	$25	$656
SSW w/Strppng (38 x 64mm)	$25	$840
SSW w/SPG + STG (25mm)	$34	$1294
DSW (38 x 140mm cavity)	$46	$3241
Roofs		
Upgrade 1 (RSI 7.4)	$7	$126
Upgrade 2 (RSI 10.6)	$13	$305

Note: Values apply to wall or roof components ONLY; incremental costs taken from UNIES, 1992.

Table 3: Cost Implications of Alternative Wall and Roof Components

reduce conductive heat loss from 25% to 65%, depending on the method used. In addition to increasing thermal resistance, air leakage is also reduced because the air barrier can be separated from the interior sheathing, where it is constantly pierced by electrical and mechanical fixtures. By adding insulation on either side of the structural framing members, there is less thermal bridging, and sound transmission is reduced, making for a more pleasant and comfortable interior environment.

The inherent advantages of the Grow Home in terms of energy efficiency are due to its relatively small exposed wall area. The total heat loss through the wall component, not including doors and windows, accounts for a small fraction of the total heat loss. Consequently, the savings to be gained from building superinsulated walls is less pronounced than it would be for larger, detached homes. Considering that these walls usually take up more floor space, the use of double stud walls in the Grow Home is not a feasible option.

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Guidelines

- Where space limitations are not critical, consider replacing the basement with either a crawlspace or a slab on grade to reduce both construction costs and energy consumption.
- Upgrade wall construction according to budget, unit type and space limitations. At the very least, consider replacing the exterior sheathing with rigid insulation to reduce heat flow and thermal bridging. For larger, single-family detached homes, double-stud walls could reduce thermal bridging substantially and provide a virtually air-tight assembly.
- Select roof trusses to accommodate consistent thicknesses of insulation up to and beyond the top plates of exterior walls.
- Add as much insulation to the roof space as the budget will allow.

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Construction Details

Background

In an average home, about 1/2 of the total indoor air volume is replaced every hour by outdoor air which leaks into the house. This air leakage accounts for approximately 25% of the total heat loss through the building envelope. Not only does this significantly increase energy consumption, but it also contributes to the rapid deterioration of the building fabric as well as to poor indoor air quality. Warm, exfiltrating air carries with it vapour from within the building, which may condense inside the envelope as it cools, causing concealed moisture damage. Infiltrating air, on the other hand, carries pollutants from exterior sources as well as harmful emissions from building materials inside the envelope to the interior of the home. Poor indoor air quality has often been associated with air-tight construction, under the belief that air leakage was somewhat beneficial in that it replenished interior air with "fresh" exterior air. It is now recognized, however, that there is no redeeming quality in air leakage, and that indoor air quality should be controlled through proper material selection and mechanical ventilation.

Controlling air flow across most parts of the building envelope is a fairly simple process, since many common building materials, such as plywood, waferboard, drywall and polyethylene, are effective air barriers. The problem lies in the manner in which these materials are assembled; at the joints between sheets of the same material, but particularly at the intersection of different building components. Most air leakage occurs in areas where the envelope is pierced, such as window and door openings, service penetrations, and where the envelope intersects with floors, roofs and basement walls.

The difficulty in achieving air-tight details is that the work of several trades often comes together at these points, with the work of one affecting that of another. In a standard residential wall, it is not uncommon to find 4 or 5 trades working in the same part of the building. Carpenters, plumbers, electricians, drywall installers and mechanical ductwork installers all work with the envelope, piercing and patching newly-formed gaps at different stages during the construction process. It is therefore not surprising that the majority of building defects occur in the building envelope, and that inadequately designed or constructed details are a primary cause of these failures. With proper attention given to detail and craftsmanship, air leakage through these areas and problems associated with air leakage can be significantly reduced.

Objective

The objective of this section is to investigate how durability, energy-efficiency and indoor air quality can be improved through proper detailing. The energy implications of air-tight construction are evaluated for rowhouses and semi-detached units.

Potential for Improvement

With a little extra effort placed on detail design and construction techniques, significant energy savings can be achieved while improving both the durability of the envelope and the quality of indoor air. Air leakage rates in an average home range from 0.5 to 1.0 air changes per hour (ACH). A properly detailed and built wall could reduce this value to 0.1 or even 0.05 ACH. For a 150 m^2 (1600 ft^2) house, this represents a reduction of up to 348 m^3 (12 300 ft^3) of air. The cost of heating and conditioning this air in Montreal would be $455 a year. If a heat-recovery ventilator is installed to replenish indoor air, the savings would still be in the neighbourhood of $160. Furthermore, by reducing thermal bridging, heat losses through the envelope could be reduced by as much as 10%. Considering that heat losses through the basement, walls and roof account for about 57% of total heat losses in an average home, these savings can be significant.

Air Flow and Durability

The importance of placing a vapour barrier on the warm side of the insulation is well known. Without a vapour barrier, warm, moist air from within the building can diffuse through the materials towards the cold exterior. As it cools, condensation can occur inside the wall. Considering that the problem may persist undetected for some time, the consequences could be severe. The effect of concealed condensation can range from deterioration of the insulation

Envelopes, Details and Building Failures

The effect of inadequate detailing on building performance has been a subject of concern both in North America and Europe. Data from the Bureau Securitas (a French agency) provided by an American subsidiary of *Socodec* shows, in a study of 10 000 failures between 1968 and 1978, that 78% of all design deficiencies are related to poor detailing, accounting for 59% of all costs of repairs (Cusens, 1985; Loss, 1987; Paterson, 1984). The same study found that 37% of failures were a consequence of inadequate design, while 51% were due to inadequate construction.

While the overall trends in North America are similar, design deficiencies account for a larger percentage of building failures. An analysis of over 4000 cases between 1978 and 1982 by the *Architecture and Engineering Performance Information Center* in Maryland found that design deficiencies were resposible for 60% of all failures, and that 28% of these were architectural (Loss, 1987) Envelope failures have been estimated to account for 90% of all architectural failures (CE, 1981), with simple detail problems like the leaky roof, window or skylight amounting up to the single most important source of failure in the entire builing inventory (Loss, 1987).

material (and loss of thermal performance) to structural damage from rotting framing members. Freezing water at the outer layers of the wall could damage the finishes irreparably. Cracking and spalling brick, for example, may be a symptom of inadequate vapour resistance.

While the importance of providing a vapour barrier cannot be overstated, the potential damage caused by air currents is much more severe. Assume, for example, that a wall containing a 0.1 mm polyethylene vapour barrier is exposed to interior conditions of 21°C and 30% RH (relative humidity) and exterior conditions of -21°C and 80% RH for one month. Approximately 6 grams of vapour would flow through a one-square meter section of this wall by diffusion (through the materials), creating only a thin layer of frost on the inside surface of the exterior sheathing. If an opening with a net area of 625 mm (1 in^2) would be cut in this wall, perhaps through an electrical outlet box or service penetration, 2600 m^3 (91 818 ft^3) of air would enter and exit the cavity under a 10 Pa pressure difference, which is equivalent to a 15 km/h wind, in the same period of time. This would amount to about 3000 kg of air and 14 kg of water that is crossing the wall cavity. Even if only 10% of this vapour condensed, the amount of water deposited on the sheathing would be about 1400 grams, or 233 times the amount that would be transferred by diffusion (Quirouette, 1985). This is why the construction of air-tight assemblies is critical if the building is to perform efficiently and last for decades.

Principles of Joint Design

The technical requirements of a building envelope are essentially to control the flow of water, vapour, heat and air between the interior and exterior environments. In principle, the migration of these elements could be controlled fairly simply: water is kept out by means of a weather barrier placed on the exterior of the wall; vapour is kept in by means of a vapour barrier placed close to the interior surface of the wall; heat flow in both directions is controlled by insulation; and air flow is controlled by means of an air barrier.

At the joints between building components, these principles remain unchanged. The challenge is to prevent the migration of air, vapour, heat and water across any gap that may be formed when the envelope is interrupted. Accordingly, there are three factors to consider in envelope detailing.

1. *Elimination of Thermal Bridges:* The level of insulation varies at different sections of the envelope. In a standard stud wall, the thermal resistance varies from RSI 3.52 (R-20) between the studs and plates, where the insulation rests, to RSI 1.21 (R-7) at the studs and plates. Where floors intersect the wall, the thermal resistance can be reduced to about RSI 0.33 (R-1.9) if the space between joists is not insulated. The problem is most pronounced at the foundation wall, where the concrete often forms a direct link between the interior and exterior environments. Thermal bridges such as these can be avoided by placing insulation on either side of the conductive material to interrupt the flow of heat, or by changing or reorienting the conductive material to eliminate the bridge altogether. Ideally, the thermal resistance should remain consistent throughout the entire wall.

2. *Location and Continuity of Vapour Barrier:* Requirements for the vapour barrier are that it be continuous and that it be placed on the warm side of the insulation, where it can intercept vapour before it cools enough to condense. If this is not possible or practical, the 2/3 rule should be used, whereby at least 2/3 of the total R-value of the wall is placed on the cold side of the vapour barrier. This is usually sufficient to prevent condensation inside the wall.

3. *Continuity and Rigidity of Air Barrier:* The air barrier material could be either rigid, as is the case with plywood or drywall, or a membrane such as polyethylene. Because air barriers can be subjected to high pressure differentials, they should be rigid enough to withstand rupture and dislocation. When a membrane such as polyethylene is used as an air barrier, it is recommended that it be installed tightly between two rigid materials for this purpose. The air barrier can be made continuous at the intersection of building components by either caulking and/or gasketing between rigid materials, or by wrapping a membrane around the intruding component. Unlike vapour barriers, the location of the air barrier in the wall is not important. When a membrane is intended to act as both vapour barrier and air barrier, as is often the case with polyethylene, its location within the envelope should be taken into consideration.

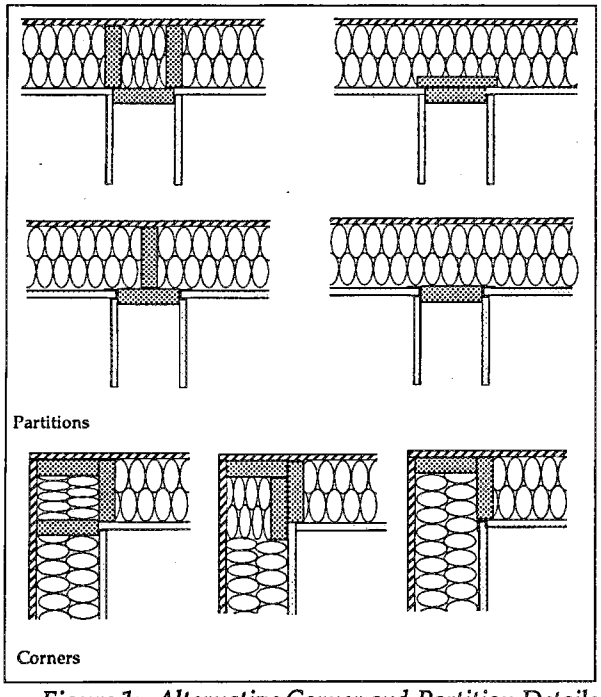

Figure 1: Alternative Corner and Partition Details

Critical Joints

There are several locations where maintaining the integrity of the air barrier/vapour barrier system requires special attention:

- between sheets or layers of the same building material, such as drywall, polyethylene, etc.
- where interior partitions meet walls and ceilings
- at the sill plate over a basement wall
- where floors meet exterior walls
- where the roof meets the exterior wall
- at openings and penetrations in walls, roofs (ceilings) and basements, such as:
  - doors and windows
  - electrical outlets/fixtures
  - service penetrations

While the design principles are the same for all of these details, the manner in which they can be executed varies from one situation to the other. Most of the concepts and procedures presented here are based on R-2000 recommendations. More detailed information can be found in the *R-2000 Builders Manual,* published by the Canadian Home Builders' Association, or in the reading references listed at the end of this section.

Efficient Framing

One of the simplest ways of reducing heat loss through thermal bridging is by reducing the overall mass of the structure. There are several ways of reducing the number of framing members. One method is by increasing the spacing between studs from the standard 400 mm (16") to 600 mm (24"). This reduces the fraction of the wall surface taken up by lumber from 14.1% to 10.9%. If the floor structure could be designed so that the joists line up with the wall studs, the second top plate could also be eliminated, reducing the framing component of the wall to 9.4%.

The number of framing members could also be reduced at the corners and where interior partitions intersect exterior walls. The convention of using 3 or 4 studs at the corners and 2 studs at the end of partitions is not as much for structural purposes as it for the need to provide adequate nailing surfaces for interior finishes. The use of blocking strips and/or drywall clips to support the interior finishes can reduce the number of framing members substan-

tially. Corners can be framed with no more than 2 studs, while partitions can be supported without using any studs (Figure 1).

Floor Details

There are two general ways to maintain the continuity of the air barrier at the intersection of the exterior wall with floors, roofs and partitions, depending on the material used as the air barrier. When a sheet of polyethylene is intended to act both as an air barrier and a vapour diffusion retarder, the "membrane" approach may be used. With this method, the polyethylene sheet is wrapped under and around the header joist so that it forms a continuous barrier from the interior membrane of the wall below to that of the wall above. Alternatively, the "rigid" air barrier approach may be used, whereby gasketing and/or sealants are applied between various structural components and rigid sheets (usually drywall) to provide a continuous sequence of materials which are impervious to air. While the method for ensuring continuity of thermal, vapour and air barriers across the building joints will vary from one application to another, the effort normally requires only additional care and craftsmanship during construction. The added material costs are usually modest.

Membrane air barrier method: The procedure for installing a continuous membrane requires that a 600 mm (24") strip of polyethylene be sandwiched between the top plates of the lower wall during its assembly, and draped to the outside while the floor structure is being assembled. Once the subfloor has been installed, the membrane is wrapped around the exterior of the header joint and over the subfloor towards the interior, where it is held in place while the upper wall is erected over it. The remaining protruding strips above and below the floor assembly are then attached to the polyethylene on the interior faces of the structure after the insulation has been installed (Figure 2).

The process is similar for the sill detail (at the basement) except that the polyethylene strip is sandwiched between the top of the foundation wall and the sill plate. This ensures that any moisture emanating from the concrete does not penetrate and deteriorate the sill plate. When the basement wall is insulated on the exterior, the membrane can simply extend past the header joist to the top of the footing between the insulation and the concrete.

The only drawback to using this method is that the polyethylene sheet, which also acts as a vapour diffusion retarder, shifts from the warm side of the assembly (at the walls) to the cold side (at the header joist), which may result in condensation inside the wall at the ends of the floor joists. By recessing the header joist by 38 mm (1.5") an extra layer of rigid insulation could be accommodated at the header, ensuring that 2/3 of the total R-value of the wall remain on the cold side of the vapour barrier. This not only reduces the risk of condensation, but also reduces the thermal bridge at this point. Batt-type insulation representing no more than 1/3 of the total R-value of the strip can be placed on the interior side of the header joist, which provides a continuous and steady level of insulation across the intersection.

An alternative way of providing continuous insulation and air seal without recessing the header joist is to install strips of batt-type insulation between the floor joists, starting at the header. This is then covered with an air barrier, cut to fit between the joists, which is sealed all around (i.e. to the subfloor above it, the joists on the sides and the air barrier of the wall below it). All gaps and joints in the subfloor must also be sealed. This method may therefore not work well when plank subfloors are used.

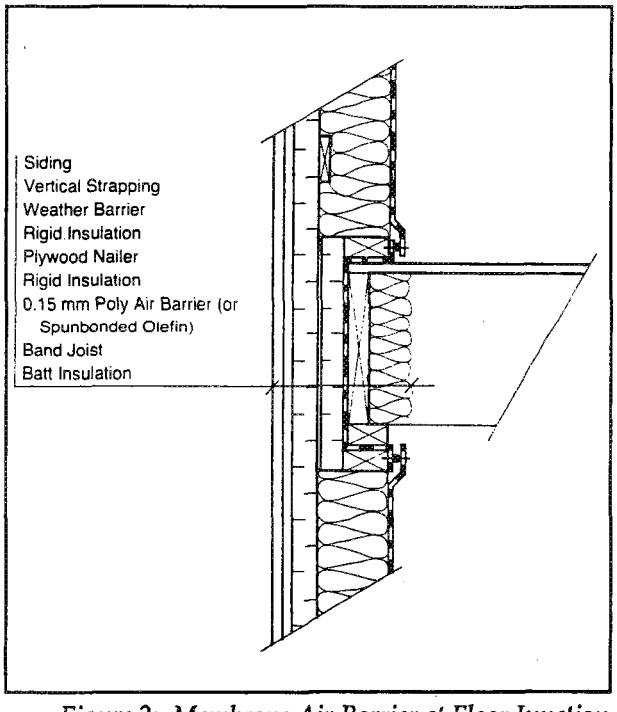

Figure 2: Membrane Air Barrier at Floor Junction (CHBA,1985)

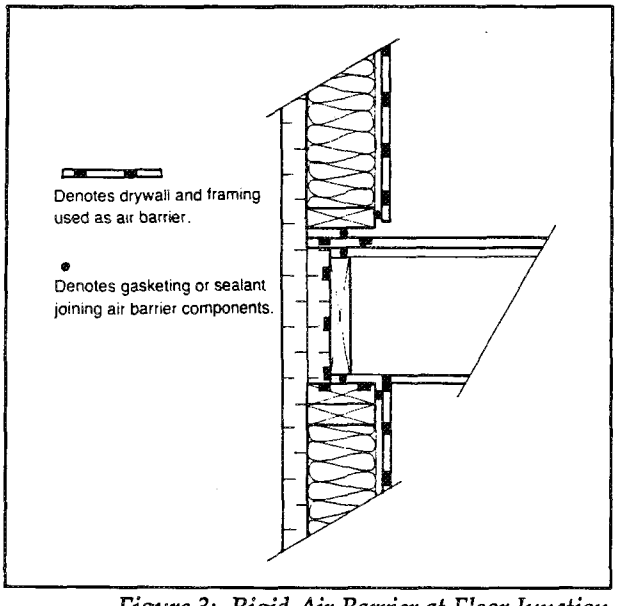

Figure 3: Rigid Air Barrier at Floor Junction (CHBA, 1985)

Rigid air barrier method: The rigid air barrier method uses the components of the structural frame and the drywall as the air barrier. By applying gasketing and/or sealants between the plates, the header joists and the subflooring, a continuous rigid air barrier is formed across the joint. The drywall is then sealed to the top and bottom plates, completing the air-barrier system (Figure 3). When truss floor joists are used, a continuous barrier can be achieved by installing a rigid sheathing strip at the header. In any case, all vertical joists in the header or sheathing at the floor level must be sealed.

One advantage of using the rigid air barrier approach is that the components of the frame can be recessed at will to accommodate finishes of varying thicknesses. Where aluminum siding joins with brick veneer, for instance, the components of the floor and wall assembly can be shifted, as illustrated in Figure 4.

Partitions

The intersection of the interior partitions with the exterior wall should be detailed not only to ensure continuity of the AB/VB system, but to reduce thermal bridging and provide sufficient nailing surface for the interior finishes. One way of doing this is to finish the entire interior surface of the envelope with drywall prior to the installation of interior partitions. Once the polyethylene is installed, it is immediately covered and protected with drywall. By applying the vapour/air barrier and drywall in a continuous fashion over a flat surface, the probability of leakage due to improper sealing is reduced. Alternatively, the partition can be erected leaving a gap between it and the exterior wall frame, into which the drywall could be slipped (Figure 5). This technique can be applied to walls as well as ceilings, but cannot be practically implemented if the wall is load-bearing.

Another approach is to wrap a polyethylene strip around the end stud of the partition and/or the top plate, before it is lifted into position. This strip would then be sealed to the main membrane covering the rest of the walls (Figure 6).

Service Penetrations

Whenever plumbing, mechanical or electrical components penetrate the building envelope, precautions should be taken to ensure that the continuity of the air barrier is not disrupted.

Plumbing components which penetrate walls can be in the form of drain pipes and vent stacks (usually plastic) and water supply pipes (usually copper). Due to the difficulty in sealing around circular shapes, it is recommended that a wood panel sheathing backing board be installed flush with the inside face

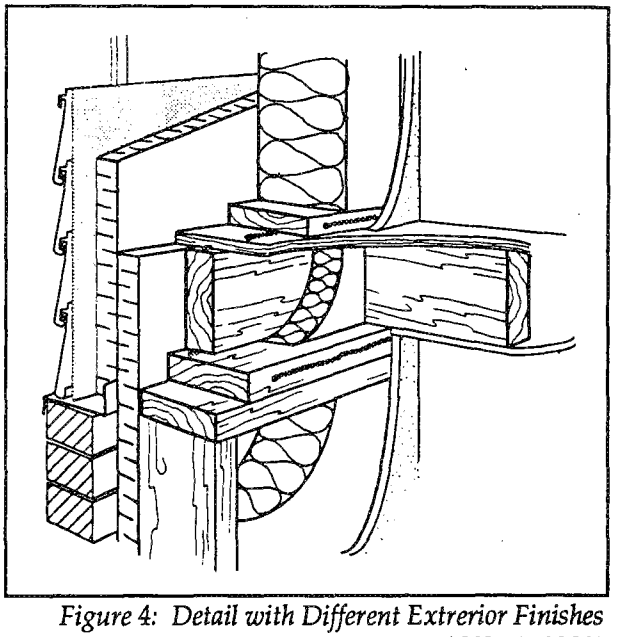

Figure 4: Detail with Different Extrerior Finishes (CHBA, 1989)

of the studs wherever plumbing components pierce the air barrier (Figure 7). To accommodate expansion and contraction of pipes, holes in the backing board should be drilled slightly larger than the actual diameter of the pipe. This also simplifies assembly and eliminates noises caused by moving pipes rubbing against the walls of the opening. The gap is then sealed with a caulking component or other sealer, and the membrane or rigid air barrier is sealed to the backing board.

Electrical system penetrations occur at the main service conduits and the main service box (if located on the exterior wall), at electrical outlet and switch boxes (both interior and exterior) and at any point where wiring passes from one wall to another (usually through the top plates and end studs of interior partitions). In any case, the integrity of the air barrier can be maintained by applying the same principle of using a solid backing through which the conduits can be passed and sealed. When wiring passes through top plates or end studs, the framing member itself serves the purpose. Electrical boxes used for outlets, switches or lighting fixtures can be sealed by providing an air tight enclosure around the electrical box which is attached to the air barrier. This enclosure can be built on site or purchased, as a wide range of products designed for this purpose are available. When a rigid air barrier approach is used, whereby the drywall acts as the air barrier, the electrical box needs to be made air tight and sealed to the drywall. Specially-made boxes are available

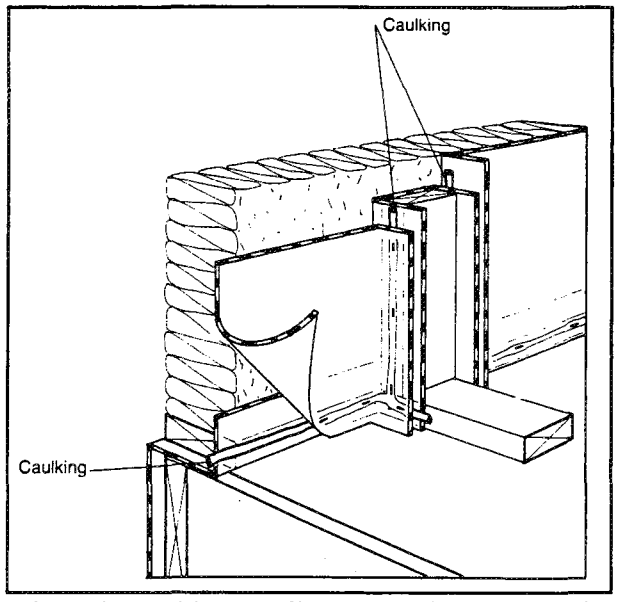

Figure 6: Partition Installation; MembraneAir Barrier (CHBA, 1985)

which have a compressible gasket that is sandwiched between the cover plate and the drywall (Figure 8). Wires penetrating the box behind the drywall must also be sealed by means of gaskets or caulking.

Ductwork for heat-recovery ventilators and exhaust fans can be sealed using the same techniques, except that sheet metal backing plates should be used for warmer surfaces such as chimney flues. Compatible sealants, capable of withstanding the higher temperature, should also be used.

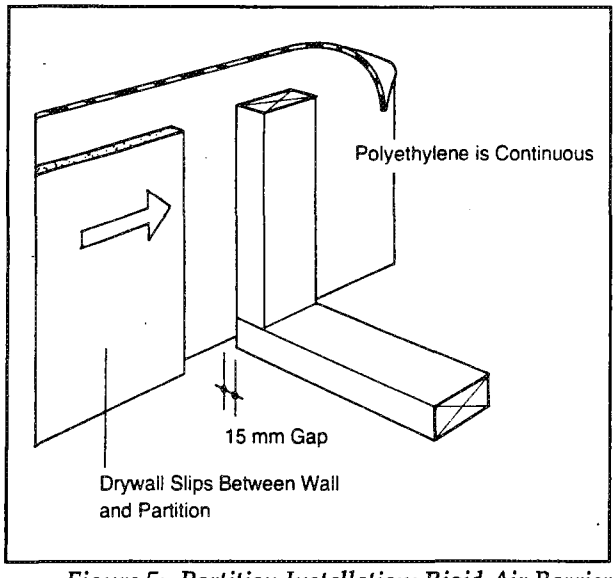

Figure 5: Partition Installation; Rigid Air Barrier (CHBA, 1985)

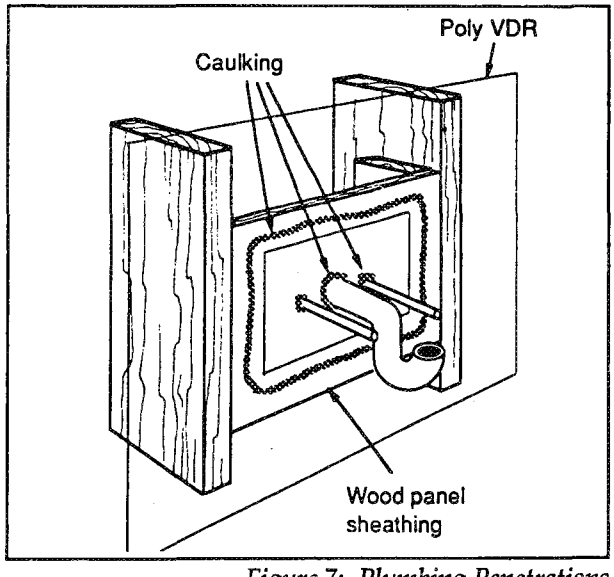

Figure 7: Plumbing Penetrations (CHBA, 1989)

The best way to maintain a continuous air/vapour barrier, however, is to avoid service penetrations altogether. With interior strapping or double-wall construction, most of the electrical, plumbing and mechanical components can be kept away from the membrane, facilitating the construction of an air-tight envelope (see R-2000 section).

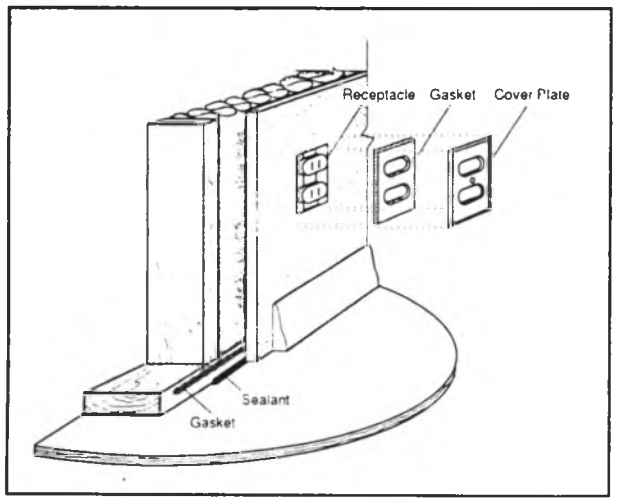

Figure 8: Electrical Outlet (CHBA, 1989)

Windows and Doors

In order to accommodate any shrinkage of the structural frame and to facilitate installation, doors and windows are installed in rough openings in walls that are usually 25 mm (1") wider and deeper than the door or window frame, which is then fitted into position using shims. The potential for heat loss through conduction or air flow across this gap is significant, and could result in severe damage to the frame and/or structure resulting from condensation inside the wall. It is therefore very important that this space be properly insulated and sealed. The standard approach has been to stuff scraps of batt-type insulation into the gap and cover it with the interior trim. This approach does very little to restrict air flow across the space, and is not particularly effective in reducing conductive heat flow since compressing batt insulation reduces its thermal resistance.

Continuity of the AB/VB system could be maintained using the same principles that were used for service penetrations and interior partitions. For doors and windows, there are four options. The first uses a continuous strip of polyethylene which is sealed to the window/door frame and extended to overlap the polyethylene on the inside face of the wall. While this method is relatively easy to implement and is widely used, it can only be applied in cases where a membrane air barrier approach is used. Alternatively, an effective air seal can be achieved by using wood panel sheathing wrap, drywall or foams and tapes. These may be used with both membrane and rigid air barrier systems.

Polyethylene wrap: This option uses a 0.15 mm (6 mils) polyethylene strip 600 mm (24") wide which is wrapped around and sealed to the window/door frame, such that one half of its width overhangs on the interior side. A bead of acoustical sealant is used to seal the polyethylene wrap to the frame. Staples are applied through the wrap and bead to hold the polyethylene in place, and glass fiber-reinforced tape is placed and stapled over the caulking bead to prevent the polyethylene wrap from slipping off the frame during installation (Figure 9). The window/door is then installed in the usual fashion, shimmed into place and the gaps filled with batt-type insulation. Sealing the overhanging wrap from the win-

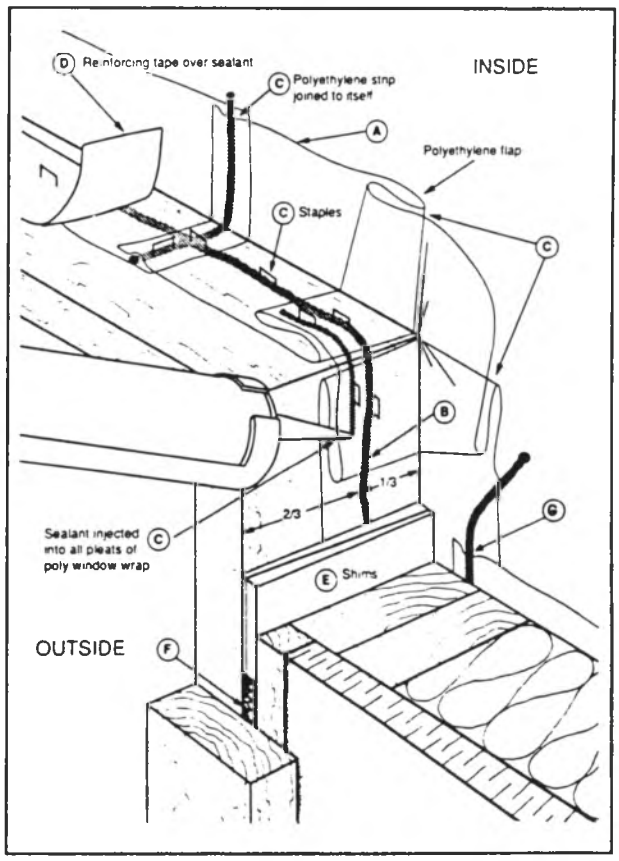

Figure 9: Air Sealing Windows; Polyethylene Wrap Method (CHBA, 1989)

dow to the interior polyethylene on the walls ensures an airtight assembly.

Plywood Wrap: When metal or PVC windows and doors are used, the plywood wrap method is very convenient. This involves framing the rough opening about 25 mm (1") wider and higher than normal, and lining it with wood panel sheathing which is sealed to the air barrier (Figure 10). The window is installed in the liner with the gaps insulated and sealed. The interior and/or exterior finishes are installed over the liner.

Drywall: This method, used most commonly with wood frame windows, is the simplest way of sealing openings with a rigid air barrier. The rough opening is framed in the usual way, the window is installed and the drywall is sealed directly to the window frame (Figure 11).

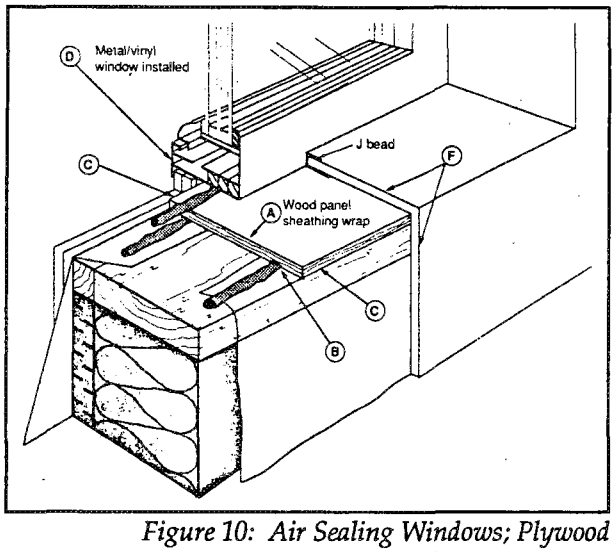

Figure 10: Air Sealing Windows; Plywood Wrap Method (CHBA, 1989)

Foam/tape: With this approach, the air barrier is sealed to the rough opening, and the window is installed in the usual manner. The window frame, wood panel sheathing frame extension, or jamb extension is brought flush with the edge of the drywall, and the shim space is then filled with batt insulation and sealed with foam or tape (Figure 12).

Analysis

Efficient framing and careful detailing will not only prolong the life of a house, but can produce substantial construction and energy cost savings. As mentioned earlier, increasing stud spacing from 400 mm

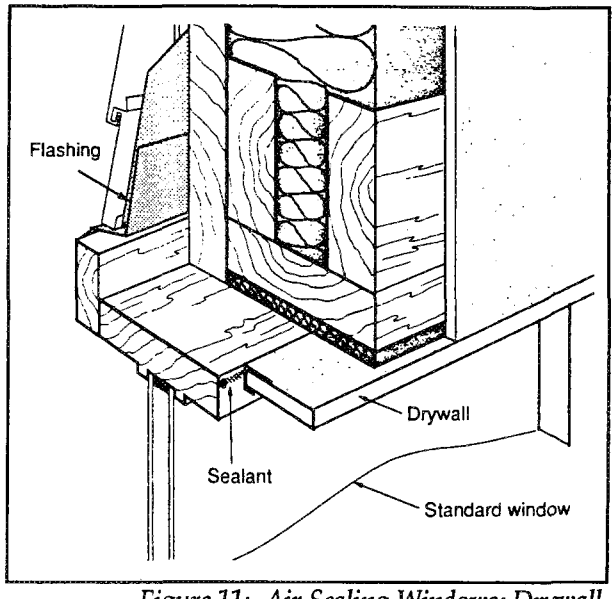

Figure 11: Air Sealing Windows; Drywall Wrap Method (CHBA, 1989)

(16") to 600mm (24") reduces the fraction of the wall taken up by wood members from 14.1% to 10.9%, while lining up floor joists with wall studs (and eliminating the second top plate) could bring this value down to 9.4%. In a standard wall, this means that the effective thermal resistance of the wall (accounting for thermal bridging through the studs) is increased from RSI 3.19 (R-18.1) to RSI 3.27 (R-18.6); an improvement of 4%. Similarly, failure to insulate the header space between floor joists can reduce the effective resistance of that portion of the

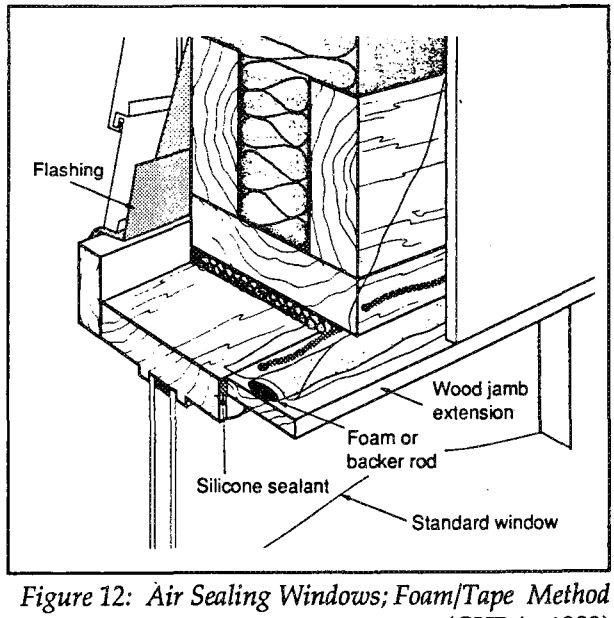

Figure 12: Air Sealing Windows; Foam/Tape Method (CHBA, 1989)

wall from RSI 3.52 (R-20) to RSI 0.38 (R-2.2). Considering that the header area takes up 9% of the wall above grade in a 2-storey home, omitting this insulation could increase heat loss by up to 83%.

Although the header space is usually filled with batt insulation, limited access may result in the insulation being stuffed tightly into the gap. If the insulation is compressed by 25 mm (1") in the process, the thermal resistance will be compromised by 10% (Chiarelli, 1989).

The impact of efficient framing practices and compressed insulation on energy consumption for the Grow Home is shown in Table 1. Since a relatively small fraction of heat is lost through the walls, actual savings from reduced thermal bridging are limited. Efficient framing practices could reduce heat loss by 189 watts in a semi detached home. Although this represents 19% of total heat loss through the walls, it translates into annual savings of approximately $13. The value in reducing thermal bridges is mostly in avoiding condensation and premature deterioration of the envelope assembly, and conservation of natural resources. The reduction in overall frame mass represents cost savings of $539, and material savings of 433 kg of lumber with 5262 MJ of embodied energy (see *Unit Planning Principles*).

Air-tight detailing: The savings that may be realized from air-tight joint detailing are more substantial, even in small homes. An average Canadian house has an effective leakage area of 2 cm^2 per square meter of wall. This represents the sum of all gaps and cracks that are manifested in the building's skin. In

Detail	Effective Resistance (RSI) [1]	Reduction in Heat Loss (W)	
		Rowhouse	Semi-det
Increased Stud Spacing	3.19	14	32
Alignment of Floor Joists with Wall Studs	3.27	5	12
Eliminantion of Corner and Partition Studs	3.30	24	48
Proper Insulation Between Floor Joists	3.52	43	97
Total Heat Loss Reductions (W)		86	189
Energy Consumption; Montreal (KWh)		126	276
Energy Costs (@ $0.0469/KWh)		**$6**	**$13**

[1] *Adjusted for thermal bridging*
[2] *Compared to standard construction with an effective RSI of 3.19 for the walls and 1.21 for a 38 x 140 mm stud*

Table 1: Impact of Efficient Framing on Heat Loss

Detailing Quality	Heat Loss (W)	Energy Consumed (KWh)	Energy Costs
Average SD (0.45 ACH)	2223	3247	$152
Average RH (0.3 ACH)	1482	2164	$102
Air-tight (0.10 ACH)	494	721	$34
Very air tight (0.05 ACH)	247	361	$17

Table 2: Impact of Air-Tight Construction on Energy Consumption

a quality home, this value may range from 0.7 to 1.5 cm^2/m^2. For energy-efficient, air-tight construction, the effective leakage area can be reduced to anywhere from 0 (negligeable leakage) to 0.7 cm^2/m^2 (CMHC, 1988).

For the Grow Home, the effective leakage area calculated for average building practices would be 197 cm^2 for the rowhouse and 327 cm^2 for the semi-detached home. For average wind speeds of 15 km/h, these translate into infiltration rates of 26 L/s and 43 L/s, respectively, or 0.28 ACH and 0.46 ACH.

Detailing Quality	Energy Consumption		Total Costs
	Heating (KWh)	HRV (KWh) [1]	
Average SD (0.45 ACH)	3247	——	$152
Average RH (0.3 ACH)	2164	379	$119
Air-tight (0.10 ACH)	721	884	$75
Very air tight (0.05 ACH)	361	1010	$64

[1] *Mechanical ventilation required to make up difference between reduced infiltration rate and average rate (0.45 ACH)*

Table 3: Energy Costs with Air-Toght Construction

Considering that average homes generally exhibit infiltration rates of 0.6 to 1 ACH, it can be seen that the Grow Home loses less heat from infiltration simply by virtue of its design. With tighter joints and better craftsmanship, these savings can be improved further.

A reduction in infiltration rates from 0.3 to 0.1 ACH, for instance, may reduce the monthly volume of air leaking into the house by 48 400 m^3. The energy required to heat this air for one heating season would be approximately $68 (Table 2). For a semi-detached home, increasing the air-tightness of the envelope to the same level could save up to $118. For very well sealed joints, which could reduce infiltration rates to 0.05 ACH, these savings could reach $85 for the rowhouse and $135 for the semi-detached home.

Even if the cost of operating a heat recovery ventilator (to make up the difference in air infiltration) were accounted for, the savings would still be attractive (Table 3). Assuming an operating efficiency of 65% (i.e. 65% of outgoing heat is recovered and used to heat incoming exterior air), the savings could range from $55 for a rowhouse to $88 for a semi-detached house.

Construction Costs: The cost of building to these standards is difficult to quantify, as it depends significantly on the experience, skill and integrity of the builder and the subtrades as well as on material costs. For the purpose of analysis, it was assumed that upgrading the air-tightness of the envelope would require a corresponding increase in labour for carpentry, installation of insulation and vapour barrier, and for electrical and mechanical work. Cost increases of 3% and 5% were calculated for labour associated with these operations. They also include the cost of any additional material that may be required (sealants, air-tight electrical boxes, etc.). The 3% increase is for air-tight construction to meet R-2000 standards (0.1 ACH) while the 5% increase is for very tight construction (0.05 ACH).

Detailing Quality	Energy Savings	Incremental Constr Costs	Payback Period (years) [1]
Air-tight (0.10 ACH)	$77	$230	3.3
Very air tight (0.05 ACH)	$88	$381	5.1

[1]True payback period; based on discount rate of 10% and 4% escalation.

Table 4: Cost Implications of Air-Tight Construction

All factors considered, it was found that the additional costs incurred for the construction of air-tight assemblies pay for themselves within 3 to 5 years in energy savings (Table 4). Considering that the life of the building would be prolonged and that healthier indoor environments would ensue, the extra time and effort required for air-tight building detailing is a worthwhile investment.

Summary

Efficient framing and air-tight detailing is beneficial in several respects. By cutting down on lumber requirements, material and labour costs are reduced, as well as the energy embodied in the building materials. Thermal bridging and air leakage are reduced, along with the probability of condensation,

Guidelines

Durability and energy efficiency can be improved significantly by detailing to reduce thermal bridging and air flow as follows:

- Fill in spaces between joists with batt and/or rigid board insulation; do not compress batt insulation
- Increase stud spacing to 600 mm (24") from 400 mm (16") where possible, and line up floor joists with wall studs to eliminate the need for a double top plate
- Frame using only 2 studs at the corners, and eliminate the extra wall studs at the intersection with interior partitions by using drywall clips and/or blocking.
- Seal all gaps formed when plumbing, electrical and mechanical systems pierce the envelope; a rigid backing board with holes drilled into it makes for a good, easy-to achieve seal.
- Use specially-made plastic boxes and/or caps to seal around electrical outlets, switches and lighting fixtures, or used strapped walls to ensure continuity of the air/vapour barrier system.
- Ensure air-tight window and door installation by using foams, polyethylene wrap around the window frame, plywood liner inside the rough opening, drywall sealed directly to the window frame or tape.
- Build air-tight connections at the floor/wall junction by either wrapping the membrane air barrier around the header joist, or by sealing between consecutive rigid materials with gaskets and/or caulking.
- Ensure that the air barrier/vapour barrier system is not interrupted at the partitions by either installing the polyethylene and drywall before the partitions are erected, or by wrapping the polyethylene around the end studs of the partition wall and sealing it to the main barrrier.

making for a more durable assembly and a healthier indoor environment with controlled ventilation. Finally, the energy required to heat and condition infiltrating air is substantially reduced, cutting down operating costs and making for a more efficient and sustainable building.

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Prefabricated Wall Systems

Background

It is commonly believed that the prefabrication of housing holds many advantages over conventional construction methods. The assembly of units, panels or components under factory-controlled conditions yields a higher quality product which generally results in more energy-efficient homes. Due to the quick and efficient assembly which takes place on-site, the effect of poor weather conditions, particularly in cold climates, is reduced as is the potential for damage due to inadequate material storage and vandalism. Clean-up time and material costs are also reduced since there is less wastage, construction management and trade coordination can be simplified, and the need for large teams of skilled on-site labour for multiple-unit construction is substantially lowered.

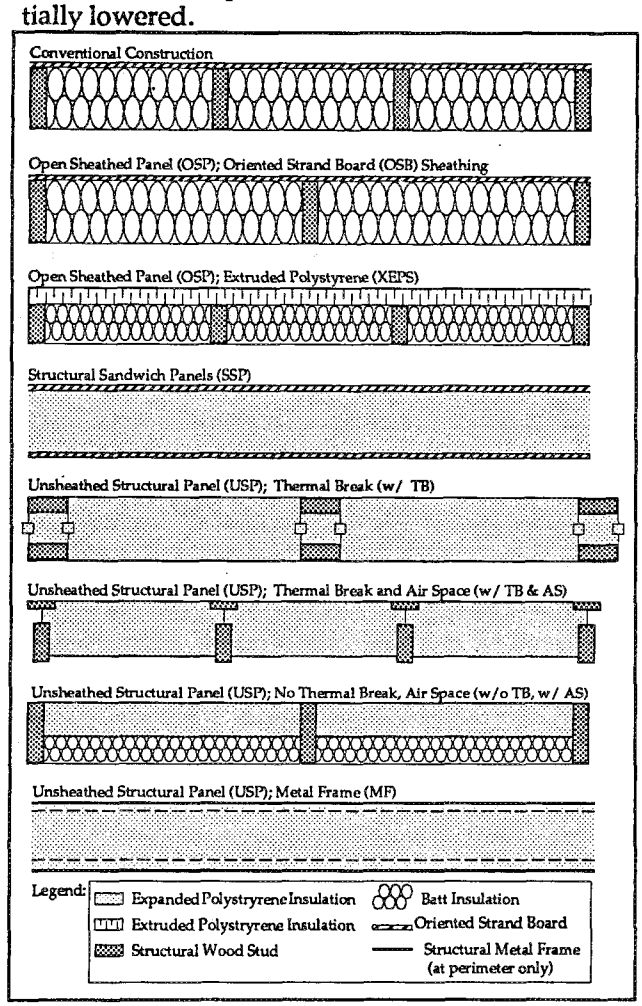

Figure 1: Horizontal Sections of Prefabricated Wall Systems

Objective

The objective of this section is to review the types of prefabricated wall systems available to the North American home builder and to examine the cost implications of using these systems. Energy and construction costs were estimated for a semi-detached Grow Home.

With the growing demand for affordable housing, increasing costs of materials and labour, and a heightened concern for energy-efficiency, builders have recently begun to re-examine their options for the delivery of housing. The depressed economic climate in recent years has given builders an incentive to look into new markets and explore alternative construction methods. This trend has resulted in a growing interest in prefabricated building systems, particularly panelized construction.

Prefabricated Panel Systems

There are numerous types of prefabricated systems, subsystems and components which can be combined at various levels to provide a complete system package. Nine types of panel systems are applicable to wood-frame residential construction, which can be divided into three categories: (1) open sheathed panels (using conventional construction methods), (2) structural sandwich panels, and (3) unsheathed structural panels (Figure 1).

Open sheathed panels (OSP): These are available in almost as many different variations as conventional wall construction. The most common systems are built either with 38 x 140mm. studs with plywood or waferboard sheathing, or with 38 x 89 mm studs and extruded polystyrene sheathing. In either case, the panels are delivered open on the interior to facilitate the installation of electrical and/or plumbing services. Batt insulation is usually installed on site, and is sometimes supplied by the manufacturer.

Structural sandwich panels (SSP): Also known as *foam core panels*, these consist of a core of rigid foam insulation which is laminated between two facing materials. In its most basic form, the sheathing materials may be either plywood or waferboard. More complete options offer exterior and/or interior finishes which replace the basic facing material and become an integral structural part of the panel.

The core material contains pre-cut electrical chases, and may be either one of four different types of insulation: moulded bead expanded polystyrene, extruded polystyrene, polyurethane or polyisocyanurate. A variety of options are available for the joints between the panels (Figure 2).

Unsheathed structural panels (USP): USP's, or *composite panels*, are built using a combination of wood or metal structural elements combined with rigid foam insulation infill, usually expanded polystyrene. There are four basic variations of these systems available (with different configurations for their structural elements) which provide a continuous thermal break and/or an air space on the interior of the panel. Horizontal chases for electrical wiring are often cut into the insulation to accommodate electrical wiring.

For each of the systems, it is possible to "add value" to the panel by integrating a larger portion of the building envelope during fabrication. Added components vary from air barriers to exterior and/or interior finishes. The extent to which the panels are finished has different implications for the builder and the worker who will select and install the system.

Quality and Energy Efficiency

One of the biggest advantages of prefabricated panel systems is the superior level of quality which can be achieved through the manufacturing process. The quality of prefabricated wall systems can be evaluated in terms of three interrelated characteristics: craftsmanship, technical performance and durability. The system's craftsmanship governs its potential to achieve consistent levels of performance from one application to another. The wall's technical performance, particularly with respect to its air-tightness, will affect the rate of deterioration due to condensation. Fire and sound resistance, critical for dividing walls, will contribute to the quality of the unit's interior environment. The panels' durability depends on the various materials' resistance to several elements, and on the probability of exposure to these given the panels' design.

Prefabricated panel systems are generally capable of technically outperforming walls built using conventional construction methods. *Structural sandwich panel systems*, particularly those with urethane or

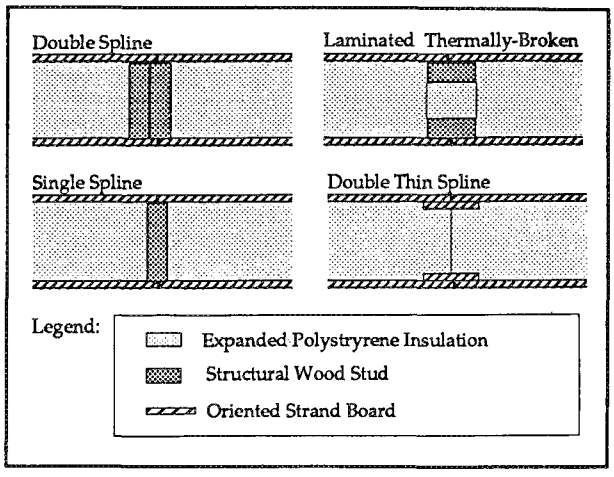

Figure 2: Joint Types for Structural Sandwiich Panels

isocyanurate foam, provide excellent insulation value for a given thickness. This is due partly to their continuous thermal break across the joints, particularly with the double spline variation (Figure 2). These panels also result in the tightest assemblies, due to their exceptionally well-fitted joint systems and the possibility of extending the exterior skin below the floor level, allowing for a continuous barrier across the end of the floor section. High levels of performance are easy to accomplish due to the inherent simplicity of the design. The critical nature of the lamination process, however, requires a relatively high level of quality control. Among the questionable characteristics is a susceptibility for these systems to ridge at the joints because of inadequate allowance for thermal expansion, and a possibility of panels delaminating (Andrews, 1992).

Unsheathed structural panels appear to provide good performance in all respects, but benefit from few extraordinary characteristics. The panels' biggest advantage is that they can overcome the inadequate workmanship which may be found in conventional construction without resorting to very unfamiliar building techniques. The use of expanded polystyrene foam between the structural elements significantly improves the performance of the wall in that area which is a key failure point in conventionally-built walls: discontinuous insulation and air barrier caused by improper installation. Tight friction-fit joints and the ability to accommodate electrical boxes without interrupting the continuity of the insulation provide an attractive advantage over conventional construction methods. Furthermore, the relatively simple manufacturing techniques (some make no

use of adhesives) to provide continuous thermal breaks and adequate air barriers make them likely to achieve consistent performance levels.

Conventional construction and *open sheathed panels* are considered to have the lowest overall technical performance potential, due to the lower thermal resistance of batt insulation, thermal bridging caused by the framing members and the unsealed joint that occurs between the insulation and the studs. The biggest advantage of conventional panels appears to be its durability, due not as much to the materials' ability to resist deterioration as to the panel's ability to retain its structural integrity. Due to their lack of dependance on the insulation material for structural stability, temperature variations, rodents (which have been known to burrow through rigid foams) and chemicals have less of a damaging potential on *open sheathed panels*. While their susceptibility to moisture damage remains higher than that of other systems, these panels benefit from the fact that the interior of the wall can be relatively easily inspected and repaired. Stick-build methods are the least preferable option due to the high variability of craftsmanship and susceptibility of materials to damage from inadequate site storage.

Material Wastage

As is the case with any manufactured component, waste generation from prefabrication of panel systems is less than what could be expected from site construction. Assembly of the wall system in closed, controlled environments ensures that materials are used efficiently, and "scrap" pieces of materials are more easily recovered and reused. Furthermore, the fact that the unit is closed within a short period of time reduces delays due to bad weather. The probability of vandalism and theft is reduced because there is less material stored on site, and the cost of replacing materials damaged by inadequate storage and exposure is also reduced. Since there is less material wastage, the cost of clearing and removing debris is lowered. Considering that the construction of an average house in central Canada produces some 2.5 tons of waste (25% of which is dimensional lumber and an additional 15% manufactured wood products), the savings could be substantial, particularly in large developments (CMHC, 1991).

Prefabrication in Canada

Despite its many advantages, the use of prefabricated homes in Canada has been relatively slow in gaining acceptance. The number of manufactured homes sold in Canada currently account for 15% of total housing starts, as compared to 43% in the United States (not including mobile homes) and 90% in Sweden (Baristow, 1985; Cooke, 1993). The reasons for this are varied and remain a question of debate. Industry fragmentation, lack of economies of scale, negative public image, discriminatory zoning practices, inadequate capital and financing, declining housing demand and unstable markets, lack of access to prime locations, limited marketing capabilities, and poor consumer servicing and warranties are reasons most often cited(Baristow, 1985).

Cost Implications

The cost per unit floor area of prefabricated systems will vary significantly depending on the type, size and configuration of the housing units. Designs which lend themselves to simplicity and repetition are more likely to result in attractive savings, since they optimize the prefabrication process. A recent study compared construction costs for single-family detached units using modular prefabrication to those using conventional construction, and found that there were no significant savings to be gained through prefabrication (Friedman, 1992). A more recent study commissioned by the Société d'habitation du Québec and the Canada Mortgage and Housing Corporation found that savings of up to 6% are possible with some types of prefabricated panel systems for both single-family detached and rowhouse units (Ginter, 1992).

Transportation and lifting costs associated with the delivery of prefabricated systems, however, can be significant, and in some cases capable of reversing potential savings to cost increases. The possibilities for transportation and assembly of prefabricated components will vary depending on both the manufacturer and the product. In addition to the actual transportation distance, costs will depend on the

equipment used, number of trips required, number of homes built as well as on the party who assumes the delivery.

Most manufacturers deliver the panels themselves on specially-equipped trucks. The panels are normally delivered and lifted into position in two separate trips – the first at completion of the first floor platform, and the second upon completion of the second floor. This approach has the advantage of eliminating the need to store the product on site, and therefore reducing the possibility of damage due to exposure and vandalism. It also eliminates the cost of hiring an independent crane. For a small project consisting of one or two homes, however, the delivery in two trips may not be cost-effective, particularly when longer distances are involved. Alternatively, the components may be delivered by an independent party who will deposit the panels on site, leaving the responsibility for storage and lifting to the contractor. The availability of larger trucks from independent transportation companies may reduce the number of trips required, and may be cost-effective for larger projects in remote locations.

Practical Limitations

Since the units' attractiveness is largely a function of personal taste and priority, the contractor's ability to offer a range of options to the prospective buyer is important. The ease with which a unit can be adapted to meet particular demands, both during the manufacturing and construction phases, is therefore a critical factor in the decision to adopt a method or product. In a recent survey of 107 builders and architects conducted by the Structural Insulated Panel Association, the most commonly cited reason why respondents might not use structural insulated panels was the concern about design limitations (Winter, 1991). During the occupancy phase, the ability for the buyer to customize the dwelling, be it through modification or decoration, is also of concern. Any method which will inhibit or restrict this freedom should be interpreted as a deficiency, regardless of the technical quality which may be gained.

Another important practical requirement is ensuring that the product or method does not disrupt the existing operational efficiency and simplified lines of communication that exist in the homebuilding industry. The traditional construction process consists of a sequence of work packages of fairly narrow scope. The tasks of any one particular trade are well defined, and the work of one affects the performance of the other. Innovation may occur within any one of these, but its acceptance is hindered if it involves more than one trade, or if the change in one trade affects the work of another. If we divide the house into its physical building elements, a hierarchical arrangement of systems (envelope), subsystems (walls), components (windows) and materials (glass) would result. The larger the element, the greater the operational and physical interdependence between trades. Therefore, the effect of an element lower in the scale (eg. glass material) is less than it would be on an element higher up in the hierarchy (eg. window unit, wall system), making it more susceptible to change.

Flexibility

In the case of prefabricated panel systems, the product's flexibility is derived from the possible size and configuration of the panels and its openings, and from the ease with which electrical (and sometimes plumbing) services can be manipulated in the manufacturing, construction and occupancy phase. In the latter phase, this involves the ability to inspect and access the envelope's components for repair or replacement.
Due to their similarity to conventional construction, the *open sheathed* and, to a lesser extent, *unsheathed structural panels* were found to be the more flexible alternatives. Although structural modifications on site are limited, the installation of electrical and plumbing services remains relatively unrestricted. The inverse is true for the *structural sandwich panels*, which can easily be modified structurally but provide little leeway for the arbitrary placement of lighting and plumbing fixtures. After occupancy, modifications in this regard do not appear to be any easier.

The *structural sandwich panels* offer the highest flexibility on site, since openings can be cut in the panels at any time with relatively little reconstruction required. Although the size of the opening is limited by the panel size and the cutting operation may be more difficult, it is the only panel system which can have openings cut into it at any location even after the wall has been erected. The biggest drawback of the *structural sandwich panel* is its flexibility after occupancy. Inspection and repair of the insulation,

which is a critical structural component in these types of panels, is difficult if not impossible, even if all finishes are removed. Furthermore, the ability to hang heavy objects or accessories which require structural support, such as grab bars, may be restricted, particularly after occupancy.

Integration with Standard Operational Routines

As subsystems, it is possible for prefabricated panels to integrate unobtrusively into the established operational routines. Most products that are available however, as they are currently being manufactured, distributed and installed, do not generally fulfill this objective. The practicality of the systems in this regard are governed by three factors: the number of building trades that are affected by the system (with respect to traditional stick-build methods), the level of skill required for assembly and the need for special tools (lifting, cutting and fastening).

The *open sheathed panels'* ease of assembly is a major asset for these systems. Although the idea of erecting panels rather than studs is not a familiar one for most builders, the use of standard components and construction methods facilitates both the assembly process and the probability of acceptance. Service trades are not affected by the system, and no special tools are required.

While the assembly of the *structural sandwich panels* themselves provides a simple, straightforward and efficient process, the unusual design of the system requires that some training be carried out. The integration of electrical services remains a problem, since higher cooperation is required between the carpenter and the electrician. Furthermore, special cutting tools, ranging from larger saws to hot knives, are required if any modification is to be carried out on site. The problem could be somewhat alleviated if the openings are cut in the factory, where unconventional skills and tools are readily available. Although some of the system's flexibility would be compromised, the simplification and reduction of on-site labour could lead to savings, while modifications to the openings would still be possible.

Due to their lighter weight and slightly more conventional design, the *unsheathed panel systems* appear to have a higher chance of integrating with the builders' standard operational routines than the *structural sandwich panels*. Estimates for site labour from the manufacturers indicate that these systems also benefit from the most efficient assembly on site. In some cases, however, what appears to be a simple assembly procedure may result in complicating, or at least extending the task for the builder. The absence of a sheathing material, for instance, requires that diagonal strapping be added to the exterior of the wall. Although not technically required, it is recommended that fiberboard sheathing membranes be installed on the exterior of the wall panels for acoustical reasons, detracting from the potential savings. Where a panel runs parallel to floor joists, a second joist may need to be installed close to the header joist to facilitate nailing of the wall panel (accessible only from the interior) and to improve structural performance. Otherwise, the wall would be anchored to the floor sheathing.

Analysis

The use of prefabricated panel systems can lead to substantial savings in both construction and operating costs, while facilitating the management task and productivity of an experienced builder. Operating costs are reduced by virtue of the systems' improved thermal resistance, reduced thermal bridging and air-tight qualities. Table 1 summarizes these energy savings for the nine types of panel systems. The effective thermal resistance (adjusted for thermal bridging) of the walls could be increased by at least 8% with open panels using insulative sheath-

Wall System	Thermal Resistance (RSI) [1]	Conductive Heat Loss (W)	Energy Consumption (KWh) [2]
Conventional Construction	3.177	1139	3379
Open Sheathed Panels			
• w/ OSB Sheathing	3.177	1139	2254
• w/ XEPS Sheathing	3.420	1058	2134
Structural Sandwich Panels			
• w/MEPS Core	3.925	922	1932
• w/XEPS Core	5.017	722	1634
• w/PUR/ISO Core	7.091	510	1320
Unsheathed Structural Panels			
• w/TB	3.546	1021	2078
• w/TB & AS	3.385	1069	2150
• w/o TB; w/AS	3.223	1123	2230
• w/Metal frame	3.738	968	2000

[1] Adjusted for thermal bridging
[2] Includes infiltration losses, assuming 0.1 ACH for prefabricated systems and 0.3 ACH for conventional construction

Table 1: Energy Performance of Wall Systems

Wall System	Annual Heating Costs	Total Cost (incl labour)	Transp. Costs (Montreal)
Conventional Construction	$203	$57,720	——
OSP/38x140 w/OSB shthng	$135	$55,971	$600
OSP/38x89 w/XEPS shthng	$128	$56,145	$600
SSP/MEPS/OSB both sides	$116	$58,947	$500
SSP/MEPS/added value [1]	$116	$53,493	$500
USP/ TB	$125	$56,487	$150
USP/ TB/added value	$125	$55,726	$150
USP/TB & AS	$129	$57,094	$470
USP/no TB; AS	$134	$57,406	$500

[1] Contains Innearseal Siding; compared (more appropriately) to a home with aluminum siding.

Table 2: Cost Implications of Wall Systems

ing, and by as much as 123% for structural sandwich panels with polyurethane cores with a proportional decrease in heat loss. Assuming that average infiltration rates could be reduced from 0.3 ACH to 0.05 ACH, additional savings of 1125 KWh could be realized for each of the systems, accounting for the cost of operating a heat recovery ventilator to make up the difference in infiltration rates. Cumulative savings in energy consumption vary from 1125 KWh for the open sheathed panels to 2059 KWh for the structural sandwich panels, which translate into annual cost savings of $68 and $123, respectively.

While savings in construction costs could vary significantly depending on the size, configuration, grouping and location of the units, prefabricated panel systems can usually provide a competitive alternative to conventional construction methods. Table 2 compares estimated heating costs (associated with heat loss through the envelope) with initial construction costs for several systems. The construction costs for prefabricated wall systems vary from $53,493 to $58,947. These figures account for labour costs, assumed at $85/hr for a crew of three consisting of one framer and two helpers, and for additional labour requirements (5%) to install electrical wiring in some of the systems. Transportation costs are for the Montreal area, with factories located between 20 and 150 miles from the project site. It is evident that transportation costs account for a significant portion of the system costs. For projects located further from the manufacturer, these transportation costs may turn cost savings into cost overruns.

The cost implications of using prefabricated panel systems could be significant (Table 3). When both operating and construction cost savings are accounted for, annual costs to the consumer could range from $86 to $373. While one of the systems which resulted in cost overruns could pay for itself in 3 years with the reduced energy consumption, the other was found to be unfeasible from an economic point of view. Investment in this case would be for reasons other than economy, including reduced wastage, efficient resource utilization and overall comfort.

It should be mentioned that these costs could vary substantially for different locations and manufacturers. Some of the systems which resulted in incremental cost increases could prove to be cost-effective in other locations, and vice versa.

Wall System	Energy Savings	Cost [1] Savings	TOTAL Savings	Payback Period
OSP/38x140 w/OSB shthg	$68	$88	$156	——
OSP/38x89 w/XEPS shthg	$75	$75	$150	——
SSP/MEPS/OSB+OSB	$87	-$1727	$1814	No Payback
SSP/MEPS/added value[2]	$87	$286	$373	——
USP/ TB	$78	$83	$161	——
USP/ TB/added value	$78	$141	$219	——
USP/TB & AS	$74	$12	$86	——
USP/no TB; AS	$69	-$186	$255	3.0

[1] Contains Innearseal Siding; compared (more appropriately) to a home with aluminum siding.

[2] Equivalent annual payments to finance initial contruction cost difference on a 25-year mortgage; assumes 10% disount rate and 4% escalation;

Table 3: Economic Implications of Wall Systems

Summary

For uncomplicated designs, it is safe to say that prefabricated panel systems can, for the most part, provide a competitive alternative to conventional construction. The savings that are possible, however, can vary substantially depending on the type of panel system and the degree of prefabrication. "Added value" panels, which have interior and/or exterior finishes included, provide higher savings than basic systems. Prefabricated panel systems using conventional methods are generally capable of providing the highest percentage of savings over the equivalent stick-build value, indicating that system for system, economies through prefabrication are possible. Heating costs for these types of systems, however, while lower than those of conventional construction, were the highest among the prefabricated systems studied.

In addition to construction and energy cost savings, prefabricated panel systems could be of benefit to both builders and consumers, and society as a whole. Prefabrication may result in less material wastage, which not only benefits the environment, but lowers the cost of clean-up and trash removal for the builder. The faster assembly process could also translate into savings in overhead and financing costs. Material damage and construction delays due to poor weather conditions could be reduced, and the possibility of vandalism and theft is decreased since the envelope can be closed in a matter of hours. Specialized labour restrictions are reduced, as are warranty commitments for the builder, which are passed onto the manufacturer. The construction task is generally simplified, and, consequently, the managerial burden relieved.

Guidelines

When selecting prefabricated wall systems, consider the following points:

- Distance from site to maunfacturer
- Experience of carpentry, electrical, plumbing and mechanical trades in working with prefabricated wall systems
- Cost of the system and transportation/lifting services offered by the manufacturer
- Flexibility of the system, both for on-site modification and post-occupancy adaptation
- Pesticide/rodent treatment given to foam insulations
- Quality of materials used in the manufacturing process, including foams, sheathings, lumber and adhesives
- Number and design repetition of units to be built
- Simplicity of unit configuration and modular dimensioning

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Building Materials

Background

Construction of environmentally sound housing involves everything from the design of the unit to its orientation, site planning and location. At the most elemental level, the choice of materials can have a substantial effect on practically all aspects of sustainability. In examining the environmental impact of building materials and comparing their characteristics between alternatives, the entire life cycle of the material should be accounted for, from the acquisition of raw materials, through production, packaging, delivery, use and disposal. This "cradle to grave" existence of the material can affect the environment in many ways.

The manner in which raw materials are acquired, the process by which the building component is manufactured, and the packaging and distribution of the finished product will have a significant impact on the environment. Material extraction and energy consumption may represent a depletion of finite natural resources. Mining activities can result in land and habitat loss, while endangered species can be harvested out of existence. Damage to land, water and air may be caused by improper disposal of waste materials generated at every stage in the process. The effects of building materials on indoor air quality, the potential for a product to be recycled or reused, and the waste generated from its disposal are major concerns in the latter stages of the product's life cycle.

The selection of materials based on life-cycle analysis often involves some compromise. The process is aimed at optimizing cost, durability and sustainability. What may appear to be an environmentally-sound product in one respect may exhibit compromising qualities in another. Aluminum, for instance, is known to have no harmful emissions and is a durable, recyclable building product. The process of extracting and manufacturing aluminum, however, is very energy-intensive. Conversely, high formaldehyde emissions from particleboard can seriously degrade indoor air quality, and its extensive use as a core product with plastic laminates makes it very difficult to recover for recycling. Its manufacture, however, is highly efficient, since it is made almost entirely of wood scraps and sawdust. Put simply, specifying particleboard instead of lumber saves trees.

Objective

The objective of this section is to examine the environmental impact of various building materials throughout their life cycle. The cost of replacing some common building products in the Grow Home with more environmentally-sound alternatives is evaluated.

In the absence of reliable, quantitative data, many decisions are often based on qualitative assessment. Although life-cycle analysis of building alternatives is a complex and difficult process, a basic knowledge of what a building product is made of and how it is manufactured can be useful in selecting alternatives to minimize the impact of building materials on the environment.

Life Cycle Impact of Construction Materials

The environmental impact of a building product can be assessed by examining how natural resources (including energy) and waste materials are utilized at several stages of its life cycle (Figure 1).

Acquisition of raw materials: The mining, harvesting or extraction of raw materials to manufacture a building product may deplete existing natural resources or cause damage to land, water, air and habitat. Consideration should be given to whether the resource is renewable or recyclable, and to whether or not it involves an endangered species (see Introduction to Part I). Improper disposal of contaminated solid, liquid or gaseous waste that is produced in the acquisition of raw materials can pollute the environment, while extensive mining and harvesting operations can disturb natural cycles of the eco-system.

Processing/Manufacture: The processing and fabrication of materials and components requires energy and generates waste. Some manufacturing processes recover waste products, which are either reworked into the process or sold to other manufacturing industries. Contaminated waste may

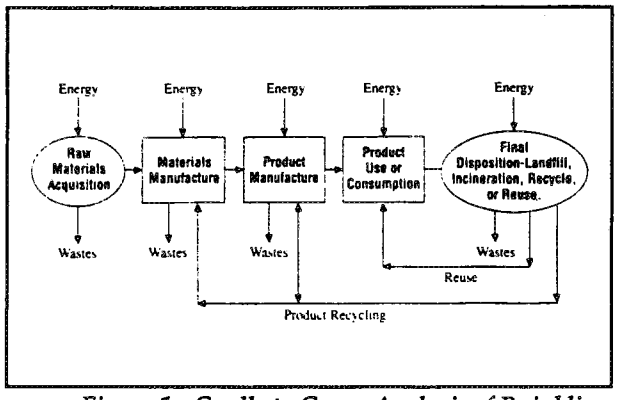

Figure 1: Cradle to Grave Analysis of Buiulding Products (from Hunt et al., 1992)

be treated prior to disposal or destroyed by incineration. When there is no recyclable use for a hazardous material, strictly regulated disposal procedures may reduce potential harm to the environment.

Packaging/Distribution: The type and amount of packaging used for a product and the energy required to distribute it to its point of use are important environmental considerations. In the construction of an average 2-storey house in central Canada, up to 14% of the total waste volume is typically cardboard and other packaging (CMHC,1991b). The ability to recover, reuse or recycle these containers could have a considerable impact on the solid waste stream.

Local availability of raw materials and building products is also of concern. Imported products, for instance, may be environmentally sound in many respects, but require more transportation energy when delivered to their final destination.

Construction/Assembly: Materials which are assembled into finished components under factory-controlled conditions usually make more efficient use of resources, and disposal of waste from a factory is more easily controlled. Scraps from materials which are formed, trimmed or assembled on-site are more likely to be disposed of improperly, since the quantity of waste generated from a single house or group of houses may appear to be insignificant or less threatening to the environment. Materials that may otherwise be useful and recyclable may end up polluting the environment in landfills.

Use/Occupancy: The durability and maintenance requirements of a building material can also have a substantial impact on the environment. Less durable materials require more frequent replacement. Untreated materials based on natural, renewable resources may require more energy and harmful maintenance products to stay useful and acceptable in appearance. The environmental benefits associated with a particular product may lose their significance if it only has 1/2 or 1/3 the useful life of an alternative product. Energy consumption, waste generation, resource depletion or eco-system effects associated with a particular quantity of a material must be multiplied by an appropriate factor if it is to be compared with a more durable alternative.

Demolition/Renovation: The fate of building materials when a house is partially or fully demolished is an important environmental concern. At the final stage of their life cycle, some building materials can be reused for similar applications or recycled as raw materials for manufacturing other marketable products. Other materials have no useful purpose in the post-consumer phase and need to be disposed of in landfills or incinerated.

The fact that a building material is reusable or recyclable is not a guarantee that it will cause less harm to the environment. A market for these materials must exist, and a collection program, by industry or government, must be in effect if any real improvement is to take place. Furthermore, the material must be in a form that makes it easy to recover. Materials that are bound or integrated with other building materials may be difficult to separate, or it may be economically unfeasible to do so. When materials such as these need to be disposed of in landfills, their ability to biodegrade is an environmental asset. In the absence of a recovery program or a possibility for the material to biodegrade, incineration of the material may recover some of its embodied energy.

Building Materials

Some general environmental characteristics of common building materials have been summarized from the American Institute of Architects' Environmental Resource Guide, and are presented below. Resource depletion, waste generation, and eco-system effects are environmental considerations which need to be assessed at every stage in a material's life cycle. Emissions from materials during the occupancy phase of a building's life cycle, and the

effects that these emissions may have on occupant health are also of concern. These considerations are covered in the section *Healthy Indoor Environments* and, with the exception of occasional references, were omitted from the discussions which follow.

Concrete

Concrete is a mixture of water, sand and gravel held together by a major binding agent called cement. It is a stable, durable and fire-resistant material that may be moulded into its final form on site, or manufactured into building components that are assembled as masonry units. It is an effective thermal mass which can be used in walls and floors for passive solar design. The making of concrete, however, relies heavily on extensive mining operations. While crushed rock and sand make up the principle mass of concrete, limestone, silica, alumina, iron, gypsum, clay, and coal or natural gas are required to manufacture cement. The extraction of these materials may result in loss of land and habitat, and water quality may be degraded from improper disposal of rinse water, not only from the mining activities, but also from manufacture and fabrication of concrete components. Risks to air quality may result from dust emissions in nearly all phases of manufacture, transportation and use. Carbon dioxide (CO_2), sulphur dioxide (SO_2) and partially combusted organic materials are emitted from combustion of coal or gas, which are used to operate high-temperature kilns in the making of cement.

One of the biggest environmental concerns of concrete stems from land use for disposal of demolition debris, which may account for 67% by weight and 53% by volume of all demolition debris in North America (AIA, 1992). While state of the art technology and improved management practices have been able to reduce manufacturing waste by over 90%, little has been done to recycle concrete from demolished structures.

The environmental impact of concrete can be reduced by dimensioning materials carefully and precisely to minimize off-cutting, and by returning excess concrete to vendors for remixing. Waxes or synthetic non-stick treatments can also be used for forms. Soil contamination from water waste can be reduced by minimizing water used to wash equipment, and preventing run-off from wetting of concrete for curing. Thermal, fire-resistance and durability advantages of concrete should be exploited to their full potential.

Metals

Aluminum: Aluminum is a strong, durable material which, depending on the finish, requires very little maintenance. It's light weight and high workability make it attractive for architectural design. Aluminum scrap can be recovered, recycled and reused endlessly.

Aluminum is processed from a fine, white powder called alumina, which is made from bauxite ore. Although bauxite comprises about 8% of the earth's crust, it is a finite resource. High-grade deposits of bauxite ore are found in tropical and subtropical countries like Australia, Jamaica and Brazil, from which most of the of the North American supply originates. The most common way of extracting bauxite is through strip mining, a process whereby large tracts of land are cleared of trees and soil. The bauxite layer (up to 5 meters thick) is stripped off, and the soil is then replaced. Vegetation is often replanted, depending on the country's reclamation laws. While the latter may reduce long-term effects on the eco-system, some tropical forest and species may be lost.

Although the extraction of raw materials and the manufacturing process generate large amounts of waste, its disposal is strictly regulated, and much of it can be recovered or treated to reduce harm to the environment. Alumina production generates large volumes of mud containing trace amounts of hazardous substances. For every 100 kg of aluminum, 2 kg of hazardous solid waste containing fluoride and cyanide are generated during the manufacturing process, which is deposited in a controlled disposal site. Most airborne emissions produced during smelting and forming are either treated or destroyed, but a small amount of carcinogenic hydrocarbons escape incineration. Large quantities of water are required for aluminum production, most of which is treated and recycled. Fabrication and finishing may also produce heavy metal sludge and large amounts of waste water, which require treatment and controlled disposal. While all finishing processes affect the environment, anodizing and powdered paint coatings are the least harmful.

One of the biggest drawbacks of aluminum is that its production requires large amounts of energy, accounting for 1.4% of the annual world energy consumption (AIA,1992). This energy requirement could be reduced by about 80% when recovered scrap and recycled aluminum is used in the production process rather than bauxite ore. Aluminum used in construction, however, is difficult to recover because it is usually incorporated into building assemblies in a manner which is difficult to separate or dismantle economically. Furthermore, there is no established recovery system in the building industry to guide the process.

The energy consumption attributed to aluminum production can be reduced by specifying aluminum products made from recycled scrap. Designing and detailing to avoid mixed-material assemblies can facilitate recycling of aluminum at demolition. Alternatively, other materials that consume less energy can be specified in applications where the advantages of aluminum are not needed.

Steel: Steel is a strong, durable and workable building material. Unlike aluminum, however, it is subject to corrosion and, consequently, requires more maintenance and needs to be replaced more often. Environmental concerns focus on land and habitat loss from mining and mineral resources depletion. Improper disposal of processing waters from mining and milling operations may affect water quality, and several emissions produced in the making of steel can contaminate the air. These include combustion emissions from ore refinement, combustion emissions from blast furnace operation (for the production of raw iron), and basic oxygen furnace emissions from the production of steel. Pollution from these emissions, however, have been reduced by about 90% over the last decade due to advances in the steel-making process.

Environmental damage is substantially reduced by virtue of the fact that steel is among the most recyclable materials on the market. It is easily separated from the waste stream magnetically and processed into a high-quality product, which provides a substantial amount of savings in energy and raw materials. This quality makes steel an environmentally attractive alternative to many other materials.

Wood

The use of wood in construction is encouraged because of its many positive environmental characteristics. The embodied energy of wood and wood products is less than that of any comparable building material. Waste can be recycled into wood chips for composite wood products, incinerated to generate energy, or ground up and used as compost, as it is biodegradable. Wood ash generated from incineration can be disposed of in a landfill, used to make adhesives, or sold for various purposes.

The only major concern about wood is the potential damage to forests caused by extensive harvesting. Although wood is a renewable resource, sound management practices are required to restock wood resources and restore forests to their original state. While several forest management practices are being implemented in North America to replenish temperate forests as they are depleted, more extensive efforts will be required if demand for lumber increases. Sustainable management practices such as these may not be present or sufficient for more exotic, imported woods.

Regardless of the type of wood or wood product used, harm to the environment can be minimized if efficient building practices are used to reduce consumption, and construction waste is reused or recycled (see *Unit Planning Principles*).

Tropical Woods: These woods are harvested from tropical rain forests or monsoon forests, which are located in a belt around the equator between the Tropic of Cancer and the Tropic of Capricorn. Examples include some types of mahogony, jelutong, kapur and sapele. More than half of the plant and animal species on Earth can be found in these forests. The variety in color, grain and workability found in tropical woods make them very popular for interior paneling and furniture. However, at the current rate of deforestation, tropical forests will be gone by the middle of the next century, and some popular tree species may become endangered due to overexploitation (AIA, 1992). Furthermore, most harvesting operations are inefficient and leave large amounts of debris behind. Scientists believe that for every cubic meter of wood extracted from forestry

operations in Southeast Asia, one cubic meter of wood debris is left behind and an additional 0,25 cubic meter of wood is lost in the processing (Wagner, 1989).

The environmental impact of such operations can be relieved by applying sustainable yield management principles. Currently, less than 1% of natural primary forest is managed under these principles. Ensuring that the wood purchased comes from a responsible source that has been certified for forestry operation is one precaution which should be taken. Using alternative wood species that are not endangered is another. Information concerning international wood sources and species can be acquired from the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and from the Woodworker's Alliance for Rain Forest Protection (WARP).

Plywood and Composite Wood Products: Wastage in wood fiber has been significantly reduced through the development of plywood and composite wood products. Approximately 90% of particleboard, for instance, is sawmill waste. Oriented strand board and plywood are high quality materials made from below-average wood fiber. Waferboard uses low-value species such as poplar, which at one time were cut and left behind while high-value species were extracted. Since they make use of wood chips, products like waferboard and oriented strand board use a higher percentage of the harvested log than solid lumber components.

The only major concern with these products has to do with the adhesives used to bind the product into shape. Products which make use of urea formaldehyde adhesives, such as hardwood plywood or particleboard, have substantial formaldehyde emissions which can seriously compromise indoor air quality (see Healthy Indoor Environments). Recovery of waste material in the post-consumer phase may also be difficult if the wood product is bound into an assembly with other materials. This is usually the case with particleboard. It is often laminated to plastic sheets or decorative coatings, which is why very-little post-consumer recycling is taking place.

Thermal Insulation

There are several types of thermal insulation materials available, and their environmental impact varies significantly from one to the other. Generally, they can be divided into three groups: fiber glass/mineral wool, cellulose, and foam.

Fiber glass and mineral wool insulations come in a variety of forms including batt, board, blanket and loose fill. Fiberglass is manufactured from sand, limestone (for calcium and magnesium) and borax (for boron). Mineral wool is manufactured from either diabase and basalt rock or from slag from an iron ore blast furnace. The principle environmental concerns with these products are the effects of mining operations on land, water and air quality. Small amounts of toxic gases, particulates and volatile organic compounds are generated during the manufacturing process, but they are usually treated prior to release. Most of the solid waste is recycled back into the process. Some of the fibers in the finished product are possibly carcinogenic, which may seriously compromise indoor air quality if they are not adequately contained within the building envelope (see Healthy Indoor Environments).

Cellulose insulation is made from recycled newsprint that is reduced to fiber form in mechanical mills, and treated for fire resistance. It is available as loose fill or wet spay fiber base. There is no significant waste generated at any phase during its life cycle.

Foam insulations can be polyurethane, polyisocyanurate, extruded or expanded polystyrene, or phenolic. Polystyrene and phenolic foams are available as boards, while the other two may be either boards or foamed in place. All of these materials, with the exception of phenolic foam, are made from pure, by-product or waste stream petrochemicals and their derivatives. Phenolic foam is produced from benzene, which is derived from crude oil, and olefins, which are derived from natural gas.

The biggest environmental concern with foam insulations is the effect of chlorofluorocarbons (CFCs) on the earth's ozone layer. CFCs are used as blowing agents in the production of polyurethane, polyisocyanurate, extruded polystyrene, and phenolic foams. Expanded polystyrene is blown with pentane gas, which is not ozone-depleting, but contributes to ground-level smog. Most CFCs have now been replaced with much safer substances. Alternative blowing agents for polyisocyanurate and phenolic foams, however, are not yet commercially available.

Most insulation materials can be recycled or reused, although very little post-consumer recovery is currently taking place. Polystyrene is a thermoplastic, which means it can be heated and remoulded into a new product. Other foam insulations, like polyurethane and phenol products cannot be remoulded, but can be recycled as filler. Unlike metals, however, products made from recycled plastics are not of the same quality as virgin materials, due to natural degradation and contamination. Fiber glass, rock wool and slag wool can also be recycled or reused, but most insulation products are disposed of in landfills. One of the problems with exploiting the recycling potential of thermal insulation is that there is no organized infrastructure set up to collect and process the waste. Furthermore, recovery of insulation products may be difficult because they are usually bound to other building materials.

All factors considered, cellulose insulation appears to be the most environmentally-sound alternative, although its use may be restricted because it is mostly available as loose fill. It has the lowest embodied energy of any insulation material, since most of it (75-80%) is made of recycled paper and cardboard, and it is an effective insulator. While the tendency for loose fill insulation to settle may reduce its thermal performance, several precautions could be taken to avoid loss of performance (Bomberg & Solvason, 1980a, 1980b).

Sealants

There are hundreds of sealants on the market with different formulations suited for particular applications. Many of them are proprietary products, making it difficult to acquire detailed data on energy consumption, waste generation and resource depletion. Most modern sealants are based on plastic resins, which make use of hazardous or toxic chemicals. The disposal of waste generated from the production of sealants is strictly regulated, and manufacturers often recover and rework batches of defective product rather than disposing of them. As plastic resins, environmental concerns also include natural resource depletion, since most are based on petrochemical feedstock, and energy consumption. Since many sealants contain harmful chemicals, minimizing waste and emissions are the most effective environmental strategies in the specification of sealants. Selecting a durable product, well-suited for a particular application and properly applied, can help reduce the negative effects of sealants on the environment.

Linoleum

Linoleum is very durable, greaseproof, waterproof, resistant to burns, and is produced as sheets or tiles. It is made from natural, degradable materials such as linseed oil, resin and cork powder, most of which are derived from renewable resources that are not endangered. While scrap linoleum from fabrication is recovered and reused, wastes from construction and post-consumer use can safely be discarded in a landfill. The only environmental drawback to linoleum is that it requires more energy to make than its most popular alternative (vinyl), due largely to transportation requirements as it is generally imported.

Vinyl Flooring

Vinyl has become a popular flooring material because it is a cost effective, durable and care-free material. While this reduces the need for energy and potentially harmful maintenance products, vinyl products affect the environment at every stage of their life-cycle. Most of these problems stem from the use of polyvinyl chloride (PVC), which is the main component of vinyl flooring. Solid, liquid and gaseous waste generated from the production of PVC are highly toxic, and their disposal is strictly regulated. Most of the wastes (95%) from the manufacture of the flooring product are either recycled or incinerated. Scraps from installation and use, however, are usually disposed of in landfills. Although these scraps are recyclable, there is no collection or recovery system currently in operation. Since PVC has a high caloric value, it may be worthwhile to recover this energy through incineration if recycling is not feasible. However, there is some concern that chlorinated combustion products may restrict the incineration of PVC products (Young, 1991).

Carpets

Environmental concerns in residential carpeting are not only with the carpet itself, but also, and perhaps more so, with the carpet cushion and adhesives used in its installation. Of the four carpet fibers which

now dominate the market, three (nylon, olefin and polyester) are synthetic, derived from petrochemical products. Wool, the fourth fiber, is natural, but has a small percentage of the market (1%) since it is more costly than the others, less stain resistant and does not wear as well. Some manufactures make extensive use of recycled plastic containers in the fabrication of synthetic carpet fibers, and waste materials from several industries are used for some types of carpet cushions.

There are two major environmental concerns arising from carpeting. The first deals with waste materials generated from the production of styrene butadiene (SB) latex, used in some carpet fibers, cushions and adhesives. SB latex production results in emissions of toxic air pollutants that may present very high public health hazards for surrounding communities. Off-gassing of this material after installation can seriously compromise indoor air quality. The second concern is with the disposal of waste waters from the fiber-dyeing process. This process requires very large volumes of water -- about 257 litres (68 gallons) for every square meter of carpet. For saxony carpets, which are batch dyed, 3 to 4 times more water is required than other carpets. In addition, carpet dyes remain in the waste water after treatment and may pose a threat to water quality when disposed.

As is the case with some types of rigid foam insulations, some cushion foams used under carpets have traditionally been expanded with CFC blowing agents, which contribute to the depletion of the ozone layer. CFCs are, however, being phased out and many foams are now being made with other blowing agents.

Paint

Paint consists of three main components: a carrier, (or matrix) which may be either water or organic solvents that evaporate as the paint dries; a binder, which contains resins and oils, that keep the paint together and make it adhere to a surface; and pigments, which give the paint color and durability. Most paints contain materials derived from petrochemical products, either in the carrier, binder or pigment. Some alternative "natural" paints have been developed that are made from renewable resources such as plant resins, ethereal oils and mineral fillers and pigments. Supplies of these materials, however, may not be sufficient if the demand for natural alternatives reaches that of conventional paints. While natural paints can significantly reduce harm to the environment, they require more expertise in their preparation and application, and are not normally available in a wide range of colors.

The manufacture and use of paints produces several types of waste, many of which are hazardous if improperly disposed. Waste from equipment cleaning, obsolete stock and returns from customers are mostly recovered and reworked into marketable products. Disposal of those wastes which cannot be recovered is strictly regulated. At the post-consumer phase, safe disposal of left-over paint can be achieved through municipal collection and recycling programs which are being increasingly implemented in many communities.

Embodied Energy

Embodied energy is a useful indicator of the environmental impact of a manufactured product. It is the sum of all the energy required throughout a product's life cycle, from the acquisition of raw materials through its manufacture, distribution, assembly, use and disposal. It accounts for energy contained within the material, such as feedstock petroleum used to make plastics, as well as energy required to process the material into its final form and deliver it to its destination. It is not unusual for the embodied energy in a building to be equivalent to 10 years worth of operating energy (AIA, 1992 b).

The embodied energies of several common building products are shown in Table 1. The values were derived from input/output data supplied by Statistics Canada (Sheltair, 1991). While energy comparisons between alternative building materials by weight may be misleading, some meaningful patterns emerge among products with similar applications. Products made from plastics or metals, for instance, including siding, flooring and plumbing components, have the highest energy intensity by weight than any other building material. Recycled paper products, such as cellulose insulation, require 64% less energy to make than mineral wool or fiber glass, and 98% less than polystyrene board. The energy intensity of gypsum wallboard is almost the same as that of converted paper products, but using

Building Product	Energy Intensity (MJ/kg)
Plastic Pipe Fittings & Sheet	188.59
Carpeting & Fabric Rugs, Mats, etc.	74.42
Paints & Related Products	40.34
Tiling, Rubber, Plastic	31.82
Metal Pipes, Fittings & Sidings	68.02
Beams & Other Structural Steel	20.78
Mineral Wool & Thermal Insulation	18.35
Building Paper	12.01
Plasters & Other Gypsum Basic Products	4.48
Converted Paper, Gum, Wax	4.36
Veneer & Plywood	14.62
Fabricated Wood Materials for Structures	11.85
Millwork	9.87
Miscellaneous Wood	8.96
Lumber & Timber	7.38
Bricks and Tiles, Clay	2.14
Concrete Basic Products	0.81
Sand Lime Bricks and Blocks	0.71
Ready-Mix Concrete	0.54
Natural Stone, Basic Products	0.37
Crude Stone	0.14
Source: Sheltair, 1991	

Table 1: Embodied Energy of Building Materials

a recycled wallboard product may be preferable from an environmental perspective, since it depletes less resources and reduces the amount of solid waste entering our waste stream.

The use of wood and composite wood products can significantly reduce energy consumption. Whether it is used for structural or decorative purposes, the embodied energy of lumber and timber is usually much less than that of any other comparable building material. As a siding material, lumber consumes approximately 7 MJ/kg, as compared to 68 MJ/kg for metal and 189 MJ/kg for vinyl. When used for structural purposes, wood requires 13% less energy by weight than steel. Processing lumber into composite wood products increases its energy consumption, but it remains well below that of alternative materials. Roofing shingles, waferboard and particleboard require 21% more energy to make than solid lumber, while products containing wood veneers like plywood require twice the energy.

The firing process that clay products are subjected to makes them inefficient energy consumers when compared to alternative products like concrete or stone. Weight for weight, replacing a clay brick wall with concrete brick, poured-in-place concrete or stone can reduce the embodied energy of that wall by 62%, 75% and 93%, respectively. While masonry products are shown to have by far the lowest energy intensity by weight of any other building material, they also have the highest density. The effect of materials on energy consumption would need to be considered in context, and will vary significantly depending on the application.

Building Materials and the Grow Home

The fact that the Grow Home (as most North American homes) uses wood as a structural material is a good start as far as the environment is concerned. As a renewable, recyclable and energy-efficient resource, wood provides an attractive alternative to masonry and concrete. Its use as a finish, both interior and exterior, can also help the environment and reduce energy consumption even further.

The energy intensity of alternative finishing materials, insulation and sheathing is shown in Table 2. The weight of specific materials in their applied form was calculated to give energy values per square

Building Component	Energy Intensity (MJ/kg)	Energy Intensity (MJ/sq.m.)	Grow Home (MJ)
Exterior Wall Finishes			
Vinyl Siding (254 mm)	188.59	634.39	75,238
Metal Siding (203 mm)	68.02	130.33	15,457
Cedar Siding (254 mm)	7.38	47.86	5,677
Stucco (22 mm)	0.14	6.84	811
Brick (concrete)	0.81	152.04	18,032
Brick (clay)	2.14	338.35	40,128
Stone (50 mm)	0.14	20.51	2,433
Interior Floor Finishes			
Carpeting	74.42	186.65	11,152
Parquetry	7.38	46.95	2,805
Vinyl Tile (kitchen & bath)	31.82	217.50	4,720
Ceramic Tile (kitchen & bath)	2.14	33.42	725
Interior Wall Finishes			
Paint (2 coats)	40.34	10.42	2,933
Wallpaper (vinyl)	31.82	8.56	2,410
Wallpaper	4.36	0.80	225
Wall Insulation			
Fiber Glass (152 mm)	18.35	33.78	3,614
Cellulose (spray; 152 mm)	4.36	16.47	1,763
Extruded Polystyrene(100 mm)	188.59	1144.94	122,508
Roof Insulation			
Fiber Glass (202 mm)	18.35	51.95	2,234
Mineral Wool (blown, 225 mm)	18.35	131.75	5,665
Cellulose (blown, 208 mm)	4.36	22.81	981
Roofing			
Asphalt Shingles	12.01	123.20	6,838
Cedar Shakes	8.96	70.02	3,886
Concrete Tile	0.81	37.58	2,086
Sheathing Materials			
Plywood (15.9 mm)	14.62	119.95	29,591
OSB (15.9 mm)	8.96	49.04	12,098

- *Conversion factors to kg of product were taken from Sheltair, 1991b*
- *Embodied energy for exterior wall finishes assumes full replacement ie. all walls finished with the same material*

Table 2: Alternative Building Materials

meter of surface area. The total embodied energy in each component was then calculated for a semi-detached version of the Grow Home. The estimates reveal that significant energy savings can be achieved without radically modifying the house's appearance, performance or cost.

Replacing the plywood floor, wall and roof sheathing with oriented strand board results in a 59% reduction in embodied energy for that component. Similarly, replacing the fiberglass insulation in the walls and roofs with cellulose reduces the energy content by 56% and 51%, respectively. For a standard Grow Home, these changes alone result in energy savings of 20,597 MJ (Table 3). At 278 KWh/GJ, these savings are equivalent to 5,726 KWh, which is about 75% of the annual heating energy required to compensate for losses through the envelope. The appearance or performance of the house have not been changed significantly, and construction costs have only been increased by a about $73. Furthermore, natural resources are being used more efficiently.

Building Material	Environmental Benefits	Energy Savings (MJ)	Added Constr. Cost
Sheathing			
Plywood to OSB	59% less embodied energy efficient use of resources (better use of wood fiber)	17,493	-$368
Insulation			
Fiber Glass to Cellulose	56% less embodied energy; less resource depletion (recycled product); biodegradable	3,104	$441
Roof Shingles			
Asphalt to Cedar	43% less embodied energy; less resource depletion (renewable resource)	2,952	$1,001
Siding			
Vinyl to Cedar	92% less embodied energy; less resource depletion (renewable resource)	38,124	$788
Brick			
Clay to Concrete	55% less embodied energy	9,986	Negl.
Flooring			
Carpeting to Parquetry	75% less embodied energy; less resource depletion; less toxic waste	8,347	$724
Vinyl to Ceramic	85% less embodied energy less toxic waste	3,995	$908
	Total	84,002	$3,495

- *Construction costs include labour, material, equipment, contractor's overhead and profit.*
- *Exterior finishes include brick on full front elevation and on the first floor side and back; siding on second floor side and back.*

Table 3: Energy and Cost Savings for a Semi-Detached Grow Home

The use of alternative finishing materials can also result in significant savings in energy and other resources while reducing the amount of toxic waste being generated. By replacing the carpet and vinyl flooring with parquetry and ceramic tile, an additional 12,342 MJ of embodied energy can be saved. Using cedar boards and shingles instead of vinyl siding and asphalt reduces energy consumption by 41,076 MJ, while switching the brick material from clay to concrete saves another 9,986 MJ. When added to the savings from sheathing and insulation, the embodied energy of the house is reduced by 84,000 MJ, or 23,352 KWh. This is equivalent to the energy required to heat the Grow Home for at least 4 years.

It should be kept in mind that these changes only illustrate the potential for improvement, as they are limited to a few products. Significant improvements, both in energy content and environmental qualities, can be achieved by considering other alternative products. The use of wallpaper, linoleum, concrete tiles and stone, for instance, are worth exploring. New paints, adhesives and wallboards, made of natural or recycled material, are becoming available while other environmentally-safe alternatives are under development. While some unconventional products may require special skill and attention in their installation, their durability and performance relative to conventional alternatives does not appear to be compromised.

Summary

Any analysis of the environmental impact of a building material, or comparison between different alternatives, should consider the entire life cycle of that material, from its cradle to its grave. Life cycle analysis is a difficult process, which involves many variables. In the absence of quantitative data, many decisions regarding material selection are based on qualitative assessments, often with some compromise being made between one environmental benefit and another.

The stages in a product's life cycle which must be considered for a meaningful assessment include acquisition of raw materials, processing and manufacture of raw materials into building products, packaging and distribution of these products, construction, use and, finally, their eventual recovery

and/or disposal. The environmental impact at every stage of the material's life cycle can be in the form of energy consumption, waste generated, natural resource depletion, and damage to land, water, air and habitat, caused by pollution or disturbance of the natural cycles of the eco-system.

The goal in selecting environmentally-sound building products is to maximize use of recycled or recyclable materials, and to ensure that the mining, harvesting and extracting of raw materials does not pose a threat to existing resources or endangered species. The amount of energy that goes into the material at every stage of its life cycle should be minimized, as should the amount of waste generated.

The Grow Home's environmental qualities can be significantly improved without adversely changing the house's appearance, performance or cost. Replacement of some basic construction materials provided an indication of the potential for improvement. By selecting more environmentally-friendly sheathing, insulation siding and flooring, the savings in energy content alone are enough to heat the home for 4 years or more. These same changes make more efficient use of natural resources while minimizing the amount of waste generated. The situation may be improved much further if similar consideration is given to several other building materials and components. Furthermore, many companies have started developing new products which are less harmful to the environment. Recycled wallboard products, natural paints, and low-emission adhesives, sealants and maintenance products are rapidly entering the market. With a wider selection of alternative products, green building practices may become more accessible and cost-effective for the average builder.

Guidelines

Following some general rules when selecting building materials could help the environment:

- Give priority to products that have recycled content or that are made from renewable and/or recyclable resources.
- Use products that can be reused or recycled at the end of their life-cycle, or that can be disposed of safely (biodegradable).
- Do not use products that rely on endangered species.
- Consider land, water, air and habitat degradation that may be caused by mining, harvesting or extraction of raw materials.
- Avoid materials that produce significant amounts of hazardous waste or use hazardous substances in their manufacture.
- Select durable, low-maintenance products.
- Reduce, reuse and recycle waste generated during construction, both from material and packaging.
- Consider the embodied energy of building materials; use products that require less energy to make them and that are locally available.

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Windows

Introduction

Heat losses through the building envelope can occur through any of three mechanisms: conduction, convection and radiation. In all three cases, windows are the weakest link in the thermal performance of a building envelope, and, as such, represent the most important investment in the construction or renovation of any dwelling. They are also highly variable in price, appearance and performance, making their selection an ambiguous and sometimes difficult process. This section outlines the factors which affect a window unit's energy performance and provides guidelines for its selection, installation and integration into the dwelling's general layout.

Background

Residential end uses, including heating, cooling and operating, account for approximately 20% of the total energy demand in Canada. Heating and cooling requirements are largely controlled by the envelope design, of which windows represent the single largest source of heat loss. The size, type, location and orientation of windows in the unit play a critical role in the dwelling's energy efficiency. While high-performance windows are available, they are usually too expensive to be used in the context of affordable housing. Considering that the window unit is arguably the most significant investment insofar as energy efficiency is concerned, their selection and installation should be carried out carefully.

Anatomy of a Window

It is best to discuss window units in terms of their components. There are two basic parts which have to be considered: the frame and the glass, or glazing unit (Figure 1). There are two types of frames within a window unit. The first is the outer frame, which is anchored to the wall, and the second in the interior frame (sash), which encloses the individual glazing units and can be opened in a variety of ways. The glazing unit consists of two or more layers of glass or plastic, separated by spacers and coated in various ways to control heat gains and losses.

Objective

The objective of this section is to examine the characteristics of window units that will determine their energy efficiency, and to evaluate the effect of these characteristics on total energy consumption of a Grow Home-type unit.

Factors that Determine Energy Efficiency

There are three ways in which heat can be lost across a building envelope and a window unit (Figure 2). The first is conduction, which represents the heat component lost through the materials themselves. It occurs both through the frames and the glass, and depends strictly on the properties of the materials themselves.

The second way in which heat can be lost is through infiltration, which occurs by air flowing across an opening or cavity (infiltration of cold air, or exfiltration of warm air). In an installed window unit, there are three joints where this can occur: between frame and wall, between frame and sash and between the sash and glazing unit.

Infiltration is minimized by providing as air-tight a joint as possible. In the joint between the frame and the wall, this is controlled entirely by the installation procedure. In the other two cases, it is controlled by means of gaskets.

Finally, radiative heat losses, which occur across an air space, are dependent on the ability of the glazing to transmit, absorb and reflect radiation. They are controlled by means of special coatings applied to the glass surface.

Frame

Coupled with edge losses from the glazing unit, conductive heat losses through the frame can account for up to 20% of the total heat losses from the window unit. The selection of an appropriate frame material is therefore not simply a question of appearance. Wood, for instance, is a good insulator, but is easily damaged and has a high maintenance requirement. Metal (aluminum) requires much less maintenance, but is a very good conductor. The selection of

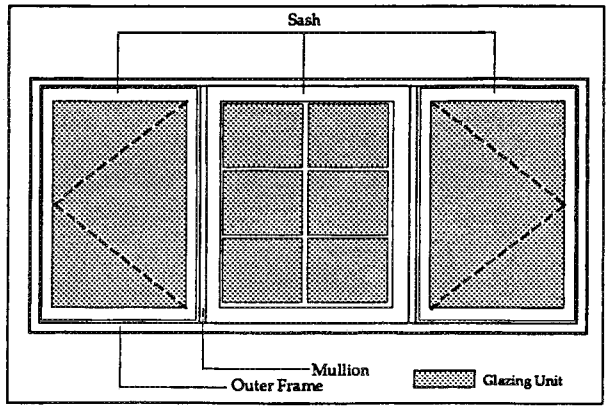

Figure 1: Parts of a Window Unit

an aluminum frame must ensure that it is designed with a thermal break. A thermal break is a separation which uses materials with a lower thermal conductivity (cellular foam, rigid PVC, polyurethane, wood, etc.) to keep frost from entering.

Metal frames are also very susceptible to temperature changes, and will expand and contract significantly on a seasonal, daily or even hourly basis. The joint between the glazing unit and the sash must therefore be flexible enough to accommodate any movement without breaking the glass. Plastic (vinyl) frames are maintenance free, but, like metal frames, are susceptible to temperature changes. Finally, some frames use a combination of materials, usually a wood core covered with either aluminum or vinyl. These are intended to take advantage of thermal qualities of wood while protecting it with either vinyl or aluminum and reducing the maintenance requirement.

Infiltration losses between the frame and the sash depend on the number and type of operable components and on the type of gasket (Figure 3). There are several types of windows categorized by the type of operation: fixed, awning, hopper, casement (out or in - as in French windows), sliding, single hung, double hung, pivoted (vertical) and multiple (for cleaning and ventilation). It is also possible to have window units manufactured with combinations of these.

Generally, windows with fewer operable parts are more energy-efficient. The more linear feet of joint, the more heat lost through leakage. Fixed windows are best in this regard. As far as the type of operation is concerned, pivotal components are more energy efficient, since they make use of compression seals. Sliding parts are least effective in terms of air leakage.

It should be mentioned that the general quality and craftsmanship of the window are critical. A poorly-assembled casement window from one manufacturer, for instance, can be susceptible to more air leakage than a well-crafted sliding unit from another manufacturer. A poor seal can overcome the advantages of using a casement or awning window.

Glazing Unit

All three types of heat losses mentioned earlier occur across the glazing unit. These losses are controlled by the type and number of layers present in a glazing unit, the type of space that separates them, the type of coating (if any) applied to their surface, and the type of gas that fills the cavity between them. Figure 4 illustrates several possible alternatives for glazing units along with their thermal resistance.

The actual thickness of either the air space or the glazing is less critical. The thickness of the glazing is determined for structural purposes. The air space

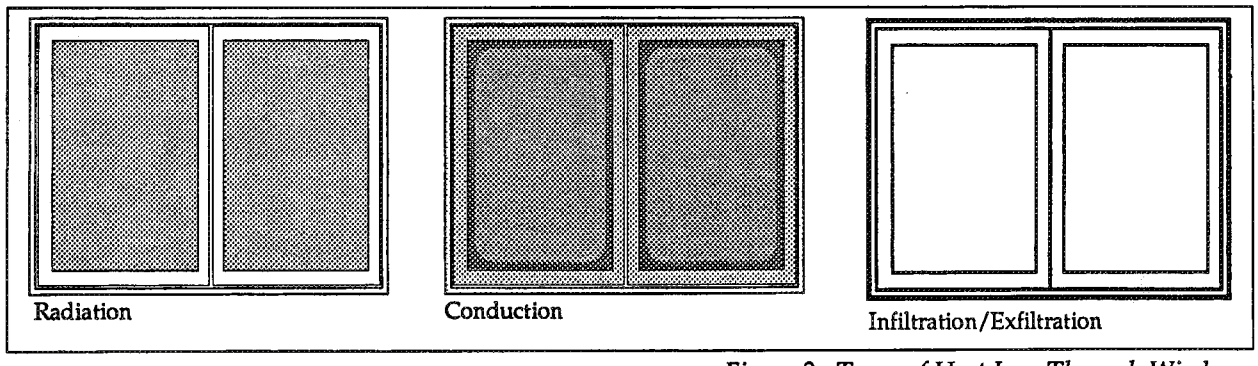

Figure 2: Types of Heat Loss Through Windows

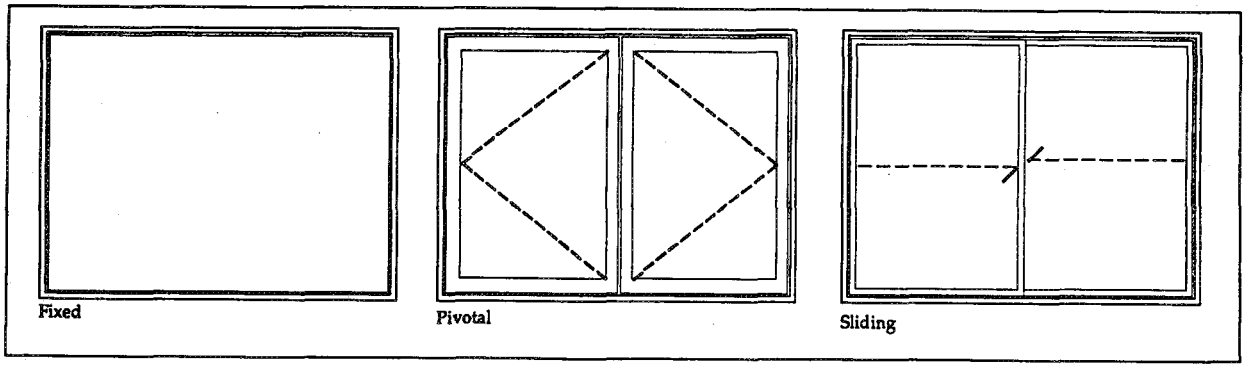

Figure 3: General Types of Window Frames

may range from 3/8" to 1", with an incremental increase in R- value. The wider the gap, the greater the convective heat losses, since air is allowed to circulate more freely within the cavity. The thinner the gap, the greater the conductive heat loss. Units are usually built with a 1/2" airspace and two 1/4" sheets of glass, to give a total width of 1".

The number of layers has a more significant effect on the energy performance of the window unit, and adding layers is an effective way of improving the unit's R-value, which increases by approximately 1 K-sq.m./W with every layer added. Only conductive and convective heat losses are reduced, however, with no significant effect on radiative heat loss. Therefore, the addition of layers reaches a point of diminishing reductions:

- 1 to 2 layers- 50% initial reduction in energy loss
- 2 to 3 layers-33% further reduction in energy loss
- 3 to 4 layers-25%further reduction in energy loss

The addition of layers is also an effective way of reducing noise transmission. The intermediary layer in units with three or more layers can also be a thin plastic film. These units can be very efficient, especially with a low-e (emissivity) coating, but they are not as durable as other options, and there is no substantial increase in thermal performance

Conductive losses can also be reduced by using a low-conductivity gas like argon, sulphur hexaflouride or carbon dioxide, which can increase the thermal resistance of the unit by 12 to 18% while reducing sound transmission.

The function of the spacer bar is to seal the unit so that no air or moisture enters the air space. It consists of a hollow metal section sealed with an organic compound. To ensure that there is no moisture, a chemical drying agent is put in the spacer bar, and small holes drilled so that any moisture that gets into the air space can be absorbed. This is an important characteristic to look for when evaluating windows. A quality window should last for years; any indication of condensation on the inner leaf of the glazing unit is a sure sign of a poor quality or defective window unit. Condensation on the interior of the home is a different issue altogether and is not necessarily the sign of a poor window. Since much of a

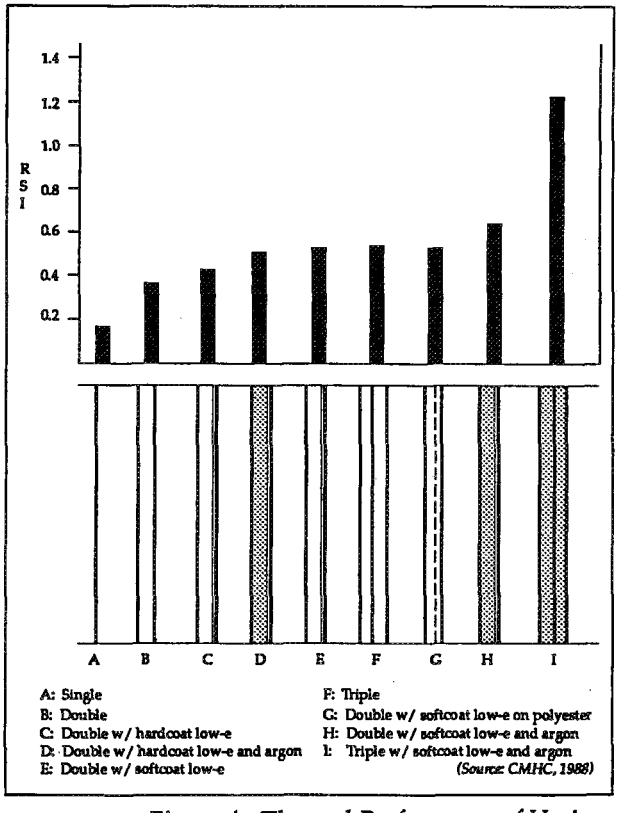

Figure 4: Thermal Performance of Various Glazing Units

window's heat loss is from the edges, insulative spacer bars, such as butyl metal, are also available that reduce conductive heat loss along the glazing unit's perimeter.

The problem which remains is that of radiative heat transfer, both across the air space and through the glass to the interior. A variety of coatings can be applied at different parts of the window to control radiative heat flow. These include tinted or reflective coatings, which are intended to reduce glare and solar heat gain, or low-e coatings, which allow most of the shorter wavelength IR radiation to go through, but reflect back into the building most of the larger-wavelength radiation. The result is a thermal resistance close to that of a triple-glazed unit, which tend to be heavy, cumbersome and expensive, not only because of the extra glazing, but because of heavier duty operating mechanisms that are required.

Installation

The joint between the frame and the wall is the final but critical link in an energy efficient envelope. The performance of this joint relies entirely on the installation procedure and sealing material used. Generally, the installation should provide an air-tight seal while allowing for differential thermal or structural movement between the frame and the wall.

The air-tight qualities of the joint can be ensured by using backer rod and sealant. Batt insulation alone is not sufficient to stop air movement; the unit must be caulked. For gaps smaller than 17 mm, a silicone sealant is recommended. Wider gaps should be filled with polyurethane. Expanding foam can also be effective, but care should be taken not to overfill the cavity joint. This may apply stress on the window frame, causing the frame to deform and bend, resulting in windows that are difficult to open.

Frame Type	Infiltr. Rate L/s	Heat Loss (W)	Energy Consumed (KWh)	Annual Heating Cost
Awning/Casement	1.78	94	137	$6
Single Hung	4.89	258	377	$18
Double Hung	6.67	352	514	$24
Single Slider	4.00	211	308	$14
Double Slider	5.78	305	445	$21

- *Infiltration rates calculated from effective leakage areas of average window frames (ASHRAE, 1989)*
- *Energy consumption is for the Montreal area; heating costs assumed at $0.0469/KWh*

Table 1: Effect of Frame Type on Energy Consumption

The upper part of the window should not be shimmed, so as to allow for some movement. Sufficient tolerance should be provided in the rough opening of the structural frame, no less than 1/2" on the top and sides. The top flange should also be secured when using metal window frames in a manner that will allow for shrinkage of wood frame. The transfer of loads to the window frame should be avoided.

Energy Implications

The energy implication behind the use of various window types will vary depending on building type, size and orientation. In a rowhouse version of the Grow Home, windows occupy some 25% of the total exposed wall area, and account for 45% of the total heat loss. The selection of energy-efficient windows is therefore an effective way of reducing energy costs.

Conductive heat losses were calculated for different frame types, materials and glazings. Single glazing units and metal frames with no thermal break were omitted from the analysis because they are not suitable for cold climates. Although super efficient triple-glazed units can significantly reduce heat loss, they were thought to be inappropriate for a Grow Home due to their high costs.

While the glazing component accounts for most of the heat lost through window units, air leakage between the outer frame and sash and conductive heat losses through the frame itself can significantly affect energy consumption. Table 1 shows the heat loss attributed to infiltration for different types of window frames. The use of pivoting mechanisms with compressive seals, as is the case with awning and casement windows, can reduce infiltration losses by up to 75% compared to sliding mechanisms found in double hung windows. The single sliding window, which appears to be the next best alternative, has on average more than twice the air leakage of a comparably-sized casement window. Annual cost savings which could be achieved with casement or awning windows range from $8 to $18.

The edge losses from the frame in a window unit can also be reduced by specifying frame materials that are less conductive to heat flow. Replacing a thermally-broken aluminum frame with a wood or wood

Frame Material	RSI (window unit)	Heat Loss (W)	Energy Consumed (KWh)	Annual Heating Cost
Thermally-broken aluminum	0.49	1307	1909	$89
Wood or wood clad	0.59	1093	1597	$75
Vinyl	0.69	442	646	$30

- *Glazing assumed to be double with low-e coating, argon and insulative spacer*
- *Energy consumption is for the Montreal area; heating costs assumed at $0.0469/KWh*

Table 2: Effect of Frame Material on Energy Consumption

clad frame can save $14 in annual heating costs, which represents 15% of the total heat loss from the window unit (Table 2).

The type of glazing chosen will have the most significant effect on heat loss. Table 3 shows the energy implications of progressively upgrading a standard, double glazed unit with a 12.7 mm (1/2") air space and aluminum spacer. The addition of a low-e coating to reduce radiative heat flow can save 608 KWh annually. Filling the air space with argon reduces the space heating requirement by an additional 192KWh, while replacing the spacer with an insulative-type bar can save 192 KWh. The energy costs associated with heat loss through each of the 4 types of glazing units range from $75 to $122. The cost of upgrading the glazing unit ranges from $239 for the addition of a low-e coating to $259 for an argon-filled unit and $408 for a full upgrade, including low-e coating, argon gas and insulative spacer bar (Table 4). With respective energy savings worth $29, $37 and $47, the investment can pay for itself in 9 to 12 years.

Glazing Type	RSI (window unit)	Heat Loss (W)	Energy Consumed (KWh)	Annual Heating Cost
Double, air, alum. spacer	0.36	1780	2599	$122
+ low - e coating	0.47	1363	1991	$93
+ argon gas	0.52	1232	1799	$85
+ insulative spacer	0.59	1093	1597	$75

- *Window frame assumed to be wood*
- *RSI values from Scanada, 1992*
- *Energy consumption is for the Montreal area; heating costs assumed at $0.0469/KWh*

Table 3: Effect of Glazing Type on Energy Consumption

Glazing Type	Energy Cost Savings	Incremental Cost Increase	Payback Period (years)
Double, air, alum. spacer		Standard	
+ low - e coating	$29	$239	11.7
+ argon gas	$37	$259	9.3
+ insulative spacer	$47	$408	12.6

- *Cost savings from heat loss; heat gains not accounted for*
- *Incremental costs from Scanada, 1992*
- *Energy consumption is for the Montreal area; heating costs assumed at $0.0469/KWh*

Table 4: Payback Period for Different Glazing Types

It should be noted that these savings do not account for solar heat gains through the window, which can significantly reduce the space heating requirement. In a recent study, energy simulations using several types of windows were conducted on 39 different housing types. The analysis revealed that the incremental cost increase required for super double glazed units (low-e, argon and insulative spacer) can pay for itself in 3.5 years for an electrically heated house (Scanada, 1992).

Summary

Significant reductions in heat loss could be achieved by selecting higher quality windows. The savings are most pronounced for a rowhouse, since the window area accounts for a greater portion of the exterior wall area. Switching from double hung to casement windows, which have compression seals, can reduce infiltration heat loss by 71%. The use of poor thermal conductors like wood and vinyl in the frame (instead of thermally-broken aluminum) can reduce overall window heat loss by 15%. Finally, upgrading the glazing unit by adding a low-e coating, argon gas and an insulative spacer can save at least $47 annually in heating costs, which is approximately 15% of the total energy bill attributed to heat loss through the envelope.

With solar heat gains accounted for, the investment required to upgrade from a standard window unit (RSI 0.31) to a high performance unit (RSI 0.59) can pay for itself in 3.5 years. Because of the high level of quality control which is possible in window manufacturing, the selection of higher quality windows is a simple and effective way of substantially reducing energy consumption.

Guidelines

Following some general rules when selecting window units could lead to significant energy savings:

- Select materials with low thermal conductivity, such as wood and wood-clad frames.
- Select window units with less operable components.
- In operable windows, select pivot-type mechanisms (casement, awning) over the sliding type (horizontal sliders, double hung).
- Select best glazing unit composition affordable; at the very least, double-glazed units with low-e coatings should be used.
- Ensure that a quality (tested) spacer bar has been used.
- Take proper care during installation to ensure an air-tight seal between window frame and rough opening.

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Mechanical Systems

Background

The North American construction industry has seen many technological advancements since World War II. Houses today are more energy efficient and are less subject to deterioration due to moisture (see section on R2000 building technology). Because building envelopes are more air tight, concern for air quality has increased and with it, the need for mechanical ventilation.

The selection of heating, ventilating and air conditioning equipment for homes is made complex due to the wide variety of systems and technologies that are available. The appropriate alternative will depend on the size, configuration and grouping of the units, among other factors.

The design of the Grow Home represents a starting point for residential housing with regard to energy consumption. Its narrow-front design and configuration reduces heat loss by as much as 45% compared to conventional housing. However, due to these same characteristics, the space conditioning issue must be addressed carefully.

Selecting a Mechanical System

There are several functions which can be performed by a mechanical system, including heating, cooling, humidification, air purification and ventilation. For this project, two types of distribution systems are considered: convection and forced-air. Table 1 summarizes the air conditioning functions performed by the different systems. Indoor space restrictions are associated with the different types of systems.

Objectives

This section investigates the options available for residential mechanical systems, and evaluates the cost/benefit potential of each as it relates to narrow-front housing development

The central systems (forced-air) require limited space in the basement of the house and have to be attached to a network of conduits to force the air through the house. The implementation of such systems thus requires pipe chases and wall sections which allow for the installation of ducts. The convection systems, such as the ductless heat pumps, electric baseboard heaters and the fan assisted room heaters are more flexibly located inside the house. For the two electric systems mentioned above, it is recommended that they are placed under windows when possible. The ductless heat pump, on the other hand, is usually installed on exterior walls close to the ceiling . Fortunately, it is not necessary to install the units on exposed walls if the implementation is planned prior to construction which allows the builder to insert the connecting pipes inside the walls. Finally, air-air heat pump systems require an outdoor heat exchanger. In rowhouse developments, this might

	Category	Type	Functions				
			Heat	Cool	Humidification	Purification	Ventilation
A	**Electrical**						
1	Central	air forced	X		X	X	X
2	Baseboard	convection	X				
3	Fan-assisted	convection	X				
B	**Heat Pump**						
1	Geothermal	air forced	X	X	X	X	X
2	Air central	air forced	X	X	X	X	X
3	Ductless	convection	X	X	X		
C	**Oil/Gas**						
1	Central	air forced	X		X	X	

Table 1. Basic Mechanical System Alternatives

cause a problem due to the limited width of the lot on which the houses are built. Furthermore, although modern systems are much improved, such heat exchangers are considered noisy, which might also be problematic in rowhouse developments.

Another factor to consider, when selecting a mechanical system, is the availability of energy. One must be aware of the cost of gas and electricity before deciding to install any system, as the energy rates can greatly affect the life time cost of the system.

While some of the functions described in Table 1 are essential for a comfortable living environment, the costs associated with the selection of more sophisticated systems may be problematic in the context of affordable housing. An evaluation of systems must take into consideration three basic factors: cost, efficiency and effectiveness.

It is understood that making affordability a critical factor in choosing a mechanical system might restrict the options that are feasible at the present time. However, systems judged to be expensive in the scope of the Grow Home project are nonetheless analyzed, thus providing references for the future.

Efficiency and effectiveness will help us compare the systems. Efficiency represents the ability of a system to transform a power source into usable energy. It is a measured value usually provided by manufacturers. Effectiveness, on the other hand, measures how much of the energy produced is actually used to condition the environment.

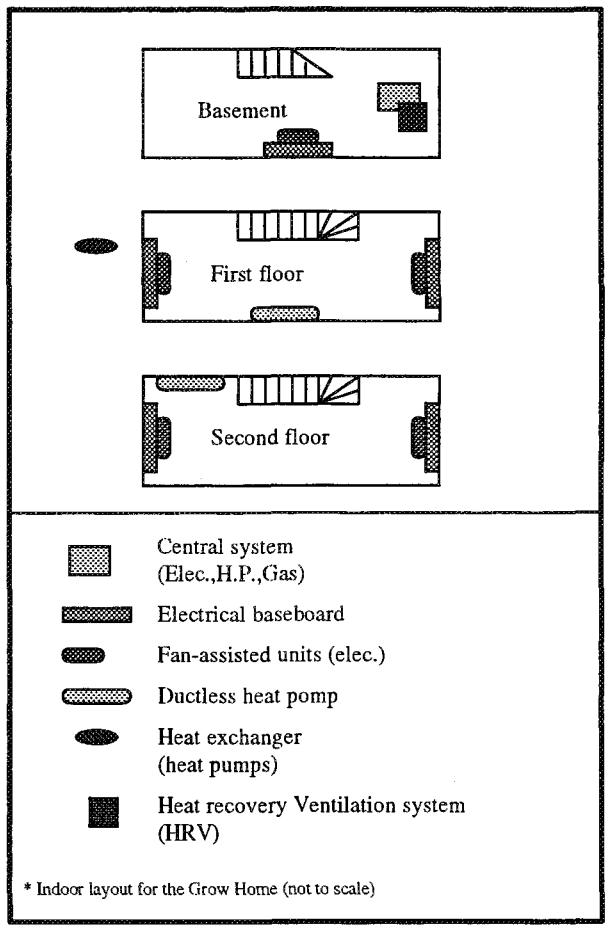

Figure 1. Suggested Layout

Heating, Ventilating and Air-Conditioning Alternatives

The possible alternatives may be divided into three categories, depending on their main source of energy (Table 1). As mentioned previously, the physical restrictions differ from one type of system to another. A suggested layout for the different systems described below is shown in Figure 1.

A. Electrical Systems

Electrical systems use electricity as their source of power. Since all of the energy put in the system is transformed in heat (except energy used by fans and other such devices) their gross efficiency is commonly rated at 100%. In the electrical system, a current is passed through a resistor that, in turn, generates heat. There are three basic types of electrical systems: forced-air, baseboard and fan-assisted units.

1. Forced-Air Electrical System (central furnace)

The electrical furnace is a central unit that distributes hot air in the house through a network of ducts. Such systems produce heat efficiently and effectively as heat is forced through the different rooms of the house. However, systems with a heating capacity less than 10 000 W, for small houses such as the Grow Home are hardly available, making the initial cost for the system higher than it should be.

2. Room Heaters (baseboards)

The permanently mounted baseboard heater is probably the most common type of room heater. Ideally installed under windows, they have a 100%

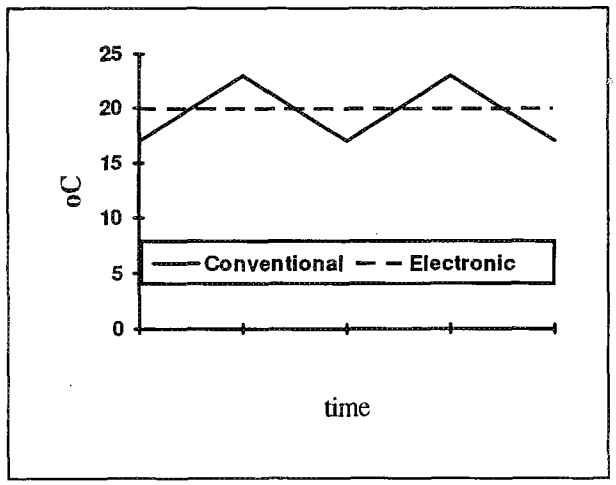

Figure 2 - Electronic Thermostat Precision (Source: Convectair-NMT)

gross efficiency. However, their effectiveness is significantly compromised, since only a portion of the heat delivered is actually used to heat the air. Individual controls are located in the different rooms, allowing independent temperature control. However, the time delay between temperature readings (conventional thermostat) and baseboard reaction is long and often leads to wasted energy and very warm temperatures in the vicinity of the baseboard heater. The electric baseboard system requires a lot of power to operate, but its very low initial cost probably justifies its popularity.

3. Room Heaters (fan assisted)

The wall mounted fan assisted units are growing in popularity. In addition to circulating the air for better effectiveness and comfort, some systems include a pre-heat device to reduce energy consumption. Indeed, the heating element is consistently kept at a "ready to heat" temperature in order to reduce the electrical load generated when initiating the heating of an element (resistor). The fan assisted units consume less energy than the standard baseboards due to forced convection, the pre-heat device and the built-in electronic thermostat that provides better temperature control (Figure 2). Like the baseboard units, the fan assisted units come in different sizes, shapes and capacities.

B. Heat Pumps

A heat pump is a system designed to transfer energy from one place to another. These systems are increasingly popular due to the high level of comfort they bring and also because of their high efficiency. Another appealing characteristic is its reversibility, indeed a heat pump cools or heats your environment depending on the season. Efficiency for the heat pumps is computed in terms of Coefficient of Performance (COP). It is a ratio of the overall energy output over the energy input; for example, the electrical systems described previously have a COP equal to 1 (100 % efficiency). It is interesting to note that because the heat pump transfers energy, the COP can be much higher than unity. The costly work input (electricity to run the pump) is thus less than the amount of energy delivered to the building (Wark, Thermodynamics, 1988). There are mainly two types of heat pumps, based upon the heat sink with which they are associated; ground source and air source.

1. The Geothermal Heat Pump

The geothermal heat pump, also called a ground source heat pump, is a device that uses ground water as a heat source or a heat sink. Pipes (loops) containing a thermodynamic liquid are installed in the ground and the system transfers the energy available from the ground to the interior of the building or vice-versa (Figure 3).

A central heating unit, usually located in the basement of the house, forces conditioned air through the duct

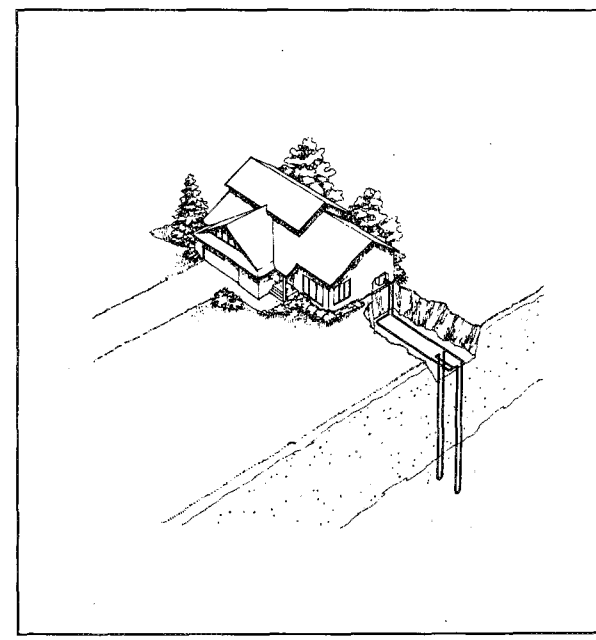

Figure 3. Vertical Loops for Geothermal Heat Pump (Source: GeoSolar Canada)

network into the house. It performs several conditioning tasks and can also be attached to the hot water distribution system to pre heat the water and thus increase the overall efficiency. However, these systems have certain energy limitations due to their energy transfer technology. When operating in cold climates such as Canada, the ground source heat pump supplies about 70 % of the heating demand, and auxiliary heating systems have to be installed to compensate for the heat pump's limitation (Energy Mines and Resources Canada, 1989). The typical ground source heat pump operates with a coefficient of performance (COP) of approximately 3.5, varying with size and climate.

2. *Air-Air Heat Pumps*

The air source heat pump draws heat from the outside air during the heating season and dumps heat outside during the cooling season. There are two possibilities with this category of systems : the central unit and the ductless unit.

The central unit is composed of an outside heat exchanger attached to an indoor central unit which forces air through duct network. The air-air heat pump is also limited in terms of energy supply during cold periods and auxiliary systems (including electrical resistors to heat the air within the duct network) have to be considered (EMR Canada, 1989).

The ductless heat pump system is a fairly new product. It is composed of an outside heat exchanger

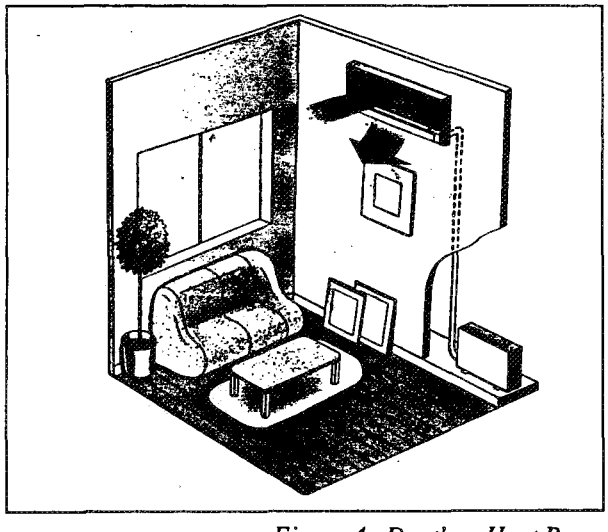

Figure 4 . Ductless Heat Pump
(Source: Mitsubishi Electric Canada)

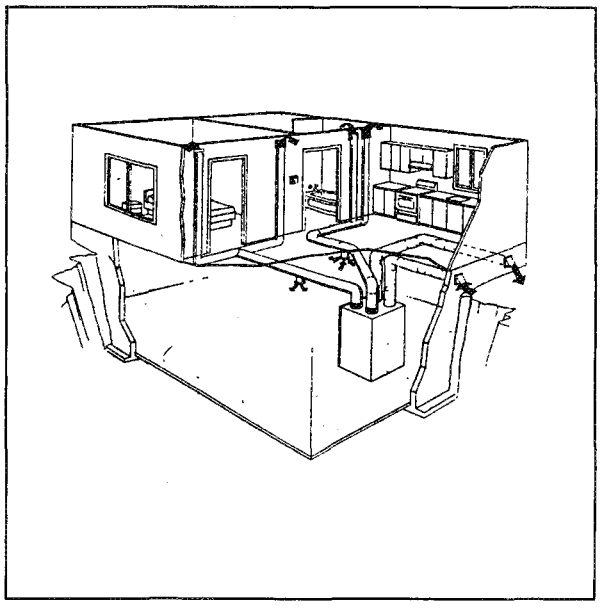

Figure 5. HRV System
(Source: Venmar Ventilation Inc.)

and of several wall-mounted units inside the house, and therefore no duct network is required. The units are connected through pipes running inside the walls (Figure 4) and should ideally be installed on exposed walls.

The ductless heat pumps have a coefficient of performance of about 3 and are thus economical to operate. However, the initial cost of the system for a small house such as the Grow Home is high and the need for auxiliary heating devices would increase the total cost.

C. Gas & Oil Heating Systems

The efficiency of gas and oil-fired furnaces has significantly increased in the past few years. With new technologies, such as the condensing furnace, their efficiency can be as high as 90% and above, whereas traditional systems had efficiencies around 65% (EMR Canada, 1989). However, systems with a heating capacity of less than 10 000 Watts are not yet available and the initial cost associated with efficient systems such as the condensing gas furnace is high.

D. Ventilation Systems

A ventilation system is a device that replaces stale and humid air by allowing fresh air inside the building. Since 1990, the National Building Code stipulates that every newly constructed home must

be equipped with a mechanical ventilation system (National Building Code 1990, 9.32.3) to provide air changes in different parts of the house.

For example, according to the regulation, the Grow Home requires a total air flow of 40 liters per second (l/s) combined with one third of an air change every hour. A substantial amount of heat can be lost in the process. However, if the house is equipped with a Heat Recovery Ventilation system (HRV), up to 80 % of that heat can be recycled, and heating and cooling costs can be kept moderate (EMR Canada, 1989).

A number of Canadian manufacturers provide such equipment in different sizes and shapes. Installation of the system will require minimal space and a duct network will be needed in order to distribute the air (Figure 5). It is also possible to add heating elements (resistors) in the duct network to pre-heat the fresh air that goes into the house.

Analysis

The heat load of a house determines the capacity of the mechanical system to be implemented. For the

	SYSTEMS	EFFICIENCY	ADVANTAGES	DISADVANTAGES
A	**Electrical**			
	Central	100%	High efficiency High air quality	High initial cost Central control Space requirement
	Baseboard	100%	Very low initial cost Individual room control Silent Easy to install	Poor heat distribution Low effectiveness
	Fan-assisted	100%	Low initial cost Good heat distribution Excellent thermostat control Individual room control Silent	Space restriction (furniture)
B	**Heat Pumps**			
	In general		Very high efficiency Low operation cost Environmentally friendly Reversible (heat and cool)	High initial cost Auxiliary system (cold climate) Outside heat exchanger
	Geothermal	COP 4	Highest efficiency (COP)	Land requirement (soil) Central control
	Air central	COP 3.5	High efficiency	Central control
	Ductless	COP 3.5	Excellent thermostat control Individual room control	
C	**Oil/Gas**			
	Central	90%	High air quality High efficiency	High initial cost Fossil fuels Central control

Table 2 - Advantages and Disadvantages of Heating System Alternatives

	ALTERNATIVES	CAPACITY (W)	INITIAL COST*
A	**Electrical**		
	Central	15 000	$5 000
	Baseboard+HRV	4 000	$2 000
	Fan-Assisted+HRV	4 000	$2 500
B	**Heat Pump**		
	Geothermal	7 000	$7 000
	Air Central	10 000	$6 000
	Ductless + HRV	5 500	$6 000
C	**Gas/Oil**		
	Central	15 000	$6 000
	* Cost estimates from Manufacturer's Representatives		

Table 3 - Estimated Cost of Heating System Alternatives

Grow Home, the heat loss was estimated at 4000 W. As a matter of interest, a conventional free standing house with the same material properties would have a heat load in the order of 7000 W.

For fair comparison of systems in terms of functional capacity, the installation of a heat recovery ventilation system (HRV) should be considered for the non-central systems. Cost of the HRV systems were added to the initial cost of these systems which have no ventilation capacity.

A financial comparison of the alternatives (Table 3) reveals that systems involving a central heating unit require a much larger initial investment. In fact, for the central furnaces (electrical and gas-fired), the geothermal heat pump and the air-air heat pump, initial costs are above $5000. In addition, considering the low heat load requirement of the house, the payback period associated with the central heating systems would be very long. This makes it difficult to justify such alternatives on a purely economic basis.

From a different point of view, the central systems alternatives fulfill the efficiency and effectiveness criteria; like the other systems, their efficiencies range from 90% to 100% (EMR Canada, 1989). It is from the effectiveness view point, however, that they are the most advantageous. Central heating systems distribute the conditioned air through the house (via a duct network) maintaining an excellent level of comfort as most of the systems are equipped with humidification and purification controls. However, these air quality controls along with the temperature control are also centralized and do not allow individual room control (except for some sophisticated and expensive vane control systems) leading to an increase in energy consumption.

The convection systems (electrical baseboard, fan-assisted units and ductless heat pump) on the other hand, have independent controls that allow the users to adjust the temperature to their needs in the different rooms. Furthermore, with the assistance of an HRV system, stale air is removed and air quality is maintained uniformly throughout the house. As for the initial investment, the two electrical alternatives (baseboard and fan-assisted units) are the most economical.

With regard to the environment, it is clear that the heat pump is the most appropriate alternative (EMR Canada, 1989). By using renewable energy (ground or air), these systems have a very low annual energy consumption. However, in community development, other environmental factors such as noise pollution must be considered. In addition, it was mentioned that the unique design of the Grow Home is very efficient in itself and a significant amount of energy will be saved no matter which mechanical system alternative is selected.

Summary

Given the relatively small heat load of the Grow Home and its cost limitations, the fan-assisted electrical room heaters, combined with a heat recovery ventilation system appear to be the most cost-effective solution. It is the most satisfying alternative at this time and fulfills all the criteria set prior to the analysis. It can provide a comfortable indoor environment at a moderate operating cost. The system also allows for future expansion as the needs of the occupants change. From the development point of view, this alternative allows the developer sufficient flexibility as it does not require specific site conditions and units can be stacked. Finally, electricity (the main power source of the alternative) is available at affordable rates in Quebec. However, one must be aware that mechanical systems are being extensively studied and that other alternatives might become more advantageous in the future.

Guidelines

When selecting a mechanical system for a residential building, factors such as cost, efficiency and effectiveness have to be considered. The selection will greatly depend on the type of house, the availability of energy as well as the climatic data for which the mechanical system is implemented.

Further Reading

Heating & Cooling with a Heat Pump. Energy, Mines and Resources Canada. This brochure includes valuable information about heat pumps and their characteristics.

Heating with Natural Gas. Energy, Mines and Resources Canada. This brochure includes valuable information about gas furnaces and their characteristics.

Heating with Natural Electricity. Energy, Mines and Resources Canada. This brochure includes valuable information about electrical appliances and their characteristics.

Energy Saving Guide. Hydro-Quebec. Contains information about measures to take in order to minimize energy consumption.

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ASHRAE Handbook, 1989 Fundamentals. ASHRAE, Atlanta, 1989

Energy, Mines and Resources Canada. Heating & Cooling with a Heat Pump

Energy, Mines and Resources Canada. Heating with Natural Gas.

Energy, Mines and Resources Canada. Heating with Electricity.

Venmar Ventilation Inc., HRV systems

Mitsubishi Electrical, Heat pumps systems

Geo-Solar Canada, Heat pump systems

Convectair-NMT Inc., Electrical room heater systems

Water Efficiency

Background: *The Problem*

Water has been coined as "the elixir of life" and concern for water as both a necessity and a possible hazard has been with humans throughout their existence on earth (Eagleson, 1991). Canada contains 20 per cent of the world's fresh water resources. On the surface, it seems hard to believe that this endless supply of fresh water could in any way be threatened.

However, two thirds of Canadian river flow is northward, away from the most populous regions, and many of our lakes lie in uninhabited areas. The sources which are tapped are therefore coming under significant pressures. Demand for potable water has increased more than six-fold in the past ninety years, 75 percent of this increase occurring over the past 25 years. Some 33 percent of Canadians rely on groundwater as their source of drinking water (Decker, 1992). In a number of regions the rate of water withdrawal has outstripped the groundwater aquifers' natural discharge rates, a situation that threatens to become commonplace in the coming decade (REIC, 1991).

Objective

The purpose of this section is to investigate the feasible technologies and options for using water more efficiently in a new affordable home. It should equip the home builder with the information necessary to provide a water efficient dwelling along with supporting arguments to substantiate the benefits for all.

Along with increases in potable water demand come increases in the amount of water that must be purified and wastewater that must be treated. Costs of providing sewage treatment and water purification are rising constantly as more and more treatment is required to ensure discharge that is safe for the environment. These cost increases will accelerate even more with the need to expand existing physical plant capacities, construct new facilities and upgrade water and wastewater infrastructures. Moreover, increasing resistance to rising taxes and a growing demand for other community services has made reconstruction of

A Builder's Perspective
(Excerpts adapted from Cook, 1993)

Historically, home builders' interest in plumbing equipment has revolved around two concerns: how much does it cost and when can you (the plumber) start? It has been the subcontractor who chooses the equipment in preparing a competitive quote based on standard industry requirements. Unless the builder requests something different, minimum requirements often become maximum expectations.

However, the future of the home building industry is being shaped by four major factors: affordability, infrastructure availability, energy in all forms and occupant health issues. Water conservation directly impacts on all of these factors in a very positive manner and offers tangible benefits and opportunities for the building industry and society as a whole.

Affordability: This is the area where there is the greatest misunderstanding. If asked, the majority of builders would say that water efficient fixtures are prohibitively more expensive and impact on affordability. This is no longer the case. There is a variety of water efficient fixtures and equipment now available at little or no additional cost. In the context of the total price of the house, these additional costs are inconsequential. For the homeowner the investment is paid back in less than a year. It is also important to note that these fixtures require no new knowledge or training for their installation.

Infrastructure Availability: In order to be able to provide for growth in the home building industry, the infrastructure required must be available. Today, fewer and fewer dollars are being allocated to new infrastructure, and there have already been cases of new subdivision freezes because of local

(continued)

A Builder's Perspective
(continued)

water supply shortages. The situation is simple - no infrastructure, no growth; no growth, no industry. Water conservation offers a great window of opportunity for the industry to extend the life of the existing infrastructure and avoid impending expenditures.

Legislation: The water issue has not escaped the attention of government. Recent changes to the Ontario Plumbing Code will mandate 13.25-litre flush toilets by August 1993 and 6-litre flush toilets by January 1996 (Gates, 1993). It can be expected that the other provinces will be following this trend as well. Therefore water efficiency is just around the corner even for those members of the industry who react only when legislated to do so.

The time has come for the builder to take the steps necessary to ensure a positive future not only for the environment, but for the industry. "Greening" can improve a company's public image by demonstrating a responsibility towards the environment. Water efficiency makes simple economic and environmental sense while having no impact on the lifestyle of the consumer.

these systems more difficult and more expensive. This has resulted in a deferral of necessary work on infrastructure upgrades and expansion, and a growing back-log of maintenance and replacement work. For home builders the consequences have ranged from lower density subdivisions to outright bans on further development (CANMET, 1991).

These problems also translate into higher costs for the homeowner. To finance necessary infrastructure upgrades, maintenance and expansion, municipalities can either increase taxes, raise water rates, or impose an additional surcharge on builders on a per lot basis, a "lot levy" that is simply passed directly to potential home buyers. The second option, raising water rates on a user-pay basis, is being considered by a growing number of municipalities. At present, water rates do not cover the full costs of operating and maintaining municipal water systems. A 1985 report on water systems in Canada found that only 82 percent of water supply, 85 percent of water distribution, 50 percent of sewage collection and 65 percent of wastewater treatment costs were being recovered through water rates charged to the user (REIC, 1991). Given this situation, the federal government stated in its "Green Plan For A Healthy Environment" (1990) that "the key to conserving water is paying a fair price for the water we use." Accordingly, it was predicted in 1991 that in many parts of the country water rates would increase by as much as 50% over the next 5 years (CANMET, 1991).

Water Efficiency = $ Saved + Healthier Environment

Water efficiency makes simple economic and environmental sense. When consumers must pay for every drop they use and must also pay to heat this water for most uses, an effort to reduce consumption is obviously very desirable. Table 1 shows the savings per person that would be realized by a reduction of 45

Province	Mean Water Rate in 1992 ($/m³)	Savings per year per person with 45% reduction in water consumption
Newfoundland	0.26	$14.95
Prince Edward Island	0.27	$15.52
Nova Scotia	0.42	$24.14
New Brunswick	0.66	$37.94
Quebec	0.31	$17.82
Ontario	0.92	$52.89
Manitoba	1.36	$78.18
Saskatchewan	1.17	$67.26
Alberta	0.85	$48.86
British Columbia	0.32	$18.40
Territories	1.61	$92.55
Canadian Average	**0.65**	**$37.37**

Table 1. Water Rates and Potential Savings

percent in water consumption according to the mean provincial water rates across the country.

Reduced flow from homes would result in less diluted effluent, which is advantageous as municipal treatment plants operate more efficiently with concentrated sewage. Plant operating costs for treatment are also directly proportional to the volume of wastewater to be treated. Further, studies have shown that reductions in wastewater production in the order of 10 percent can significantly extend the life and operating efficiency of existing facilities, while postponing the need for costly infrastructure expansion (REIC, 1991). Lower consumption would also accommodate more users on the same system. All of these factors would translate directly into benefits and savings both for the community and the individuals within it.

Potential Improvement

One of the best ways to reduce water consumption and the production of wastewater is through the use of water efficient fixtures. Off-the-shelf technology exists today to reduce household water consumption by up to 50 percent with no detectable changes in lifestyle for the users. Any measure that will reduce the demand for potable water and the production of wastewater has very tangible benefits, both environmental and economical.

Misconceptions About Water Efficiency

There is often a misconception that "conserving" water will inconvenience consumers, although this is not the case. A toilet flush in a well designed, efficient fixture, for example, can be just as effective as a conventional toilet flush, because the smaller amount of water is concentrated in a brief, carefully engineered pulse with much higher peak-flow rates. Showers delivered by modern low-flow showerheads are often stronger and more pleasant than the flow from a conventional showerhead. Flow delivered by low-flow faucet aerators can be powerful and more effective for washing hands and dishes. Therefore, as the service delivered by the efficient devices is the same as or better than that given by the less efficient fixtures, the user experiences no inconvenience loss of service (Rocky Mountain Institute, 1991).

Further concern with lower water flow has been the suggested problems which may result from reduced hydraulic loading in sewers. This concern generally stems from an underestimation of the contribution of non-toilet sanitary sewer inflow and infiltration to sewage transport. Sewage transport is not impaired by low consumption fixtures. This has been confirmed in demonstrations in communities where substantial savings have been achieved with no detectable impacts on system operation (REIC, 1991). In fact, in over 20 years of worldwide use of ultra-low-volume toilets, there has never been a single verified report of a sewer-line problem occurring as a result of reduced water flow from toilets (Vickers, 1990).

Saving Water: Where do we start?

While industry uses a great deal of water, most people are unaware that domestic (household) use accounts for nearly half (44%) of municipal water consumption (Figure 1). Therefore if we could reduce water use at home by 45%, total municipal water consumption would be reduced by approximately 20%.

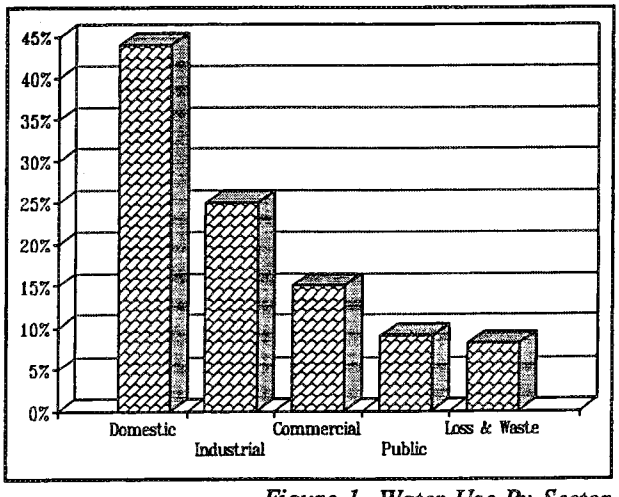

Figure 1. Water Use By Sector

During the summer months, outdoor use causes domestic water consumption to increase dramatically. Replacing conventional landscapes with xeriscapes could significantly reduce outdoor water use (see next section on Xeriscapes: Water Efficient Landscapes).

Inside the home, the main area of consumption is the bathroom, which accounts for 75% of domestic use (Figure 2). Efforts for water conservation should therefore be concentrated here, targeting toilets and showerheads in particular. Aerators for faucets also offer an inexpensive way to save water and homeowners seeking even higher efficiency can obtain water-efficient appliances.

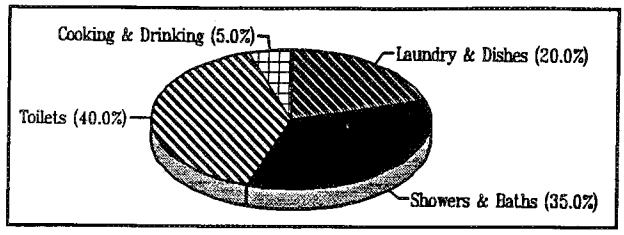

Figure 2. Domestic Water Use

Water Efficient Technologies

The following savings can be realized with more water efficient fixtures and equipment.

1. Water Closets: A conventional toilet uses as much as 20 litres or more of fresh water with each flush. In terms of efficiency, the ratio of water to waste in this case is a wasteful 80 to 1 (REIC, 1991). Installation of a low consumption toilet (which most major toilet manufacturers market) would reduce the flow to about 13 litres per flush. However, even greater savings can be achieved by using an ultra-low-volume (ULV) toilet. A ULV uses only about 6 litres per flush, reducing water consumption of toilets by 70% and total indoor water use by 28%. These toilets use various technologies to achieve efficient flushing of the fixture, the most common being the use of an well engineered tank and bowl system to induce sufficient siphonic action. The washdown performance of these fixtures is at least as good as conventional toilets while also providing significant water savings.

2. Showerheads: The conventional showerhead has a typical flow rate of 20 litres per minute or more. In the past, the use of various types of flow restrictors resulted in unsatisfactory performance. Today, however, there is a wide range of water efficient showerheads on the market which have been engineered to provide flows which may be even more pleasant than conventional fixtures but use less than 10 litres per minute. An even greater advantage is the money which can be saved by reducing hot water consumption and hence energy requirements (Figure 3).

3. Faucets: The cheapest investment in water efficiency is on aerators for faucets. Some faucets are manufactured with aerators, although attachments are available for conventional faucets as well. For only a few dollars an aerator can reduce the excessive flow from a conventional faucet of 13.5 litres per minute by more than 50%. This flow of 13.5 litres per minute is

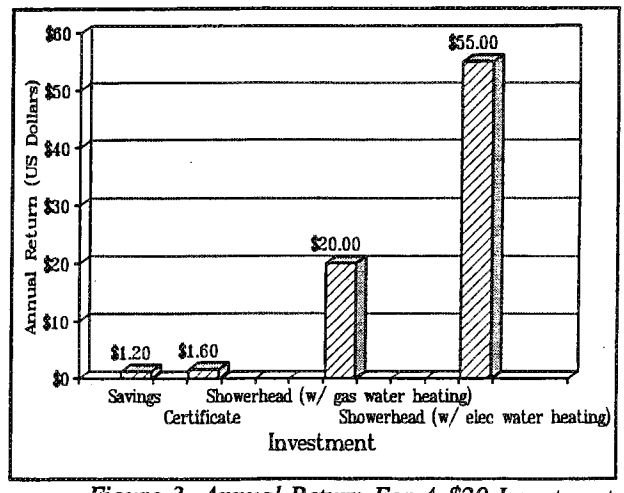

Figure 3. Annual Return For A $20 Investment
(Rocky Mountain Institute, 1991)

generally more than what is needed or can be used. In bathrooms this flow can be reduced to 2 litres per minute. In the kitchen, where more water pressure and volume is required, a reduction to 6 to 9 litres per minute would still provide sufficient service while reducing consumption by 25% (REIC, 1991). The appropriate aerator must therefore be selected according to the intended use.

4. Appliances: The homeowner who seeks further savings in both water and energy should consider purchasing efficient appliances. Both dishwashers and clothes washers which use these two resources economically are available. These appliances may be more expensive, but when the cost of water and energy are examined, the savings that can be achieved make them very attractive options. By carefully considering the operating costs and the associated payback period, these appliances can result in savings of hundreds of dollars over their life times (Marbek Resource Consultants, 1988). Consulting the "Energuide" (E.M.R., published annually) is a good way for homeowners to investigate appliance efficiency.

5. Other: There are various other more complicated and expensive ways of saving water including pressure-reducing valves, water and grey water reuse, rain water use and cisterns.

Pressure-Reducing Valves: It is not uncommon to find water distribution systems operating at twice the necessary pressure (Brooks, 1988). Excess water pressure generally leads to wasted water in sinks and showers. Special valves, installed in the main, can

effectively and economically reduce household water pressure at a cost of under $50. Studies have shown that decreasing water pressure can result in a decrease in use of 3 to 6 percent (REIC, 1991). However, the associated payback period is long, especially once water use has already been reduced by fixtures within the homes.

Cisterns: One inch (25.4 mm) of rainfall can provide approximately 1.8 litres of water per square foot (0.0929 m^2) of catchment area. A cistern used to collect and store this water can capture as much as 75% of the annual rainfall on the catchment (REIC, 1991). However, many present plumbing codes do not allow non-potable, non-municipal sources to come into the dwelling. Even when indoor use is permitted for non-potable uses, costs are high because of the size of the system and the amount of extra plumbing required (Cook, 1993). Though cisterns may be somewhat attractive for outdoor watering purposes, xeriscaping is a more cost efficient and environmentally sound option. Cistern installation is expensive and from a cost/benefit standpoint the use of cisterns seems to be unjustified, particulary for smaller, affordable homes.

Water Reuse: Grey water is water which has been used but contains no sewage (ie. from showers, bathroom sinks and laundry rooms). While use of grey water for various purposes such as flushing toilets is being explored, most municipalities have restrictions on its use for health reasons. Another setback is the significant change in plumbing systems required to accommodate this reuse. Even grey water which would be used for outdoor watering would most likely require some type of pretreatment.

Analysis: Every Drop Counts

The savings realized by implementing the more feasible measures outlined previously would be significant. To analyze their impact, a typical Grow Home household of three persons was chosen. This hypothetical example assumes a home with one and a half bathrooms, a clothes washer and a kitchen with a dishwasher. Using the Canadian average indoor consumption of 350 litres per person per day (Environment Canada, 1991), this household would use water according to the breakdown in Table 2.

Using conventional fixtures, this family would use 1050 litres of clean water per day, or 383 cubic meters of water per year. If the house was in the city of Toronto, this would translate to an annual water and sewer services cost for the family of $307 at the municipal rate of $0.802/m³ (Gates, 1993). That is over $100 per person. By comparison, in Calgary, where rates are higher at $1.046/m³ for water and sewer services (Gates, 1993), this family's consumption would cost them $401 for one year. This does not include the cost of heating water for showers and other uses.

Toilet @ 20 L/flush	
• assume 5 flushes per person per day	= 300 L/day
Shower @ 20 L/minute	
• assume one 6 minute shower/person/day	= 360 L/day
Bathroom Faucet @ 13.5 L/minute	
• assume 2 minutes* of use per day per person for toothbrushing, washing, etc.	= 81 L/day
Kitchen Faucet @ 13.5 L/minute	
• assume 5% of indoor use for cooking and drinking	= 54 L/day
Dishwasher @ 40 L/load*	
• assume 2.25 loads/person/week*	= 39 L/day
Clothes Washer @ 225 L/load*	
• assume 2.25 loads/person/week	= 216 L/day
TOTAL INDOOR USE PER DAY (with conventional fixtures)	**=1050 L/day**

* adapted from Gates (1993)

Table 2. Water Use: Conventional Grow Home

Living in a "Green" version of the Grow Home on the other hand, the same family of three could realize the water savings outlined in Figure 4, without any change in their habits.

With all of the fixtures installed, the result is a daily savings of 160 litres per person, reducing consumption from 350 litres to 190 litres per person per day (Table 3). Our hypothetical family would now only use 570 litres per day - a reduction in indoor water use of 45 percent. If their place of residence was Toronto this would mean a savings of $140 per year, while a Calgary family would save $183 per year. Table 1 summarizes what this potential 45 percent savings would mean across the country. The average Canadian family of three would save $112 per year, just by

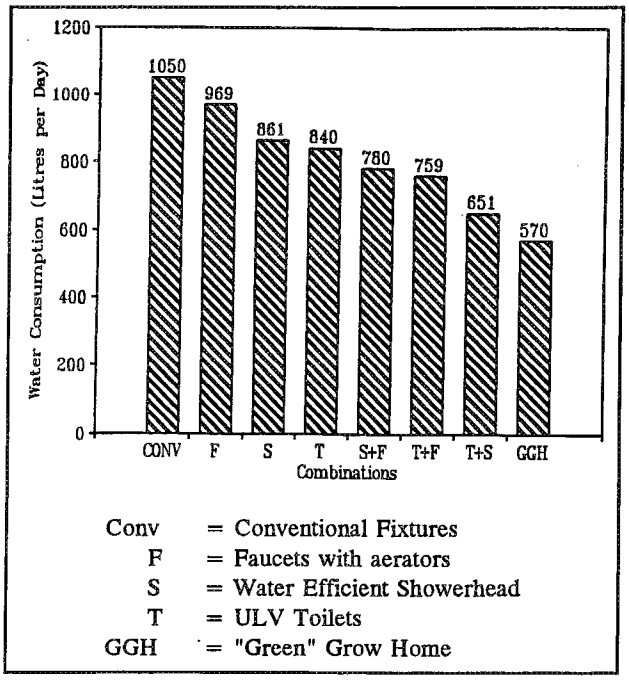

Figure 4. Savings For Various Fixture Combinations

Applications	Conventional Consumption	Water Saving Device	Water Savings	
			Per Unit	L/day/ capita
Toilet	20 L/flush	Low Flush Toilet 6 L/flush	14 L/flush	70
Shower	20 L/min	Low Flow Shower 9.5 L/min	10.5 L/min	63
Faucets				
Kitchen	13.5 L/min	Aerator 7.5 L/min	6 L/min	4*
Bathroom	13.5 L/min	Aerator 2 L/min	11.5 L/min	23
			Total Savings (L/day/capita): 160	

*based on 25% savings in kitchen water use thanks to aerator (REIC, 1991)

Table 3. Water Efficient Devices and Savings

making the water efficient choice.

As was mentioned earlier, the family seeking further water savings could purchase water efficient appliances. The savings would vary depending on the models, but average values for dishwasher and clothes washer reductions in water use per load would be 19 litres (Brown and Caldwell, 1990) and 50 litres respectively. Including these two appliances and the more efficient fixtures listed in Figure 4, the same family of three would use a total of 523 litres of water per day (Table 4), a 50% reduction from the 1050 litres per day that would be used with conventional appliances (Table 2). This new total translates into a savings of $125 per year for the family according to the average Canadian rate of $0.65/m^3. It is important to emphasize that this savings is achieved with no effect on the daily lifestyle of the occupants - saving water is just a matter of doing away with the installation of inefficient water-using devices typically found in Canadian homes and using environmentally responsible fixtures instead.

Toilet @ 6 L/flush	
• assume 5 flushes per person per day	= 90 L/day
Shower @ 9.5 L/minute	
• assume one 6 minute shower/person/day	= 171 L/day
Bathroom Faucet @ 2 L/minute	
• assume 2 minutes of use per day per person for toothbrushing, washing, etc.	= 12 L/day
Kitchen Faucet @ 7.5 L/minute	
• assume 25% savings in kitchen water use thanks to aerator	= 42 L/day
Dishwasher @ 21 L/load	
• assume 2.25 loads/person/week	= 20 L/day
Clothes Washer @ 175 L/load	
• assume 2.5 loads/person/week	= 188 L/day
TOTAL INDOOR USE PER DAY (with efficient fixtures)	= 523 L/day

Table 4. Water Consumption : "Green" Grow Home

Water Heating: As noted earlier, reducing water use would also have a substantial impact on reducing the energy bill. Hot water for showers, laundry and washing dishes comprises about 20% of a household's typical energy bill, and a Canadian family of four may spend as much as $600 per year to heat their water (Environment Canada, 1990).The Grow Home family of three could therefore be paying up to $450 per year for hot water heating if they were using conventional water fixtures. A large amount of this energy is

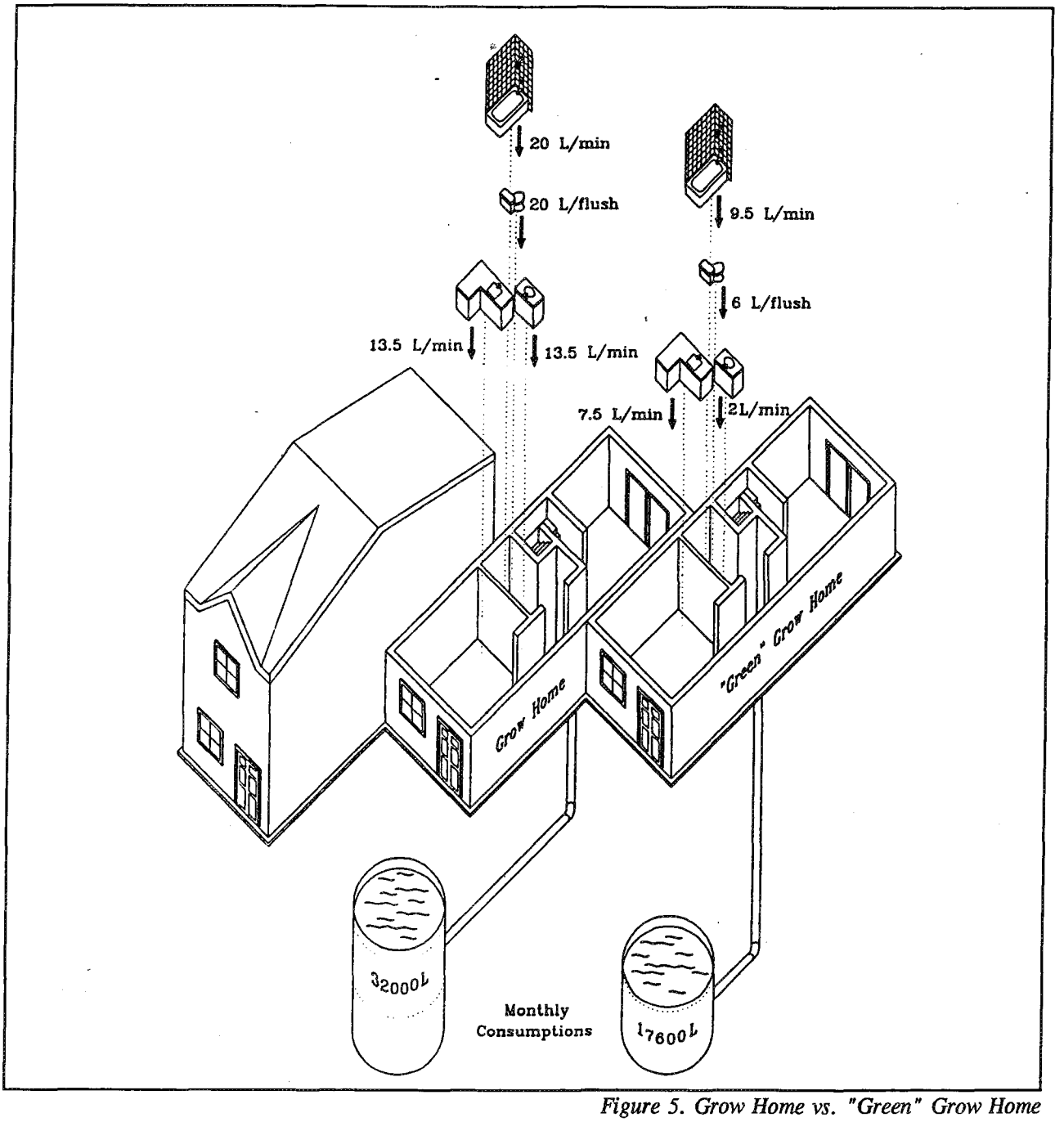

Figure 5. Grow Home vs. "Green" Grow Home

wasted as stand-by losses where heat is lost through the walls of the tank and pipes. By setting the thermostat back from 60°C to 50°C and insulating the tank and hot water pipes, a reduction in water heating costs of about 25 percent can be achieved (Environment Canada, 1990). Using these measures, the savings in the Grow Home would be about $110 in the first year for an initial investment of under fifty dollars. An advantage of the Grow Home is that its size and layout require less piping - which means less area for heat loss and less pipe to insulate.

Using some 70% of household hot water in its flow (REIC, 1991), even after proper insulation, a conventional shower (20 litres/minute) would cost the Grow Home family of three about $236 per year for hot water. A more efficient showerhead, using only 9.5 litres per minute, would reduce this hot water

heating cost by $110 over the year. Similarly, faucets with aerators would also reduce energy consumption and save money. The cost of an aerator is paid back at least once a year in saved water heating costs (Rocky Mountain Institute, 1991).

Water efficient appliances can also result in substantial energy savings. Up to 80% of the energy required to operate a dishwasher is used to heat the water. The corresponding figure for a clothes washer can be as much as 90%. For figures on energy and water consumption as well as payback periods on these and other appliances the reader should consult the "Energuide" published by Energy, Mines and Resources each year.

Payback

The following payback calculations (Table 5) are based on a Grow Home with the water efficient fixtures listed in Figure 4. Savings are based solely on water charges in this analysis and as it is shown, the return is significant. The water efficient fixtures installed at the six locations specified pay for themselves in 8 months. In other words, in only 8 months the initial extra cost of approximately $74 for all six devices has been recovered and every 8 months after that an equivalent value is saved again.

Fixture	Initial Cost Difference	Payback Period*
Toilet (2)	$60	15 Months
Showerhead	$ 5	1 Month
Faucets (Aerators) Bathroom (2) Kitchen	 $ 6 $ 3	 5 Months 13 Months
Complete Water Efficient Package	**$74**	**8 Months**

*based on 10% Discount & 4% Escalation

Table 4. Payback Periods

Moreover, the assumed price differentials in Table 5 are conservative, as often water efficient fixtures cost no more than non-efficient fixtures (Regional Municipality of Waterloo, 1992). Once energy consumption for heating water is included, the payback period is reduced to 6.5 months.

Summary

Implementing water efficiency is beneficial for everyone. Homeowners save money on both water and energy bills without having any change in lifestyle. For the builder, water efficiency ensures further growth opportunities for the industry while providing what will surely be a service that will be in growing demand. Society as a whole benefits as treatment plants operate more efficiently, less energy is consumed and a healthier environment is maintained.

Guidelines

What to look for:

- toilets with a maximum flow of 6 litres per flush
- showerheads with a maximum flow of 9.5 litres per minute
- kitchen faucets or aerator attachments with a maximum flow of 9.5 litres per minute
- lavatory faucets or aerator attachments with a maximum flow of 5 litres per minute
- proper insulation of the water tank and pipes
- water efficient appliances

Further Readings

"Water Efficient Fixtures Catalogue"
Regional Municipality of Waterloo
The Regional Municipality of Waterloo is a Canadian leader in water efficiency. This catalogue includes all fixtures which met regional specifications as well as regional and government standards. A general description of each device is given, including water consumption, availability and whether or not it has received CSA approval.

"Water-Efficient Technologies: A Catalog for the Residential/Light Commercial Sector"
Rocky Mountain Institute
This catalogue is an extensive American version of the Waterloo publication. It includes every type of efficient

fixture known at the time of publishing. However, many of the devices listed are not available in Canada.

"Energuide"
Energy, Mines and Resources Canada
The "Energuide" Program is designed to help consumers choose the most energy efficient appliances for their homes. It includes extensive information on the six major household appliances as well as explanations on payback, appliance life expectancies and special features.

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Xeriscapes: Water Efficient Landscapes

Landscape designs which minimize irrigation water requirements are referred to as "xeriscapes". The term is derived from the Greek word "xeros" meaning dry (Cox, 1991). Basic principles include not only careful plant species selection but an integrated approach to maintenance and design. If xeriscape principles are implemented, it is reasonable to expect 60 to 70% water savings (Ferguson, 1987). In many climatic regions, irrigation, or water supply in addition to rainfall, can be eliminated. These savings can be achieved without diminishing the aesthetic value or opportunities for human activity. Therefore, they are appropriate for medium-density, affordable homes, such as the Grow Home.

Background

Although water is abundant throughout Canada, the supply is threatened by increased demand, as discussed in the Water Efficiency section. Due to seasonal water use by plants in Canada, water demand can increase by 50% or more during the summer, putting a heavy strain on water systems (Regional Municipality of Waterloo, 1990). In the United States, lawn watering accounts for 29% of annual household water consumption at 140 000 litres annually (Robinette, 1984). In most western states, the largest residential water use is landscape irrigation, accounting for 40% of household consumption (Ferguson, 1987). This explains why lawn watering is one of the first areas to be restricted in any water shortage situation (Robinette, 1984).

Landscape irrigation both increases the demand for water and the pollution of groundwater if fertilizers, pesticides and herbicides are used. Muggas et al (1992) indicate that inorganic fertilizers have a high leach rate. Leaching of nitrogen and chemicals into the water table occurs particulary on sandy soils and heavily irrigated plantings. Residential irrigation produces 10 times more toxic chemicals per acre than the agricultural sector (Petrovic, 1989). Due to the tendency to over-irrigate, chemical water run-off and leaching is increased in conventional landscapes over xeriscapes.

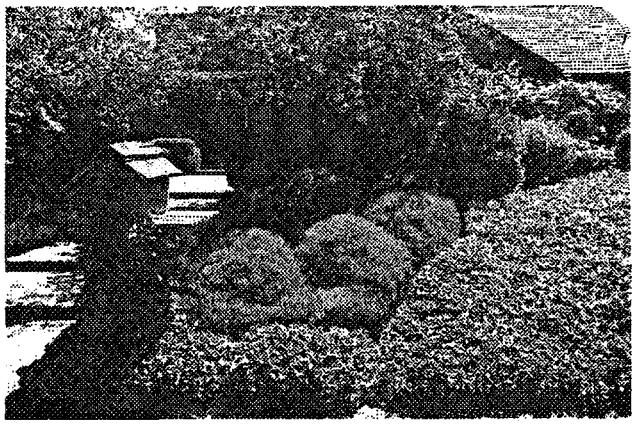

Figure 1: Visual impact of a xeriscape

Objective:

This study will explain the principles and benefits of xeriscapes. It will compare the payback period required by xeriscapes to recoup the additional capital cost over the conventional approach.

Landscape Ordinances

The adoption of water conservation has become widespread throughout the United States as a result of droughts and water shortages particulary in the south west. Most landscape ordinances in Arizona and Californian cities regulate the area of turf. In Phoenix, turf limitation ordinances require home-owners to obtain a permit prior to lawn installation. Meza Arizona offers a rebate to home owners that install xeriscapes and zeroscapes, which are landscapes comprised of inert materials such as crushed rock (McPherson, 1989).

Xeriscape Benefits

In addition to reducing water consumption, the principles of xeriscaping reduce maintenance and consumption of other resources which affect both water and air quality, such as fuel, fertilizer, herbicides and pesticides. When species selection is matched with water conditions, plants are also more adapted to resist pests and diseases. According to Kramer (1987), the relationship between rainfall and growth exists because water deficits affect almost every process in plants. Thus, implementing xeriscape principles will promote not only cost savings and resource conservation but long-term plant health.

Aesthetics

In an attempt to test the acceptability of water conserving landscapes, Thayer (1982) conducted a study of public response to eight alternatives. Respondents stated that the alternatives with a 50% reduction in irrigation water were as acceptable as the typically irrigated control landscape with turf. Another survey in San Francisco tested residents' response to landscapes that used only 40% as much irrigation water as those of nearby communities. The residents reported that they were pleased with their lush, green surroundings (Nelson, 1985). Figure 1 illustrates the visual opportunities with xeriscapes.

Water Relations

Water stress results from lack of sufficient rainfall to replace the water removed from the soil through evaporation (from soil and leaf surfaces) and transpiration, which is water taken up by plant roots (Kramer, 1987). The combined effect, known as evapotranspiration (ET), is affected by sunlight, air temperature, wind speed and humidity (Lindsey and Bassuk, 1991). For example, for every 6°C increase in temperature, water loss is doubled (Coder, 1990). However, not all rainfall is available for ET since significant amounts can be evaporated before reaching the ground, intercepted by the canopy foliage, lost by surface run-off or percolated beyond the root zone. Although water availability may fall below the plant's ET rate, during a drought period, for example, most species can tolerate water deficits of 50% of their ET rate without critical long-term effects (Harris, 1983). However, trees generally tap sources of water in soil far deeper than turfgrass roots and therefore can survive longer drought periods without irrigation (Thayer & Richman, 1984).

Xeriscape Principles

Xeriscapes conserve water and other maintenance inputs through the following principles: 1) limit use of turf areas only for specific social and recreational functions, 2) select water-efficient plants suited to the local site conditions including climate, soil type and site drainage, 3) define water-use zones for plants with similar water requirements, 4) group trees, shrubs and groundcover in beds, 5) improve the water holding capacity of soil, 6) use mulches to reduce evaporation and prevent weed growth, 7) use an efficient irrigation system that prevents loss of water to evaporation and surface run-off, 8) collect rainwater for irrigation. These principles will be discussed in the following sections.

• Limit Turf Areas

If 10 000 residences water their front and back lawns for a half hour each, they would use 16 350 000 litres of water, according to the Regional Municipality of Waterloo (RMW) (1990). In a CMHC estimation (1991) of a typical suburban lawn (350 square metres), water consumption was up to 200 000 litres per year. According to the Ontario Ministry of Agriculture and Food (OMAF) (1990), irrigation should be carried out at weekly intervals with about 3 cm of water per application. At this rate, a 100 square metre lawn would require 60 000 litres in irrigation water annually for average Ontario conditions.

While trees and shrubs often use 10 or 20% more water than would an equivalent area of turf (Harris, 1983), grouped beds of species that are well-adapted to site conditions require less water than average turf areas. Using a calculation method from the Toro Company (1983), even at peak water use rates for cold climates, native, average sized, established shrub beds of 100 square metres require approximately 11 500 litres per year and trees require 20 000 litres. Thayer and Richman (1984) note that groundcover can be established requiring half the irrigation of an equivalent area of turf. Ferguson (1987) compared the water requirements of the following plant types with those of average lawns, as shown in table 1.

Plant type	Water-use reduced from lawn
xeric native plants	73%
average tree and shrub	30%
ground cover	23%
vines	39%

Table 1: Water-use comparison (from Ferguson, 1987)

A comparison of water use by McPherson et al (1990) considered plant size and species water requirements. Irrigation requirements were assumed to be 7.6 cm per year for each tree and shrub for mesiscapes, which are average water-use landscapes, 15.2 cm for xeriscapes and 114.3 cm for lawns. An estimation of irrigation requirements for trees is included in the analysis section of this chapter.

• Select Well-adapted Species

Native plants can usually more easily accept the climatic water restriction for their particular region (Hightshoe, 1988). However, not all native plants will be suited to the specific site conditions (Thayer & Richman, 1984). For example, Hightshoe (1988) compares the available soil moisture requirements of native tree and shrub species ranging from very high (over 30 cm) to very low (0 to 3 cm). Also, evergreen plants are usually more drought tolerant than deciduous plants (Clark & Kjelgren, 1990). Deep-rooted species with high root-shoot ratios are best able to cope with water stress (Kramer, 1987).

Mature trees and shrubs are better able to cope with water stress than seedlings or newly transplanted material. After a 2-5 year establishment period, water requirements are significantly reduced (Cobham, 1990). Thus for long-term health, water conservation should not be expected until at least after the second year. A study in Seattle from Lindsey and Bassuk (1991) indicates that while 100% of trees irrigated during the first two years

after transplanting survived, only 20% survived without supplemental watering.

The irrigation requirement of turf discussed previously refers to average lawns. However some turfgrasses, particularly in the perennial ryegrass and tall fescue species, will require less water than other turfgrasses (RMW, 1990). Table 2 shows the range in ET rates of various turfgrass species (Beard, 1985). In addition to species selection, other maintenance practices such as aeration and thatch removal will reduce the lawn's irrigation requirements (Thayer & Richman, 1984).

Common Name	ET rate (cm/wk)
Tall fescue	5.1-8.9
Perennial ryegrass	4.6-7.9
Kentucky bluegrass	2.8-4.6

Table 2: Range in summer mean ET rates of cool-season turgrass species (from Beard, 1985)

- **Define Water-use Zones**

Water-use efficiency can be achieved by defining "hydrozones" or areas of water-use intensity (Thayer & Richman, 1984). Zoning should respond to the frequency and types of human activity and aesthetic needs as well as site constraints such as slope, drainage, shade and wind conditions (Ferguson, 1987). Figure 2 illustrates four levels of irrigation intensity associated with site requirements. The principal hydrozone accomodates the greatest level of human impact and the largest subsequent water and energy use. This generally occurs in the rear yard lawn area, not the front where turf is used as visual ground cover (CMHC, 1991). Therefore, xeriscaping principles do not necessitate the elimination of lawn areas. Rather, turf should be limited to active human-use areas.

Areas that are visually important but less physically affected by human activity occur in the secondary zone. Minimal hydrozones receive little or no human use and require few or no maintenance inputs. Elemental zones require the fewest inputs. A further consideration in planting lay-out is shade. Shaded areas reduce evaporation, and therefore need less irrigation. Almost 50% reductions in water loss through evapotranspiration occur in turfgrasses if the light intensity is reduced from full sunlight to dense shade (Beard, 1992).

- **Group Plants in Beds**

Typically, urban trees are planted in isolation. This alters

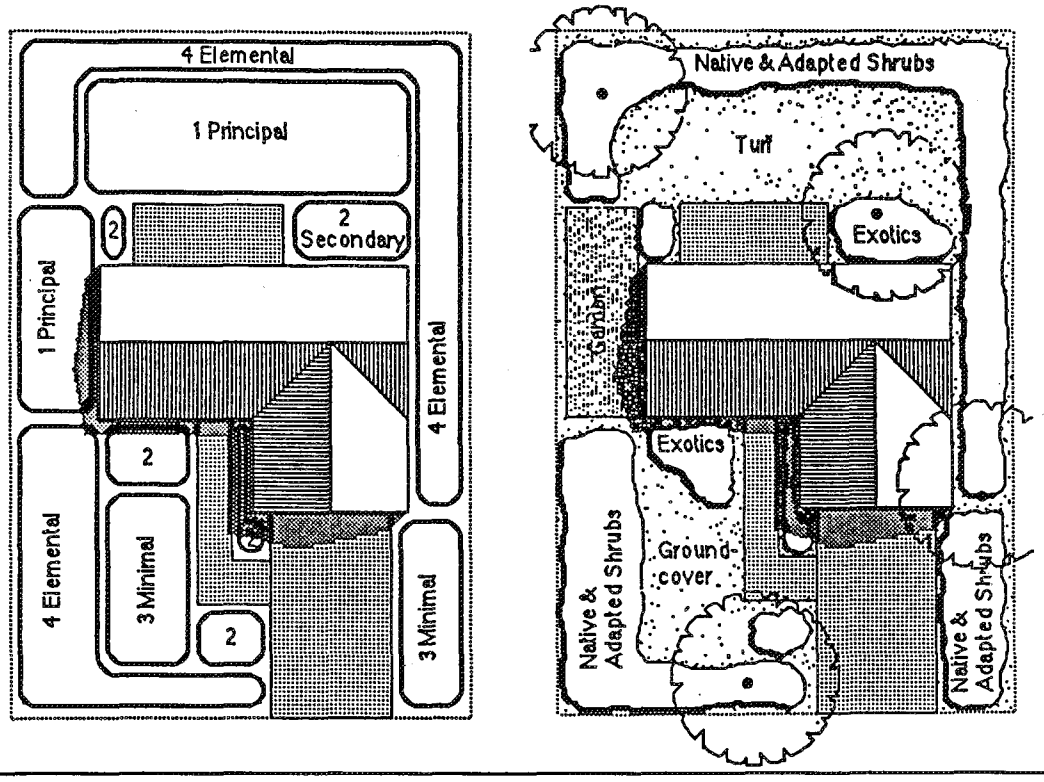

Figure 2: Hydrozones for a single-family residence showing four levels or water intensity and human use (from Ferguson, 1987)

the environmental factors which a tree would encounter in the continuous canopy frequently found in forests (Clark & Kjelgren, 1990). It increases the potential for evapotranspiration since the relative humidity and wind surrounding the tree is lower than in the closed-canopy forest. According to Harris (1983), this results in water requirements that are two to three times that of grouped beds. In addition, trees in isolation are typically planted in turf areas. Turfgrasses compete with trees for water, dominate the root zone and lead to drought stress for the tree (Baine, 1986). According to Cobham (1990), planting trees and shrubs in mown grass is clearly the worst possible option. Figure 3 illustrates the decrease in root density by up to 90% for trees grown in turf compared to trees grown in mulched beds (Watson 1989). Water relations would be improved by mulching under trees.

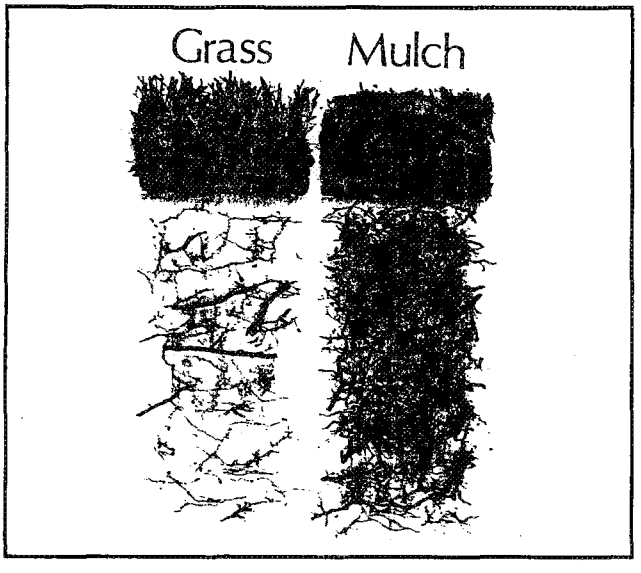

Figure 3: Comparison of tree root growth in the top soil layers under grass or mulch (from Watson, 1989)

In urban areas, root zones are restricted due to containerisation or proximity to pavement. For example, a 10.7 metre high tree would require a planting area 7.6 metres in diameter and .9 metres deep in a sandy loam soil (Kramer, 1987). Typically, street trees and other urban plantings are planted in areas smaller than this. Compaction is also a problem of urban plantings in high-use areas. This reduces aeration and the water holding capacity of soils. Thus, depending on their lay-out, plantings may be subject to physiological drought even if soil water is present (Kozlowski, 1987).

- **Use Mulches**

The benefits of mulches include: reducing soil temperature, minimizing evaporation or soil moisture, eliminating weed growth, reducing soil compaction and slowing erosion. As mulch decomposes, it improves soil fertility (Hyland, 1992). Bark chips and shredded tree mulch are the most effective at reducing water loss as seen by a comparison in Table 3 from Smith and Rakow (1992). This study indicates the percentage of evaporative water loss saving by various mulch treatments relative to a bare soil control plot. Smith and Rakow recommend that the depth for mulch be 3.8 cm. Increasing this depth would cause reduction in oxygen and water penetration.

Mulch type	Mulch depth	
	3.8cm	7.6cm
Shredded bark	43.8%	43.8%
Gravel	48.7%	52.6%
Wood chips	27.3%	26.7%
Fine bark	33.1%	35.9%

Table 3: Percent evaporative water loss saving compared to control in 20 L containers. (from Smith and Rakow, 1992)

- **Amend Soil**

Amending the soil, particulary during planting, will improve water holding capacity. Fifty percent humus content added to most gardens will reduce the watering requirement by as much as 75% (Granger, 1991). One of the most economical sources of organic amendment is the home compost, as discussed in the Waste Disposal section (Hyland, 1992). However, annual fertilization can negatively impact water relations. Supplemental fertilizing can increase leaf area and decrease root-shoot ratios thus decreasing the tree's ability to deliver water to the crown (Clark and Kjelgren, 1990). According to Baine (1986), topsoil can boost herbaceous growth which competes with trees for water.

- **Improve Irrigation Systems**

Approximately 25-50% of water used for residential landscape irrigation is wasted (CMHC, 1991). Evaporation and run-off occur because of the soil's inability to absorb water and because water falls onto pavements. Well-designed and maintained irrigation systems will operate at efficiencies greater than 80% as compared to the average efficiency of 35% (Beck, 1991). Because of the high evaporation rates of sprinklers, some water is lost before it hits the lawn. Soaking hoses use 25-50% less water than sprinkler or regular hoses (Robinette, 1984). Systems using timers, sensors or tensiometers are the

most water efficient.

Drip or micro-irrigation systems minimize water loss due to evaporation. These subterranean systems deliver water at a slow rate directly to root areas thorough porous tubing (RMW, 1990). Drip irrigation is estimated to save 25-75% of the water used in conventional systems (RMW, 1990). However, the capital cost of a drip irrigation system is approximately 45% higher than a sprinkler system (Holmes Irrigation, 1993). Sprinkler systems are more suited for lawn irrigation than drip systems.

Although water conservation can be achieved through a more efficient irrigation system, selecting appropriate species and implementing the previously discussed design considerations should eliminate the need for an irrigation system in many Canadian climates. In these cases, the range of plant species which would require no irrigation if xeriscape principles were followed would not be restrictive.

• Collect Rainwater

Planted areas can be used as water collectors to enhance water percolation into the soil (Robinette, 1984). Vegetation shields the soil surface from the impact of falling water, slows the velocity of run-off, maintains the soil's capacity to absorb water and holds soil particles in place, thus preventing erosion. The site should be designed to drain rainwater toward planted areas. Even paved areas with limited traffic can be graded to drain into planted areas, although grading areas with toxic residue from cars into planted areas should be avoided. To prevent standing water from accumulating and being wasted through evaporation, cisterns act as storage mechanisms. Covered rain barrels or cisterns can be used to collect rainwater or treated greywater (CMHC, 1991). Saucers or swales can channel rainwater to planted areas of high water-use species (Ferguson, 1987). However, these systems tend to be very expensive, as indicated in the Water Efficiency section.

Example of Potential Savings with Xeriscapes

A study by the North Marin California Water District (Nelson 1987) compares the use of water, labour, fertilizer, fuel and herbicide for traditional landscapes and water conserving projects. The following three criteria were part of the water conserving designs: 1) limiting use of turf in narrow pockets, 2) using turf on less than 40% of the total landscape area and 3) locating turf in one area, with a turf perimeter of not more than 30 linear feet. Non-turf areas were planted with predominantly water conserving tree and shrub species. Water-loving plants were

Parameter	Traditional Landscape Avg.	Water-Saving Avg. Landscape Avg.	Decrease Amount	Decrease %	Unit Cost ($)	Savings $/du	Savings %
Water applied to landscape							
per du - 100 m3	2.18	1.0	1.1	54	2.83/m3	28.37	37.8
per du per day - L	594	272	322	54			
over entire area - cm	135	68.0	66	49			
Labour expended							
turf per du - hours	7.1	4.2	2.9	41	11.30/hour	33.39	
nonturf per du - hours	6.1	5.8	0.3	5		3.30	
total - hours	13.2	10.0	3.2	25		36.69	48.9
turf per 90 m2 - hours	10.0	13.0	3.0	30			
nonturf per 90 m2 - hours	5.9	4.6	1.2	21			
Fertilizer applied *							
turf per du - kg	15.0	5.12	9.93	66	.45/kg	8.31	
nonturf per du - kg	2.1	1.5	.59	28		0.49	
total per du - kg	17.1	6.62	10.5	61		8.80	11.7
turf per .1 m2 - g	21.0	16.0	5.1	24			
nonturf per .1 m2 - g	2.0	1.1	0.85	43			
Fuel (gasoline) used +							
mowing and hauling turf - L	6.66	3.4	3.2	48	3.8/L	0.84	
hauling nonturf clippings - L	1.5	1.1	0.45	29		0.12	
total - L	8.25	4.58	3.6	44		0.96	1.3
Herbicide applied							
turf area per du - g	18.0	0.8	17.0	95	28/g	0.42	
nonturf area per du - g	14.0	24.0	9.9	67		0.24	
total area per du - g	32.9	25.0	7.4	22		0.18	0.3
Total savings per du - $						75.00	

du=dwelling unit, *typically a fast acting mix similar to 16N-6K-8P, +average round-trip haul distance to dump was 22.0 km

Table 4: Comparison of maintenance inputs for traditional and water-conserving landscapes (from Nelson, 1987)

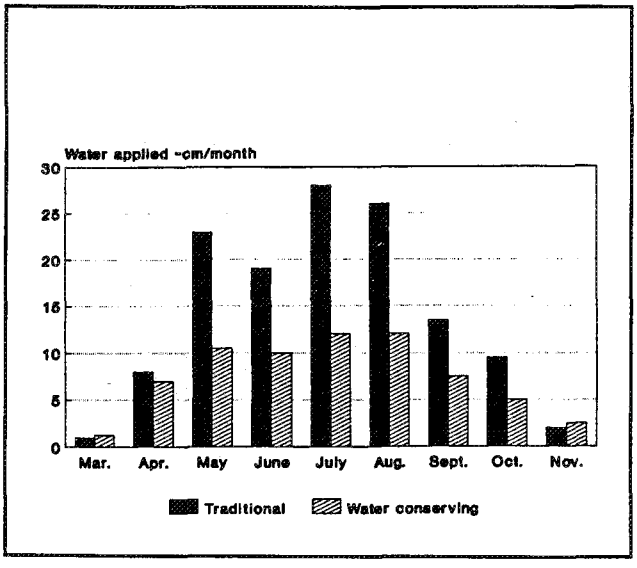

Figure 4: Water applied to traditional and water conserving projects in North Marin California study (from Nelson, 1987)

located in drainage areas and intensely shaded zones. Table 4 indicates the following savings: water requirements were reduced by 54%, labour by 25%, fertilizer by 61%, fuel by 44% and herbicides by 22%. Overall savings for the water conserving alternatives were $75.00 per unit per year over a total of $145. This is a 51% cost reduction. Figure 4, from this study, compares the water-use of the traditional and water conserving landscapes.

Analysis

While the majority of turfgrass species have been quantifiably assessed for water requirements, as indicated in Table 2, water-use assessments for trees and shrubs are lacking (Beard, 1992; Lindsey and Bassuk, 1991). However, rough estimates can be obtained by calculating the available moisture potential, which is the capacity of soils to hold water that will be available for plants (Hightshoe, 1988). This can be determined from the total average annual rainfall for the region during periods of evapotranspiration (ET) and the soil's available water content. This can then be compared to the available moisture requirements of certain species. For example, an average annual rainfall accumulation for Ottawa during ET periods is 52.8 cm (The Toro Company, 1966). With an average loam soil, 20-25% of the rainfall will be available for plants (Hausenbuiller, 1985; Harris, 1983), as shown in Figure 5. Approximately 25% will be lost through evaporation and 50% through percolation and run-off. A mulch will decrease evaporation losses by 43% as seen in Table 3. Therefore, available water for this example is 18.8 cm.

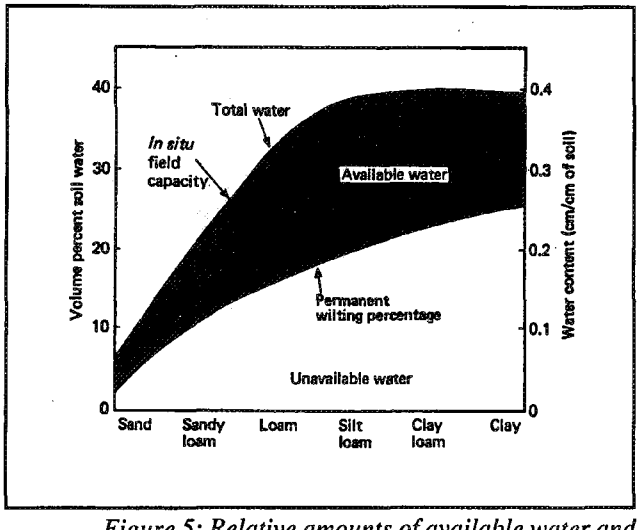

Figure 5: Relative amounts of available water and unavailable water in soils of different textures (from Kozlowski, 1987)

Using Hightshoe's data for available soil moisture capacity, the tree species in the very low to low categories require less than 15 cm of available water. In addition to the many shrub species which would require no supplemental irrigation except in drought periods, this data identifies the trees which could be used on this site including certain species of the following: spruce, birch, carya, catalpa, hawthorn, cornus, ash, gleditsia, pine, poplar, cherry, oak, elm and viburnum. Thus, the palate of plants would not be restrictive. Since the available water estimate is a seasonal average, it does not account for occasional drought periods which would require additional water. A further limitation of this approach is that it does not account for specific wind, radiation and temperature data (Chong, 1993).

Although the Ontario Ministry of Agriculture and Food (OMAF) quantifies an average annual turf irrigation requirement of 60 000 litres for an area of 100 square meters, similar average estimates are lacking from other Canadian regions (Ross, 1993; Holl, 1993). However, average evapotranspiration rates of different turfgrass species, such as those indicated in Table 2, are available (Beard, 1985). By multiplying an average ET rate of the cool-season turfs in cm per week by the number of ET weeks for the specific region, a total water requirement can be calculated. Irrigation water requirements can be determined by subtracting this figure from the average rainfall accumulation during ET periods for the region.

While the primary objective of xeriscaping is to reduce water consumption, implementing these xeriscape principles will result in conservation of other resources consumed in annual landscape maintenance. For example, while turf requires mowing every seven to ten days (Turgeon, 1990) pruning and thinning of average trees

and shrubs after establishment occurs less than once per year. According to Cobham (1990), only 7% of the area of a typical shrub planting will require pruning each year and rejuvination is required every 15-20 years. In comparison to the 12 hours required annually for the mowing of 100 square metres of turf, an equivalent of 1.6 hours is required annually for pruning the same size area of shrubs (Cobham, 1990; Wright, 1980). Pruning constitutes the majority of annual maintenance operations for trees and shrubs. This would result not only in time saving for the resident but savings in fuel or electricity.

According to OMAF (1990), approximately 15 kilograms of fertilizer is required annually for 100 square metre lawns. Alternatively, research suggests that most woody plants do not benefit from fertilizers (Rubin, 1989; Harris, 1983). Therefore, fertilizer can be eliminated. By eliminating bare soil through dense plantings or use of mulch, weed control after plant establishment in the xeriscape should occur without the need for herbicides or hand-removal (Ortho Books, 1990). Thus, the material and time spent for weeding would eventually be eliminated. According to calculations of standard minute values from Cobham (1990), annual labour requirements in hours for 100 square metres of turf, trees, shrubs and groundcover are 16.6, .75, 1.85 and 5 respectively. As previously discussed, material and labour requirements for woody plants would be higher in the first 2-5 years prior to establishment.

Table 5 shows calculations of payback periods utilizing this material and labour data. Figures for capital cost calculations were obtained from the Canadian Tire Catalogue (1992) and Yardsticks for Costing (Hanscomb

Initial Costs:

Conventional Landscape	($)	Xeriscape 1 (with no Lawn)	($)	Xeriscape 2 (with 25% Lawn)	($)
sod and topsoil (installed)	750	deciduous trees	360	deciduous trees	360
deciduous tree	180	shrubs	625	shrubs	625
gas or electric mower	240	ground cover	938	ground cover	891
spreader	20	unit pavers	880	lawn	188
irrigation system	380	loppers	26	loppers	26
rake	15	pruning shears	16	pruning shears	16
tree-care tools (see below)	66	saw	24	saw	24
total	1651	**total**	2869	gas or electric mower	240
		Capital Cost Difference (between conventional and xeriscape with no lawn)	**1 218**	spreader	20
				irrigation system	76
				rake	15
				total	2481
				Capital Cost Difference (between conventional and xeriscape with 25% lawn)	**730**

Annual Maintenance Costs:

Conventional Landscape	($)	Xeriscape 1 (with no turf)	($)	Xeriscape 2 (with 25% turf)	($)
fuel	5.00	fuel	0	fuel	1.00
water	56.00	water	0	water	14.00
fertilizer	14.00	fertilizer	0	fertilizer	3.50
herbicide	9.00	herbicide	0	herbicide	2.00
total	84.00	total	0	total	20.50
time	16.8 hours	time	2.3 hours	time (hours)	6.5
		Annual Cost Saving	**84.00**	**Annual Cost Saving**	**63.50**
		Total Years for Payback	**33**	**Total Years for Payback**	**20**
		Annual Time Savings (between conventional and xeriscape with no lawn)	14.5 hours	Annual Time Saving (between conventional and xeriscape with 25% lawn)	10.3 hours

Table 5: Payback period calculation of 100 metre square lot comparing conventional landscape to two xeriscape aternatives (for average Ontario conditions)

1992). Refer to the Water Efficiency section for water rates by province. After calculating initial cost difference and annual cost savings, a life-cycle cost calculation, as discussed in the introductory section, was used to calculate the payback periods. Two xeriscape alternatives were evaluated: 1) elimination of turf and replacement with unit pavers and 2) 25% of landscape area for turf. A desirable standard of maintenance is assumed. Annual maintenance data is for established plants.

As indicated in Table 5, the payback periods are 33 years and 20 years for Xeriscapes 1 and 2 respectively. However, this result does not account for the annual time savings. Therefore, another payback period was calculated involving annual maintenance with hired labour, equipment and materials at a rate of $25.00 per hour. If residents hire maintenance companies to do the labour and provide the materials and equipment, the payback period for Xeriscapes 1 and 2 are 6.5 and 5.5 years respectively. Figure 6 compares the payback periods for the first two xeriscape examples with the hired labour exampes.

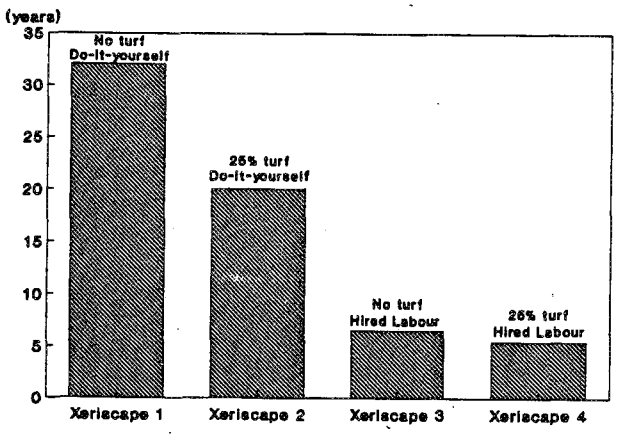

Figure 6: Payback periods for xeriscapes with and without hired labour, equipment and materials

Given the range of climatic conditions across Canada, the saving potential of xeriscapes varies from one region to the next. Accounting for the difference in irrigation water requirements and the cost of water discussed in the Water Efficiency section, payback periods for two other regions were calculated. The payback period for Xeriscape 1 in Winnepeg would be 8.5 years, whereas the investment would not be recovered in Vancouver. Therefore, economic incentives for implementing xeriscapes are clearly more attractive in some regions than others.

Summary

The calculations for the 100 square metre example in the analysis section can be applied to the smaller Grow Home lot. Although the annual cost savings for xeriscapes are impressive, the payback periods required to recoup the significant difference in capital investment are longer than most residents would prefer. This is particularly important where affordability is an objective. The payback period is more desirable in dryer climates, where the annual water savings and cost per litre are highest. If residents wish to reduce the initial cost investment, smaller, less expensive nursery stock can be planted.

The payback periods are impressive with the hired labour, materials and equipment examples. Despite the long payback periods in the first two examples, the inital cost differences are modest. This can be easily out-weighed by the other xerixcape benefits. For example, studies of residents response to xeriscapes indicate the pleasing aesthetic effect of these landscapes. Moreover, when economic incentives are balanced with promoting the benefits of resource conservation in both a local and global context, reducing the annual inputs of landscape maintenance makes good sense.

Guidelines

Xeriscapes conserve water and other maintenance inputs through the following principles:

1) Limit the use of turf areas only for specific social and recreational functions,
2) select water-efficient plants suited to the local site conditions including climate, soil type and site drainage,
3) define water-use zone for plants with similar water requirements,
4) group trees and shrubs in beds,
5) improve water holding capacity of soil,
6) use mulches to reduce evaporation and prevent weed growth,
7) use an efficient irrigation system that prevents loss of water to evaporation and surface run-off,
8) collect rainwater for irrigation

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Waste Disposal

"Your garbage is a terrible thing to waste." (Régie, 1990)

Introduction

The conventional practice of routinely landfilling wastes is now faced with severe limitations: leachates from sites are not being contained and are polluting our groundwater; odours raised from landfills are causing concern in subdivisions near or on sites' buffer zones; and, landfills are filling faster than expected. Action must be taken to alleviate these problems otherwise we will be faced with profound economic, social, health and environmental consequences (Kett, 1988).

The municipal solid waste stream in Canada is among the largest in the world on a per capita basis. It is estimated that Canadians produce 1.7 kg of waste per capita per day. In comparison, Sweden produces 0.8 kg of waste per capita per day (Env. Canada, 1992b). As shown in Figure 1, residential sources account for 33% of the total non-hazardous waste generated in Canada. In 1988, Canadians generated 30 million tonnes of waste. This translates to approximately 10 million tonnes of waste from residential areas (Env. Canada, 1992a).

Objective

In this section an assessment of the waste stream from typical households will be made and solutions for its disposal will be examined with respect to high density 'Grow Home' housing.

Figure 2 shows that large cities as well as smaller metropolitan cities will see increasing waste generation rates in the coming years. If the current situation persists, landfills will fill up faster than originally anticipated (Kett, 1988). In addition, siting and development of new landfill sites is difficult because the public does not want a landfill in their own community. This is commonly referred to as the NIMBY (not in my backyard) syndrome which is the single greatest obstacle to the development of new landfills.

Problems of waste disposal will lie in space

Waste Management Facts

- In Montreal, landfill disposal fees are rising dramatically. In April 1988, the tipping fee at the Miron landfill site was $12.44/tonne of waste. In January 1992, the tipping fee rose to $40.00/tonne of waste (Bureau de Consultation de Montréal, 1992).

- Some cities in the United States are charged tipping fees of $^{us}66 to $^{us}110/tonne of waste (Dussault, 1990).

- Cities will be turning towards weight based solid waste collection. Minnesota implemented the first system of this kind in the United States. The city is minimizing costs by emphasizing labour saving technology, and active public participation in landfill waste diversion (Williamson, 1993).

- The city of Montreal foresees regulations banning the disposal of wastes containing more than 30% of recyclable material (Bureau de Consultation de Montreal, 1992).

- Both the cities of Montreal and Halifax, and the province of British Columbia are implementing integrated waste management systems to reduce the volume of waste being landfilled. Included in the systems are recycling and composting schemes (City of Halifax, 1992; Ville de Montreal, 1990; National Round table on the Environment and the Economy, 1991).

- One landfill site in Toronto opened in 1983, expecting to close by the year 2000. However, later estimates predicted the facility would approach its capacity by 1991 (Kett, 1988).

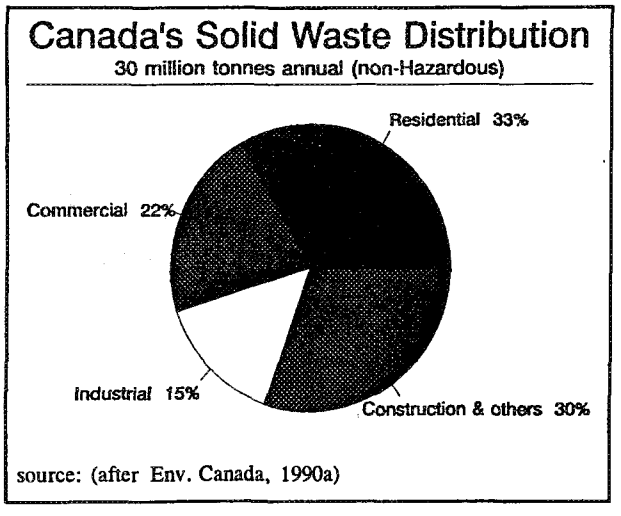


Figure 1. Canada's Waste Distribution

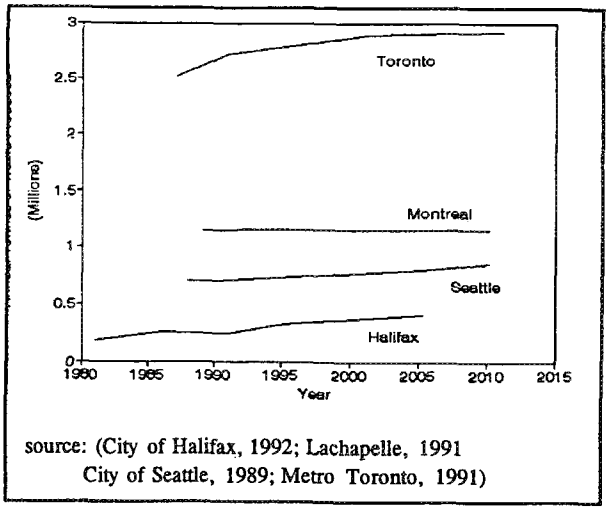


Figure 2. Waste Generation Rates

limitations and in depletion of our resources. Through recycling of waste, home builders can help alleviate this problem (Régie, 1990). Recycling constitutes recovery of materials from the waste stream in order to provide raw materials for the production of new products (Tchobanoglous et al, 1993).

Waste Management

There is a need to diminish the quantity of waste being directly landfilled. Table 1 shows that there is a tremendous landfill diversion potential. Up to approximately 75% of domestic waste can, in theory, be diverted. Landfill space requirements, disposal costs paid by communities (which are transferred to taxpayers) and the burden on the environment through use of new raw materials can be reduced through recycling and year round composting. A pilot study in the Mississauga area resulted in a diversion of 31% of residential wastes from local landfill sites (McFarlane, 1990).

Being of high density, Grow Home communities offer a suitable environment for improving waste management schemes. Communal composting can be implemented which would divert organic materials and diminish the land requirements which are needed to compost. Also, the high density housing would lend itself well to recycling centres within the development, thus minimizing space needs for waste disposal in the kitchen areas. These two schemes will be individually discussed.

Material	Composition %	Amount Kg/capita/day
Compostables:		
Food	28.0	0.160
Lawn + Garden Waste	5.5	0.031
Misc. Compostables	8.6	0.049
	42.1	0.240
Recyclables:		
Newspaper	9.6	0.054
Kraft/Corrugated	4.7	0.027
Office Papers	1.8	0.010
Mixed Recyclable Paper	4.4	0.025
Glass Food/Bev. Cont.	5.0	0.028
Alum. Food/Bev. Cont.	0.5	0.0028
Tin Food/Bev. Cont.	2.3	0.013
Ferrous Metals	1.9	0.0017
Non-Ferrous Metals	0.6	0.011
PET Bottles	0.3	0.0034
HDPE Bottles	0.8	0.0045
Other Plastic Containers	0.2	0.0011
	32.1	0.1815
Non-Recyclables:		
Magazines/Glossy	5.2	0.029
Plastic Packaging/Film	4.0	0.023
Textiles	3.1	0.018
Rubber/Leather	2.0	0.011
Disposable Diapers	3.3	0.019
Wood Waste	1.0	0.0057
Hazardous/Medical	0.8	0.0045
Misc Non-Compostables	6.4	0.036
	25.8	0.1462
Total	100.0	0.5677

source: (City of Halifax, 1992; Env.Canada,1992a and b)

Table 1. Domestic Waste Composition

Composting

Composting is a process whereby biodegradable organic materials are subjected to bacterial decomposition. The end product is a humus-like material called compost (Tchobanoglous et al, 1993).

Table 1 shows that approximately 40% of the residential waste stream consists of compostable materials. Composting can be done at the community level and/or at the household level.

Composting is an inexpensive way of diverting a significant part of residential waste from the landfill. Compost is also useful around the house. It can be used as an organic fertilizer, soil conditioner and mulch thus reducing the need for expensive fertilizers. Compost will help produce plants which are more disease resistant with better flavour, colour and reproductive capacity (Compost Management Associates Ltd., 1990).

1. Choice of the Composter: There are many types of composters commercially available. Figure 3 shows three common types of composters that can be used for home composting: bins (or boxes), food digester, or worm composters.

Bins and boxes can be either bought for approximately $40 to $45 per home unit (Compost Management, 1992; Lachapelle, 1991) or built from waste materials such as recycled construction wood pallets. Due to their volume, these composters are particularly useful when yard wastes are to be decomposed. However, they also accommodate kitchen waste. They are neat in appearance, hold heat easily (which is needed for efficient composting) and deter animals. Lids on bin composters keep rain off the composting material. Decomposition can be quite rapid (approximately 2 weeks) if the pile is turned regularly (Campbell, 1990).

Worm composters use earth worms to decompose the organic material. Commercially available units range between $60 and $85 (Club Organico, 1993). They may also be constructed with readily available materials. They are simple to operate and composting can be done indoors. The resulting compost is nutrient rich, and is therefore a good fertilizer. In addition, it is an effective way to compost food wastes. Unfortunately, such composters can attract fruit flies; however, this can be overcome as indicated in the trouble-shooting box on the next page. They need to be protected from temperature extremes and care must be taken when the compost is being removed (Campbell, 1990).

Food digesters are also commonly referred to as "green cones." They cost approximately $40 per unit (Compost Management, 1992) and are easy to use once installed. Meats, poultry, and fish can be composted without generating unpleasant odours. Installation requires digging and the composter must

source: (Compost Management, 1992).

Figure 3. Composters

Home Composter Trouble-Shooting
source: (Campbell, 1992) and (Durham Region)

The following information outlines possible problems and remedies which can occur when composting.

When **unpleasant odours emanate** from the compost pile, the problem can be attributed to a pile that needs aeration and/or a pile that is too wet. Turning of the pile can increase aeration. Moving the pile to a sunnier location, adding dry material such as leaves, and putting a lid on the composter can help keep the pile from getting excessively wet.

A dry pile, a frozen pile or completion of the composting process, may be possible causes of an **inactive composter**. A dry pile can be corrected by adding water to moisten the mix. Activity in frozen piles will resume again in the spring when the temperatures are more favourable. A mature compost, one which will not compost any further, looks dark and crumbly and, smells earthy but not mouldy nor rotten. This compost is ready for application to the garden as a soil conditioner or fertilizer.

Insects, animals, or pests are around the composter. They can be attracted when meats and fatty foods are accidentally placed in the composter. These organics should be removed or dug into the existing compost. Other solutions would be to put a lid on the composter and/or to enclose the composter with wire mesh.

There are **weeds in the composter**. Possibly weed seeds have been added with grass cuttings. The solution would be to remove the weeds, turn the roots towards the sun, and leave them to die on the pile.

The **compost is damp and warm only in the centre**. The pile may be too small, in which case more material should be gathered.

be moved periodically. Nutrients and enzymes are added to help the process (Compost Management Associates Ltd., 1990).

All factors considered, the bin type composter seems to be the most appropriate choice. It is more suitable for yard trimmings, a better animal deterrent and can be either built or bought for a single housing unit. In addition, they can also be built to accommodate the waste from more than one household. Accommodating more than one unit per composter would save yard space. The required dimensions and volumes will be discussed in a later section.

2. How to Compost: The following organic materials can be composted: leaves, lawn and garden clippings, fruit and vegetable wastes, scraps, egg shells, coffee grounds with filter papers, tea bags, nut shells, and wood ash from a fireplace or wood stove. The following organics should not be included in a home composter: pet wastes, charcoal or coal ashes, ripened weeds, meats, bones, fats, dairy products, and oils or oily foods (Environment Ontario, 1991).

With simple preparation and minimal maintenance, composting could take approximately two weeks. Three basic rules are needed to achieve this: chop the organics into small pieces, aerate every three days (e.g. turning with a pitchfork) and blend the organics into the existing pile. The pile should be located away from uncontrollable water sources (e.g. away from the edge of a roof top). However, a water supply should be readily available to add moisture if the pile dries out. A shaded area in the summer would help to ensure that the pile does not dry. A level ground location should be found which gives reasonable drainage (Campbell, 1990).

The largest pile volume should not exceed 2 m^3 in order to ensure proper aeration of the pile (Compost Management, 1992). The maximum height of the pile should be between 1.2 and 1.8 meters to ensure proper aeration (Campbell, 1990).

The estimated annual volume generated per household is 740 litres of compostable waste. The estimated composter volume needed (taking into

account the stock piling of organics in the composter during the cold months) would amount to approximately 330 litres per household (0.33 m^3) (Compost Management, 1992).

In the Durham and Ottawa regions of Ontario, the home composter program has been found to be responsible for approximately a 15% reduction in the municipal solid waste stream. The reduction translates into approximately 240 kg/household/year diverted by home composting from landfill sites. In the report on the Durham area, 65% of the participants in a compost pilot project were satisfied with a composter volume of 290 litres.

Recycling

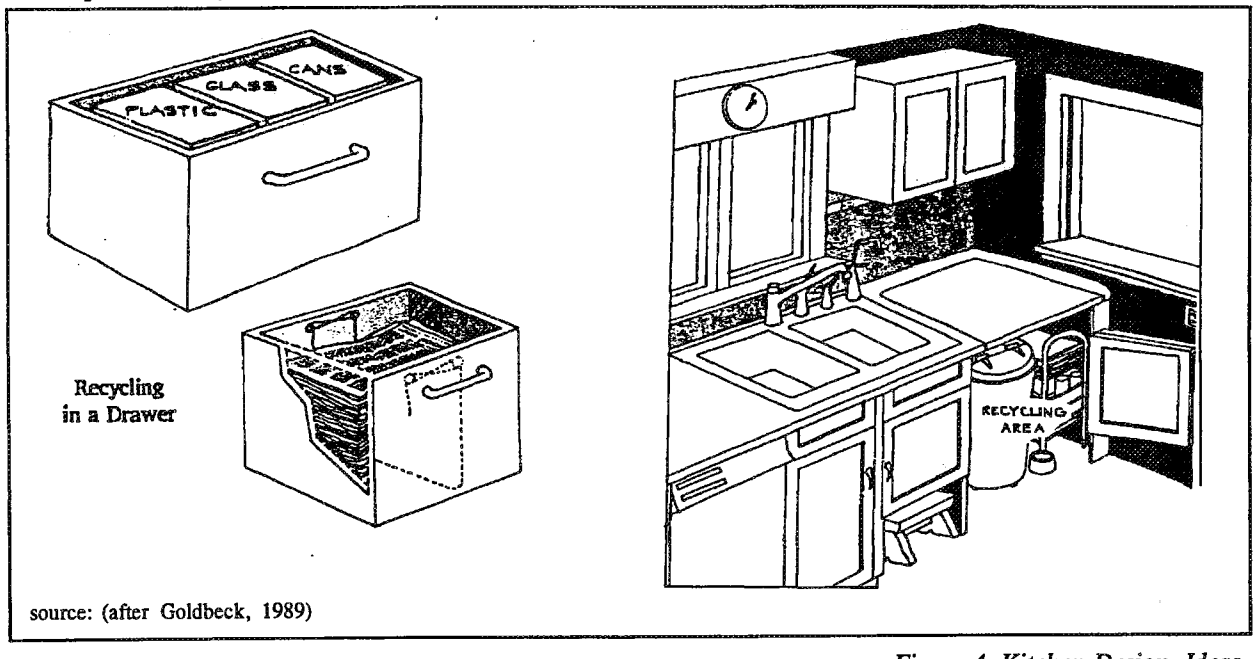
Another way of reducing the burden of waste accumulation on landfills is to recycle. From Table 1, we can see that there is a potential for diverting a significant amount of recyclable materials from landfill sites. Ideally, up to 32% of residential waste can be recycled: an average of 20.5% in the form of paper, 5.0% glass, 5.3% metals and 1.3% plastic. These materials can be separated from the waste stream either at the source (household) or at a centralized facility.

As a home builder, source separation of recyclables can be promoted by including an area for a recycling centre in the kitchen. The kitchen is a convenient area since most of the waste is generated there (Goldbeck, 1989). One convenient area for a small recycling centre would be under the sink. Other kitchen design ideas are shown in Figure 4.

When a recycling scheme in a Grow Home development is compatible and acceptable to the community, recycling centres can be established outside in common areas. A high density housing configuration in clusters with common parking would lend itself well to common recycling centres. Location of these centres in parking areas would be convenient for the home owners and the collection vehicles. An enclosure may be needed to deter vandals and animals. Figure 5 shows possible locations of these recycling centres. Also shown in Figure 5 are the locations of common composters (in common areas) and individual composters (in individual backyards).

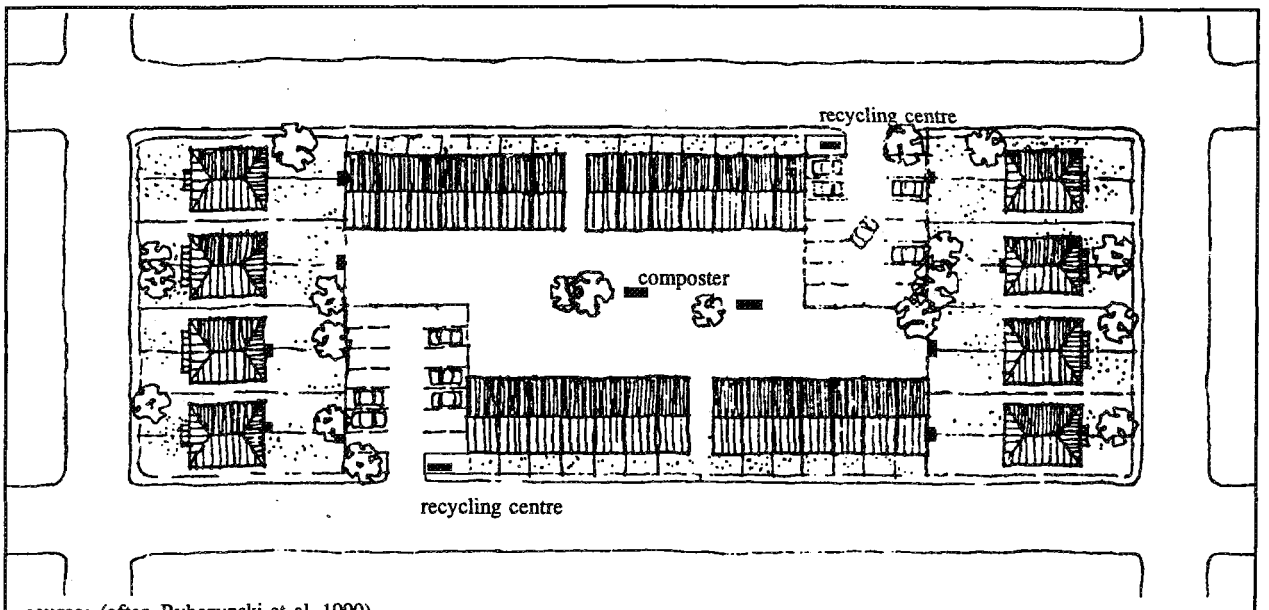
The recycling centres could consist of multiple rolling bins as shown in Figure 6. The rolling bin centre would save on kitchen space allocated to recycling since the recyclable materials could be disposed of at will. A small bin would then be needed in the kitchen for temporary storage.

In Montreal, rolling bins are used when 8 to 30 units can be serviced from a common point, which is



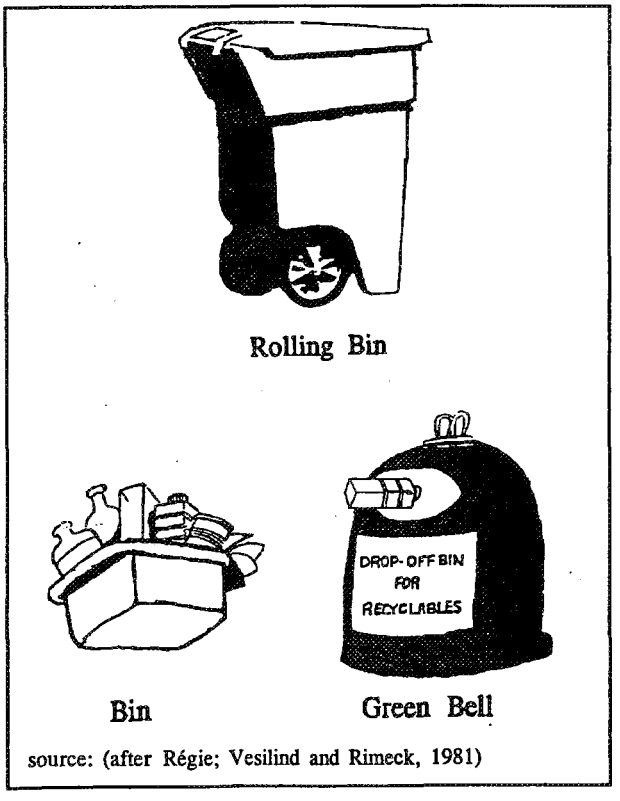
source: (after Goldbeck, 1989)

Figure 4. Kitchen Design Ideas



source: (after Rybczynski et al, 1990)

Figure 5. Housing with Recycling Centres and Composters



source: (after Régie; Vesilind and Rimeck, 1981)

Figure 6. Recycling Bins

usually the case with apartment buildings. One 360 litre bin is used for paper and a 240 litre bin is used for collecting metals, glass and plastics (Morissette, 1993). Alternatively, green bells, which hold a volume of 2,500 litres (2.5 m^3), can serve about 500 units.

To promote even greater participation in recycling efforts, curbside recycling can be put into effect. Curbside recycling requires more storage space in the home, since the content of the individual recycling bins are collected on average once a week (Morissette, 1993). On the other hand, curbside recycling requires less effort on the part of the home owner. A study in Burlington, Vermont showed that curbside recycling had a participation rate of 70%. Participation rates for apartment buildings with rolling bins have not been estimated; however, experience has shown that the convenience of curbside recycling dramatically increases levels of participation (Fleschner, 1992). In Montreal, recycling programs do not service the entire city. However, it has been found that citizens travel to work with their recyclables and drop them off for recycling in areas serviced by green bells. As a consequence, the green bells in Montreal are often overflowing, thus showing the willingness of people to recycle (Morissette, 1993). Figure 6 illustrates the three types of recycling containers.

Household Hazardous Materials

Household hazardous wastes can cause severe damage to the environment and to the food chain (Régie et al). At present, there is not much that can be incorporated into a housing project to help this situation. The best solution is to find alternate products which are more environmentally friendly. There are curbside collections, mobile depots and permanent depots which collect household hazardous materials. The cost to collect these wastes range from $1,500 to $6,300 per tonne (City of Halifax, 1992).

Analysis of Potential Savings
Composting

As was seen in Table 1, approximately 240 kg/household/year of compostable waste can be diverted. This represents 40% of residential waste, or 13% of the total municipal waste stream, which may be diverted from landfills.

Table 2 shows the total costs of home composting, community composting and landfilling for Canadian communities (the tick marks indicate data which is unavailable). The cost to home compost is based on various costs such as the average cost of a composting unit, municipal administration costs, project monitoring and data collection costs, and the composter delivery and promotion costs. These composting costs are amortized over a 10 year period which is the estimated composter's longevity as per the manufacturers' warranties (Compost Management, 1992). Since landfilling seems to be the most expensive and home composting the least expensive method of dealing with waste, the cost difference between these two gives the maximum savings due to home composting on a per tonne basis. For example in Toronto, using the estimated 240 kg/household /year compostable waste diversion and an average savings of $129/tonne (i.e. landfill cost of $150/tonne minus the average home composting cost of $21/tonne) of waste of home composting over landfilling, an estimated savings of

Community	Total Costs, ($/tonne of waste) including collection, transportation, and processing costs			Maximum Saved ($/tonne of waste)
	Home Composting	Landfilling	Community Composting	
Toronto, Ontario	-	150 [2]	-	129
Pickering, Ontario	24 [1]	135 [1]	88 [4]	111
Newcastle, Ontario	19 [1]	135 [1]	88 [4]	116
Montreal, Quebec	-	80 [3]	-	59
Halifax, Nova Scotia	-	78 [2]	-	57
Vancouver, British Columbia	-	70 [2]	-	49
Ottawa, Ontario	-	46 [2]	-	25
Fredericton, New Brunswick	-	43 [2]	-	22
Edmonton, Alberta	-	15 [2]	-	-6
Regina, Saskatchewan	-	12 [2]	-	-9
average	21	not applicable	80	not applicable

- initial cost of a new landfill: $137,500,000 for approximately 16,000,000 tonnes which translates to $8.6/tonne of capacity (Lachapelle, 1991),
- initial cost of home composting is $40 (Toronto area) to $45 (Montreal) per composter,
- the maximum savings are calculated by subtracting the home composting cost (where they are not available, use the average value) from the landfilling cost,

source: [1] Compost Management, 1992; [2] CMHC, 1991; [3] Gazette, 1993; [4] Durham.

Table 2. Cost Comparison

Community	Cost to Landfill the Recyclable Materials ($/household/year)	Home Composting Payback Period (months)	Community Savings per 100 households ($/year)
Toronto, Ontario	30	8	3096
Pickering, Ontario	27	9	2664
Newcastle, Ontario	27	9	2784
Halifax, Nova Scotia	16	22	1416
Montreal, Quebec	16	21	1368
Vancouver, British Columbia	14	24	1176
Ottawa, Ontario	9	50	600
Fredericton, Ontario	9	58	528
Edmonton, Alberta	3	none	none
Regina, Saskatchewan	2	none	none

Table 3. Waste Management Parameters

$31/household/year (i.e. 0.240 tonnes/household/year multiplied by $129/tonne) to the community can be calculated. On the other hand, in Regina, the negative savings demonstrate that landfilling is cheaper than home composting therefore the money to be invested in home composting may be better in a bank. The last situation is anticipated to change due to increasing landfill costs thus rendering home composting more appealing as a method of waste disposal.

Assuming that the savings to the community are transferable to the home owner through municipal taxes and using a discount rate of 10% and an escalation rate of 4%, Table 3 shows the calculated payback periods for different communities using the data available in Table 2 (where data is missing, average values were used). This is consistent with payback periods found in the United States (Glenn, 1993). When home owners build their own bins, the payback periods are significantly reduced.

The estimated composter volume needed is approximately 330 litres (0.33 m^3) for year round composting. This would require a 1 m^2 area in each backyard for an individual backyard (area includes composter and surrounding space). If common areas are available in the development, communal composters can be built to accommodate wastes from 6 households. A communal composter is limited to 6 households since a compost pile should be restricted to a 2 m^3 volume to ensure proper aeration. Assuming a pile height of 1.25 m, an approximate area of 1.6 m^2 (with surrounding space) would be needed. The latter would alleviate space constraints on individual backyards.

In light of the values shown above, home composting is the most cost-effective approach available. Certain communities have incentive programs in place. For instance, the Ontario Ministry of the Environment will pay 50% of the cost of the home composter. This program is applicable until the year 2000 (Compost Management, 1992).

Recycling

Based on typical densities from Tchobanoglous et al (1993), the estimated volumes of recyclable materials listed in Table 1 are: 30 litres/household/week of paper, 3.0 litres/household/week of glass, 3.0 litres/household/week of metals, and 2.4 litres/household/week of plastics. These volumes translate into approximately a total quantity of 0.200 tonnes/year of diverted waste. This is roughly equal to 11% of the total municipal solid waste.

In Montreal, recycling costs range from $28 to $38 /household/year (Gazette, 1993) and in the City of Halifax curbside recycling (including revenues from sales) costs approximately $27/household/year (City of Halifax, 1992). Comparing these recycling costs with the equivalent costs of landfilling in Table 3, recycling would cost approximately the same (for the three first cities) or more than landfilling. While curbside recycling does not achieve significant monetary savings, it does reduce environmental impact and extend landfill lifetime. Alternatively,

recycling costs can be reduced using rolling bin or green bell recycling centres. Table 4 shows that the rolling bin option costs significantly less to the community than curbside recycling. A rolling bin recycling centre can accommodate 24 units on the basis of two 360 litre bins for paper and one 240 litre bin for plastics, metals and glass. Approximately 3 to 4 m^2 of area would be needed for such a centre. Green bell collection costs are not currently available but are expected to be the least of the three options.

Type of bin	Collection Costs ($/unit/year)
Regular bin	22
Rolling bin	16 to 17
Green bell	not available

source: (Morissette, 1993).

Table 4. Collection Costs

Savings to the Community

The combined effect of composting and recycling would translate into 0.440 tonnes of waste diverted per household per year. A Grow Home development of 100 units would divert 44 tonnes/year from landfilling. Due to the recycling costs being approximately the same or higher than landfilling costs, composting alone can save the community landfilling costs. Savings are shown in Table 3. This would also save valuable landfill space. Over a 10 year period, 440 tonnes of waste would be diverted.

Savings in pollution from not extracting more natural resources can be achieved by implementing such waste managements strategies.

Summary and Guidelines

Society has awakened to the fact that we have responsibilities towards the environment. In the past, social responsibilities were largely human centred. Humans are positioned at the end of the food chain and therefore have a greater risk of suffering from a poisoned environment. Therefore, we have to make an effort to protect our environment, not only for its sake but for our own sake as well (Buchholz,1993).

Recycling should be viewed not just as part of the solution to our solid waste disposal crisis, but also as a means to conserve and replace natural resources (Richard, 1990). Previous studies have shown that up to 27% of municipal solid waste can diverted from landfill. Recycling and composting are becoming a fact of life and housing designs should reflect this.

Guidelines

- The recycling scheme must coincide and be compatible with the community's integrated waste management system.

- If green bells are to be used they should be away from overhead power lines and away from areas where noise is of concern.

- Approximately 6 households can be grouped on one composter.

- Composters should be located at an easily accessible area for the cold and warm months of the year.

- Recycling centres, if approved, should be located where home owners and collection vehicles are easily accessible.

Additional Reading

For more information on home composting read: Campbell, S. (1990) Let It Rot! The Gardeners Guide to Composting, Pownal, Storey Publishing.

For more ideas on kitchen design ideas read: Goldbeck, D. (1989) The Smart Kitchen: How to Design a Comfortable, Safe, Energy-Efficient, and Environment-Friendly Workplace, New York, Ceress Press.

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Healthy Indoor Environments

Background

Building materials have undergone significant changes during the last 45 years or so, many of which have led to more efficient and cost-effective construction alternatives. The introduction of composite wood products for instance, such as hardwood plywood, fiberboard and particleboard have provided cost-effective alternatives with reasonable performance and durability. These products make more efficient use of natural resources, since a higher percentage of the log can be used, and the potential for using recycled materials, scrap wood chips and sawdust can be exploited. Similarly, stain-resistant carpets of synthetic fibers, thermally-efficient rigid insulation boards and a variety of coatings, cleaning agents and furnishings have broadened the design options and facilitated the assembly, operation and maintenance of buildings.

Many of these innovations, however, which have become commonplace in the homebuilding industry, have a tendency to emit odorous, irritating or, in some cases, toxic compounds into the surrounding air. If effective ventilation is not provided, the concentration of harmful pollutants can compromise the physical and psychological well-being of the occupants. The degree to which individuals may be affected depends on personal susceptibility, concentration of pollutants and duration of exposure. The symptoms of exposure to poor indoor air quality (IAQ) are varied, and the result can range from mild discomfort to total disability.

While the diagnoses and prevention of problems associated with poor indoor air quality is not an exact science, the need to address the issue has become a topic of great concern. A World Health Organization committee estimates that up to 30% of all new and remodeled buildings worldwide may have problems with IAQ (Goldberger, 1993). Ventilation standards are being revised, and product emissions monitored to promote what have been termed "healthy," "safe," or "clean" environments. Achieving good air quality is quickly becoming an integral and essential part of the design of comfortable and healthy interior building environments, along with the control of temperature, humidity, lighting and acoustics.

Objective

The objective of this section is to review the maincauses of poor indoor air quality, and to examine alternative construction materials which can reduce harmful emissions. The cost of replacing some finishing materials and furnishings in the Grow Home is evaluated.

Causes of Poor IAQ

There are two basic causes of poor indoor air quality: inadequate ventilation and excessive contamination. Deficiencies in ventilation may be due to inadequate design, improper installation, or negligent operation or maintenance of the heating, ventilating and air conditioning systems (HVAC). Excessive contamination is caused by harmful emissions from products which come into direct exposure with the indoor air, or from polluted outdoor air which is somehow allowed to enter the building.

While the cause of the problem can be defined as a high concentration of pollutants in the air, the source and mechanism by which the problem has manifested itself progressively over the years is somewhat ambiguous. The origins of poor indoor air quality have often been associated with reduced ventilation resulting from energy conservation measures adopted in the 1970's. Most sources of indoor air pollution, however, have little or nothing to do with energy conservation (Levin, 1993a).

Energy Efficiency and IAQ

The drive toward the design of energy-efficient buildings may be indirectly associated with poor indoor air quality in that it created a tendency to concentrate on thermal control for HVAC, with supply of fresh air being incidental. In an attempt to reduce the amount of energy required to heat and condition incoming exterior air, ventilation rates may be reduced to inadequate levels.

The ventilation required for good IAQ, however, requires fairly modest amounts of energy. Furthermore, in most buildings with IAQ problems, the amount of fresh air intake is not the main cause of the problem. Ventilation systems often do not function as designed, or are improperly operated and maintained (Cutter, 1991).

Symptoms Related to Poor Indoor Air Quality

(adapted from AIA,1992)

Buildings whose occupants experience health and comfort problems associated with being in the building are termed "sick buildings." The pattern of symptoms experienced by the occupants are known as the sick building syndrome (SBS) and building related illness (BRI). Both of these are associated directly to indoor air pollution, and are not used in relation to discomfort caused solely by inadequate temperature or humidity conditions.

SBS manifests itself with complaints of symptoms of acute discomfort, the cause of which is not known. These symptoms may include headaches, dry cough, dry or itchy skin, dizziness and nausea, difficulty in concentrating, fatigue, and sensitivity to odours. Most of the complainants report relief upon leaving the building. BRI, on the other hand, occurs when exposure to indoor contaminants results in a clinically defined illness, disease or infirmity. Symptoms of BRI include cough, chest tightness, fever, chills and muscle aches. Complainants may require prolonged recovery times after leaving the building.

Complaints may also occur from an illness contracted outside the buildings, acute sensitivity (such as allergies) of certain individuals, job-related stress or dissatisfaction, or to other psycho-social factors. Nevertheless, studies have shown that such symptoms may be caused or exacerbated by indoor air contamination. While it is normal for some occupants to experience one or more of such symptoms, complaints from a substantial percentage of building occupants is a clear indication of IAQ problems.

Air-tight Buildings and IAQ:

The development of air-tight building technologies is not in itself regarded as a direct cause of poor IAQ. Cases of indoor pollution levels which are worse than the exterior air were recorded as far back as 1973, when high air leakage levels were common (Levin, 1991). The argument follows that houses with high infiltration levels are not predisposed to better indoor air quality because of the higher volume of "fresh" air entering the building. Infiltrating air leaking across a building envelope may carry with it several pollutants either from the exterior or from inside the envelope, while both infiltrating and exfiltrating air are sources of heat loss.

Contamination from outdoor sources, such as pollutants from motor vehicle exhausts, plumbing vents as well as exhausts from the building itself (toilets and kitchens), may enter the building through air leaks, thereby decreasing the IAQ. Similarly, carbon monoxide and nitrogen dioxide from attached or underground garages which have not been properly isolated or sealed from the living spaces can pollute the interior environment.

The design for air-tight assemblies is therefore not only acceptable but recommended in the provision of healthy environments. Controlling the quality of indoor air requires that the amount, rate, distribution and content of incoming air be controlled. This is not possible if there is a high level of air leakage.

Contamination and IAQ

Changes in outdoor air ventilation alone only affect IAQ partially and indirectly. It is the relationship between ventilation rates and pollutant sources that ultimately determines the quality of indoor air.

Ineffective ventilation and/or humidity control can in itself provide a source of contamination. Bacteria, moulds and their spores, pollens, viruses and other biological contaminants are associated with high levels of moisture. Excessive moisture may be in the form of stagnant water (which may accumulate in humidifiers and cooling coil condensate caps, ceiling tiles, carpeting, insulation and internally lined ductwork), or in the form of excessive humidity.

While a properly designed and functioning mechanical system reduces the possibility of contamination from biological sources, the key to healthy indoor environments rests in the control of contaminants from building materials, particularly those which come into direct contact with the interior

air. Abundant, harmful pollutant sources have resulted from new building materials, furnishings, equipment and cleaning products.

A common misconception about IAQ is that adequate ventilation alone is sufficient to reduce unwanted pollutants. While the provision of effective ventilation is critical in achieving good indoor air quality, reducing pollutants at the source is far more effective.

Designing for Healthy Environments

While the causes and effects of poor indoor air quality are known, designing for a healthy environment is no simple task. Many of the issues involved in IAQ are not exact sciences. Sources of pollutants can be identified, but there is rarely enough information to evaluate the exact impact of design decisions on the occupants. Little is known about the effect of pollutants on human long-term health, or the degree of harmful pollutants emitted from materials in the built context (eg. in building envelopes). Furthermore, there are many strongly interrelated factors that determine IAQ.

The process of designing for IAQ is based mostly on the identification and avoidance of materials that are known to be strong sources of odours, irritants or toxins, and on ensuring that adequate measures are taken to provide sufficient ventilation to occupied spaces.

Ventilation:

Ventilation removes and dilutes pollutant concentration. The amount of ventilation required depends on pollutant source strength, types of contaminants, and occupant characteristics. Increasing the rate of fresh air intake alone, however, does not guarantee that a healthy indoor air quality will result. Attention must be given to the design, installation, operation and maintenance of the entire HVAC system, whether it be integrated or a system of baseboard heating complemented with a heat-recovery ventilator (HRV). Even with high ventilation rates, for instance, buildings may suffer from poor IAQ if there is an uneven distribution of air or insufficient exhaust mechanism. There are several factors which merit careful consideration, as they are common causes of indoor air problems (AIA, 1992b).

Sufficient intake: Dilution of indoor pollutants is achieved, first and foremost, by increasing the rate at which outdoor air is supplied to the building. Whatever air is brought in, however, needs to be heated and/or conditioned to provide comfortable thermal and humidity conditions, which in turn requires energy.

Continuous flow: minimum ventilation rates should not be determined solely by the thermal conditioning needs of a building. Systems that operate at reduced or interrupted flow during certain portions of the day (as is the case with variable air volume systems) may elevate indoor contaminant levels and impair their removal. Minimum ventilation rates should therefore be defined by air cleanliness and distribution, as well as temperature and humidity.

Even distribution: Uneven air distribution may result in variable temperature and humidity conditions in different parts of the building. Not only would this compromise the general quality of indoor air, but may result in the occupants' interfering with the operation of the mechanical ventilation system. Areas which have uncomfortable drafts, for instance, may tempt the users of the space to block the air registers if they emit uncomfortable hot or cold air. Ensuring adequate and even air distribution requires that the placement of barriers that disrupt air flow, such as partitions and furnishings, be anticipated.

Location of supply and return registers: The placement of supply and return registers too close to one another may lead to uneven fresh air distribution and inefficient removal of contaminants. At the exterior of the building, air supply vents that are installed too close to the exhaust vents may redirect contaminated air back into the building. Similarly, the placement of supply vents near other sources of outdoor air pollution, such as loading docks, parking and heavy traffic areas, chimneys and trash depots, can provide a pathway for contaminants to enter the building's ventilation system.

Operation and Maintenance: Improper maintenance of a mechanical system can cause the system itself to become a source of harmful pollutants. Lack of periodic cleaning may cause the system to become

clogged and reduce or eliminate airflow. Particular attention should be given to the possible accumulation of water anywhere in the system, which may foster harmful biological growth, such as fungi and bacteria which can be distributed throughout the building.

Air cleaners: While air cleaners are an important part of any HVAC system, they cannot in themselves adequately remove all the pollutants found in indoor air. They are generally effective in removing airborne particles, but special filter systems are required to remove specific contaminants (Table 1).

It is possible, for example, to reduce gaseous pollutants if the cleaner contains special material, such as activated charcoal. While these materials are usually effective in removing specific pollutants, none is expected to remove all gaseous pollutants typically found in indoor air. As is the case with all filters, they require periodic cleaning and filter replacement to function properly.

Sources:

In many cases, there is some kind of tradeoff to be made in the selection of healthy materials. Particleboard, for example, is very attractive from an environmental perspective in that it is made mostly from sawdust, which saves resources. The binders used in its manufacture, however, are toxic, and while less toxic adhesives are available, the performance of the product is diminished. The exercise becomes one of finding the right balance between replacement needs and toxic emissions.

The process is complicated because there are no simple rules to follow. There is a common misconception that natural is better. Compounds like arsenic, lead, formaldehyde and asbestos are naturally occurring substances which are much more toxic than many synthetic substitutes, and have been used in building products or equipment. Furthermore, natural materials are usually susceptible to quick degradation, and require treatment and/or protection with compounds which may emit toxic substances. Carpets made of wool, for instance, require protection in order to control pests. Some natural fibers are also less stain resistant, and may require industrial solvents for cleaning that are sources of contamination in themselves.

Type	Characteristics
Mechanical Filters	• flat or pleated; effective at removing particles • flat filters are effective at removing large particles • pleated filters, such as high-efficiency particulate air filters (HEPA), collect the smaller, respirable particles
Electronic Air Cleaners	• use electronic charge to remove airborne particles • may also produce ozone, a lung irritant
Ion Generators	• use electronic charge to remove airborne particles • may also produce ozone, a lung irritant

Table 1: Types of Air Cleaners

While many of these factors are either not quantifiable or implications unknown, IAQ can be improved through careful material selection if two aspects are understood: the mechanism by which pollutants are released into the air, and the characteristics of the product as they relate to emissions.

Origin of Pollutants

Emissions from building materials and products are produced at all phases of building's life cycle. Most, however, can be controlled by careful consideration during the design phase. Emissions from a building material can originate from three sources: the product itself, the surrounding air, and products used to clean and maintain it.

1. Nature of the Product: Emissions that come directly from the building materials can be either wet or dry. Wet product emissions are usually solvents, water and other substances emitted from products that involve a wet process, such as paints, sealants, adhesives, caulks and sealers, during and after application. While most of these substances form an integral part of the product, some may be emitted from solvents used to clean process products during application. In either case, emissions are usually highest while the material is drying, which usually takes a few hours or days. Many products, however, may continue to emit substances at lower concentrations for weeks, months and even years.

Dry product emissions come from products which do not involve a wet process on site but emit harmful substances nevertheless. Solvents which were used in manufacturing the product or its constituents are emitted, usually in an initial outburst when the product is first exposed. This is most noticeable in

cases where the product was packaged soon after its manufacture, which did not give the more volatile substances a chance to escape. The high initial concentration of emissions may also be due to changes in the product during transportation, storage and handling. Examples of dry product emissions include those which come from carpets backed with styrene butadiene rubber latex (SBR) and composite wood products, such as particleboard, made with formaldehyde-based resins.

2. *Surrounding Air*: Building surfaces may also emit substances and particles which they have absorbed from the surrounding air. While all surfaces adsorb molecules of chemical substances and compounds from the air they are exposed to, the process may be permanent or reversible. The degree to which a substance is adsorbed depends on the chemical characteristics of the compound, and on the virtual surface area (texture) of the surface (sink material). The sink material becomes loaded partially in proportion to the concentration of pollutants in the air. It can store pollutants during periods of high concentration and emit later when concentration is low.

3. *Cleaning and Maintenance* : Substances used to maintain building surfaces and equipment could be strong sources of pollutants. Although these materials are not generally part of the original construction, their use is determined to a large extent by decisions made at the design stage. Proper material selection which accounts for required cleaning agents and durability (which will determine the rate of replacement necessary) can significantly reduce emissions from maintenance. Maintenance products which have strong odors or irritating constituents should be avoided where possible.

Selection of Healthy Materials

There are several factors which need to be considered in the selection of materials for healthy indoor environments. While many of these factors deal with the material itself, the context in which the material is to be applied, the company that supplies it and its cost implications should also play an integral role in the decision. (Levin, 1993b)

Type of pollutant: The characteristics of a product's or material's expected emissions, including the type of compounds and chemical composition, will determine the timing and gravity of air pollutants which are likely to be found in the air at any given time. The volatility of the compounds will determine how quickly they will be dissipated into the air. Volatile compounds will leave the products very quickly, but a large quantity of emissions may adsorb on sinks, causing them to be present for an extended period of time. While less volatile compounds are released at a lower rate, they may persist for extended periods.

Impact of pollutants: The effects of particular emissions on occupant health and comfort, both physiologically and psychologically must also be considered in order to estimate the potential harm which may be caused by the product or material. In most cases, an acceptable concentration of a contaminant needs to be evaluated in terms of toxicity, irritancy and odour. Emissions with carcinogenic and teratogenic potential, for instance, are generally unacceptable. Irritation and toxicity effects are also unacceptable, but concentrations resulting from a single product rarely reach levels that will cause serious effects by themselves. Odour may be acceptable, depending on the application and the strength of the odour relative to its detection threshold. Its character is also critical in determining the odour's acceptability.

Amount of emissions: Two factors will determine the amount of pollutants that will be emitted into the air. The first is the quantity of the material that will be used in the building, and the second is the amount of pollutants that the material will emit over its useful life.

Location, temperature and humidity: Some types of emissions are affected by changes in environmental conditions, such as temperature and humidity. Others may be affected by air currents. Fibrous pollutants found in insulation, for instance, may not be harmful if an air-tight envelope prevents them from entering the home.

Sink Potential: A material may act as a secondary emission source if it has a high sink potential; that is, an ability to adsorb and re-emit pollutants. Total surface area and material characteristics will determine a product's sink potential. While very little data is available to quantify the exact effect of various materials, it can be generalized that the rougher the surface, the greater the sink potential. Glass and steel, for instance have a very low sink potential, while textiles adsorb relatively high

amounts of pollutants. Wood and plastics are intermediate.

Maintenance requirement: The impact of expected maintenance routines on IAQ will depend on the frequency of maintenance required and on the nature of material and processes required to perform maintenance. Ideally, products which require no maintenance are best. Alternatively, products than can be maintained with water or dry cloths are benign. Products that require the frequent use of solvents are least desired.

Availability of information: Some products, such as carpets, particleboard and other manufactured wood products, are subject to standard testing procedures, the results of which can be compared. Manufacturers of these products who do not disclose full emission test reports should be considered with skepticism, if considered at all. In cases where testing is not common or standardized, the manufacturer should disclose the product's contents and a description of the manufacturing and treatment that is likely to affect its emissions.

Manufacturers' IAQ program: The willingness of manufacturers to take steps to improve a product's performance in terms of harmful emissions should also be taken into consideration in the selection of a product. Pretreatment and aeration of a product prior to its installation in a building, for instance, could significantly improve that product's IAQ performance.

It should also be mentioned that considerations for good IAQ are not limited to house construction . Many furnishings are made of particleboard products or have lacquered finishes which have high levels of emissions, sometimes for lengthy periods. While the selection of furniture is usually beyond the responsibility of either the architect or the builder, it might be useful to include suggestions for furniture selection in an owner's manual, along with recommendations for cleaning products, and maintenance of ventilating equipment.

IAQ and Building Materials

The most harmful indoor contaminants emitted from building materials can usually be traced back to a few ingredients. Most harmful emissions originate from adhesives, products that require polymerization or foam expansion, vinyl products (particularly those with plasticizer) and maintenance products such as waxes and cleaning agents (Table 2).

The use of adhesives in building materials is one of the biggest problems associated with poor IAQ. Multi-purpose adhesives used for carpeting, sheet and tile flooring initially emit volatile organic compounds (VOCs) at very high rates. Adhesives used as binders in composite wood products like particleboard and plywood are major sources of formaldehyde in homes, but not all glue-bonded products emit harmful levels of pollutants. Products

Principle Pullutant [1]	Building Product	Timing/ Duration
Formaldehyde	Hardwood plywood, particleboard & other glue-bonded wood products (structural products made with waterproof adhesives such as softwood plywood and waferboard have negligible emissions)	Highest emissions when new; may continue for up to a year; emissions increase with temperature and humidity
Toluene, xylene hexane, aliphatic hydrocarbons	Styrene Butadiene Rubber (SB-R) sealants; Butyl Rubber (BR) or Solvent-Based Acrylic sealants [2]	May vary from 56 to 4,932 hours, depending on drying time (see Table 2)
4-phenylcylohexane (4-PC), styrene	Styrene Butadiene (SB) latex-backed carpets	Low emissions, but may persist due to the high sink potential of carpeting
Multiple Volatile Organic Compounds (VOCs)	Vinyl tile & sheet flooring	Decrease substantially after 24 hours if well ventilated; lower emissions can continue for years
	Traditional, multi-purpose carpet adhesives, both organic solvent and water based	Highest for the first 3-6 weeks; may persist depending on sink potential of flooring material
	Latex (water or organic solvent-based) & acrylic paints	During application and drying; lower emissions may persist for months
Fibers/particulates	Fiber glass & mineral wool insulation	Most pronounced when insulation is being installed or disturbed; air-tight construction keeps fibers from blowing to the interior

[1] Many other building materials not included here also emit VOCs in negligible quantities
[2] Emissions may be acceptable when used in limited quantities or under special precautions

Table 2: Indoor Air Pollutants from Building Materials

which contain phenol formaldehyde instead of urea formaldehyde-based adhesives emit negligible amounts of formaldehyde, which does not pose a threat to IAQ. Exterior-grade, waterproof composite wood products like softwood plywood and waferboard are examples. Binders and fire retardants used in insulation products like fiberglass, mineral wool or cellulose also emit lower amounts of VOCs, but their location inside the building envelope makes it unlikely that the indoor air will be affected significantly.

Adhesive manufacturers have also developed "low-emission" adhesives, which can substantially reduce the amount of formaldehyde being released into the surrounding air. Pollutants from adhesives can be significantly reduced by specifying products made with low-emission adhesives like phenol formaldehyde, or by sealing the product to keep the VOCs from being released. Particleboard furniture and cabinets covered with laminate on all sides, for instance, can keep emissions down to acceptable levels. Alternatively, these materials can be replaced altogether with solid lumber components. Carpets can be laid using the tackless strip method, which requires little or no gluing.

Flooring products made from polyvinyl chloride (PVC), such as vinyl tile and sheets, have very high VOC emissions, particularly in the first 24 hours following installation. The main cause of these emissions is TXIB, a plasticizer which is incorporated into the product to increase workability. Although tiles contain less plasticizer than sheet materials and, as such, have fewer emissions, their impact on IAQ can still be substantial. The effect is compounded with the use of multi-purpose adhesives.

Styrene butadiene (SB) is another source of harmful VOC emissions. Sealants made from SB rubber release several toxic chemicals while curing, and are considered hazardous for indoor use despite the fact that they dry relatively quickly (Table 3). Other sealants like solvent-based acrylics emit fewer hazardous chemicals, but have longer curing times. Their safety for use indoors can only be insured if they are used in limited amounts under adequate ventilation.

Carpets backed with SB latex emit 4-PC (which is responsible for the "new carpet" odour) and styrene.

Type of Sealant	Principle VOC Emission	Indoor Safety [1]	Drying Time (hrs)
Acrylic (water-based)	(multiple)	Safe	—
Acrylic (solvent-based)	xylene	Limited	1,052
SB Rubber	hexane, toluene, xylene	Hazard	56
Butyl Rubber Caulk	aliphatic hydrocarbons	Limited	80
Oil-Based Caulks	aliphatic hydrocarbons	Safe	1,962
Silicone	xylene	Safe	487
Polyurethane	xylene	Safe	8,269
Polysulfide	toluene	Safe	4,932
Asphaltic	(multiple)	Safe	4,496

[1] Based on evaluations in Jennings et al., 1988.

Table 3: Emission Characteristics of Sealants

Although the amount of emissions are usually low, they may persist for long periods of time because of the high sink potential of carpets (Randal, 1991; Bayer, 1991). Latex-based paints have been found to emit large quantities of VOCs, but the duration of emission is limited to application and drying time. Unless other building materials and furnishings in the space have a high sink potential, sufficient ventilation during application and drying can significantly reduce the potential impact on IAQ.

The effect of maintenance products such as cleaning agents and waxes should not be underestimated. The frequent use of these products may result in constant emissions which can seriously affect IAQ, particularly with furniture and fabrics present, which have a high sink capacity.

In addition to VOCs, some building materials emit small particles which can be harmful if inhaled for prolonged periods. Fibers from fiber glass or mineral wool insulation, for instance, are suspected carcinogens. Installation of these products should only take place under well-ventilated conditions. A well-sealed envelope can keep the insulation from being disturbed by air currents, keeping most of these pollutants out of the living spaces (see *Building Details*).

While building materials can be a major source of indoor air pollution, there are several other contaminants which can originate from other sources (Table 4). Combustion gases from unvented furnaces and appliances, radon gas from soil, and particulates such as dust and pollen can seriously affect occupant comfort and health, particularly in sensitive individuals.

Analysis

The selection of materials to eliminate all forms of indoor air pollutants, as would be the case for sensitive occupants, requires careful design and construction practices in addition to the selection of proper materials. In many cases, however, simple, basic precautions can significantly improve IAQ without the need for lengthy or involved analysis. By addressing the principle sources of indoor air contamination and providing continuous ventilation, most smaller homes can have healthier environments at a reasonable added expense.

For a house like the Grow Home, the replacement of some common materials which cover a large portion of the interior surfaces can provide substantial improvements to the quality of indoor air. Substituting harmful carpets, vinyl floors, kitchen cabinets and sealants with less powerful sources is a good starting point.

Table 5 shows the approximate cost of making these replacements for the Grow Home. Installing carpeting over a cushion and using the stretched-in, tackless strip method rather than gluing SB latex-backed carpeting directly to the subfloor can cost approximately $6.46 more per square meter. Replacing the vinyl sheet flooring with ceramic tile would cost an additional $41.86 per square meter. Assuming that both the kitchen and bathrooms are covered with vinyl flooring and that the rest of the house is carpeted, the added cost of fully replacing these materials is about $1,293. The particleboard kitchen cabinets can be replaced with solid hardwood at an additional cost of $555, and silicone sealants in

Type of Pollutant	Examples	Effect on Occupant Health	Source of Contamination
Biological Growth			
Fungi	Mould, mildew	Allergic reaction and aggravation of asthma symptoms in high concentrations; irreversible lung damage (with inhalation of mould spores)	High humidity levels caused by washing, bathing, cooking, unvented clothes dryers, etc.
Chemicals			
Inorganic Gases	Carbon monoxide	Reduce endurance, worsen symptoms of heart disease, nausea, headache, dizziness, death (in very high concentrations)	Gas stoves, kerosene heaters, tobacco smoke, vehicle exhausts
	Carbon dioxide	Unlikely to affect health in low quantities that are generally found in houses	People, gas stoves, furnaces, kerosene heaters, combustion devices
	Nitrogen dioxide	Breathing difficulty in high concentrations; respiratory illness with prolonged exposure	Vehicle exhausts, industrial emissions, gas stoves, kerosene heaters
	Sulphur dioxide	Aggravate asthma symptoms and existing lung disease; breathing discomfort; lung disease with prolonged exposure	Mainly outdoor sources, unless sulphur-containing fuels are burned indoors in unvented appliances
	Chlorine	Irritation in susceptible occupants	Household cleaning and laundry products; municipal water sources
	Ammonia	Irritation in susceptible occupants	Household cleaning products
	Ozone	Coughing; chest discomfort; nose, throat and windpipe irritation	Electrostatic air cleaners, arcing electric motors, photocopiers, outside air
Volatile Organic Compounds (VOCs)	Formaldehyde & other aldehydes, hydrocarbons, alcohols, phenols, ketones	Unpleasant odors; eye, nose and throat irritation; central nervous system depressant; possible carcinogens; prolonged exposure may cause sensitization	Building materials; furniture, carpets, synthetic floor coverings, wallpapers, plastics; household products, beddings, toilettries, etc.; tobacco smoke; gas stoves, space heaters; pesticides.
Particulates			
Biological Particles	Viruses, bacteria, spores, pollen, cell debris, dust mites	Few health problems at levels normally found in houses; high concentrations of pollen grains may cause allergic reactions or aggravate asthma symptoms; bacteria growth in stagnant water may cause serious disease	Stagnant water, dust, water droplets
Non-Biological Particles	Dust, smoke, etc.	Effects may vary from mild discomfort to lung cancer	Tobacco smoke, wood stoves, open fireplaces, combustion operations; construction materials
	Fibers	Temporary eye and skin irritation; lung disease with prolonged exposure; glass fibers may be carcinogenic; asbestos causes lung cancer	Construction materials; fiber glass and mineral wool insulation
Natural Soil Gas			
Radon		May contribute to incidence of lung cancer with prolonged high exposure	Soil; improperly sealed basement floor slab

Compiled from AIA, 1992; Drerup, 1990; HWC, 1987 & Small, 1983.

Table 4: Types, Effects and Sources of Indoor Air Pollutants

the kitchen and bathroom could replace butyl rubber caulking for about $20 more. Altogether, most indoor contaminants originating from building materials could be practically eliminated for $1,868.

Material Replacement	Product Quantity	Additional Cost/Unit	Total Cost
Carpeting			
SB latex-backing; glued installation to Bonded urethane cushion backing; no adhesives	59.75 sq.m.	$6.46 /sq.m.	$385
Kitchen Cabinets & Vanity			
Laminated particleboard to Solid lumber	5.5 m.(wall) 3.2 m. (base)	$59.00 /m. $72.00 /m.	$555
Kitchen & Bathroom Flooring			
Vinyl sheet flooring glued to subfloor to Ceramic tile on mortar bed	21.70 sq.m.	$41.86 /sq.m.	$908
Interior Sealants			
Butyl rubber caulking to Silicone sealant	approx. 1 gal. (45 m.)	$21.00/gal	$20
	Total		$1,868

Table 5: Alternative Building Materials for the Grow Home

It should be mentioned that these cost comparisons are strictly for the sake of analysis, and do not reflect the many options possible. Finishing materials and furnishings, including carpets, ceramic tiles and kitchen cabinets, are available in a very wide range of prices. Some of the replacements made to improve indoor air quality can cost significantly less that what is shown in Table 5. Futhermore, most carpets for residential use are typically installed over a cushion, and make little or no use of adhesives. As such, these costs represent worst-case scenarios, or maximum cost implications for achieving good IAQ.

The replacements shown in Table 5 not only reduce the VOCs being emitted, but are also beneficial to the environment in other ways. Bonded urethane cushion pads, used under the carpet, are made mostly (90%) from scrap polyethylene. The embodied energy in ceramic tile is much lower than that of vinyl flooring, and the solid lumber product used for the kitchen cabinets also requires less energy to make than composite wood products. The added investment is made for the benefit of the occupant as well as society as a whole.

Summary

Healthy indoor environments can be achieved by carefully eliminating pollutants at the source while ensuring that adequate ventilation is provided, during both construction and occupancy. While some sources of pollution, like those found in furniture, are usually beyond the control of both home designers and builders, the proper selection and installation of building materials can contribute significantly to good IAQ. Avoiding a few of the more powerful pollutant sources, like urea formaldehyde-based adhesives, SB in sealants and carpet backings, and plasticizers in vinyl products can go a long way in reducing harmful VOC emissions. For a Grow Home, the cost of replacing particleboard, vinyl and SB products with healthier alternatives is approximately $2,000, although this figure can vary significantly depending on the alternative. Considering that the replacement products can benefit the environment in more ways than one, that the well-being of the occupants is at stake, and that the appearance of the house may be improved, this initial investment appears to be worthwhile.

Further Reading

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Guidelines

Following some general rules when selecting and installing building materials can improve the quality of indoor air:

- Provide adequate ventilation when installing insulation or vinyl flooring, or when applying wet coatings like adhesives, sealants, paints and wood finishes.
- Ensure that the ventilation system is properly designed and installed to provide a sufficient, continuous flow of fresh air to all spaces in the house.
- Keep insulation dry to prevent fungal and bacterial growths.
- Use sealants and adhesives with low VOC emissions, and specify products made with low-emission adhesives.
- Consider using solid lumber products instead of particleboard and hardwood plywoods made with urea formaldehyde (UF) -based adhesives.
- Avoid using UF particleboard in spaces where high humidity and temperatures are expected, as in kitchens and bathrooms.
- Install carpeting using the stretch-in, tackless seam method rather than gluing it down.
- Use separate cushion underlayments for carpets rather than SB latex backings that are part of the carpet.
- Ensure an air-tight envelope to prevent contaminants inside the wall from getting into the house.

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Introduction - Part II

The second part of this report considers some development project issues of scale and reviews some traditional and innovative ideas and practices affecting newly built communities. It is comprised of the following five sections, written with pragmatic objectives in mind. It is hoped that builders, architects and planning authorities will gain a better understanding of how to implement narrow-front row-houses in new communities.

Site Planning

The section entitled site planning looks at some broad and basic principles which can influence the environmental impact of any development. Site selection, land subdivision, networking and building type are all considered.

Circulation and Parking

In this section, circulation and parking are analyzed at the scale of the individual unit. Access to a dwelling includes the design and planning of streets, pedestrian and cycle paths, parking areas and proximity to transit lines. At the community level, these factors will affect the level of control in a new project. The issue of control is directly related to the level of safety and security in a new development.

Outdoor Living Areas

In this section, outdoor living areas are examined in the context of high density housing developments. Since the amount of private space must be sacrificed somewhat in these developments, communal space becomes more significant. Outdoor areas must provide visual and functional stimulation to neighbourhoods. Levels of privacy, a clear demarcation of edges, benches, landscaping and hardscaping are all essential elements. The manipulation of microclimates, including sheltering outdoor rooms from the wind and providing a balance of sun and shade, also affect the built environment.

At the level of the individual unit, a clear distinction between private and semi-private areas is important. The front yard provides a transition zone between the public and private realms of the house and a link to the fabric of the neighbourhood. It is important to have the front yard ownership defined, yet it should also stimulate resident interaction. The front entrance is significant in defining how public and private realms meet; its demarcation can be achieved by building a step, a porch or other detailing. A backyard can be defined with hedges, fences, screens and trellises to provide a sense of enclosure for more intimate activities and to maintain visual privacy.

Housing Identity

This section discusses how to achieve housing identity in a new development. To lower costs, builders rely on the repetition of forms. Stark and banal environments resulting from monotony can be avoided, however, if the designer conceives of and provides for a community image and unit identity in the initial design. For example, sequencing of views creates interest at the scale of the overall site by punctuating and varying the design in order to avoid dulness. Also, by providing a fixed number of variable elements that can be combined in interesting ways, the designer is able to create a certain degree of diversity and personalization. These qualities contribute to an appealing community image, and, in the primary design stage, can be achieved economically. If the community is appealing, increased sales and buyer satisfaction will be more profitable for the builder.

Environmental Comfort

This section examines how design can stimulate human senses in order to elicit a positive response towards the surrounding built environment. User satisfaction often depends on factors that are not quantifiable. For example, planting trees on a property can benefit a home owner in many ways: visual and audio privacy from neighbours, the smell of a blossoming tree each year, and shade from direct sunlight.

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Site Planning

Planning Principles

Sustainability can be encouraged at each stage of the design process. Planning and layout of a community is usually considered to be the first intervention of a designer but efforts to build more sustainable communities can begin much earlier. The scope of planning is wide, therefore, four phases of the planning process will be used to describe possible planning interventions that can promote sustainability. These phases are: site selection, land subdivision, networking and building type.

Site Selection

Around the beginning of the twentieth century, about 100 years after the steam train gave birth to the modern city with a thriving and dense town, electric streetcars replaced horse-drawn vehicles and make possible wide scale suburban living around many cities. Dispersed development pattterns continued through the 1930's and '40's when buses and cars, which required no special infrastructure, such as overhead wires or steel rails, introduced a new level of transport flexibility. The most significant response to this new found accessibility was the further dispersal of urban development, particularily residential development.

Through the years, dispersed, low-density development patterns have been encouraged by political and industry interests, however, there is mounting evidence that they are unsustainable. Low density developments are very energy intensive, they tend to encroach on the nation's prime agricultural land and other environmentally sensitive areas. They are also very expensive to service with linear infrastructure and other community facilities.

Some consensus has emerged recently that we should concentrate our development efforts within the existing built environment, redeveloping and infilling where appropriate, in order to conserve energy, protect outlying areas and make better use of our existing infrastructure. Although there are opponents to this form of "urban intensification", usually citing unfair government regulations and growth control measures, it is clear that the status quo will have to change. Governments at all levels can no longer afford to subsidize developments on the fringe, while also supporting and maintaining the infrastructure in older and aging neighborhoods. Low-density "leapfrogging" developments will have to be more actively discouraged, and more incentives for infilling and redeveloping under-used land within existing urbanized areas must be provided.

Objective

The objective of this section is to identify some basic planning principles which need to be addressed at the outset of any housing development, and to discuss the origins and influences of each principle on sustainability.

Land Subdivision

In Canada the manner in which land is subdivided varies from one region to another. Random or "unplanned" settlements such as the "organic" forms found in parts of Newfoundland, closely reflect the natural topography of the land.

Organic settlements tended to grow out of necessity rather than as a result of a prescribed planning interventions. Plots of land were not all of the same dimensions and natural landscape features, such as rivers and drastic changes in elevation were used to demarcate one lot from another (Figure 1).

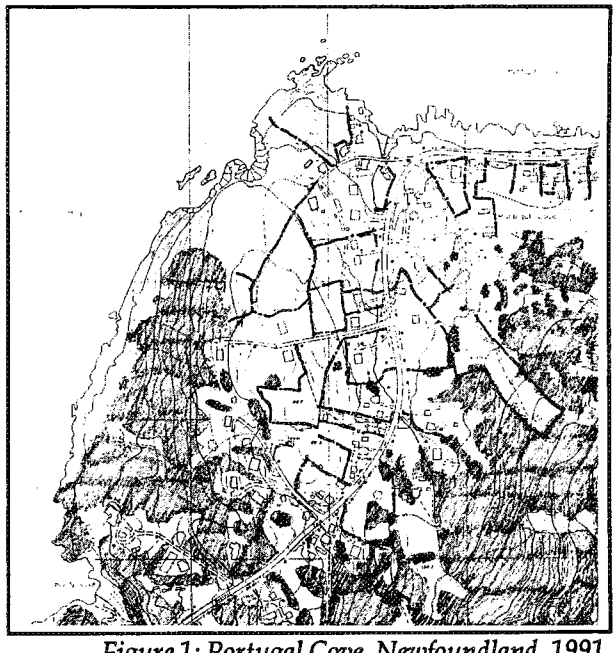


Figure 1: Portugal Cove, Newfoundland, 1991, Organic Form of Settlement

In Quebec, the seigneurial system divided land into "long lots". Each lot ensured access to both a river and a road (Figure 2). This settlement pattern was much more systemmatic in orientation than organic settlements, and showed a senstivity to hydrography, topography and the value of agricultural land.

Figure 4 shows an example of the seigneurial settlement pattern in the second half of the 19th century; the subdivision system follows the principles set out during the French colonization, a century earlier.

The "square mile" method of land subdivision extends from Ontario through the Prairie provinces to western Canada (Figure 3). This cartesian grid overlaid across the country allowed for indeterminate land division. The grid allowed for streets and blocks to meet at regular intersections; city centres could develop at any intersection, allowing for endless expansion.

The above systems for subdividing land each have their merits and are appropriate in different contexts. The problem is that the legal framework for land subdivision from region to region is often more influential in terms of design constraints than the

Figure 2: Quebec System Land Subdivision

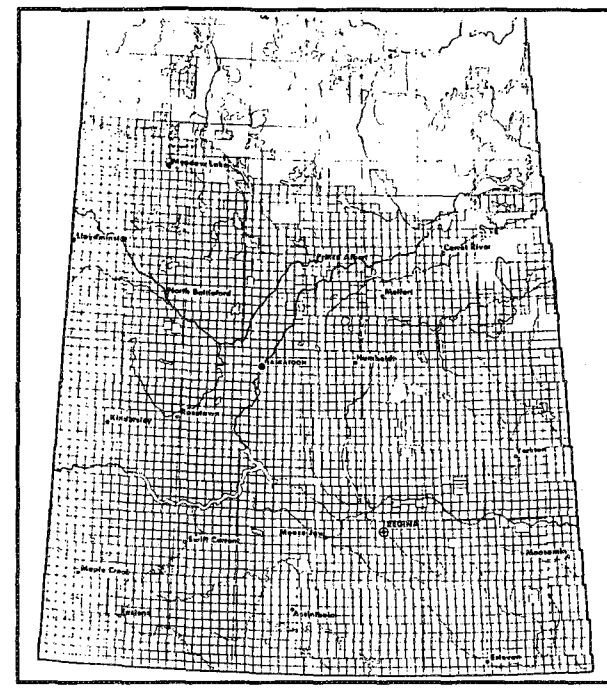


Figure 3: Square Mile Settlement Plan

natural assets of the site itself. Ensuring more sustainable developments means looking at sites beyond these legal parameters and dividing land in the most appropriate way, according to its site specific characteristics.

Networks and Utilities

When a site has been selected for a proposed development, supporting networks, or physical links, must be established to connect the sit to existing services and other amenities within the larger community. Integrated access routes must be provided for pedestrians, bicycles and cars. Ensuring convenient access to existing commercial, retail and service functions will strengthen the urban fabric of the area, promote more social interaction, and stimulate the local economy. When building within an already developed area, savings can also be realized by making better use of existing infrastructure, such as hydro and gas lines, neighbourhood schools and so on.

When building within an already developed area, the layout of the site will largely be determined by surrounding streets extending into the site, which in turn defies buildable and open spaces (Figure 4). Along with various engineering measures intended

to ensure adequate safety, sufficient street widths and efficient access to arterial highways, transportation routes can end up dominating the landscape and dictating the subsequent built form.

To help alleviate this problem, provisions should be made for alternative modes of travel. Bicycle and pedestrian paths should be planned to provide easy access between homes, employment and daily services. Pedestrian paths should also provide convenient links to the closest transit stops, ideally located within a five or ten minute walk from every house, Reducing dependence on private automobiles will ultimately reduce the amount of paved surfaces that are required, leaving more land available for other uses.

Separating pedestrian, bicylce and automobile traffic will enhance the safety of the development, particularly for children and the elderly. Pedestrian and bike paths linking open spaces and other significant landmarks can also help improve the liviability of a neigborhood and the overall "urban experience". These objectives, contributing to the development of "people places", should not be completly sacrificed in an attempt to satisfy the needs of the car.

Building Types

The density of a proposed housing development and the house forms used to achieve this density are critical determinants of the overall success of a project. Density affects a project's marketability and it determines the builder's profit margin. One of the key challenges for planners, architects and builders is choosing the most appropriate house form that will acheive a desired density without compromising inhabitants' quality of life. This challenge, and the necessary tradeoffs, changes from site to site.

Figure 5 lists the range of building possibilities that can be used for residential purposes. Depending on the site, the context and the builders' program, many options can be considered. All else being equal, the lowest-density option, the single-family detached home, is the most inefficient in terms of building materials, land, infrastructure and operating energy requirements. Large, detached homes are also less appropriate given today's changing demographic and socio-economic conditions.

Denser housing options on the other hand, consume less land per unit, require fewer building materials,

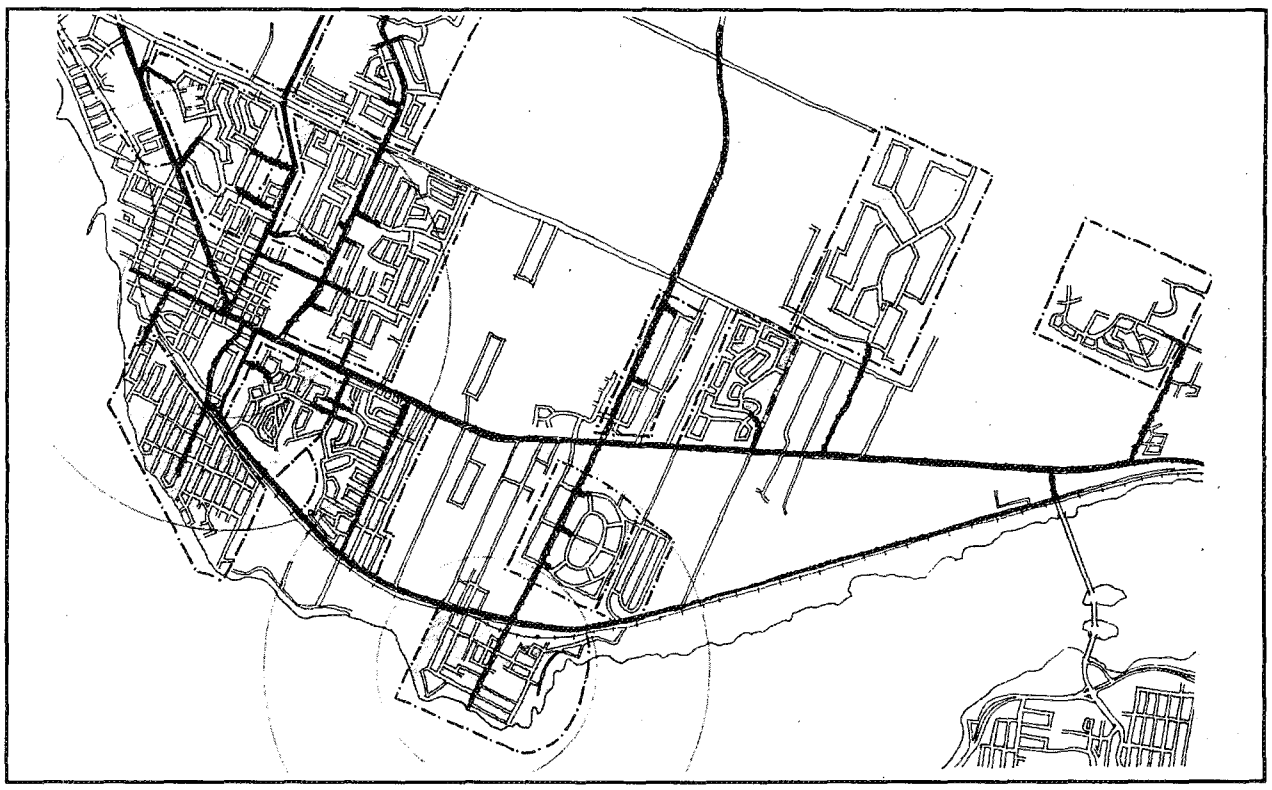
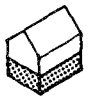
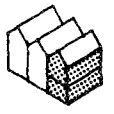
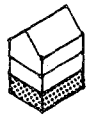
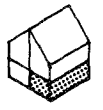
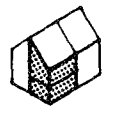
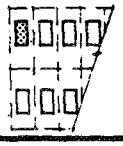
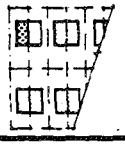
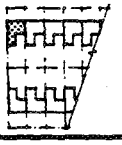
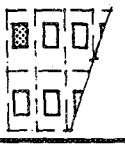
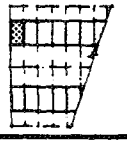
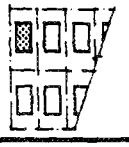
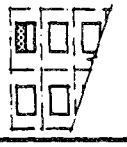
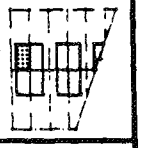


Figure 4: Main Access Routes to Aylmer, Quebec

Dwelling Type	1 Single detached	2 Semi detached	3 Joined court	4 Duplex	5 Row house	6 Triplex	7 Quadruplex	8 Back to back Semi detached
Isometric								
Plot Plan								
Dwelling units/acre (dwelling units/hectare)	8 (20)	14 (35)	16 (40)	17 (42)	19 (47)	21 (52)	23 (57)	24 (59)
Floor area ratio % open space	0.24 76%	0.38 81%	0.44 56%	0.68 88%	0.56 72%	0.60 80%	0.66 67%	0.66 67%
Unit relationship to grade	on grade	on grade	on grade	50% on grade 50% gr. related	on grade	33% on grade 66% gr.unrelated	50% on grade 50% gr. related	on grade
Access to unit	private on grade	private on grade	private on grade	50% priv. on gr. 50% priv. stair	private on grade	33% priv. on gr. 66% common stair	50% priv. on gr. 50% priv. stair	private on grade
Unit aspect	quadruple	triple	triple	quadruple	double (opposite)	quadruple	triple	double (adjacent)
Private outdoor space	on grade	on grade	on grade	50% on grade 50% gr. related	on grade	33% on grade 66% gr.unrelated	50% on grade 50% gr. related	on grade
Parking	private on grade	private on grade	private on grade	common on grade	private or com. on grade or u/g	common on grade	common on grade	private on grade

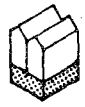
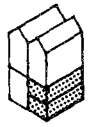
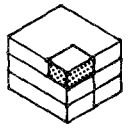
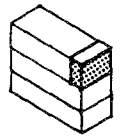
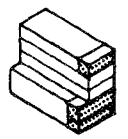
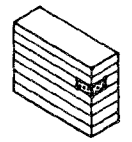
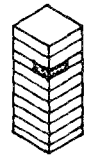
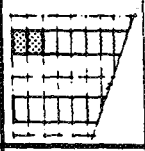
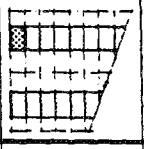
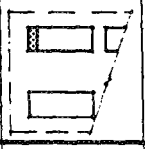
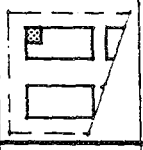
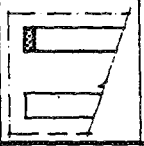
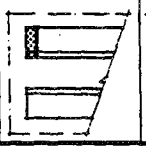
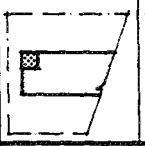
Dwelling Type	9 Stacked row house (1½ / bay)	10 Stacked row house (2/bay)	11 Garden apartment	12 3 - storey walkup apartment	13 Medium rise stacked units	14 Combined apartments & row houses	15 Slab block apartment	16 High rise point block apartment
Isometric								
Plot Plan								
Dwelling units/acre (dwelling units/hectare)	31 (77)	35 (86)	52 (128)	65 (160)	71 (175)	84 (207)	90 (222)	120 (296)
Floor area ratio % open space	0.86 72%	1.14 72%	1.06 62%	1.36 55%	1.95 68%	1.92 62%	1.78 82%	2.62 87%
Unit relationship to grade	33% on grade 66% gr. related	50% on grade 50% gr.unrelated	33% on grade 66% gr.unrelated	33% on grade 66% gr.unrelated	33% on grade 33% gr. related 33% gr.unrelated	25% on grade 75% gr.unrelated	small % on grade majority ground unrelated	small % on grade majority ground unrelated
Access to unit	33% priv. at gr. 66% priv. stair	50% priv. at gr. 50% com. stair	common stair	common stair	common elevator	25% priv. at gr. 75% com. elev.	common elevator	common elevator
Unit aspect	double (opposite)	double (opposite)	double (opposite)	single	double (opposite)	double (opposite)	single (and double adj.)	single (and double adj.)
Private Outdoor space	33% on grade 66% gr. related	50% on grade 50% gr.unrelated	33% on grade 66% gr.unrelated	33% on grade 66% gr.unrelated	33% on grade 33% gr. related 33% gr.unrelated	25% on grade 75% gr.unrelated	small % on grade majority ground unrelated	small % on grade majority ground unrelated
Parking	common underground	common underground	common underground	common underground	common underground	common underground	common on grade or u/g	common on grade or u/g

Figure 5: Housing Types and Forms (Diamond, 1976)

and servicing costs are lower, all of which enhances housing affordability.

The design challenge for denser, more sustainable developments is to make these communities, "sqeezed" by North American standards, livable and comfortable environments for all inhabitants. In Montreal, the duplex typology has been used extensively, and in many cases has acheived a comfortable balance between density and quality of life. Triplexes are also quite common in Montréal and have been very successful. Walk-up apartments, originally derived from the Parisian walk-up typology, have been modified over the years and can be found in cities throughout North America. The high-rise, which applies to buildings over four storeys equipped with an elevator, is the most extravagant of the building types. Due to the steel or concrete structure and mechanical services required, the high-rise is relatively expensive to buildi and is usually reserved for high density luxury apartments.

Narrow-front row houses, such as the Grow Home, is another typology that can acheive medium- to high-density living environments, without compromising quality of life. The narrow front row house typology is not new. Examples exist in North America and Europe and they are often cited for their appealing character. Moreover, smaller, denser houses, such as the Grow Home, are responding to the changing housing needs of today's smaller households. A post-occupancy survey of a Grow Home development conducted in May 1992, revealed that the majority of the units were occupied by young couples with one child (37.7%). This was followed by households composed of: couples (32.5%); singles (16.5%); single-parent families (9.8%); and households with two or more adults (3.6%). The survey reported high occupant satisfaction with almost all elements of the development and units (Friedman and Cammalleri, 1992).

Despite the success of the Grow Home, however, there still seems to be a social stigma associated with high-density housing options, especially in established communities where single-family detached homes are the predominant house form. This problem can be overcome if denser developments, often associated with barren and sterile surroundings, are designed with forethought and particular attention to factors which have been singled out as important in acheiving more sustainable environments: vehicular circulation and parking; outdoor spaces; environmental comfort; and housing identity. Each of these will be addressed in turn below.

Guidelines

- Select, if possible, a site within the boundaries of am existing urban area. This infill approach refers to the small lots of inner cities and to the larger patches of land between existing neighbourhoods of a municipality.
- Design for higher densities, thereby improving land use efficiency and reducing infrastructure requirements.
- Account for the pedestrian in planning communities, not just the car, to encourage neighbourhood interaction and diminish reliance on vehicular circulation.

Further Reading

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Vehicular Circulation and Parking

Background

In the development of new residential neighbourhoods, there are two main objectives to street design: access and control. For local residents, access implies access to the house, as well as proximity to a parking space from the house. Low density projects are usually planned with a portion of the lot reserved for a paved parking space. High density developments are usually designed with a common garage, and even higher density communities contain grouped parking lots.

A measure of control is necessary within a community. By controlling or limiting the speed of through traffic in a development, safety and security are ensured while access is provided. Generally, wide streets in a grid pattern tend to encourage through traffic, while the problem is less pronounced with the use of narrower curvilinear streets.

Access and Control

A street, whether public or private, is usually perceived as being part of the public realm. Controlling the access to an area is the first step in attempting to protect a neighbourhood. This can be formally imposed by building a gateway and/or checking who enters and exits the community (Figure 1). Imposing this type of physical obstacle is an example of an active control.

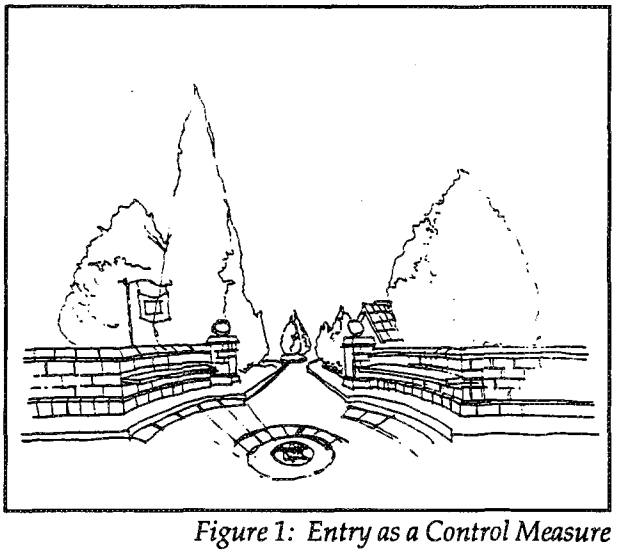

Figure 1: Entry as a Control Measure

Objective

The objective of this section is to examine some aspects of vehicular circulation and parking which will influence a project's sustainability. Several planning options are discussed.

One of the most successful planning interventions designed to actively control vehicular speed and access is the "Woonerf". A Dutch concept, the "Woonerf" forces cars to weave through obstacles, such as trees and parking spaces in order to intentionally control their speeds. Although successful in the Netherlands, the "Woonerf" cannot be transplanted to our Canadian climate without appropriate modification. The volume of snow that falls in our climate is a serious constraint. Streets must be sufficiently wide so that snow removal machinery can get through easily, witout having to maneuver around parked cars and irregular landscape features.

Passively controlling vehicle access and speed can be achieved through street design and layout. Narrow winding streets or dead-ends known only by residents are uninviting to outsiders. This passive control technique is widely used in suburban design (Figure 2). The purpose of impementing such a weaved pattern is to break one's sense of orientation and in so doing, reduce vehicular speed. This street layout also recalls the images of the "promenade" from the picturesque period in the late nineteenth century. This romantic and serene view of the newly designed neighborhood contrasts with the undesirable stereotype of residential living within the city: crowded, noisy and fast-paced.

A street hierarchy with different street widths and / or numbers of lanes for streets of differing functions also helps control access and speed. Local access streets provide frontage to lots and by design carry no traffic other than that generated on the street itself. Arteries or subcollector streets provide frontage to lots and also convey traffic received from the local access streets they serve. Collector streets conduct traffic between lower and higher order streets and between neighbourhoods and activity centres (Labs, 1991). This hierarchy of streets, however, does not always result in optimal circulation as it may not

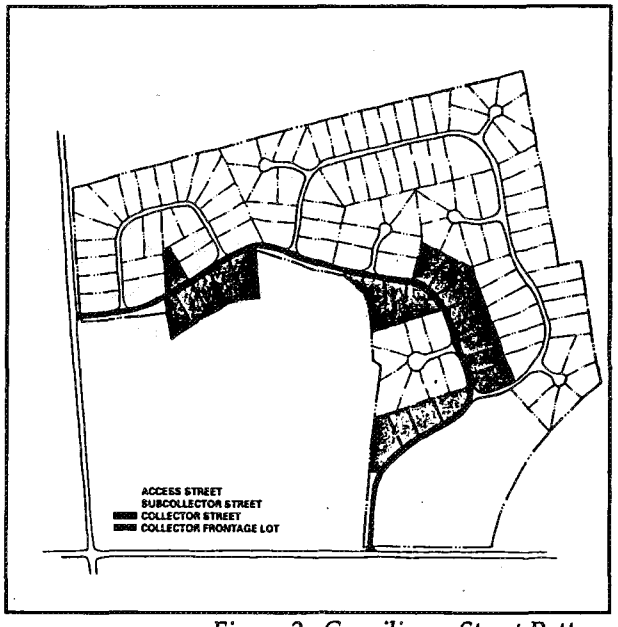

Figure 2: Curvilinear Street Pattern

always be efficient to design transportation networks that flow from a large number of local streets to a few wider roadways.

It is always difficult to provide a set of parameters that meet one set of criteria without disrupting another. Discouraging access into a particular district may increase safety but it will also inevitably result in the isolation of a neighbourhood. It might also be difficult to service the community with transit, and a car then becomes necessary to reach any services that are not provided within the neighbourhood.

Furthermore, although curvilinear streets are intended to slow down traffic, overly wide right-of-way widths, often required in new residential developments, may actually promote speeding as drivers become more familiar with roadways and less cautious in general.

Reducing right-of -way widths could help alleviate this problem. It would also increase the density of a development by reducing the face-to-face separation of houses, or the distance from house-to-house across a street (Figure 3). Existing land development standards typically require right-of-ways to be between15 and 20 metres wide. It is necessary to re-evaluate conventions such as these in order to promote more sustainable developments.

Guidelines

- Tradeoffs must be made between access and control. Hierarchical, curvilinear streets may discourage through traffic, but they also discourage rapid transit, isolate a community and increase dependence on private cars. A neighborhood's primary objectives must be assessed from site to site and priorities must be established.

- Parking in a project of 45-60 units per hectare can account for nearly 50% of the total site area. The higher the density of a development, the greater land area will have to be reserved for parking spaces. It is very important, therefore, in affordable, high density developments, to integrate these parking areas into the plan in an efficient and unobtrusive manner.

- Limited driveway and garage areas push spillover parking into the street as lot size and frontage shrink. For access streets with one moving and two parking lanes, a width of 8.5m is sufficient.

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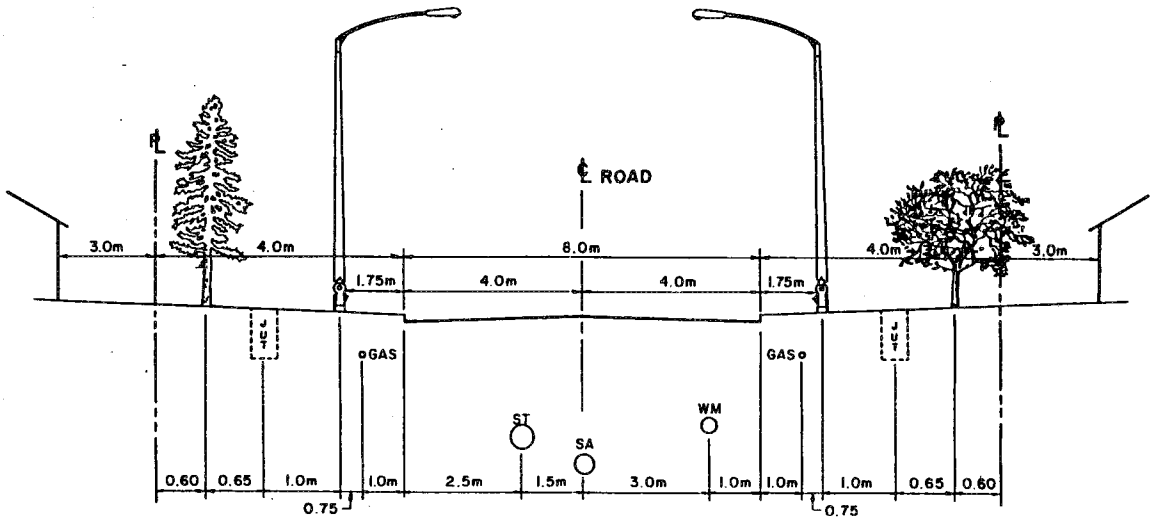
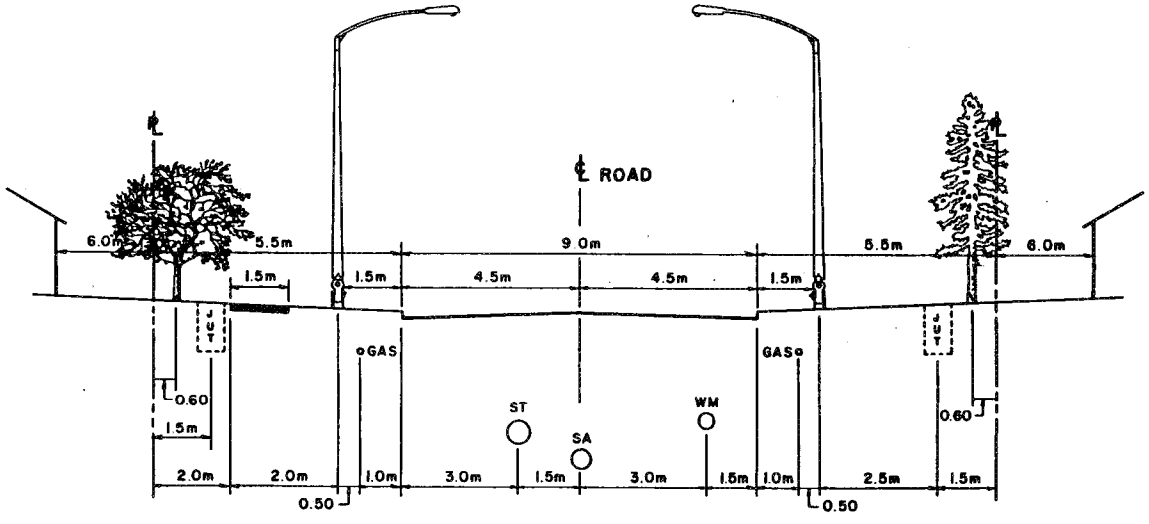


PROPOSED 16 METRE R.O.W.

22 METRE HOUSE FRONT TO HOUSE FRONT SEPARATION



EXAMPLE OF 20 METRE R.O.W.

32 METRE HOUSE FRONT TO HOUSE FRONT SEPARATION

LEGEND

CITY OF OTTAWA CR-90

ST - Storm Sewer
SA - Sanitary Sewer
WM - Water Main
JUT - Joint Utility Trench

Figure 3: Right-of-Way Alternatives

Outdoor Spaces

Background

With the increased cost of serviced land, the rising cost of living and the desire to live within a commutable distance from the city centre, high density housing has become a trade-off between the realities of affordability and the aspirations of the contemporary home buyer (Figure 1).

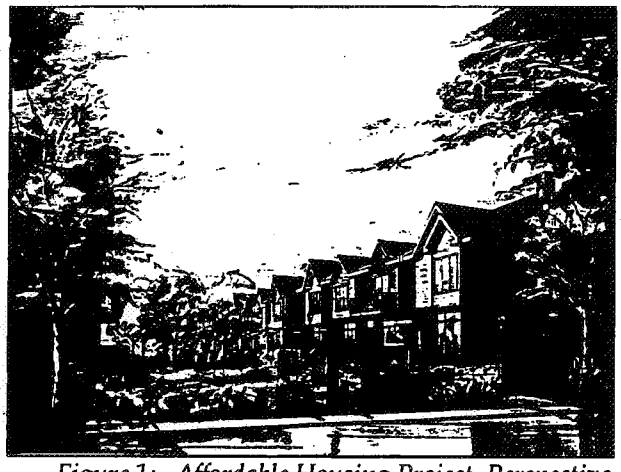


Figure 1: Affordable Housing Project, Perspective

Building high density developments implies a reduction of private outdoor space. A sustainable project is one that is economically feasible, socially acceptable and environmentally responsible. High density developments will be more attractive to potential home buyers if their need for outdoor space is satisfied. It is necessary therefore, to examine how outdoor spaces can contribute to the overall satisfaction and social well-being of the buyer. For example, how can outdoor spaces within high density housing developments be designed? How can they function in relation to one another? How can they support the individual house and the entire community? And finally, what are the social implications of these spaces for the residents?

Definitions

For the purpose of this section, it is necessary to identify the different types of outdoor spaces existing in low-rise high density, affordable communities.

Objectives

The objectives of this section are to: identify and define the different types of outdoor spaces that exist within a high density housing development; explain the importance of these spaces in relation to the functioning of a unit and the community; and describe and analyze efficient design solutions which have been used in past Grow Home developments.

Private Space: is the ground-related, outdoor space in the front and the back of a single unit. Outdoor extensions from the house, (e.g. balconies and porches) are also included here (Figure 2).

Shared Space / Semi-Private: is the ground-related, outdoor space that may benefit two or more units. This land is designated as shared space because it is not the private space belonging exclusively to one homeowner, and it is not intended to be used by the community at large (Figure 3).

Public Space: is a large landscaped space that is designed to accommodate every member of the community. Public space is designated during the site planning stage of a project (Figure 4). Public space in the form of parklands provides the possibility for

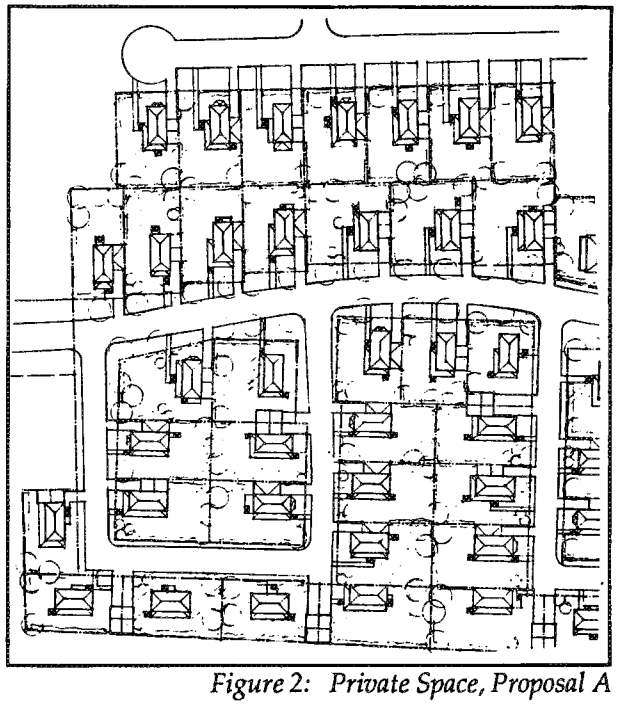


Figure 2: Private Space, Proposal A

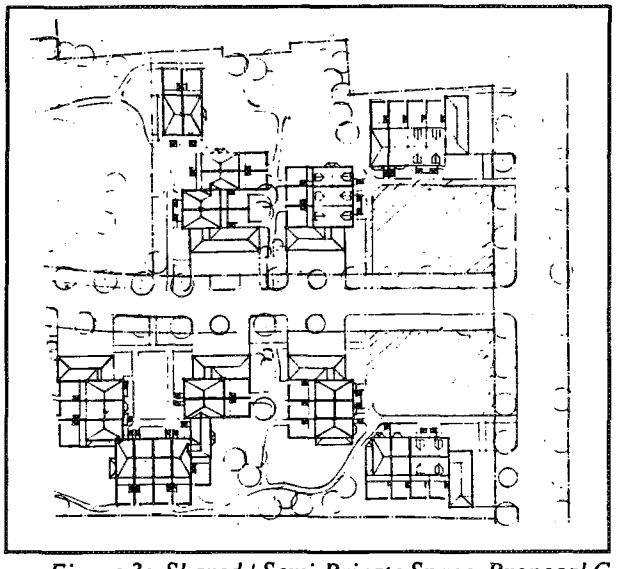


Figure 3: Shared / Semi-Private Space, Proposal C

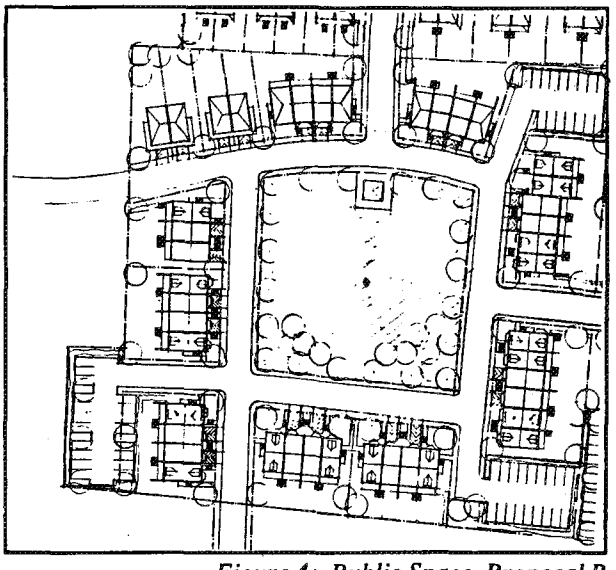


Figure 4: Public Space, Proposal B

community facilities, such as bicycle paths, a swimming pool or a skating rink.

Private Outdoor Space

The above definition specifies that private space is associated with one living unit. In Grow Home developments, the average size of a backyard is 65 sq.m and the front lawn is 20 sq.m. Although these spaces are considered small in comparison with a typical single family lot, user satisfaction can be increased by carefully considering such issues as: privacy; extensions from the house; the relationship between built and open space; and landscaping.

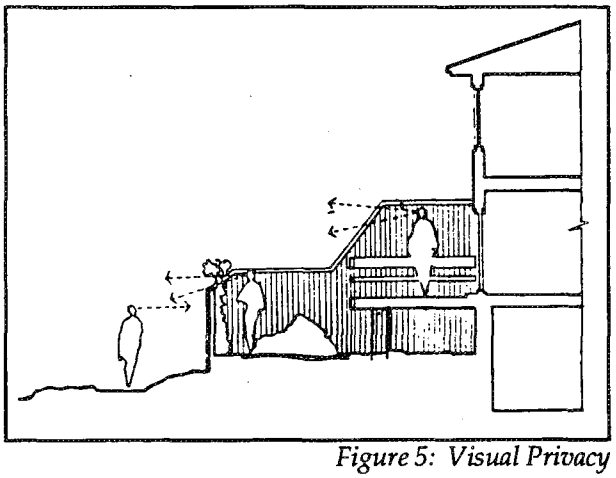


Figure 5: Visual Privacy

Privacy

The study of satisfaction is a complicated exercise, however, issues such as privacy and territoriality are particularily relevant. Privacy is a matter of regulating interaction with other people (Altman,1975). The degree of one's privacy depends on visual, acoustical and social barriers. The level of control that residents may have over their privacy significantly affects their satisfaction. Often, the dissatisfaction with units' adjoining outdoor spaces, is due to the lack of clear demarcations between private and semi-private zones, and between semi-private and public zones. Clearly demarcating these spaces with fences and other landscaping can help reduce resident frustration. Fences also ensure a visual barrier year round (Figure 5).

Extensions From the House

Optional balconies, porches and decks can help involve users in the design process and hence improve satisfaction. The Grow Home concept provides the homeowner with the opportunity to choose a front or back balcony projecting from the second floor of the unit. There is also the possibility of having a rear deck or a front porch on the ground floor, equipped with a proch roof. In a Grow Home project in Aylmer, Québec, balconies serve as extensions of the house, providing each unit with additional space (Figure 6).

In the future, balconies can be used to expand interior space, although enclosing balconies can block natural sunlight to the floor below. Porches can also be designed with sidewalls to accommodate future enclosure. The Grow Home's commitment to flexibility and adaptability allows for the easy addition of future rooms onto the basic structure. If glass is used as the primary building material, these extensions from the house could become sun rooms. If oriented properly, these rooms would also benefit from passive solar heat gains.

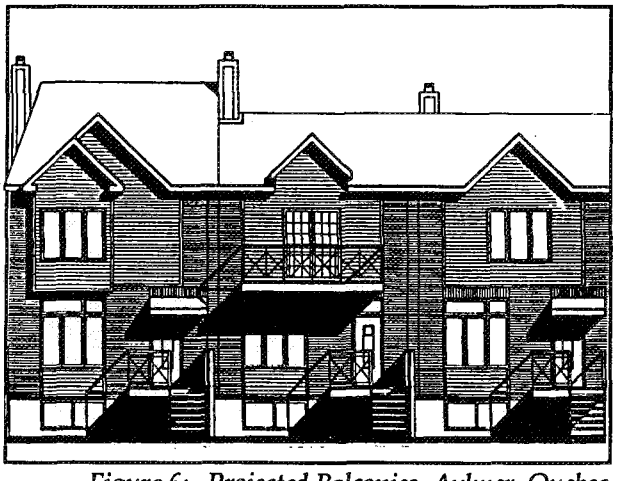


Figure 6: Projected Balconies, Aylmer, Quebec

Built and Open Space

The relationship between built and open space can also significantly affect residents' satisfaction. Privacy and flexibility can be enhanced by looking at the grouping of units in relation to the larger site. For example, by staggering units, neighboring walls can be used as protective screens from unwanted noise and views. Staggering units also relieves the monotony of a continuous repetitive facade, and the wall extentions provide residents with part of structure from which to build a future addition. Projecting the second storey past the wall of the ground floor to the rear of the house also increases the feeling of privacy and provides the opportunity for a future addition.

A change in grade between the house and the yard space may also reinforce feelings of privacy and security. In the front yard, for example, an elevated front entry will separate the entrance from the level of the road. Setbacks also ensure this physical separation between unit and street. By manipulating the level of the land at the front of a unit, the aesthetics of the home and the streetscape can be enhanced.

Landscaping Private Space

Landscaping is a critical determinant of a user's overall satisfaction with a unit's outdoor spaces. During the short summer season, outdoor spaces are constantly being used. The backyard becomes a place for dining, sports, recreation, gardening and a play area for children. Key principles, such as planting coniferous trees in areas where visual barriers are required, will help private spaces accommodate a variety of different needs.

Landscaping also includes the hardscaping of outdoor spaces. Hardscaping refers to such constructs as fences, patios, and built-in outdoor furniture. The Grow Home's hard space is simply provided as a poured concrete slab on grade. This patio provides a surface upon which children can play, and a place for patio furniture and dining.

The materials used in hardscaping outdoor spaces can be a way of ensuring a more sustainable environment. To date, the porches and patios of Grow Home developments have all been constructed of poured concrete. A variety of materials such as brick unit pavers and natural stone pavers can be used in place of the concrete. Unit pavers can absorb storm water which reduces the potential for drainage problems within the limited yard space. Different kinds of weather-treated wood or recyclable wood can also be used as alternatives to the concrete. Being a natural material, wood may also express a more relaxed, natural environment, not inherent in concrete.

Shared Space

Beyond the private space that accompanies each individual unit, there are also outdoor spaces that can be used by a number of neighbouring units. These shared spaces are an important amenity to the community because they provide a place for communal interaction. Shared spaces arise when blocks of row-houses are placed in relation to other blocks to form clusters. Some communities have used these shared spaces to motivate the entire layout of their projects. In the Quartier du Parc Vinet, Fonteneau project, green space was maximized by concentrating the building and parking areas (Figure 7).

Shared space is not usually located in the most

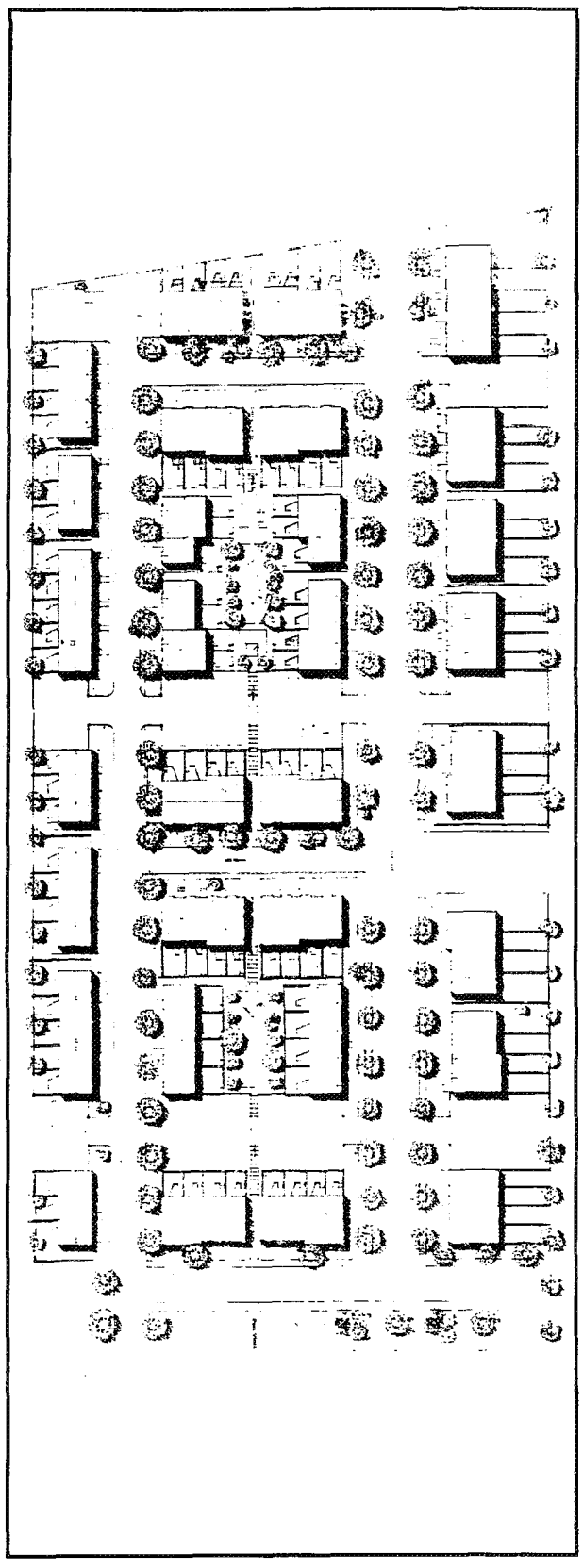


Figure 7: Site plan, Parc Vinet, Fonteneau, Montreal

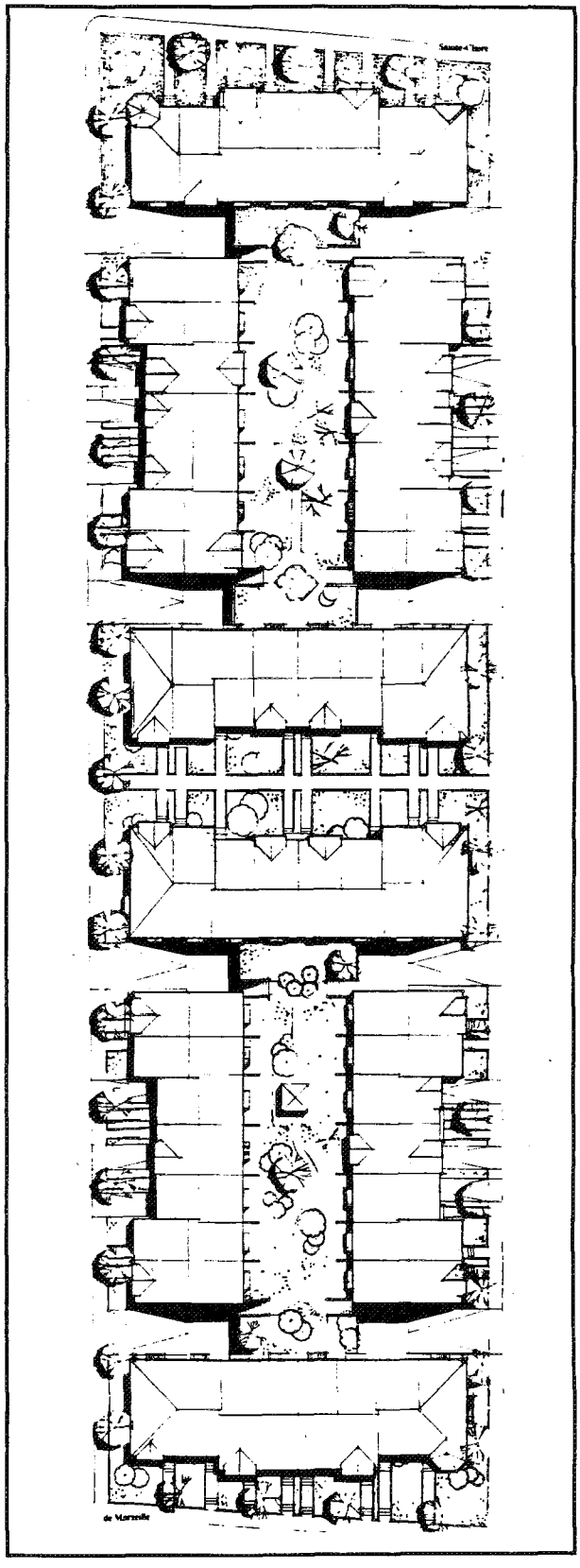


Figure 8: Site Plan, L'îlot de Marseille, Montreal

prominent of locations with respect to the site planning of the community but there is some physical demarcation, such as a paved pathway or sidewalk that directs the pedestrian to this area (i.e. semi-public space is usually set apart from the vehicular roads and may function as a small playground or public square). The *L'îlot de Marseillle* project, in Montreal, shows how sidewalks around the perimeter of the housing leads to paved areas between building blocks, which in turn leads to the more sinuous paths within the shared spaces of the development (Figure 8).

Shared Space - Uses and Location

Shared space is the space that encourages the social interaction of neighbouring homeowners. Playground structures in these areas provide a well defined place for children to gather. Other amenities, such as benches and pedestrian paths, can be enjoyed by people of all ages.

The location of shared spaces can vary according to the objectives of the designer. If shared spaces are designed to supplement limited private space per unit, it may be preferable to locate these areas behind the back yards of the units. This was done for a project in Pointe-aux-Trembles, Québec (Figure 9). Alternatively, the shared spaces may lie adjacent to a housing cluster in order to spatially define it from the next cluster. There may also be a designed progression that leads from private space to shared space to public space without crossing an intersection of streets.

Public Space

In public spaces, landscaping is a critical determinant of the overall sucess of the area. In some cases, very little landscaping is required as the land set aside by the builder as public space is dominated by natural features, such as a ravine or a pond, a forest, or interesting topographical features. Sensitivity towards these natural features, or working with the existing landscape instead of against it, can lower costs, and help prevent drainage and foundation problems.

Existing Grow Home developments have usually been built on relatively flat sites. Instead of having the existing landscape inform the designer, landscaping becomes a tool that can be used to create an interesting environment. Excavated terrain from basements can be used to shape public spaces. The level of the land may be modified to create areas of higher and lower ground. Several landscaping techniques can be used to enhance the outdoor environment by reducing noise pollution and by promoting a place for wildlife to exist. The Nashua project in New Hampshire illustrates the way buildings and landscaping can complement each other to create a desirable community (Figure 10).

Public spaces may be located around the edges of sites, acting as a buffer between the development

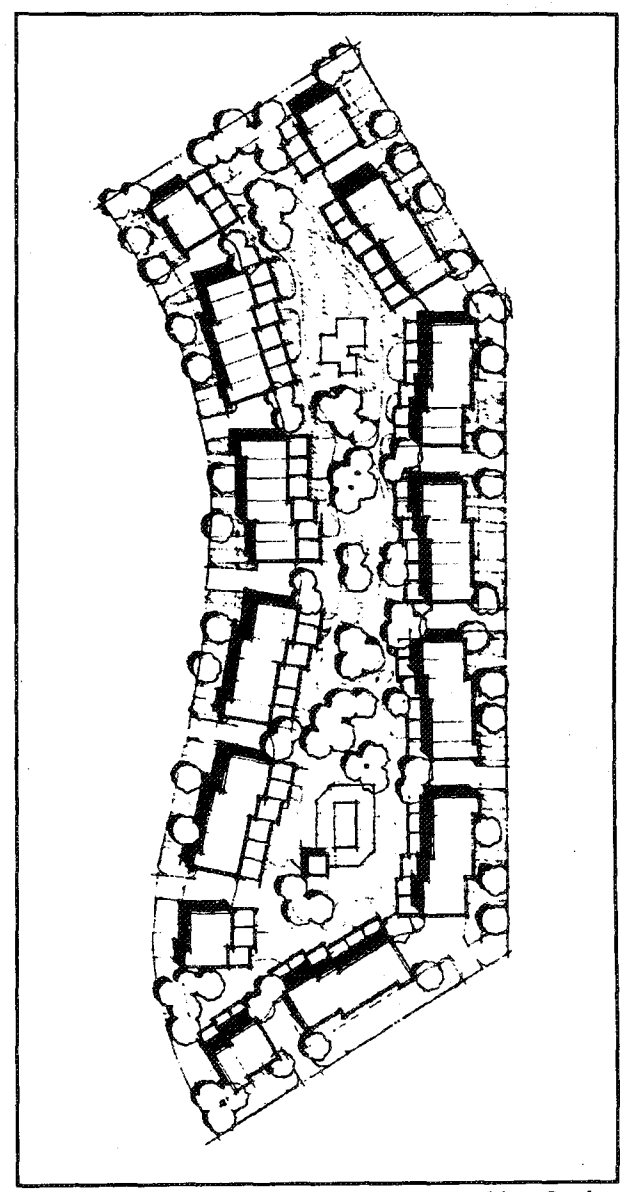


Figure 9: Site Plan, Pointe-Aux-Trembles, Quebec

and the surrounding areas, or they can act as a sound barrier from whatever may lay beyond, be it a major freeway or a busy shopping plaza.

Conclusion

Private, semi-private and public outdoor spaces comprise a significant percentage of the total area of land in a Grow Home community and yet the individual user does not own much land at all. Careful attention must be paid to the design and planning of outdoor spaces so that the user can benefit from his/her yard, neighbours can enjoy the shared spaces and the community can maximize its use of the public grounds.

Guidelines

- Make sure that spaces are well defined; trees, fences and paved areas can be used to differentiate one space from another.
- An interdependency exists between both built and outdoor spaces. Include features that will accommodate the changing needs of the user (e.g. house extensions that may later be enclosed and converted into indoor livable space).
- Use landscaping as a means to satisfy the users. Proper landscaping can increase privacy, decrease maintenance costs and enhance the natural and built environment.
- Shared spaces should respond to different user needs than a private yard; public parks should provide for certain community facilities that cannot be justified in smaller areas, and each outdoor space must be planned so that it is easily accessible.

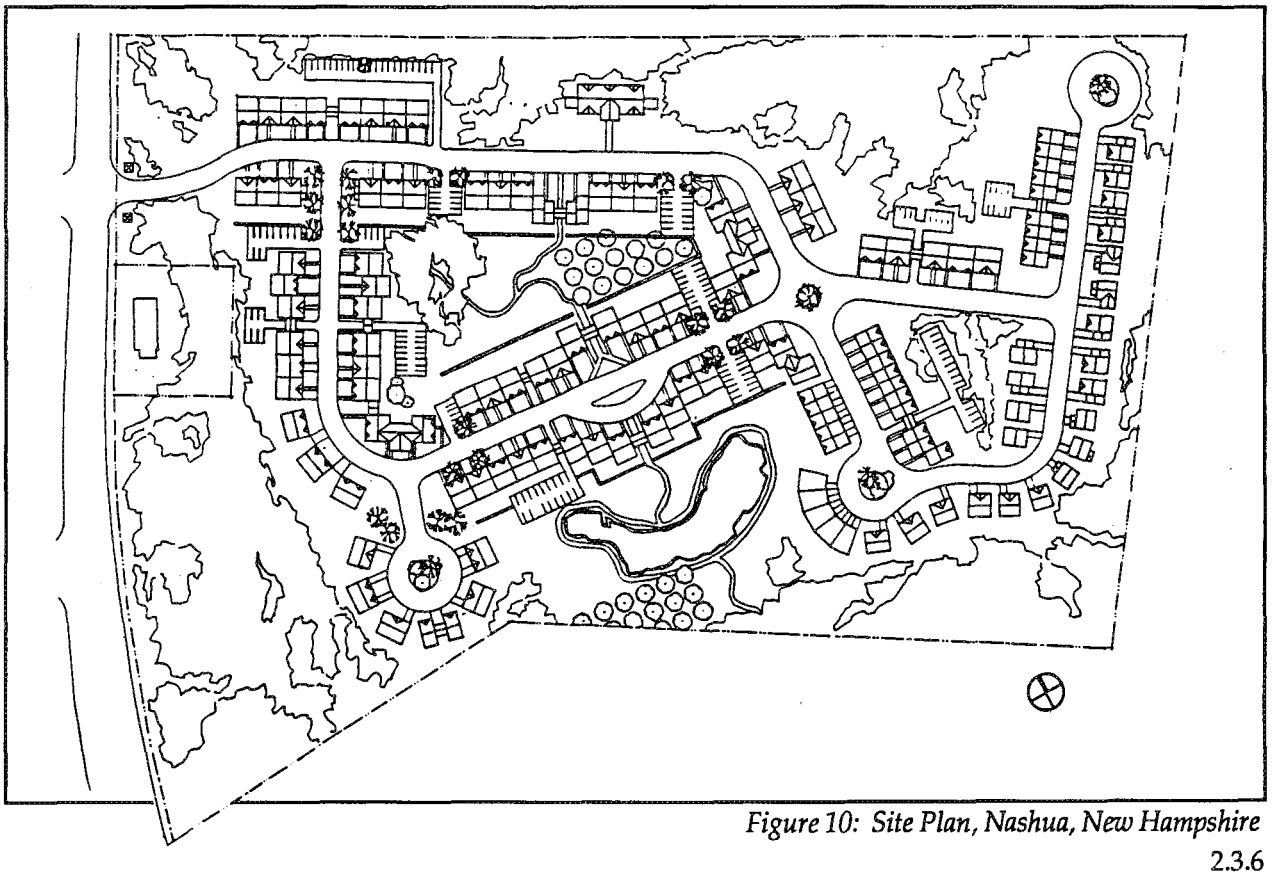


Figure 10: Site Plan, Nashua, New Hampshire

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Environmental Comfort

Introduction

Why do people find one building to be beautiful and pleasant to live in, and another dull, or simply uncomfortable? The specific composition of a building generates its atmosphere and the image that it presents. Buildings have different functions. The headquarters of a bank in the centre of a city would purposefully want to convey an image of strength, stability, and trust. For a private home this image would not suit most people; they would prefer privacy and comfort.

Environmental comfort is essential for people's satisfaction with their living spaces. Environmental comfort is about people living in spaces that appeal to their senses and provide enriching experiences to children and adults alike. It is frequently assumed that if units are affordable and all the technical necessities are in place, people will be happy. However, this is not the case. The presence of the natural environment, or the lack of it, for example, affects people. The colour green, and the feelings nature inspires in people is vital for their well being (Kaplan, 1982). The proportions of buildings and neighbourhoods, their scale, colours and materials are factors that will influence the appearance of the building, both on the inside and on the outside. An individual's appreciation of a structure comes down to a very personal level. Not only are the person's senses involved, but memory and past experiences of what one has come to see as beautiful become influencing factors.

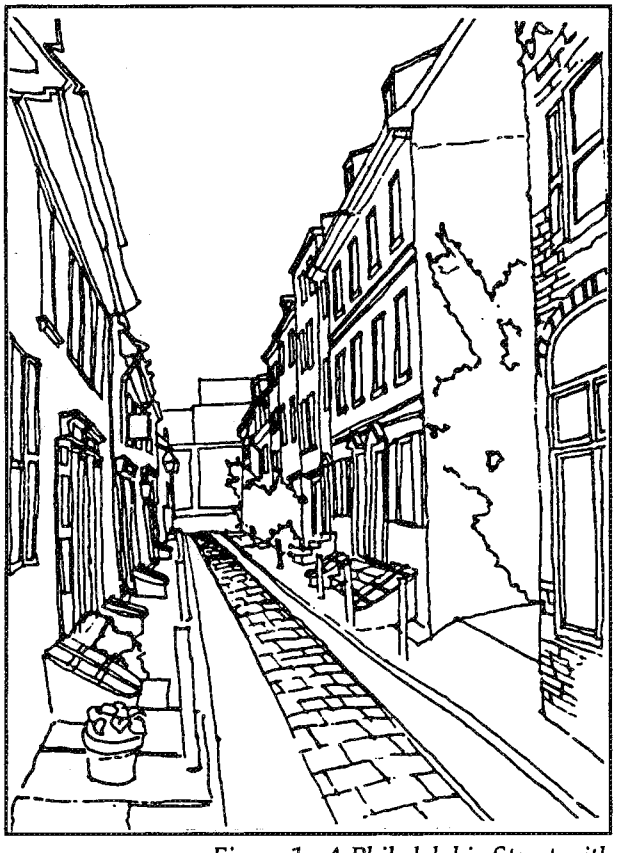

Figure 1: A Philadelphia Street with Narrow-Front Rowhouses

Objective

The objective of this section is to examine those factors which will determine the environmental comfort of a project, and to outline ways in which these factors can be manipulated to make high-density housing priojects more appealing.

New affordable housing communities have the potential to become eye sores. Deterioration of the physical and social infrastructure of a place will impact existing communities. Environmental comfort, or lack of, it has no economic boundaries. Neighbourhoods made of large expensive homes which were designed in an unharmonious way can be unpleasant and create bare and sterile environments.

Walking through many old European and North American streets made up of row-houses demonstrates that when basic design considerations (e.g. scale, materials, identity) are followed, environmental comfort can be achieved (Figures 1&2).

Medium to high density narrow-front row-housing communities and mixed densities provide architects and builders with the building blocks to design pleasant environments. It is important to recognize that a sensitivity toward all of the senses can contribute to environmental comfort.

Sight

Vision is an important and direct means of observing the environment that surrounds us. It is the sight of

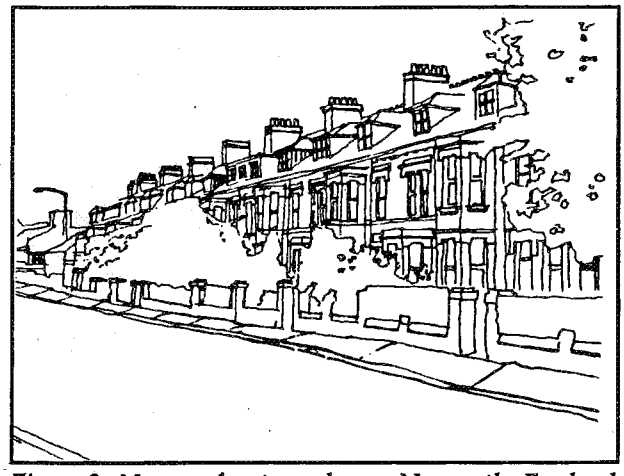

Figure 2: Narrow-front row-house, Newcastle, England

an object that influences our perception before any of the other senses. Some objects will draw our attention before others because of their colour, location relative to other elements, brightness, ugliness or beauty. Sight is obviously dependant on the light in the space under observation; without light, vision would be impossible. The shadows and shade that are cast from a bright light can dramatize a form or a view. Sight, like the other senses is closely related to memory, but also expectation.

Smell

Smell is one of the senses frequently ignored. With the exception of very disturbing smells from sources such as garbage dumps, or heavy air pollution, the influence odours may have on the atmosphere of an area is largely viewed as unimportant. Bad smells are consciously noticed, whereas pleasant and subtle, less strong odours, contributing to a feeling of well being and pleasure, are usually not consciously identified. Odours enlarge our perception of a space, giving another dimension that sight and hearing cannot give us. The sight of a tree is obvious to the eye, and will be consciously taken note of. The odors emitted by the tree will also be registered by the senses, but most often subconsciously. Smell is closely related to the feelings of pleasure, or comfort a certain place may inspire in an individual, without the person being able to identify the reasons why.

Odours evoke memories, thus, a specific scent is closely related to the individual's experiences. The odors present in an environment will affect a person's perception of that place both consciously and subconsciously. The particular odour of one area will be made up of a variety of different sources. Vegetation, soil, cars, and industry are some of them. A particular smell will give a neighborhood uniqueness and life. The natural environment, if it is not overpowered by the smell of pollution, is the main source of odors in most places,and provides pleasant, good feeling scents. Trees such as pines will produce pleasant scents as will shrubs such as lilac, lavender, mock orange, and honey suckle. Freshly cut grass is another source of natural pleasant smells.

Sound

Noise has a great influence on people's perception, and subsequent comfort in an environment. Uncomfortably high levels of noise, a form of pollution, causes stress and anxiety in people (Figure 3). One is always consciously aware of sounds and the lack of them. A deathly silent room can be as unnerving as an unbearably loud one.

Sounds convey a variety of information. Echoes give us information about the size of a space, the way in which sounds are reflected or absorbed by materials, and something about the nature of those materials. Sounds, like odors, will inspire feelings in an individual related to experience and instincts. Strange, unknown noises may make one uneasy, familiar noises may make one comfortable, and loud sudden noises can be shocking. A variety of feelings can be conveyed through different sounds - loudness, deadness, warmth, rhythm, and melody are only some of them.

There is a great psychological difference between uncontrollable noise, and controllable noise (Kaplan, 1982). The former has been found to be more stressful, because it leads to a feeling of helplessness. Not being able to control the level of noise and switch it off gives people the feeling of not being in control of their environment. People thus suffer stress and anxiety from the noise itself, and the feeling of helplessness it conveys.

The most common sources of noise pollution are car traffic, airplanes and trains. Noise levels from highways is most effectively reduced by solid barriers such as walls. The noise levels are most effectively reduced by placing tall barriers made of drywall, plywood, concrete, or glass, which will reduce sound

levels by reflecting them back to the source. Using materials with rough surfaces rather than smooth ones are less prone to reflect sound waves from facade to facade. The grouping of building relative to each other can also be manipulated to avoid this reflective effect. Vegetation in sufficient amounts can be effective in reducing noise pollution (CMHC, 1972).

Methods of reducing sound levels inside of houses include reducing window size and using glass set in resilient gaskets (CMHC, 1972). Thick and heavy building materials are more effective in reducing sound levels. Materials that are good thermal insulators are also usually good acoustic insulators. Fibrous materials such as mineral glass, or cellulose can be used to reduce sound levels inside buildings between rooms. Airborne sounds can be minimized by sealing any air leakage paths between rooms, and by sealing around electrical outlets and plumbing (CMHC, 1991). In order for people to be comfortable in their environment, they should be able to have conversations outside, hear natural sounds, and be able to sleep without being disturbed by noise pollution.

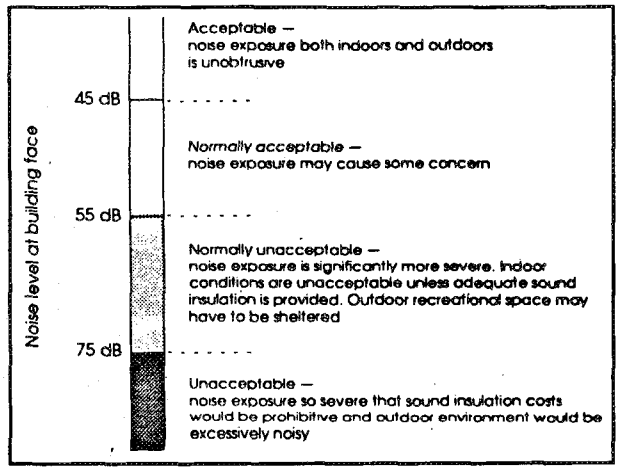

Figure 3: Noise Effects on Housing (source: CMHC Road and Rail Noises: Effects on Housing

Touch

Feeling the texture of the materials that surround us is another way of gathering information about our environment. Smooth surfaces will feel better to the touch than coarse, rough ones. The feel of the air will also provide information and contribute to forming an impression of the space. The air can feel clean, fresh, salty, hot, cold, breezy, damp, dry, stuffy, or dirty.

Avoiding touch with surrounding materials and other people is also an important issue. Human beings, although enjoying each others presence, need certain minimal distances between themselves in order to feel safe, and comfortable (Baum and Epstein, 1978). If a space does not allow for this it will immediately be noticed and that space will not be used, thus becoming useless.

Vegetation

The vegetation that surrounds a structure is a vital component of environmental comfort. Without vegetation the environment will look flat, barren and dull. Trees change the balance of a scene and the balance of scale. The presence of trees will draw the focus of the eye away from the duller aspects of a structure, to the green vividness of the vegetation. Trees and shrubs will give a sense of depth to the front of a house that would otherwise have looked flat. Vegetation can provide shade and protect against uncomfortable sun glare. Trees and plants are naturally pleasing to the eye, and will always draw attention. Trees and plants also draw other life forms to them, such as birds, which in turn produce pleasant sounds and create an atmosphere of life and well being around them. The psychological impact of trees, and the natural life force they represent, will make any environment more pleasant.

The value of vegetation is not merely aesthetic. Trees are vital in providing clean air and pleasant odors. A street with trees may have 1,000 to 3,000 particles of pollutants per litre while a street without trees could have 10,000 to 12,000 similar particles per litre (Land Design/Research, 1984). Overall, vegetation provides noise reduction and visual screening; it regulates humidity and temperature and reduces wind. It also controls air-borne pollutants.

Having trees and a garden gives people a piece of nature which is very valuable to many. A garden encourages outdoor activity while maintaining privacy.

Not all trees thrive well in the suburbs. Some are much more resistant to high levels of pollution and poor soils than others. Table 1 lists a few examples

Name	Size	Description
Canoe Birch *(Betula papyrifera)*	Height: 23 m. Spread: 11 m.	- deciduous tree; advantages of rapid growth (two or more feet per year); survives well in cold climates
Red Maple *(Acer rubrum)*	Height: 15-20 m. Spread: 12 m.	- outstanding Spring and Fall colours; dense foliage provides shade; rapid growth rate; adapts well to different types of soils; easily moved in all sizes
Sugar Maple *(Acer saccharum)*	Height: 23 m. Spread: 12-15 m.	- deciduous tree; attractive Fall colours of yellow, orange, and scarlet; easily transplanted; slow growth rate (under one foot per year); removal of dead wood is required
Norway Maple *(Acer platanoides)*	Height: 15 m. Spread: 12 m.	- withstands cold climate well; moderate growth rate (one to two feet per year); no specific maintenance requirements
Apple *(Malus pumila)*	Height: 6-9 m. Spread: 8 m.	- good garden tree; many varieties available; pink or white blossoms during Spring; apples grow in Fall; easily moved and grows one to two feet per year; pruning is necessary; requires spraying twice a year
Canadian Hemlock *(Tsunga canadensis)*	Height: 27 m. Spread: 9 m.	- evergreen tree; good for screening purposes; tolerant of cutting and can be used as a hedge; medium growth rate; can be transplanted up to a height of 4.5 m.
Siberian Crab Apple *(Malus baccata)*	Height: 4-8 m. Spread: 4-6 m.	- easily transplanted with a growth rate of one to two feet per year; its foliage is a deep green which turns yellow and orange in the Fall; pink, white or red flowers in Spring and red or yellow fruit in the Fall

Note : Other trees well suited for suburban streets are, Hedge Maple, Amour Maple, Tatarian Maple, American Hornbeam, Fringe Tree, Flowering Dogwood and Hawthorn species (Zion, 1968).

Table 1: Types of Trees Tell -Suited for City Climates

of trees that survive well in city climates and suburbs.

Shrubs relate buildings to each other and the site. Shrubs provide privacy, screening and a visual barrier. Like trees, they provide shelter from wind, dust, strong sunshine and noise. Shrubs can be used to channel vision to or away from buildings. They also provide contrasts in colour, form, and texture when placed close to buildings, pavement and water.

Shrubs are best planted in groups and bold masses to contrast with open areas and buildings. Shrubs that are grown for their large flowers to provide colour (hydrangeas, hybrid rhododendrons and azaleas) are best kept for massing with similar species and are best kept contained by walls or hedges (Tandy, 1972).

Architectural Considerations

Aesthetic appreciation relates to an individual's judgement and cannot be predicted. Buyers will frequently look for a house similar to one previously lived in. The element of familiarity and recognition is very important. A coherent environment with an even flow is pleasing to look at. A chaotic one is

Figure 4: Front Elevation, Poite-Aux-Trembles, Quebec

confusing, the eye does not know where to focus, and gathering an overall impression becomes difficult. Order and patterns thus become desirable, but at the same time, monotony must be avoided, which is dull and unpleasant. A balance between variation and monotony guided the design of the Pointe-aux-Trembles project where units of different sizes and heights were combined and formed to make one block (Figure 4).

Since the Grow Home is made up of row-houses, it becomes important to consider some of the factors that will create an aesthetically pleasing image, without becoming dull. The individual units must complement the whole, in order to create an overall block character.

The roofscape is an area where variation is desirable, providing relief from the evenly aligned facades. Variation can be achieved through differences in height, pitched roofs, dormers, and rectangular sharp edges. This was done in the Aylmer projects where a variety of roofscapes were provided in one block (refer to Figure 5 in *Outdoor Space*). The roof should be a darker colour than the facade, otherwise it will have a floating appearance. Different shades of the same colour on the roof is another way of creating variation while retaining a sense of unity to the block.

It is important to create a sense of rhythm, which is the regular occurrence of elements such as windows and doors. Colours are frequently considered a matter of personal preference. However, it is clear that if a wide variety of intense chromatic, clashing colours are used they will compete with each other, and create a messy overall appearance. Using colours found in nature, such as warm grey, blue grey, beige, terra cotta, olive, cream, and tan will generally create a more pleasing appearance (Land Design/Research, 1984). These colours do not clash with their surrounding environment, nor with each other. Light colours will cause elements to be brought out, and dark colours make them recede.

When the colours of windows and door frames are the same, a sense of consistency is created. If shutters or blinds are used they should be of the same colour and design as the window frames. Bright colours can be used in moderation to focus attention. The entrance is a focal point; it gains importance as it is approached, and the doors themselves should be balanced. Having door steps of a lighter colour than the house adds emphasis to the entrance (Land Deign/Research, 1984).

Conclusion

Environmental comfort can hardly be defined or measured, yet it is an important factor influencing people's appreciation of their living places. If sustainable developments are to be achieved, they must be designed and built so that people will choose to continue living in their homes for long periods of time; the individual unit plan must be flexible and the built environment must be adaptable.

Guidelines

- Mass buildings at the planning stage and design interior spaces at the scale of a unit with user satisfaction (economy, function and environmental comfort) in mind.
- Choose building and finishing materials carefully.
- Integrate sufficient vegetation into a new community.
- The amount of light that is allowed to penetrate a space is a significant design criteria.
- The stimulation of certain senses (sight, sound, smell and touch) can enhance the perception of built space.

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Housing Identity

Background

The repetition of unit designs, building components and simple geometries are ways to reduce the cost of housing construction. Providing unit identity, or individuality, can therefore conflict with one of the main objectives of the builder and the designer, that is, cost reduction through economies of scale. Unfortunately, repetition does not generally contribute to a general appreciation of the built environment. The implementation of repetitive elements can result in an undesireable monotony, even in up-scale neighbourhoods.

Incorporating a degree of housing identity, however, is not necessarily a costly design burden. Builders can use identity as a marketing tool to attract potential buyers and provide them with houses that better address their needs.

In previous design and research work, designers and scholars have suggested the need to provide physical distinctions within a community in order to allow for an expression of identity by the users (Alexander, 1977). User participation in the process of shaping their own environment is also seen as an essential part of increasing user satisfaction (Turner, 1979).

Sequencing

Sequencing, in a residential community, can work at both the macro and the micro scale. At the macro level, one can study the hierarchy of streets, the way that the entrance to the community has been designed and the specific landscape features that can affect the identity of a place. The *Nashua* project was designed with an identifiable entrance into the development; a front gate flanked with posts on either side summons residents and visitors off the main road and into the community (section on *Site Planning*).

Designing for diversity is essential when building-narrow-front row-housing. Although economies of scale may require the repetition of units in an entire development, creative site planning can help reduce the dullness by clustering housing blocks and providing for narrower streets. Each of the clusters or streets can be designed using various housing types, facades or building materials. Diversity can also be created through landscaping and hardscaping features. Selecting different trees and street lights for each cluster will be a way of further distinguishing between places.

Objective

The objective of this section is to briefly outline and demonstrate how design strategies that promote diversity and identity can be implemented in affordable housing. The designs for recently completed Grow Home projects will be used as models to demonstrate the potential impact that a clear identity or lack thereof can have on a community and a unit. Three strategies that are used to promote the identity of a housing development or of a single unit are explained. These strategies are sequencing, diversity and participation.

Where feasible, diversity can be achieved by providing a variety of units. Variety provides users with the opportunity to choose between different available house designs. In terms of the Grow Home, choice can be translated into a flexible design. Diversity in low-rise high density affordable housing projects can be achieved in several ways. For instance, the facade of a typical row-house block can vary while maintaining the same building materials. Also, within a housing block, window dimensions may be constant, but window placement can vary. Changing building heights is another way to help differentiate one unit from another.

Grow Home units built in Quebec have widths that vary from 4 to 6 metres. Different unit widths is a way to distinguish between neighbouring units. Alternatively, given a block consisting of units of equal width, the heights of each unit may vary according to the floor area that a user requires. There are instances where units can be stacked on top of other units.

Identity Through Participation

By encouraging user participation and designing for it, the architect and builder are ensuring visual diversity among the units and are also promoting user satisfaction. By giving the user an opportunity to

Figure 1: Building facade, L'îlot de Marseille, Quebec

choose certain design finishes, the user immediately becomes an active participant in the building process.

By facilitating user participation the advantages are numerous. Involving the user in the early stages of the building process, the builder will find that there will be a reduced amount of resistance from the client due to the responsibility they will feel toward the finished product.

Providing appropriate infrastructure that will facilitate future expansion of a unit, such as the extension of side walls, is another means of encouraging future user participation. The users will be better equipped to build their own additions and they will be able to experience the satisfaction that accompanies such an activity. The option of leaving the basement unfinished is a cost effective way to provide an extra level and it is also a way to allow the user to furnish it with what is desired.

Variety of Unit Size

The socio-economic changes that have taken place in the past few decades have altered the demand for the traditional single family house. Our experience with Grow Home projects indicates an increase in the number of "non-traditional" households. Approximately 16% of all users surveyed in a post-occupancy study were single and 10% were single-parent families (Friedman and Cammalleri, 1992). Builders now realize that the same unit design will not sufficiently accommodate different users. The need to offer a variety of unit types becomes essential.

Massing different sized units together is an example of how to achieve identity at the project scale. The L'ilot de Masrseille project shows the variety in building blocks that can be achieved by joining rowhouses of different heights (Figure 1). The differentiation between the larger and smaller units becomes better defined when expressed as individual units within a larger massing. Formally, the rowhouse block becomes a more interesting structure. End units are treated differently from middle units and roof lines are a variable to be further explored. Different blocks can include roofs with or without dormers, ground floors with or without patio spaces and different styles of windows.

Interior flexibility

Variety in low-rise high density housing developments can be achieved by providing for a flexible interior layout that facilitates a number of different partitioning options, or by allowing the user to choose different exterior features (e.g. porches and balconies), or by giving the user the opportunity to choose finishing materials prior to the completion of construction. Builders, however, are usually reluctant to employ such design strategies due to the coordination difficulties associated with the changing specifications for each unit. If managed correctly, however, providing alternatives need not be a difficult task and, in fact, can become a marketing tool.

The ability to allow buyers to adapt the internal layout of their homes to their own spatial needs is an essential part of forming a bond between the users and their dwellings. It is also seen as an essential strategy to encourage identity.

Design for interior flexibility and growth can improve a unit's sustainability. The option whereby users may "consume the amount of house that they need" according to their family size, presents an opportunity to see the house as a resource. Saving this resource and using it when it is necessary is a strategy for resource conservation.

Guidelines

- Recognize the impact that designing an identifiable housing development can have on buyers' interests. For example, the name given to a particular project has the ability to evoke an identity for a new development.
- Although a certain systematic rationale will be used to ensure sustainability, diversity of individual units, or identifiable designated areas within a development will serve to enrich the environment and encourage the social aspect of sustainability.
- Allow for user participation. People will act more responsibly toward their surroundings and feel proud of their neighbourhood if they have had the opportunity to alter their personal space. Allowing new owners to finish their basement, landscape their front yards or eventually build an additional space are ways of involving the user from the time of purchase onward.

Further Readings

Eliade, Mircea. (1957). The Sacred and the Profane: The Nature of Religion, the Significance of Religious Myth, Symbolism and Ritual Within Life and Culture. New York: Harvest Book, Harcourt, Brace & World Inc.

References

Alexander, C. (1977). A Pattern Language. New York: Oxford University Press.

Friedman, A., and V. Cammalleri. (1992). Evaluation of Affordable Housing Projects Based on the Grow Home Concept. Montreal: School of Architecture, Affordable Homes Program, McGill University.

Turner, A. (1979). "Mass Housing and User Participation", Open House. Vol. 3.

Introduction - Part III

The third part of this report illustrates alternative development plans for a site in Aylmer, Quebec. The integration of the different technical innovations and design principles discussed in the previous two sections affect the design of the units and the site layout in each of the plans.

The objective of this part of the report is to examine the costs of the alternative scenarios. Different proposals were developed of varying densities and unit types (Figures 1-4). The lower density proposal incorporates single detached units, while the higher density proposals make use of duplexes and cluster housing.

The first three proposals were chosen for further analysis in this section. Proposal A (Figure 1) uses single detached units with indoor garages by the side of the unit, on large lots. Proposal B (Figure 2) presents houses in clusters with parking in an open carport along a winding road. Proposal C (Figure 3) is composed of row-houses fronting onto streets situated around public squares. This last layout is similar to the traditional urban designs originally built in Deschènes and Aylmer.

Site History

The site selected for the three design proposals lies within the former village of Deschênes, which is now part of the City of Aylmer (Figure 5). This site, formerly occupied by the British North American Nickel plant, was developed during the First World War but gradually began to deteriorate in the nineteen thirties.

The village of Deschênes was largely self-built and consisted of working class cottages without basements. Eventually, the occupants built additions and renovated their homes to meet their needs. Despite the regular grid-like plan, the settlement grew informally. The irregular set-backs and lot dimensions reflect this settlement history.

Although a wide right-of-way, from 15 to 20m, is common in the village, the streets are only paved to a width of 7m and there are no sidewalks. The aerial view photograph and location map show that this land is a privileged site in the Ottawa region as it is by the river, close to the bridge, next to a park and in a small neighbourhood (Figure 6). Recently, a Grow Home development, *Quartier du Parc Madaire*, was constructed on this site. The site was found to be an ideal location upon which to build a high density residential community.

Design Constants

Each of the scenarios has been designed to include the following common unit and neighbourhood characteristics:

- The Grow Home unit as the intended housing type (16' x 32' i.e. 5m x 10m)
- A minimum of 1 parking space /unit
- Introduction of private streets by decreasing the right-of-way
- Reduction of front setbacks in order to increase rear yard space
- Ensuring sufficient exposure to sun light on both the south and west facades
- Locating garage/storage spaces on the north or east facades
- Providing porches on the south and west facades to benefit from direct sunlight in the later part of the day

Design Variables

The following unit and community characteristics varied with each option:

- House to lot relationship as an area ratio (density)
- Housing form: detached, semi-detached, rows, stacked, clusters
- Circulation patterns
- Open space: public, private, semi-private

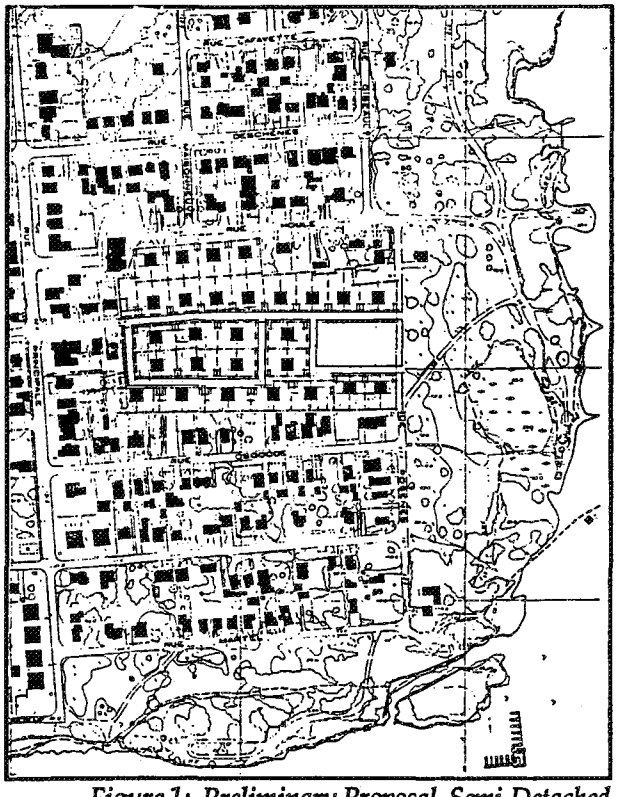


Figure 1: Preliminary Proposal, Semi-Detached

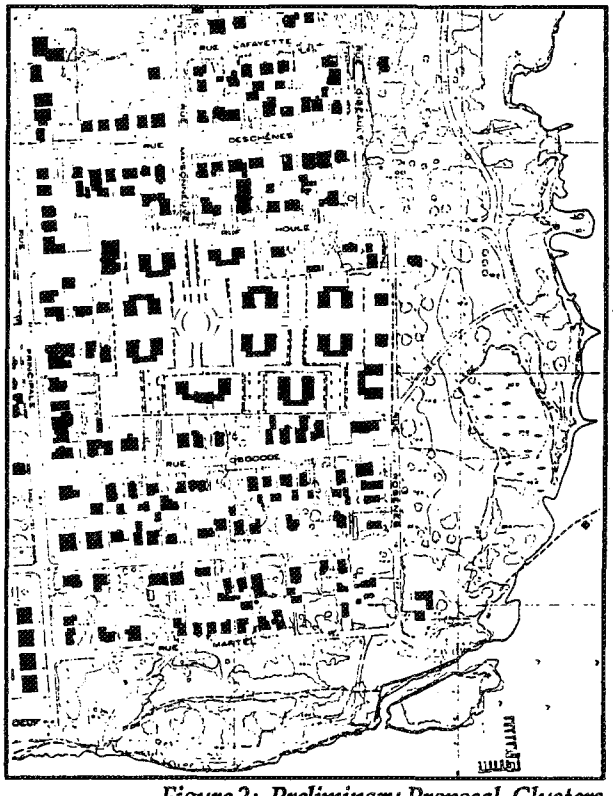


Figure 2: Preliminary Proposal, Clusters

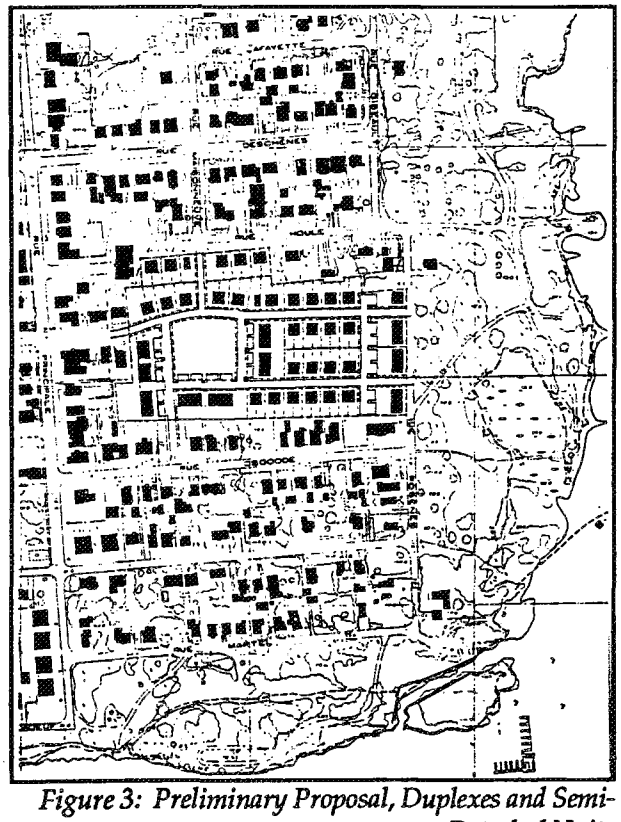


Figure 3: Preliminary Proposal, Duplexes and Semi-Detached Units

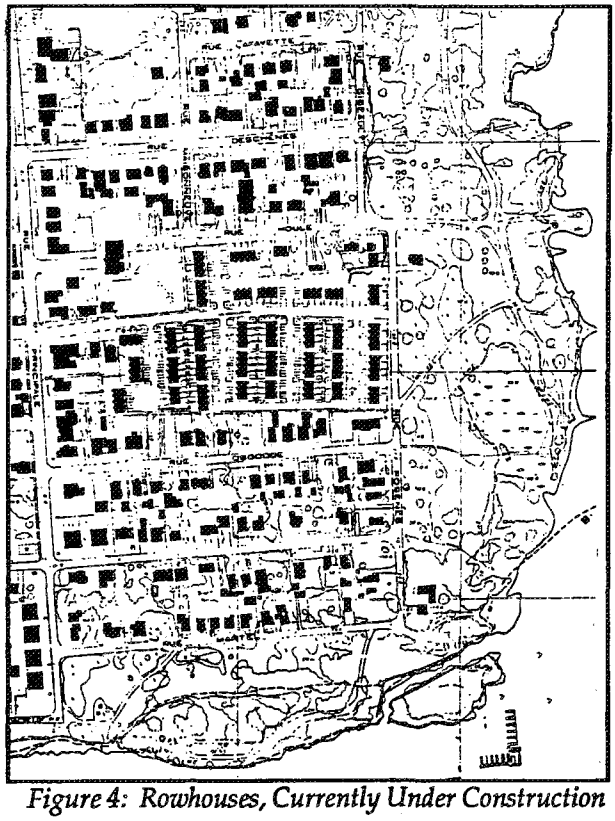


Figure 4: Rowhouses, Currently Under Construction

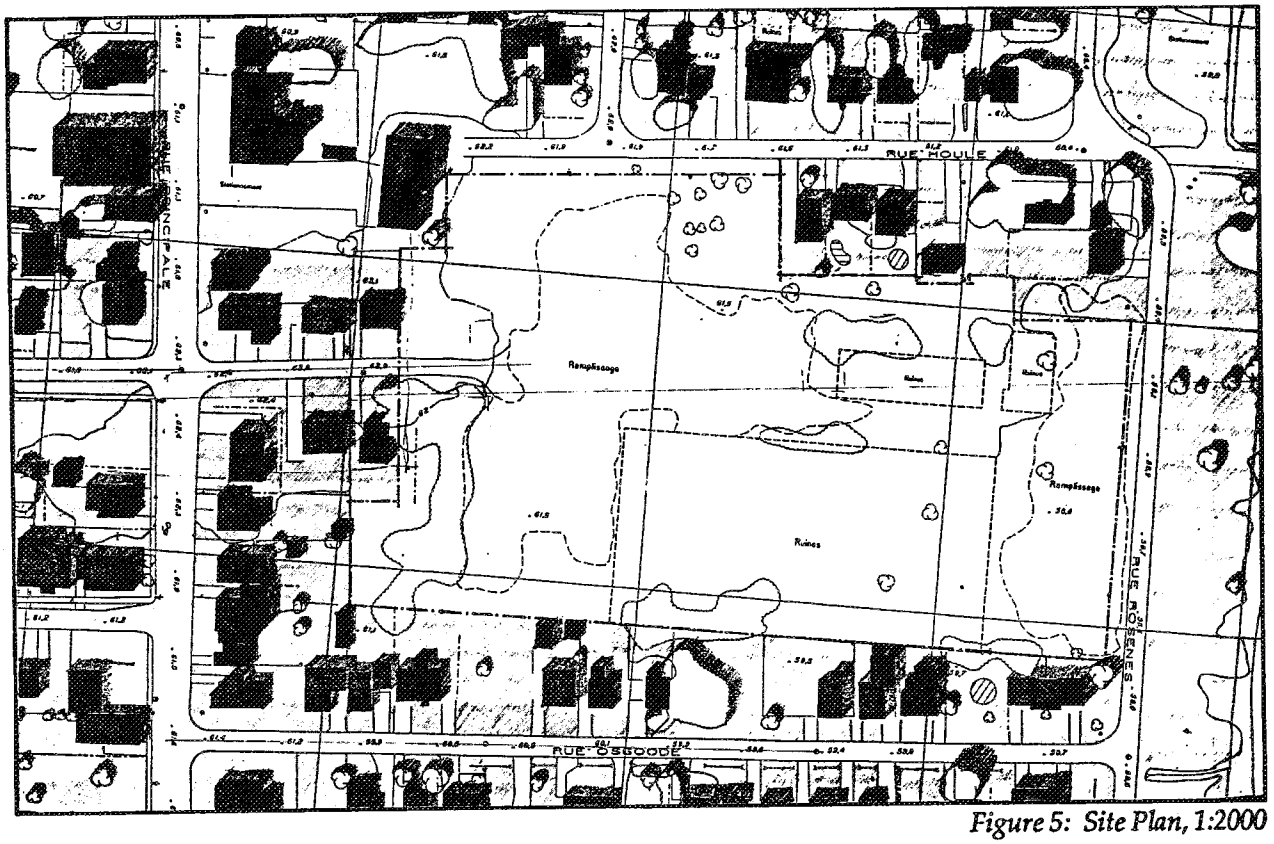


Figure 5: Site Plan, 1:2000

Figure 6: Aerial photograph, the former village of Deschênes, 1987

Evaluation of Design Options

The evaluation of the three options is based on land allotment and coverage, total project cost, cost per unit, and how these costs relate to housing typologies and parking arrangements. In all cases, density is a key consideration.

By increasing density, the cost of land per unit and site preparation costs are immediately reduced. An increase in density will also reduce the cost of infrastructure per unit. Furthermore, providing a range of housing types, from low to medium density, makes a new community attractive to a range of income groups.

The sequencing of open space is also a key consideration. The proper planning of private and public outdoor spaces can encourage social interaction and increase security. Accessing the public realm by moving directly from a private unit to the street or passing through semi-private courtyard spaces can have drastically different results in terms of individual maintenance costs, user satisfaction and potential isolation from surrounding areas.

The following three projects will graphically illustrate the potential advantages of Grow Home communities developed at different times.

Further Reading

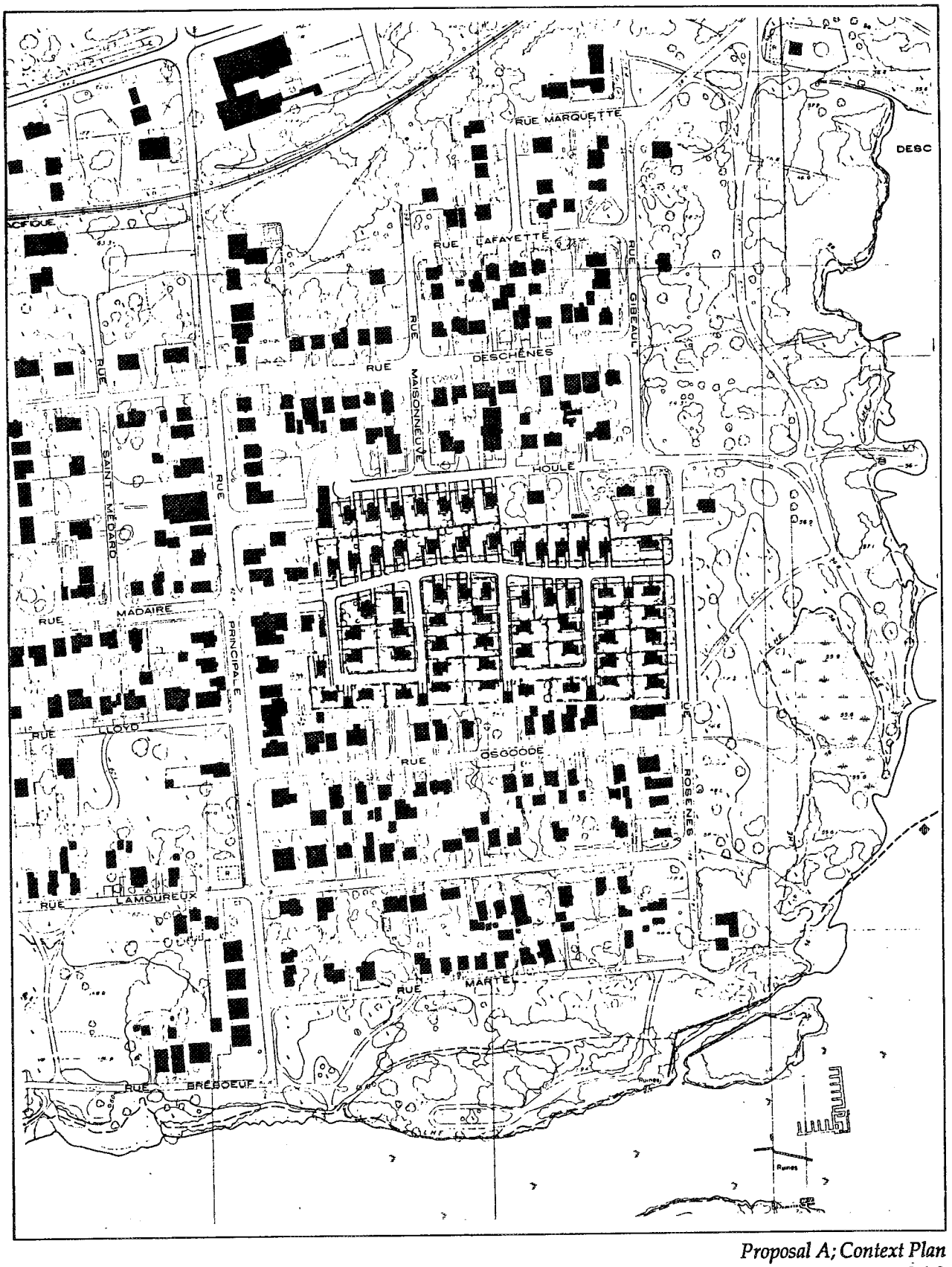
Société Candienne D'hypothèques et de Logement. (1981). Chap. 11: Espaces libres dans Aménagement des ensembles résidentiels; conseils et recommandations, pp.65-73.

Plan A
Single-Family Detached Unit

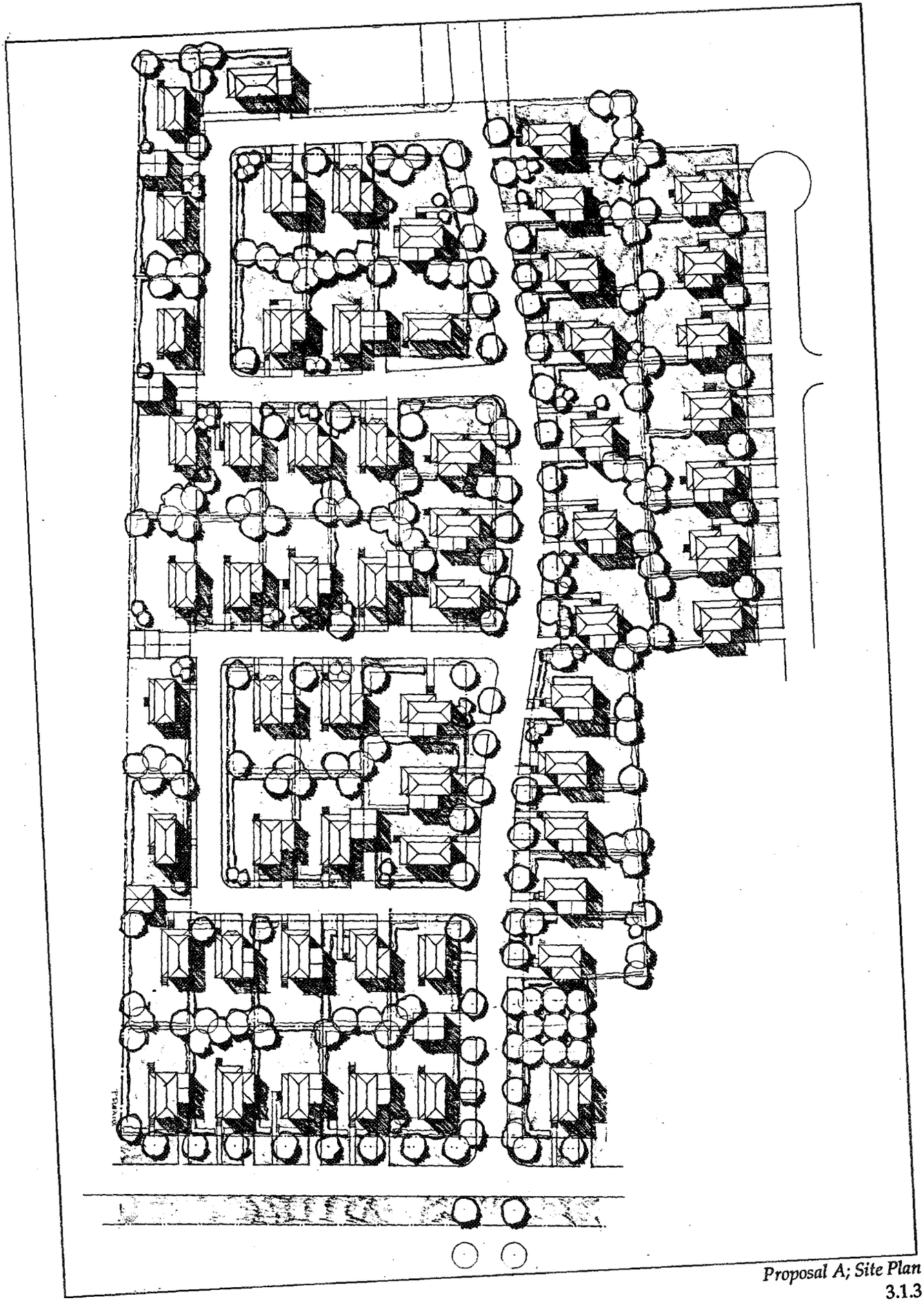
The two main design criteria which motivated Plan A were exposure to the sun and the provision of private outdoor spaces. The houses are set back from the north and east limits of the lot exposing the long sides of the units to the south. Either the north or east side of each house has an adjoining garage. The open space on each lot can be divided into three sections. The front yard is reduced to 3.5m and serves as a buffer zone between the street and the side yard. The side yard (8m) is wider than the standard lateral setback (3m) because of the zero lot line location of the house. This side yard can be considered semi-private since pedestrians can view it from the street. The backyard covers an average of 200 sq.m (12 x 16m), which is made possible by reducing the size of the front yard. The advantage of this is that it allows for a greater distance between the private rear facades of units (24m), compared with the more public front facades (16m). Since each unit enjoys generous yard space, it seemed unnecessary to also provide a public park, normally required by the municipality. The value of the 10% allocated parkland could instead be used to landscape the park to the east side of the project, across from Rosènes street.

The narrower right-of-ways for both of the looped streets that connect to the main street (see Proposal A; Site Plan) may require condominium ownership in this area due to the reduced standard. Except for those two streets, however, the right-of-way and maintenance responsibility is clearly defined by the lot lines of each property. This clear definition appeals to both builders and buyers.

Plan A is a relatively conventional proposal. It would reassure builders, please surrounding neighbours and attract potential buyers.



Proposal A; Context Plan
3.1.2



Proposal A; Site Plan
3.1.3

Building type	single detached household units

Objective: a net density of 25 units/hectare,
average lot size: 16m x 25m = 400 sq m/lot,

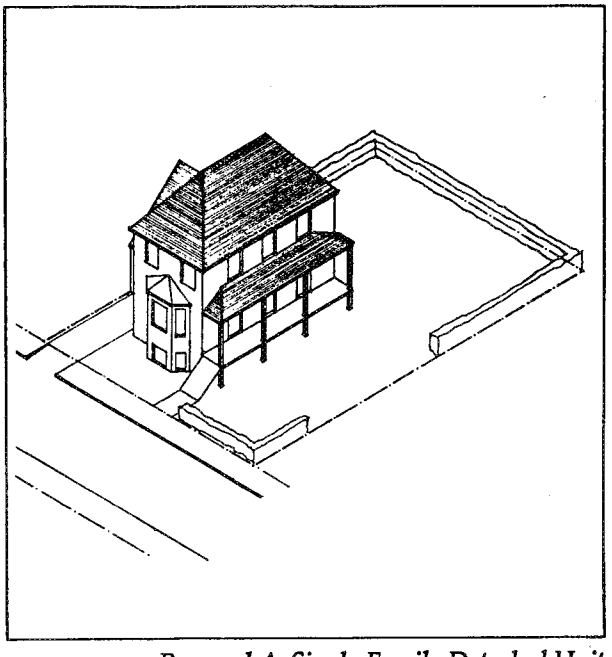
Number of unit	60

Land allotment		sq m		sq m/unit
housing		24710	76.93%	411.83
circulation		7410	23.07%	123.50
park		0	0.00%	
total		32120		535.33

Land coverage		sq m		sq m/unit
built	houses	3000	9.34%	50.00
	garages	1350	4.20%	22.50
	total	4350	13.54%	72.50
paved	streets	4110	12.80%	68.50
	parking	1295	4.03%	21.58
	sidewalks	740	2.30%	12.33
	total	6145	19.13%	102.42
green	public park			
	private yards	21625	67.33%	360.42
	total	21625	67.33%	360.42

Density	units/hectare	units/acre
gross density	18.68	7.57
net density	24.28	9.84

Proposal A; Land Allotment and Coverage



Proposal A; Single-Family Detached Unit

Land costs		3.120 hectare			total	%	per unit
	land cost/preparation	$805,000	($7,000/unit x 115 units)		$805,000	14%	$13,417
	total				$805,000	13.64%	$13,417
Construction costs		units	sq m/unit	$/sq m	total	%	per unit
	house construction	60	125	538	$4,035,000	68.37%	$67,250
	garage construction	60	11.25	538	$363,150	6.15%	$6,053
	total				$4,398,150	74.52%	$73,303
Access		unit		$/m	total	%	per unit
	infrastucture (linear m)	648		325	$210,600	3.57%	$3,510
	street (linear meter)	685		255	$174,675	2.96%	$2,911
	parking (square meter)	1295		17.2	$22,274	0.38%	$371
	sidewalk (linear meter)	370		44	$16,280	0.28%	$271
	total				$423,829	7.18%	$7,064
green space		unit		$	total	%	per unit
	trees	178		500	$89,000	1.51%	$11,125
	shrubs	76		30	$2,280	0.04%	$38
	grass and soil (sq m)	21625		8.5	$183,813	3.11%	$3,064
	fences (linear meter)			124			
	total				$275,093	4.66%	$4,585
	Total project cost				$5,902,072		$98,368

Proposal A; Cost Estimates

Plan B
Cluster Houses

Cluster housing is another housing form that can be used when planning more sustainable developments. The advantage of cluster housing is that it tends to increase a site's density, yet it also allows more open space to be preserved in its natural state. Any further increases in density would require the introduction of duplex or triplex building types.

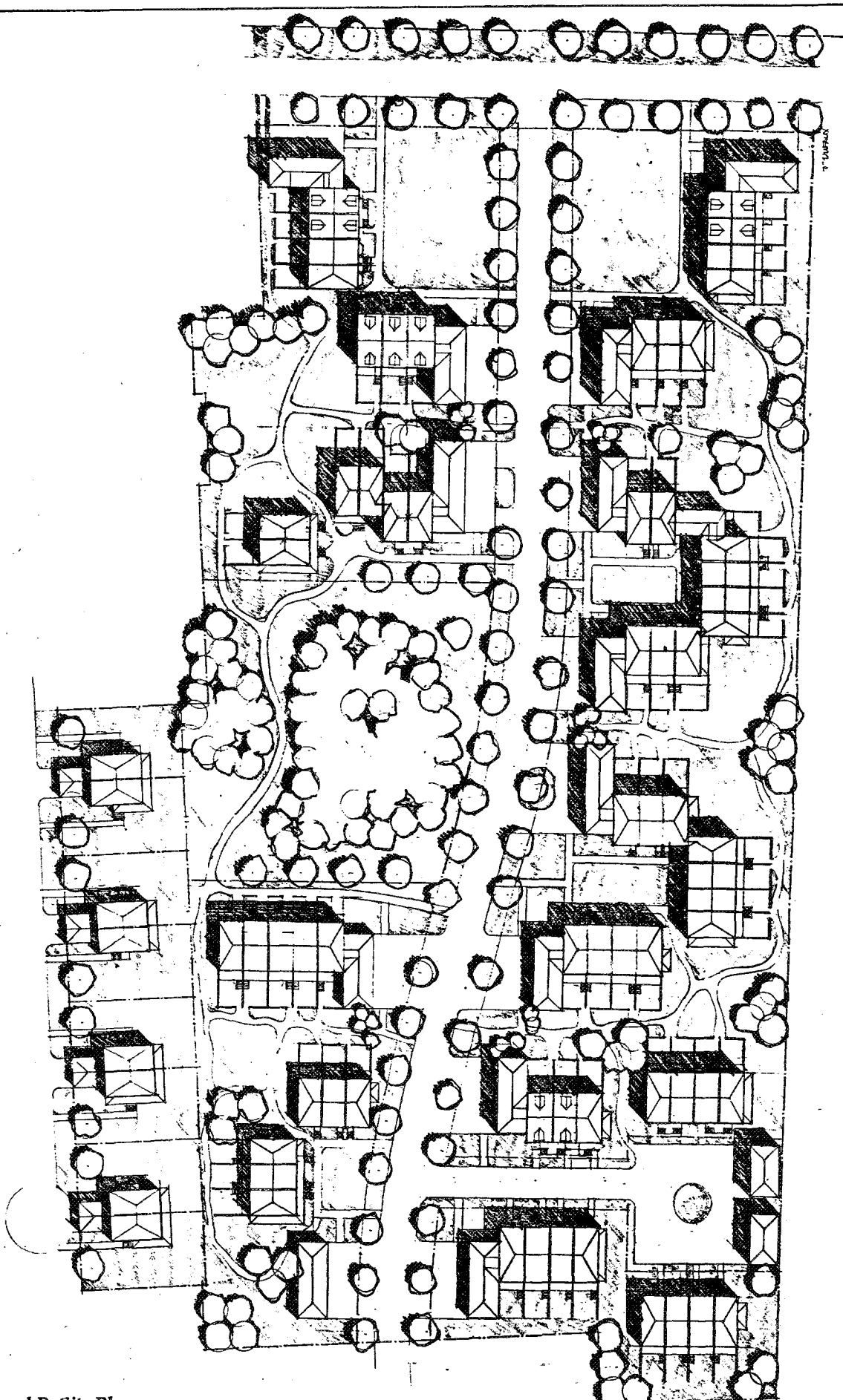
Plan B only has one road crossing the site (see Proposal B; Site Plan). Clusters of houses are situated on either side of this road. The configuration of the units form enclosed and open courtyards. Paths are used to link the courtyards through to the common green spaces.

In this proposal, outdoor space is divided among four uses. A public park, using 10% of the site area, is located in the middle of the community. House entrances lead onto semi-public courtyards. Clusters are surrounded by semi-private green space, and each unit has its own private back yard.

Cluster housing is often favoured by architects and planners as the solution makes efficient use of land and materials (see Land Allotment and Coverage, and Cost Estimates). However, cluster houses face resistance from builders and buyers. The shared spaces and the irregular dimensions imply a condominium ownership, and there is a large shared responsibility for the maintenance of the project. Each house is part of a larger group. However, North Americans have consistently preferred the individualism offerred by detached houses on private lots. Despite this, when building higher density developments, clusters are an appropriate building type. Developers can build the desired number of units and a sense of community is achieved by grouping the units together.

Proposal B; Context Plan

3.2.2



Proposal B; Site Plan

Building type	single clustered household units

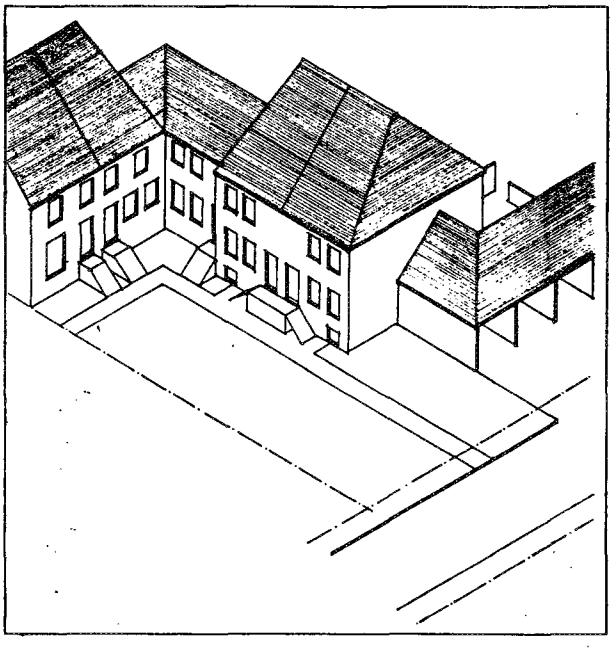
Number of unit	75

Land allotment		sq m		sq m/unit
housing		24082	74.95%	321.09
circulation		4789	14.90%	63.85
park		3260	10.15%	43.47
total		32131		428.41

Land coverage		sq m		sq m/unit
built	houses	3500	10.89%	46.67
	garages	1315	4.09%	17.53
	total	4815	14.99%	64.20
paved	streets	2564	7.98%	34.19
	parking	1552	4.83%	20.69
	sidewalks	1284	4.00%	17.12
	total	5400	16.81%	72.00
green	public park	3260	10.15%	43.47
	private yards	18656	58.06%	248.75
	total	21916	68.21%	292.21

Density	units/hectare	units/acre
gross density	23.34	9.46
net density	31.14	12.61

Proposal B; Land Allotment and Coverage



Proposal B; Typical Cluster Section

Land costs		3.120 hectare			total	%	per unit
	land cost/preparation	$805,000	($7,000/unit x 115 units)		$805,000	11.61%	$10,733
	total				$805,000	11.61%	$10,733
Construction costs		units	sq m/unit	$/sq m	total	%	per unit
	house construction	75	125	538	$5,043,750	72.72%	$67,250
	garage construction	75	9	538	$363,150	5.24%	$4,842
	total	75			$5,406,900	77.95%	$72,092
Access		unit		$/m	total	%	per unit
	infrastucture (linear m)	630		325	$204,750	2.95%	$2,730
	street (linear meter)	425		255	$108,375	1.56%	$1,445
	parking (square meter)	1552		17.2	$26,694	0.38%	$356
	sidewalk (linear meter)	642		44	$28,248	0.41%	$377
	total				$368,067	5.31%	$4,908
green space		unit		$	total	%	per unit
	trees	170		500	$85,000	1.23%	$1,133
	shrubs	20		30	$600	0.01%	$8
	grass and soil (sq m)	21916		8.5	$186,286	2.69%	$2,484
	fences (linear meter)	680		124	$84,320	1.22%	$1,124
	total				$356,206	5.14%	$4,749
	Total project cost				$6,936,173		$92,482

Proposal B; Cost Estimates

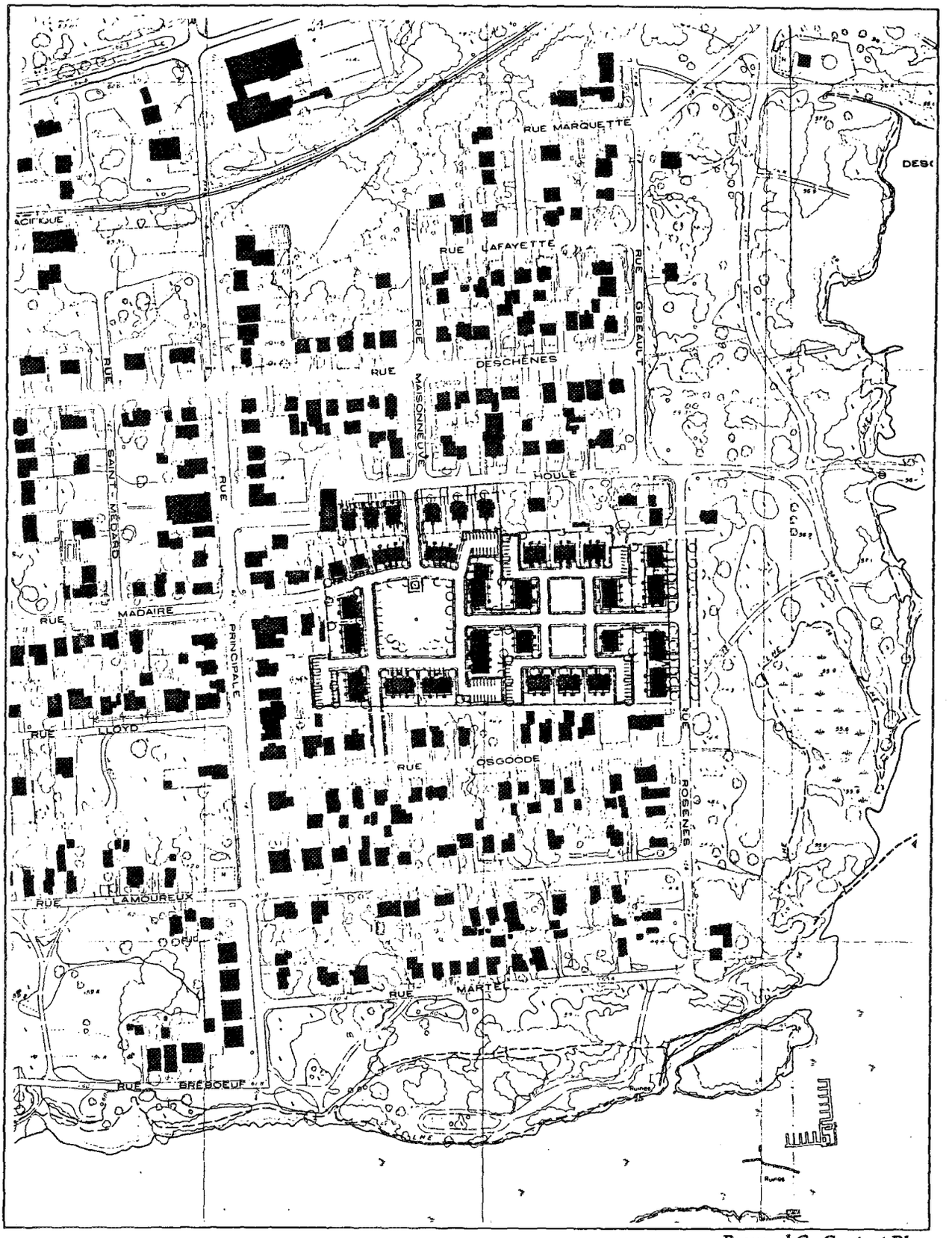
Plan C
Rowhouses on Public Squares

The final design is based on a compromise between environmental quality and providing as many units as possible with two parking spaces per unit.

One way of increasing density is to increase access to land and buildings by providing more streets. The new streets can then be lined with rows of buildings, the traditional way of planning cities. However, accommodating sufficient parking spaces becomes a problem in this scenario. Parking can either be located on individual lots in the front or back yards or it can be organized in lots accessible by lanes.

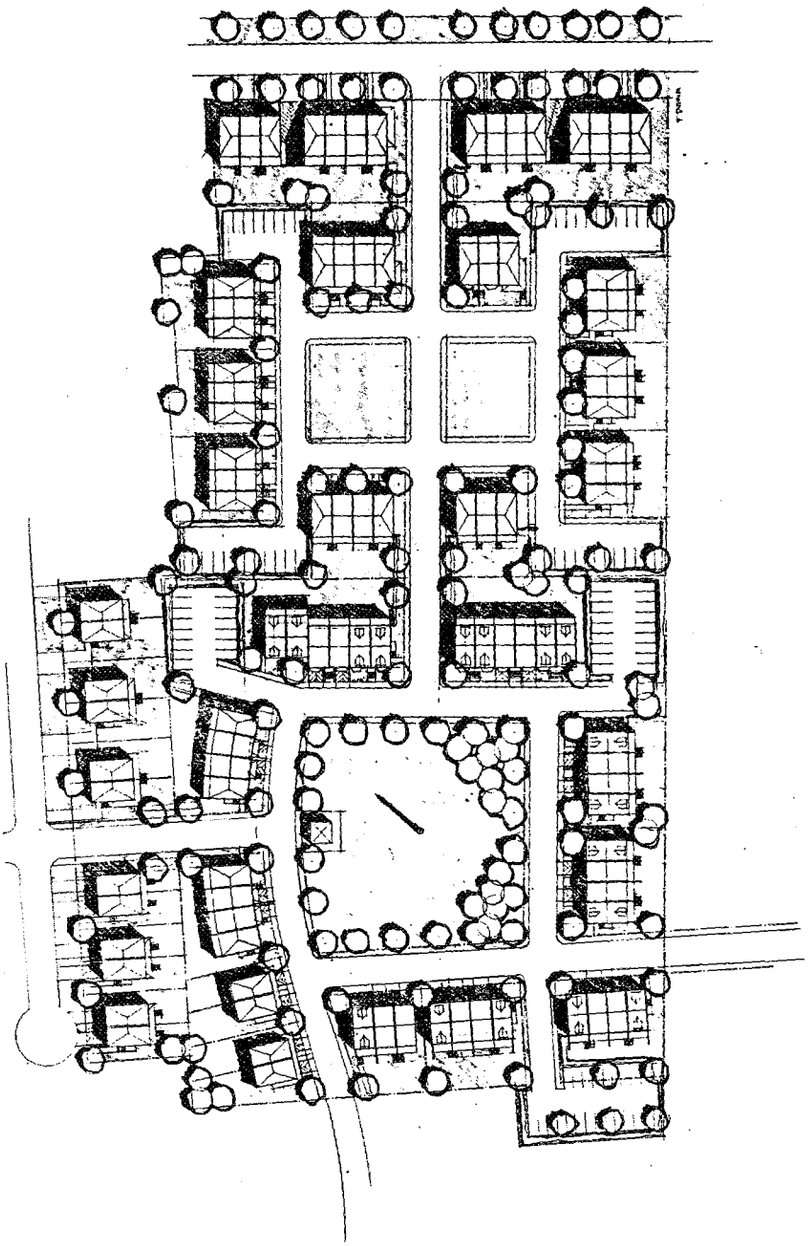
Plan C emphasizes the necessity of sharing facilities and infrastructure as a direct result of increasing density; buildings share common party walls; duplexes share the same building footprint; and parking areas are communal. The proportion of outdoor space and the area of land available for parking decline as density increases and shared open space becomes more valuable to the residents.

In this proposal, the highest density areas surround the main public squares, while the lower density buildings are located closer to the site boundaries. Overall, the proposal presents a broader range of building types than plans A or B. There also exists a variety of parking solutions including private and common parking at grade, and private and common underground garages.



Proposal C; Context Plan

3.3.2



Proposal C; Site Plan
3.3.3

Building type	Row houses on public squares	
	single household unit in semi-detached and rows duplexes in rows	
Number of unit	119	

	building	units
single household		
semi-detached	8	16
rows of 3	9	27
rows of 4	7	28
duplexes	17	34
single household with duple	14	14
		119

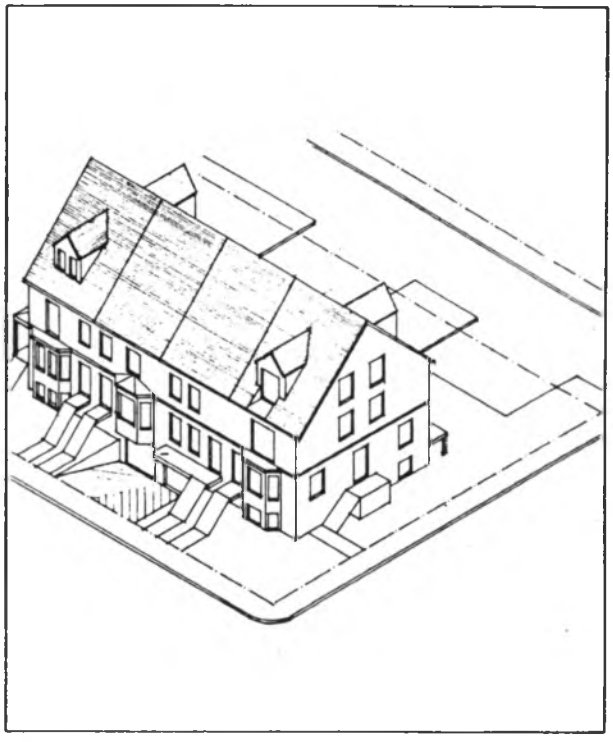
Land allotment	sq m		sq m/unit
housing	18729	58.31%	157.39
circulation	9451	29.42%	79.42
park	3940	12.27%	33.11
total	32120		269.92

Land coverage		sq m		sq m/unit
built	houses	5100	15.88%	42.86
	garages			
	total	5100	15.88%	42.86
paved	streets	4911	15.29%	41.27
	parking	3075	9.57%	25.84
	sidewalks	1807	5.63%	15.18
	total	9793	30.49%	82.29
green	public park	4148	12.91%	34.86
	private yards	13078	40.72%	109.90
	total	17226	53.63%	144.76

Density	units/hectare	units/acre
gross density	37.05	15.01
net density	63.54	25.76

Proposal C; Land Allotment and Coverage

Proposal C; Typical Rowhouse Units; Single-Family and Duplexes



Land costs		3.120 hectare			total	%	per unit
	land cost/preparation	$805,000	($7,000/unit x 115 units)		$805,000	8.66%	$6,765
	total				$805,000	8.66%	$6,765
Construction costs		units	sq m/unit	$/sq m	total	%	per unit
	house construction	85	125	538	$5,716,250	61.51%	$67,250
		34	100	538	$1,829,200	19.68%	$53,800
	garage construction			538			
	total	119			$7,545,450	81.20%	$63,407
Access		unit		$/m	total	%	per unit
	infrastucture (linear m)	755		325	$245,375	2.64%	$2,062
	street (linear meter)	750		255	$191,250	2.06%	$1,607
	parking (square meter)	3075		17.2	$52,890	0.57%	$444
	sidewalk (linear meter)	903		44	$39,732	0.43%	$334
	total				$529,247	5.70%	$4,447
green space		unit		$	total	%	per unit
	trees	154		500	$77,000	0.83%	$647
	shrubs			30	$0	0.00%	$0
	grass and soil (sq m)	17226		8.5	$146,421	1.58%	$1,230
	fences (linear meter)	1530		124	$189,720	2.04%	$1,594
	total				$413,141	4.45%	$3,472
	Total project cost				$9,292,838		$78,091

Proposal C; Cost Estimate

Analysis

Introduction

The 3 proposals presented of this section follow different sets of objectives while using the same building type: the narrow front house. The design process is based on the interpretation of previously established design principles providing endless solutions. These plans were developed to meet specific requirements and examine formal layout concepts.

The design of a unit or a community, often involves some form of compromise, particularly at the technical level. For instance it is difficult to increase the density and maximize southern exposure at the same time with narrow front houses. As units are linked into semi-detached or rowhouses, the ability to benefit from passive solar gains from southern exposure becomes limited. The amount of savings to be gained from southern exposure, in single-detached units (Plan A), are probably less than the material savings in infrastructure, energy and cost offered in cluster houses (Plan B)

A purely technical evaluation does not address the issue of aesthetic or socio-cultural values. For example, the layout of units on the site and the distances between the dwellings define the transition from the public realm to the private space providing a framework for the social network of a community. The socio-cultural objectives are not clear-cut in terms of values and meanings. They are redefined from one generation to the other, and traditional solutions can be modified to suit the evolving social, cultural and economic context. The recent building of narrow-front houses in Montreal, inspired by the Grow Home, is a typical case of a new trend supported by changes in society.

While the first part of this report examined the impact of technical improvements at the unit level, this section evaluates some more general environmental, social and economic issues as they apply to lot subdivision and site plans inthe above 3 proposals.

The Environmental Impact

Material

The single detached houses drawn in Plan A require more material than row houses, clusters or duplexes, since there are no shared wall or foundations, and exterior finishes are needed along the full perimeter

	Plan A		Plan B		Plan C	
Land allotment	single detached		clusters		row houses	
	%	sq m/unit	%	sq m/unit	%	sq m/unit
housing	77	411	75	321	58	157
circulation	23	123	15	64	29	79
park	0	0	10	43.5	12	33
Land coverage	single detached		clusters		row houses	
	%	sq m/unit	%	sq m/unit	%	sq m/unit
built	13.5	72.5	15	64	16	42.9
paved	17	90	13	55	30.5	82
green	69.5	373	72	309	53.6	144.8
Density	single detached		clusters		row houses	
	per hectare	per acre	per hectare	per acre	per hectare	per acre
gross	18.7	7.6	23.4	9.5	37	15
net	24.3	9.9	31	12.6	63.5	26

Table 7: Comparative Land Allotment and Coverage

of each unit. The cluster, Plan B, is an efficient design in terms of infrastructure, utility and access, since the units are grouped along a branch serving the clustered houses.

In general, off-street parking requires relatively large areas: the parking spot (12.5m^2) and its access (from a minimum 8m^2 for double loaded parking lot). In Plan A each unit has its own entrance, driveway and garage for an average of 22m^2 per unit. Proposals B with 20m^2/unit and C with 25m^2/unit offer some options for grouped parking: either at grade or in underground garages. Table 7 shows clearly how Plan A requires more paved area than the alternatives B or C. Plan C, which has a higher density increases the average paved area per unit compared to clusters (Plan B), to provide access to the units and parks.

Water

The Water consumption for a site plan is directly related to the type of landscape. Xeriscaping, which uses appropriate plant species, can significantly reduce the need for irrigation. As proposed in that section, only a small area (close to the unit) should have conventional ground cover like grass to be used specifically by the household. In a low density project, like A and B, xeriscaping can be easily implemented. The cluster in Plan B proposes an outdoor area with a private backyard which could be conventionaly landscaped. This design also offers a common green space and a park , which provide good opportunities for informal landscaping based on native plants and using xeriscaping principles. The public park can include a water retention pond, which helps natural irrigation of the site and reduces run-off water in sewers.

When the density increases, as in Plan C, private outdoor backyard areas represent a larger portion of the green space, and limit the informal common green space. The public parks are used more directly, especially by duplex residents, for whom these spaces are the only green outdoor space. Conventional landscaping may be more suitable for the more intensive uses of green space.

Energy

As noted previously, the single detached houses in Plan A allow a larger part of each building to be oriented south than row-houses or clusters. While the solar heat gain from southern exposure can be substantial, semi-detached or rowhouses units provide significant reduction in heat loss and enable a much more efficient use of land and infrastreucture. Heat loss from the northern walls in Plan A was reduced by locating the garages along the north or eastern side of the house. This forms a buffer between the unit and cold north winds. In northern climates, narrow front houses make sense in term of energy savings when built in rows or clusters to reduce exposure. In southern climates, especially humid ones, detached houses benefit from exposure for ventilation. This is the typical solution developed with the "Charleston" house type.

The Social Impact

Rational evaluation of design proposals does not always comply with cultural values associated with different housing types. The general public preference for single detached houses, like those in Plan A, goes against the rules of designing for effecient use of natural resources, energy, land and infrastructure. While clusters in Plan B present an improvement in this regard, they compromise the more traditional social perception of a house, whereby every unit has its own well-defined piece of land, and an individual street-facing entrance. The evaluation of social benefits must therefore consider both the symbolic value of a housing type and efficiency of resource utilization.

Plan A presents a rather conventional alternative where each property is detached and can be clearly defined through landscaping. Each household, and especially each owner is a master of "His/Her own kingdom". Although this approach has been traditionally associated with a closeness to nature and an abundance in open space to be used as playground, a large proportion of the land is used as front yard. The functional use of this space is lost. The yards and the setbacks that enforce them provide a hierarchy of intimacy from the street to the front, side and backyard which is finally used as the private outdoor space of the household.

The clusters in Plan B present a more efficient use of land, with less paved and access areas and more green spaces. This design offers a wider range of outdoor spaces. The street and the park are public, the courtyards are semi-public and provide an infor-

mal neighborhood space. The green common space surrounding the clusters is a semi-private area, while the backyard is the private outdoor space of each unit.

Plan C increases the density further. Less space per unit implies a strong definition of public and private spaces. The parks need to be easily accessed by all residents, as they are the place for common activities and the only outdoor space for duplex dwellers. Private backyards or outdoor rooms must be protected with strong edges, like tall fences, to secure intimacy. The semi-public or semi-private spaces are reduced to the minimum at the benefit of public or private areas.

Affordability is usually discussed in terms of unit purchase. However, maintenance is a substantial annual expense which cannot be ignored. The narrow-front house appeals to first-time buyers and empty-nester, many of which have limited income. The larger the house and the lot, the less money one can invest in construction and maintenance per square meter. Plan A can be an attractive neighborhood, but requires from each owner a major investment in time and money to landscape the site, since it is supported by fewer households.

The cluster proposal opens a door to shared maintenance of common areas. This economical solution promotes a sense of community which does not necessarily appeal to all new residents. The shared set of values behind such a neighborhood, where the common image takes precedence over individual expression, is in contrast with Plan A.

Plan C, with its urban layout, addresses the need for a higher density in order to bring unit prices within an affordable range. Maintenance requirements are clearly separated between the public and the private realms, which avoids the need for neighborhood interaction. The public parks and streets are under municipal responsability. Integration with the community is clearly expressed by the road network linking the new park to existing streets. Private space is defined by small front yards, and the private outdoor space consists of backyards. These smaller spaces require less direct maintenance by the owner, and may be better landscaped than larger lots.

Cost Evaluation

A brief cost estimation of the 3 plans gives a more subtle understanding of the economic implications of the design options. Affordability is certainly directly related to density, since the land and infrastructure costs are divided between more units. However some amenities, like green spaces or street networks, will affect the total development cost, and, consequently that of the unit.

The estimate is divided into 4 parts. Land and preparation costs were acquired from Denis Lefebvre of Jagdo Construction, who is currently developing that parcel of land. The costs were as follows: preparation and land ($7000/unit), underground utilities (water and sewage pipes approx. $325/linear meter), paving of streets and parking ($3000/unit) and landscaping, topsoil, grass and trees ($3000/unit). The land (115 X $7000 = $805 000) and infrastructure (approx. $325/linear meter) costs were retained for

	Plan A	60	Plan B	75	Plan C	119
	total	per unit	total	per unit	total	per unit
Land costs	$805,000	$13,417	$805,000	$10,733	$805,000	$6,765
Construction costs	$4,398,150	$73,303	$5,406,900	$72,092	$7,545,450	$63,407
Access	$423,829	$7,064	$368,067	$4,908	$529,247	$4,447
Green space	$275,093	$4,585	$356,206	$4,749	$413,141	$3,472
total	$5,902,072	$98,368	$6,936,173	$92,482	$9,292,838	$78,091

Table 8: Comparative Costs Estimates

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the cost estimate in the 3 proposals. Construction costs include garages where applicable. Access costs include the roads, parking and pathways leading to the units. Green space cost includes public and private outdoor spaces, conventionally landscaped with grass, trees and bushes. The prices used for these estimates are based on 1992 Yardstick for costing, for Montreal. The figures were compared with actual costs submitted by the current developer for verification. The total cost of one unit in the actual project under construction is close to 90% to the average unit price estimated in Plan C, which has a comparable number of units (119 instead of 115).

The cost of land and its preparation is a fixed amount which becomes smaller per house as the number of units increases. A higher density means a lower land cost per unit. This land cost represents 17% (Plan A), 15% (Plan B), and 11% (Plan C) of the total cost. The land savings in higher density developments can be offset by access costs needed to serve the higher number of units. Plan C, with twice the number of units (119) than Plan A (60), has a total average cost per unit which is only 20% lower.

Construction cost is based on a building cost per square meter. The difference between the 3 plans derives from the units sizes. In Plan A, single detached houses have a garage. In Plan C, 34 units are duplexes which means smaller units of 100 sq m instead of 125 sq m. Construction costs represent between 75 to 85 % of the total cost. Some savings could be expected from economies of scale. In this estimate, construction costs are fixed, based on built area, which does not directly affect the average cost per unit.

The access costs include streets, sidewalks and parking. This accounts for a significant fraction of the total cost. The land coverage assessment has shown major differences between Plan A, single detached houses, and Plan B, clusters. Plan B turns out to be 40% less expensive than Plan A. The higher density proposal, Plan C, has a total cost per unit only 10% higher than the cluster proposal. The efficiency of the cluster proposal, Plan B, in terms of land coverage, does not result in significant savings. Access to the clustered units depends on an extended sidewalk network which has to be taken into account.

The proportion of green space to built space isan average 5 to 1 in Plans A and B. This area is entirely subdivided into private lots in Plan A. In Plan B only 10% is exclusively private; 15% is public and 75% is common to all cluster residents. The very large proportion of common green spaces proposed by Plan B implies major landscaping costs. This investment is even more important than in Plan A, since in a detached unit development, landscaping can be left to the discretion of each household, both in terms of initial investment and maintenance. In Plan B, the shared outdoor space cannot be left to individual responsability. The initial investment has to be included in the project cost and maintenance will be the responsability of the neighborhood association . Plan C offers a green space to built space ratio of 3.4 to 1. The smaller green spaces require more intensive treatment, which increases total project cost. Backyards, for instance, need to be fenced to ensure privacy. Overall, however, final costs per unit are still lower than in Plans A and B.