RESIDENTIAL-SCALE ENERGY-EFFICIENT GREENHOUSES:

A DESIGN GUIDE AND WINNIPEG CASE STUDY

Residential-Scale Energy-Efficient Greenhouses:

A Design Guide and Winnipeg Case Study

By W. George Rudko

A practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree

Master of Landscape Architecture

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George Rudko, Winnipeg, Manitoba, 1983.

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Abstract

With the dramatic increases in energy costs of recent years, the small-scale greenhouse has undergone a complete re-evaluation. Today the attached residential greenhouse functions as a collector of solar energy, as an integral living space, and/or an ideal plant growth environment.

This study deals with the attached residential greenhouse optimized for the production of food crops with a minimum of external energy input, and specifically in the context of Winnipeg's northern continental climate. While the creation of an ideal enviornment for food crops is a prime concern, the issues of heat collection and living space are not ignored.

A historical survey and general background including present and future trends is followed by a discussion of the various requirements of vegetable crops, including temperature, light, soil, air and physical size, which define the conditions sought in greenhouse design.

Basic principles of heat and energy flow are discussed, again with specific reference to greenhouse design.

A detailed discussion of the various components of the greenhouse system, from foundations and glazing to interior design and thermal storage, comprises the main section on the specifics of greenhouse design.

Finally, a case study in Winnipeg serves to demonstrate the application of the information in a specific example. Heat flow calculations predict anticipated heating deficits or surpluses for selected months as well as test the effectiveness of thermal storage.

Intent of Study

This is a study of attached energy-efficient greenhouses optimized for food production. The intent of the study is to investigate the form determinants of such greenhouses, to define a set of principles for greenhouse design based on these determinants, and to demonstrate the application of these principles by way of a specific example.

While the study should be useful to designers with limited background in plant culture and/or solar design, it is not intented as a definitive manual on either greenhouse management or solar design. As a design guide, the background information is provided only to the extent that it contributes to the understanding of the conditions sought in greenhouse design and the means by which these conditions can be achieved.

PART 1 INTRODUCTION

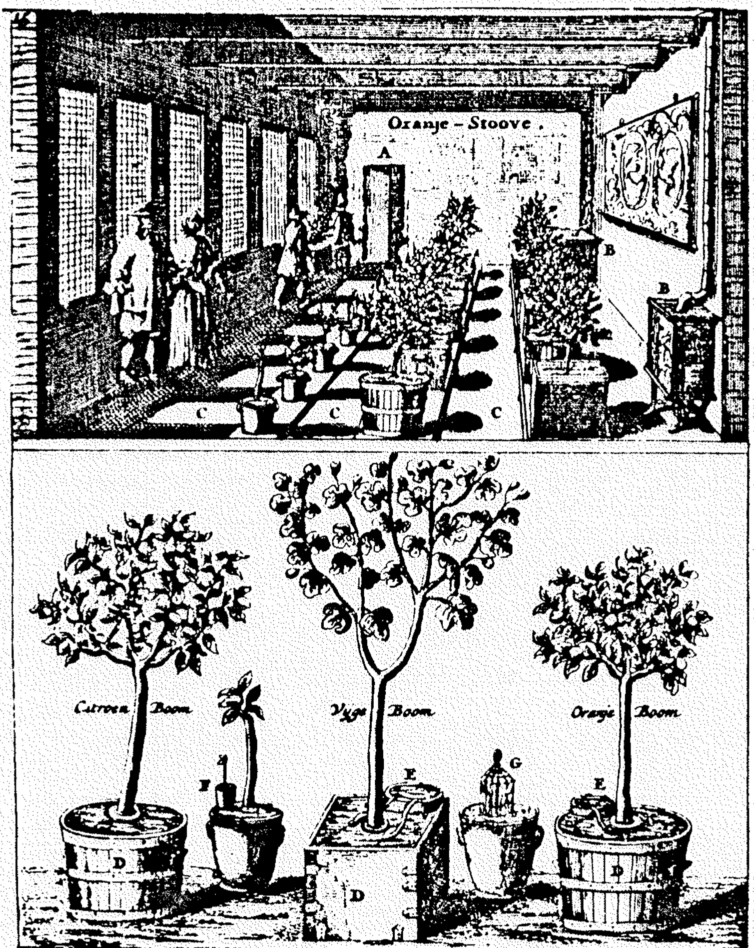
PART I Introduction

1.1 Background

For centuries man has designed and built structures which enabled him to grow plants in a controlled environment, independent of the seasons or climate. The first known greenhouses were built in ancient Rome to provide demanding emperors with vegetables such as cucumbers throughout the Roman winter.

In Europe, the coming of the Renaissance brought with it a tremendous inquisitiveness in all areas of the arts and sciences. The development of botany and horticulture, in particular, were fuelled by the ever-increasing tide of exotic plant species that world exploration revealed. Interest in these new and wondrous plants varied from scientific and medical, to purely aesthetic. The citrus trees, and especially the orange, became the darling of the aristocracy. Unfortunately, the first orange trees planted in England died during a cold winter, as, undoubtedly did many other exotics.

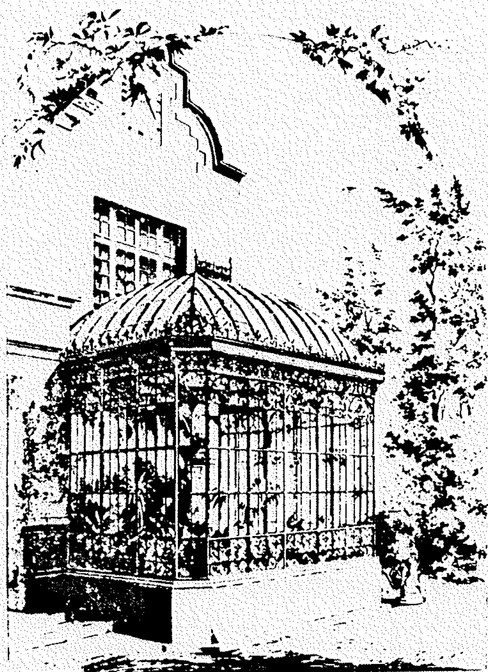
The pressure was on to devise some way of modifying the climate and the solution was to bring the plants indoors. Thus the orangerie was developed - glass walled structures which could maintain the tender citrus trees throughout the cool winters of Northern Europe, and it proliferated throughout Europe.



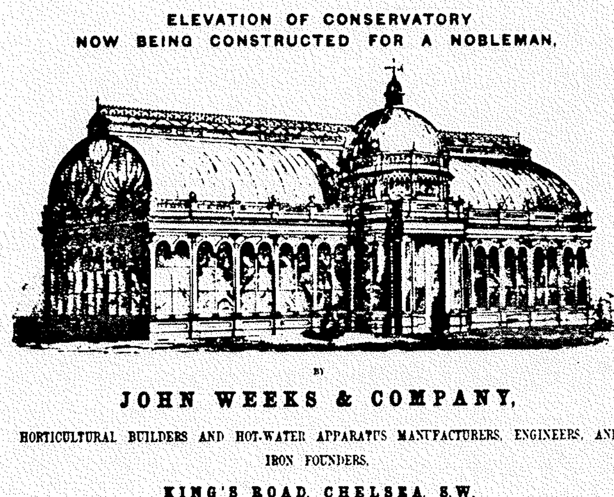
(*Den Nederlandtsen Hovenier*, J. van der Groen, Amsterdam, 1670.)

Figure 1. Interior of a Dutch orangerie (Lemmon)

In England, by 1714, the orangerie had become the greenhouse, supporting a variety of exotic plant types. During the 19th century, the greenhouse became exceedingly fashionable with the rich, with the enthusiasm of the aristocracy for greenhouses producing many spectacular structures of arched glass, wood, and steel (Figure 2).



Conservatory of a house on the boulevard Arago, Paris.
(Kopplekamm)



(Hix)

Figure 2. Examples of 19th century greenhouses

The greenhouse thus remained an item for the rich until after World War II when war-time technologies made available new building materials - most notably extruded aluminum and inexpensive glass.

These developments put the greenhouse within the reach of the average enthusiast, and glass and aluminum "hobby" greenhouses were mass produced throughout the world. No matter where they were built, these greenhouses had much the same form: vertical or near vertical walls, low pitched, symmetrical roofs, and single glazing all around (Figure 3).

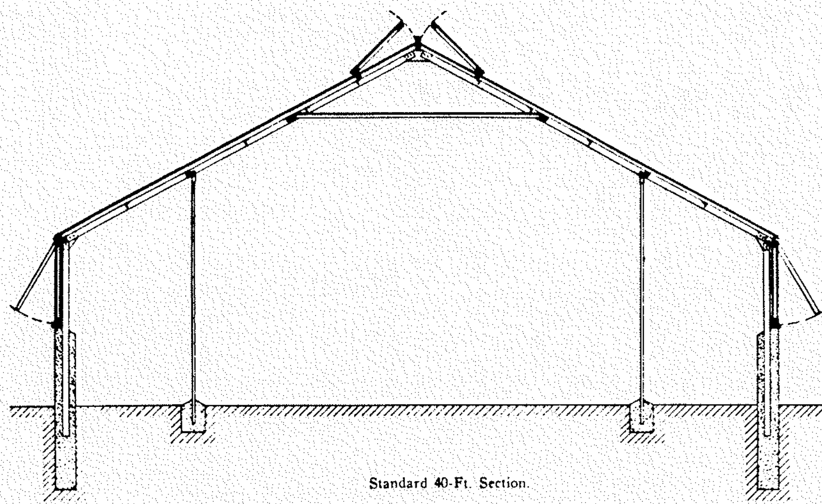


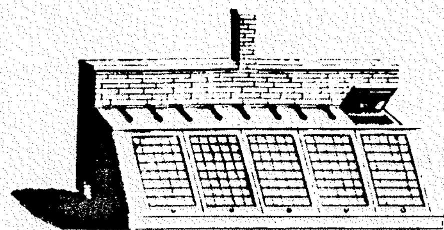
Figure 3. Conventional greenhouses

This "Dutch" form of greenhouse evolved in Northern continental Europe and was well adapted to that region's mild but overcast winters where the emphasis was on maximum light with little concern for heat loss. It was transplanted in North America, and other parts of the world, with little or no regard for climatic differences. In terms of a climate such as the Canadian prairies, these greenhouses were undoubtedly the most energy-wasteful buildings ever built. However, the shortcomings of these conventional greenhouses could easily be overlooked due to inexpensive fuels for heating.

It was not until the dramatic escalation of energy costs that the appropriateness of these designs to the Canadian climate began to be questioned.

1.2 Energy Efficient Greenhouses

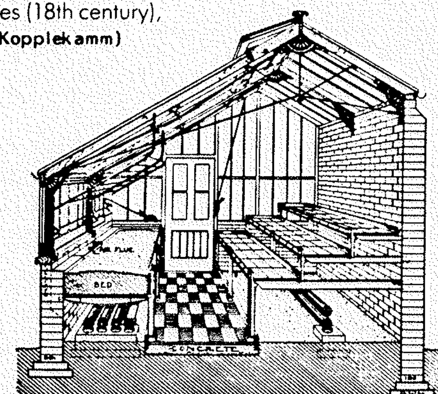
Various groups and individuals began to conduct research into more appropriate climate-responsive greenhouse designs. Most notable amongst these groups was the Brace Research Insititute at McGill University, which investigated forms appropriate to northern climates. These activities sparked a new generation of greenhouses. Often referred to as "solar greenhouses", the new forms were actually closely based upon historical examples which, although recognized as being cheaper to build and operate, were often dismissed as having inferior light distribution characteristics. 1



Dutch glasshouse for forcing vines (18th century), from Diderot's *Encyclopédie*. (Kopplekamm)

Dutch glasshouse.

(Kopplekamm)



(Clegg & Watkins)

Figure 4. Historical examples of "Solar Greenhouses"

The term "solar greenhouse" can be misleading in that all greenhouses are actually collectors of solar energy. The intent is to point out that this new generation of greenhouses embodies basic principles of passive * solar design. To be more correct, the term "energy-efficient" greenhouse would more accurately describe a greenhouse that had energy conservation as a major design objective. Conventional greenhouses make no attempt to store excess solar heat during the day and require auxilliary heat at night. An energy-efficient greenhouse makes every attempt to retain the solar energy it traps for use later when outside temperatures drop. This is accomplished with double-glazed south walls, heavily insulated roofs and north walls, thermal storage mass, and night curtains.

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* "Passive" systems are those which require little or no mechanical energy imput to utilize the sun's energy, and rely on the natural processes of radiation, conduction, and convention for collection, storage and distribution of heat.

1.3 Attached Greenhouses

A greenhouse can be either integrated with the house, or freestanding. An attached greenhouse offers a number of advantages. Besides the convenience of having direct access to the greenhouse, there is the economic advantage of having one less wall to build. An attached greenhouse is also more adaptable in terms of energy-use strategy. Since a greenhouse usually has an excess of heat during the day, this heat can be moved into the house and used there. Along with the heat comes the added bonus of humidity and oxygen which the plants have produced. The attached greenhouse can also be an integral part of the living space of the house, adding not just to the value of the house, but to the quality of life in the house. Finally, adding a greenhouse is one form of retrofit: upgrading an existing structure for improved energy efficiency. This is significant in view of the fact that it is the existing structures - not the new ones that are wasting energy. An attached greenhouse could be viewed as a machine which increases the sun's potential to do useful work at a particular site.

1.4 Heat vs. Food

It should be pointed out that two major types of attached passive solar greenhouses can be identified. The Brace Institute refers to these as type 1 and type 2 solaria. Both are attached structures with large areas of south-facing glazing. However a type 1 solarium, according to Brace's definition, cannot support plant growth, since no attempt is made to maintain a minimum temperature. Such structures supply heat to the parent building while the sun is shining and are allowed to cool down to outdoor ambient temperatures at night. Since these types are closed off from the main building and do not require heat at night, they provide a net gain in solar heat. As such they can be thought of as "walk-in" solar collectors, providing additional living space during sunny periods. It is this type which can appropriately be called "solarium" or "sunspace".

A type 2 solorium, as defined by the Brace Institute, is one in which a minimum night time temperature is to be maintained. This enables the support of plant growth and allows the space to be used both day and night. As such it can be more closely integrated with the rest of the dwelling. Because these spaces are used to nurture people and plants, control of temperature and other environmental conditions is much more important than in a type 1 solarium. Since a minimum temperature must be maintained, a greater emphasis is placed upon retention and storage of trapped solar energy within the solarium itself. As such, this type of solarium is more complex in its design, requiring a more thorough understanding and integration of the functional components. It also offers more potential and flexibility in its use than does a simple heat-producing solarium. It is this type 2 solarium that is often called a "solar greenhouse", and which will here be referred to as an "energy-efficient greenhouse".

In summary, type 1 solaria tend to be cheaper to build, more simple to operate and produce greater net gains in solar heat for the parent building. They are, however, only intermittently useable as living spaces, due to widely fluctuating temperatures. Maximum heat gain, rather than human comfort is the priority.

In contrast, type 2 solaria are more complex and require a better understanding of the principals of thermal energy transfer. They will not produce as much of a net heat gain for the parent building since part or all of the incoming heat energy is stored for later use. The trade-off is between heat and food, since growing food crops requires that a minimum night temperature be maintained. The amount of excess heat available for transfer to attached spaces depends upon the time of the year the greenhouse is used to grow crops, the type of crops being grown, and the minimum temperatures to be maintained.

In both cases it must be acknowledged that there are better ways to save energy in the home, most notably through conservation.

Energy experts agree that reducing air infiltration and adding insulation (in that order) are the most cost-effective ways of reducing energy consumption in the typical Canadian home.

However, it is obvious that greenhouses have been built in the past and will continue to be built in the future for reasons other than energy production. Traditionally, home or hobby greenhouses were used to support collections of exotic plants or as "season extenders" to start bedding plants for the outdoor garden. If the small-scale private greenhouse were designed with food production as a prime concern, a significant energy contribution would be represented in the food itself. In today's supermarket society not many people are used to thinking of food as a form of stored solar energy.

1.5 Food Production and Modern Agriculture

The concept of an energy-efficient, small-scale, food producing greenhouse is a timely one from an economic, ecological, and social standpoint, especially in light of present trends in modern industrial agriculture. Nowhere in industrial society has mechanization had such an impact in relieving human drudgery as in agriculture. However, technological advances have not come without a price. With increased mechanization in agriculture came increased dependence on petroleum fuels. Thus today while it is true that solar energy is directly responsible for nearly all our food through photosynthesis, it is also true that the high yields of primary food production are sustained by large subsidies of non-solar energy. [2] For many crops, the energy input is greater than the energy content of the produce. In California fruit and vegetable production, for example, an average of 1.4 calories of energy input is required to product each calorie of food energy. [3] This is the fuel and electrical energy required in mechanized agriculture for planting, cultivation, spraying, harvesting, cleaning and sorting. Beyond this there are additional energy inputs in the tremendous amounts of petroleum-based chemicals, including pesticides and fertilizers, that are fed into the system. For example, in 1979, Canadian farmers spent over $350 million (or 54% of total farm purchases) on pesticides. [4] The high yields of industrialized agriculture are particularly dependent upon nitrogen fertilizers produced primarily from natural gas.

Beyond the costs of production are the costs of handling and distribution - especially significant in a country such as Canada where, in spite of our image as a food producer, we must still import 75% of our total fruit and vegetable consumption, with most of it coming from the U.S. [5] Thus fresh vegetables eaten during the winter represent the greatest energy investment given the energy involved in shipping goods from California, Florida and Mexico. It has also been shown that the very vegetables most likely to be grown at home are those requiring the most energy-intensive technology. [6] Food and energy today have become intimately linked. As such, as energy increases in price, so must food.

For many people, modern agriculture's heavy dependence on pesticides is cause for concern. While proponents of modern agriculture maintain that chemical intervention is safe and necessary, there are nevertheless those who are concerned about the long-term consequences of such practices.

People involved in growing their own food at home have the opportunity to refrain from using chemicals if they so choose. Production of food in a small scale home greenhouse enables more benign forms of pest control to be used - ones which would not be feasible in large scale agriculture.

For many people, a desire for more control over inputs into their food supply is reason enough for growing their own food. For others, dissatisfaction with the quality, price, or availability of supermarket produce is another. Store-bought produce, especially in winter, often does not match up to the quality of that produced in the home garden or greenhouse. Fruit and vegetable varieties used in mechanized agriculture have been bred to withstand mechanical harvesting, sorting, and long-distance shipping. Some people feel that, because of the emphasis on varietal appearance and suitability for shipping, plant breeders have forgotten about flavour. However, plant breeding is not necessarily the reason for poor quality in the supermarket. Shipping, improper storage, and time, all take their toll. Finally, the cost of mid-winter produce is high due to the simple laws of supply and demand.

In contrast, flavour and nutrition are at their peak in freshly-harvested produce grown at home. With a greenhouse, the time span from plant to table can be minutes instead of days, and produce can thus be of a quality unobtainable at any price.

1.6 Self-Sufficiency

Apart from the safety, quality, and price of fresh food, other reasons for growing one's own food year-round could be considered less tangible. The word "satisfaction" could sum up these various non-tangible benefits. First there is the satisfaction of being more self-sufficient in a world where most people are isolated from their means of production and sustainance. The Farallones Institute in The Integral Urban House say of growing food at home that no other single activity is likely to increase the urbanite's understanding of natural systems and decrease their dependence on centralized systems.

Bob Rodale, editor of "Organic Gardening" writes: "Every day, people...are unhooking themselves from the high-energy, high-risk lifestyle. By taking more and more of their life-supporting activities from corporations and managing them personally, many readers report increased satisfaction with life, and better health."[7]

Finally, for many people, contact with soil and living plants is a pleasurable and relaxing experience. A greenhouse is a way to enjoy such experiences (with tangible fringe-benefits) throughout the year.

1.7 Societal Shifts

Today we are part of a world riding an energy shock wave in which gloom and uncertainty abounds. Futurists such as Alvin Toffler, Hazel Henderson and others explain that industrialized countries are now in a state of transition to a post-industrial society in which many of the rules will be changed. The hidden subsidies of ultra-cheap energy and raw materials which fuelled industrial growth have been eliminated. As we move into a post-industrial era, confusion abounds since the transitions are not yet widely understood as fundamental shifts in our resource base and entire production systems.

Henderson believes that we are entering an "entropy state" of spontaneous "devolution" resulting from our system's own size and complexity. Alternate lifestyles, self-reliance, voluntary simplicity, the do-it-yourself movement could all be considered part of this spontaneous devolution, and represent associated shifts in values and expectations.[8]

Toffler, in The Third Wave, also sees a philosophical revolt against the assumptions of the Industrial Age occurring, and discusses the trend towards small-scale, decentralized, and diversified forms of production. He forsees the home of the near future as an "electronic cottage" where advances in communications and computer technology will enable work and production to be centered to a much greater degree in the home. "Work" will include not only traditional market-based activity, but also production of basic needs in the home for immediate consumption. Thus the typical post-industrialist will be not just a consumer of goods, but a "pro-sumer" - one who has a greater input in the production of goods and services for his own use.[9] Food production, gardening, and husbandry will be a basic and important aspect of the electronic cottage. A facility such as a greenhouse may be viewed as more of a necessity than a luxury in the home of the future which many feel will re-emerge as a central unit in society - a unit with enhanced economic, educational and social functions.[10]

1.8 Towards a Better World

While it is not being proposed that a home greenhouse will solve the world food problem, it is recognized that any food grown by an individual, family, or community for primary consumption is food that did not have to come from the industrial food system, and as such represents a savings in energy and world resources in general. This is especially significant when viewed in the context of the world food/population crisis and the recognition that much of the "bad news" in the world today is related to the growing population pressures on the Earth's finite resources.

Much is heard about the energy crisis, but the world's arable land is also a finite resource, and one which is diminishing each year. The arable land per person in the world has been decreasing for years and this decrease is now accelerating.[11] Cities continue to consume the most productive farms lands in industrialized countries such as Canada, as well as in third world countries.[12] Desertification continues throughout the world's arid regions as desperate people farm and graze more marginal lands, trading long-term stability for short-term survivial.[13] In industrial agriculture, the significant gains in production from plant breeding, fertilizers, and pesticides have already been realized, and per capita cropland production has actually been declining since 1971. [14] The Green Revolution which spawned hopes of feeding the world's people has brought with it a number of serious side effects and some feel that it will ultimately fail unless we in the developed nations can make major adjustments in areas such as our tariff and quota policies, approach to foreign aid, diet, ideas about technology and distribution of wealth, and the operation of a number of our organizations. Indeed, Kenneth Dahlberg goes even further in Beyond the Green Revolution, saying: "Given the risk of plant disease, pests, exhaustion of critical resources (especially fuels and fertilizers), and soil erosion not to mention its associated social, political, and economic dislocations, it is doubtful that modern industrial agriculture is sustainable over the next century. There is also the evolutionary risk of so simplifying our agricultural and global ecosystems that there is some sort of serious biological collapse...the overall conclusion need not be one of doom but simply that we must trade in our current models (both intellectual and agricultural) for smaller, better, and more ecologically sound ones".[15]

This same message is echoed by many futurists, economists, and environmentalists as we enter an age of scarcity - an age of steady-state economy which favours efficiency and frugality, where innovation and integration are highly valued. New models will have to come from the ground up - from Toffers "techno-rebels", rather than a top down technological fix. The climate-responsive, energy-efficient, small-scale greenhouse is just one example of the many new models for resource efficiency.

PART 2 ENVIRONMENTAL CONTROL FOR PLANT GROWTH

Part 2 Environmental Control for Plant Growth

"As every animal has its climate and food natural to it, so has every plant an exposure, temper of air, and soil, proper to nourish and maintain it in a right state of health".[16] Thus in 1721 Richard Bradley, Professor of Botany at Cambridge University first described the relationship of plants to their environment.

The function of a greenhouse is to provide the conditions for this "right state of health"; protecting plants which grow in warmer regions from harsher climates, and making it possible to grow plants through a cold season.

In the early ninteenth century, J.C. Louden coined the term "artificial climate" in his writings on greenhouses.[17] Today, in modern science the study of the plant environment is called phyto-engineering and the physical requirements for optimum plant growth are relatively well understood.

Essentially the plant exists in two environments; air and soil, and every plant has optimum requirements of each. To limit one essential variable is to limit all the rest. This is the ecological "law of the minimum". Because plant species vary significantly in their requirements, the kind of plants to be grown and the season of use will influence greenhouse design. This section will identify the environmental conditions sought in food production.

2.1 The Type of Greenhouse

As pointed out earlier, an energy-efficient greenhouse is not necessarily a net producer of energy as well as food, in spite of such claims by some authors and greenhouse manufacturers. In fact, trying to optimize for both food production and solar collection may result in a structure which is really suitable for neither.[18] It is therefore important to consider the environmental conditions for the growth of food crops as the most important criteria in designing a food-producing greenhouse.

Before looking at the requirements of food crops, it is necessary to define the anticipated use of the greenhouse in terms of:

1. What part of the year the greenhouse will be used, and
2. what kind of crops will be grown.

First, if the greenhouse is to be used year-round, the design criteria will be quite different than for one that is to be used merely as a season extender augmenting the outdoor garden by starting bedding plants in the spring and adding a few extra weeks in the fall. This is because the temperature difference between indoors and out will obviously vary considerably with the season.

The second consideration, the crops to be grown, is also a temperature-related factor, although there are other considerations. For example, if the greenhouse is to be used year round, the crops that will most economically be grown during the winter are those which are best adapted to the lower temperatures and light conditions of winter.

If a greenhouse is to support warm-season crops throughout the winter, the design must change accordingly.

Anticipated crops will also have an influence on greenhouse design in terms of growing space, both above and below ground level. The use of vertical space will provide for more production per square meter of floor area. Tomatoes and cucumbers, for example, are much more productive than small plants such as lettuce or spinach due to the vertical space they occupy. If vertically-trained crops such as these are to be grown, it is important in the initial planning stages to ensure that wall configurations will not limit their growing space. Similarly, vegetable crops vary significantly in their rooting requirements, some having roots only a few centimeters deep, others with root penetration of well over a meter in unrestricted conditions.[19] While it may not be possible to provide a meter of soil depth, the physical size of the crops must be recognized and taken into account in the early planning stages to provide as near ideal conditions as possible. The following is a listing of vegetables grouped according to root depth in unrestricted conditions.

Shallow (.46 to .61M)	Moderately Deep (.91 to 1.2 M)	Deep (over 1.2 M)
Broccoli	Bean	Artichoke
Brussels sprouts	Beet	Asparagus
Cabbage	Beet	Bean, Lima
Cauliflower	Carrot	Parsnip
Celery	Chard	Pumpkin
Chinese cabbage	Cucumber	Squash, winter
Corn	Eggplant	Sweet Potato
Endive	Muskmelon	Tomato
Garlic	Mustard	Watermelon
Leek	Pea	
Lettuce	Pepper	
Onion	Squash, summer	
Parsley	Turnip	
Potato		
Radish		
Spinach		

Rooting Depths of Vegetables In Unrestricted Conditions (Knott, 1957)

A final consideration in preliminary planning might address the question of whether plants will be the only occupants of the greenhouse or whether or not there will be living space for people too. Plant requirements and human comfort requirements are quite compatible, and a greenhouse can be used as living space as well. If it is not, the design should be flexible enough to accommodate change should changes be desired. In-ground planting beds, for example, can make a layout relatively permanent.

Having covered these very basic considerations in conceptual design, an examination of the conditions sought in environmental control for plant growth follows.

2.2 Light

Knowledge of the light requirements of plants is important not only in the understanding of greenhouse cultural practices, but also in such aspects of greenhouse design as glazing selection and configuration and interior finishes.

Light is a form of energy. Visible light occupies a very small segment of the electro-magnetic spectrum of radiant energy which is emitted by the sun.

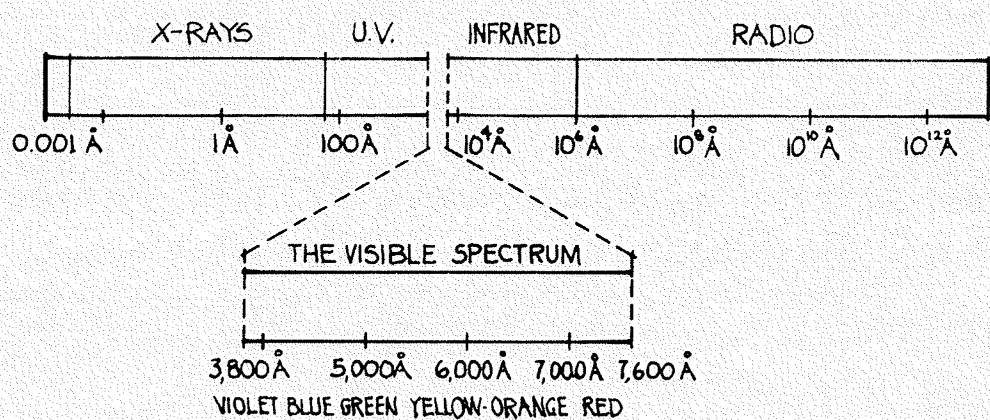


Figure 5. Light and the Electromagnetic Spectrum (Chrispeels & Sadava)

The earth receives a continuous stream of solar radiation; from x-rays to ultraviolet, visible light, and infra red. It is the visible part of the spectrum which plants use in photosynthesis, and it is photosynthesis which is ultimately responsible for all life on earth.

Through photosynthesis, plants convert the radiant energy of visible light into chemical energy. This energy is stored in the chemical bonds which link carbon atoms (from carbon dioxide) along with hydrogen and oxygen (from water) to form glucose molecules. These molecules form the basis of more complex molecules and of plant structure, and ultimately of all the major ecosystems of earth.

Plant responses to the visible spectrum of light do not correspond with the response of human vision. For example, the photosynthesis reaction is driven primarily by light in the red and blue part of the spectrum. Other major classes of plant response can be identified as 1) those that have a maximum response from red light (eg photoperiodism) and 2) those with a maximum response from blue light (eg. phototropism or bending towards or away from a source of light).[20]

The duration of the photoperiod, or day length, is significant in greenhouse gardening as it can influence important plant reactions such as flower formation, pollination, and initiation or release from dormancy. Because of this influence of day length, certain vegetables cannot be successfully grown in the short days of winter without supplemental lighting. Plant growth can also be limited by insufficient light quantity; a function of intensity and duration. Within limits, light of insufficient intensity can be augmented by a longer duration, but the actual amount of light available during winter days may limit the growth of many plants. For example, while a tomato plant does not need light intensities equivalent to full sunlight it does need 2000 - 3000 footcandles (or 1/5 - 1/3 the intensity of direct sun at high noon)[21] for a minimum of eight hours per day,[22] in order to achieve optimum growth. By contrast, lettuce is well adapted to greenhouse culture during the cloudy days of winter, and good growth can be obtained with as little as 500 footcandles.[23]

Generally speaking, any greenhouse should be designed to expose plants to as much light as possible throughout the season(s) of anticipated use. While this may seem self-evident, light, or a lack of it can be a significant limitation to plant growth in energy-efficient greenhouse designs due to the reduced glazing areas typical in such greenhouses.

If crops requiring a higher light intensity or longer day length are to be grown through periods of short days and low light intensities, supplemental lighting should be considered. This need not necessarily be considered energy wasteful, since much of the total energy of the light will end up as heat and will thereby reduce the heat required from other sources necessary to maintain minimum temperatures.

2.3 Temperature

Temperature is one of the most critical factors in raising food crops because it affects the rate of all cellular process. In absolute terms, active plant growth is limited to a range of 10 degrees to 40 degrees C. The optimum temperature for photosynthesis in the majority of food plants is somewhere between 20 degrees and 35 degrees C. Beyond that, it is difficult to generalize since plants vary significantly in their tolerance to temperature extremes. Plant needs can also vary with the stage of development, requiring different temperatures for germination, vegetative growth, and fruit development.

Generally, food crops can be divided into two major categories with regards to temperature requirements: warm season and cool season types. Warm season crops such as tomatoes and cucumbers are less tolerant of cold and require a daytime temperature somewhere between 21 degrees and 27 degrees C., while cool season crops such as lettuce, spinach, and cauliflower are much more tolerant of cooler temperatures, having minimum temperature requirements in the range of 13 degrees to 18 degrees C. The following are some common vegetables grouped according to temperature preference.

Cool Season Crops		Warm Season Crops	
Hardy (Min.4 ^{o}C) (Max.24 ^{o}C)	Half Hardy (Min.7 ^{o}C) (Max.21-24 ^{o}C)	Tender (Min.10 ^{o} C) (Max.35 ^{o} C)	Very Tender (min.10-16 ^{o}C) (Max.32 ^{o}C)
Asparagus	Beets	Corn	Cucumber
Broccoli	Broad beans	Cowpea	Eggplant
Brussels sprouts	Carrots	N.Z. spinach	Lima bean
Cabbage	Cauliflower	Snap bean	Cantaloupe
Garlic	Celery	Soybean	Okra
Kale	Chard	Watermelon	Pepper
Kohlrabi	Chinese cabbage		Pumpkin
Onion	Cress		Squash
Parsley	Endive		Tomato
Peas	Lettuce		
Radish	Parsnip		
Rutabaga	Potato		
Spinach	Salsify		
Turnip			

Plant adaptation to Heat and Cold (from Harrowsmith #41, and Knott, 1957).

Temperature requirements can vary as a function of other plant requirements. For example, under low light conditions, most plants require a correspondingly lower temperature as well. For example, recommended daytime temperature for greenhouse lettuce (Bibb) is 21 - 24 degrees C. for bright days, while 17 - 20 degrees C. is considered optimum for cloudy days.

Similarly, plants generally require lower temperatures at night. This is because respiration continues at night after photosynthesis has ceased. Respiration in plants is basically the reverse of photosynthesis whereby energy is expended for plant processes. Since the rate of respiration is temperature-dependent, much of the sugars produced during the day through photosynthesis can be lost at night if temperatures remain high. Reducing night temperatures, then, enables plants to increase their net stores of energy, and thereby accumulate food energy from the sun's energy. Figure 6 shows the relationship between photosynthesis, respiration, and plant growth.

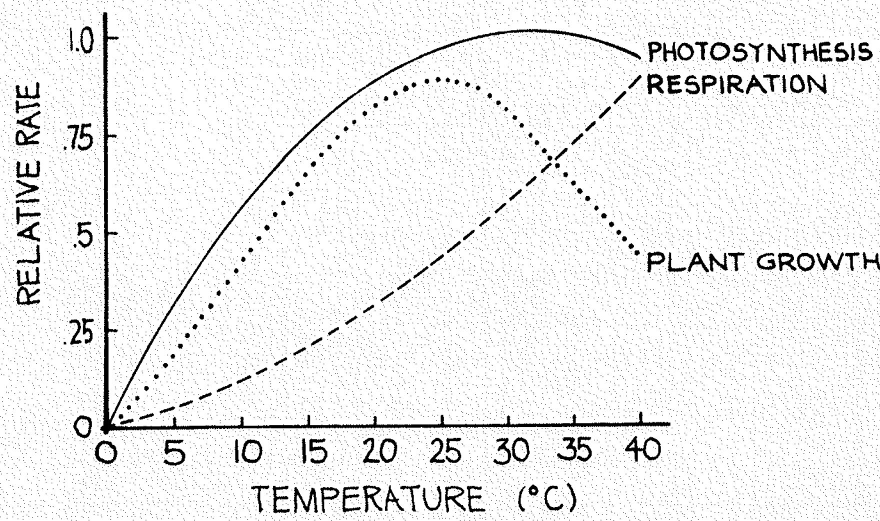


Figure 6. Photosynthesis, respiration, and plant growth. (Chrispeels & Sadava)

Generally temperature differentials of from 5 degrees - 8 degrees C. between night and day are acceptable. Tomatoes, for example, have been shown to prefer daytime temperatures of 23 degrees C. while night temperatures of 17 degrees C. are optimum for such important processes as flower development.[24] Greenhouse cucumbers prefer a range of from 27 - 29 degrees C. during daylight, to 21 degrees C. (minimum) at night. Lettuce preferences vary with type. Temperature ranges of two common greenhouse varieties are as follows:

	Day	Night
Grand Rapids	13 - 24 °C*	10 - 13 °C
Bibb	17 - 24 °C*	14 °C

* dependent on light intensity.
(Wittwer & Honma)

Knowledge of the temperature requirements of various crops provide the necessary design temperatures for making predictions about greenhouse performance. Such information is also useful in deciding growing strategies and initial planning considerations. For example, knowing the requirements of warm season crops, it may be decided to grow only cool season crops in the winter months in order to reduce the need for auxillary heat. Also, consideration could be given in the preliminary design to temperature zoning; having a cool zone and a warm zone separated by a glazed wall, providing optimum conditions for both classes of crops at the same time.

2.4 Air Quality

Besides having various needs in terms of air temperature, plants have specific requirements regarding certain aspects of air content, most notably carbon dioxide and water vapour.

Carbon dioxide is generally ignored in outdoor gardening, but is an important factor in greenhouse gardening. It is a basic requirement of the growing plant; an essential raw material in photosynthesis. Until the early 1960's, the benefits as well as the economics of CO_2 enrichment were not widely appreciated. It is now known that under many conditions, the most limiting factor in the growth of terrestrial plants is the carbon dioxide concentration in the atmosphere. (It is known, for example, that in past eras of fantastic plant growth, the atmospheric concentration of CO_2 was from 10 to 100 times today's normal level of 330 ppm).

Limitations of the atmosphere are especially significant in the growth of greenhouse crops, since the CO_2 in a greenhouse can be quickly depleted below normal atmospheric conditions, particularly in energy-efficient airtight designs. CO_2 levels in unventilated greenhouses are generally lowest on sunny days between 10 a.m. and 4 p.m. due to the increased uptake associated with the higher rates of photosynthesis. It is therefore during this period that supplemental CO_2 is most beneficial. The optimum level appears to be, for most greenhouse crops, from 1000 to 1200 ppm.[25]

Traditionally, CO_2 depletion was not recognized as a problem in greenhouses, partly because of a lack of knowledge, and probably because it was not as great a problem due to the "leaky" nature of traditional greenhouses and to the extensive use of forced ventilation to prevent overheating. The introduction of fresh outside air is obviously the easiest way to replenish depleted CO_2, but this is not very practical during cold weather. While the development of air-to-air heat exchanges could make this a more viable approach, the accepted solution is to release supplementary CO_2 within the greenhouse itself. This could be in the form of dry ice, compressed gas, or through the combusion of propane or natural gas. Whatever the method, in commercial greenhouse production the addition of carbon dioxide has proved to be relatively cheap to add, with economic returns exceeding by several times the costs of treatment.[26] Wittwer and Honma report that "results with greenhouse-grown tomatoes have been phenomenal", the most notable effects being: accelerated growth rates, earlier fruit maturity, and increases in both fruit set and fruit size. Furthermore, the response to carbon dioxide occurs over a wide range of light conditions, enabling partial compensation for low light intensities such as those found on cloudy winter days.[27]

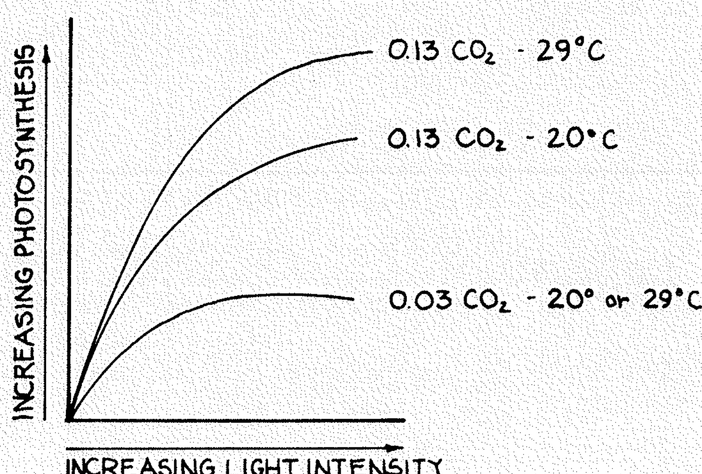


Figure 7. Effects of carbon dioxide enrichment. (Clegg & Watkins)

Air circulation is a relatively simple means of improving carbon dioxide uptake, whether levels are supplemented or not. With no air movement, the carbon dioxide at the leaf surface is depleted as it is taken up by the plant. Air circulation, therefore, maintains a higher concentration of carbon dioxide at the leaf surface, and thus facilitates uptake. (Fig. 8)

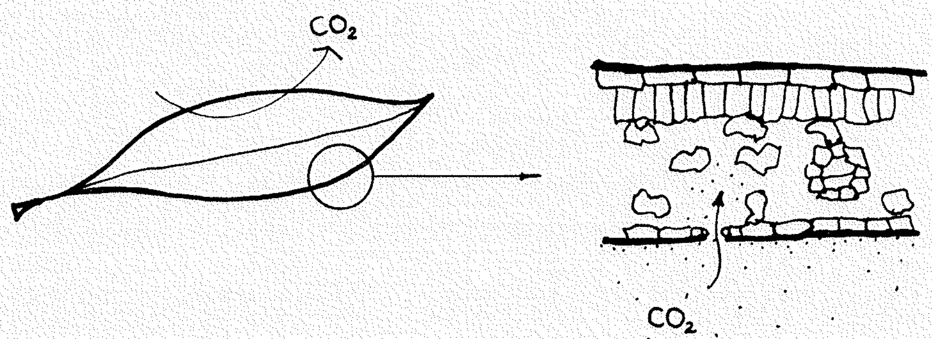


Figure 8. Carbon dioxide at the leaf surface.

Good air circulation is also beneficial to greenhouse plants in preventing or controlling the spread of serious fungal diseases which are encouraged by the high humidity often found in air-tight greenhouses. A relative humidity of around 60% is considered ideal for most plants.[28] Higher levels, besides encouraging fungal disease, causes condensation which reduces light transmission of glazings, causes wood to decay, and results in increased maintenance requirements on interior finishes, etc. Humidity levels below 60% causes the limited soil volumes in greenhouses to dry out frequently, putting stress on the plants, and requiring frequent watering. This is not only time-consuming, but can cause leaching of soil nutrients. Low humidity can also encourage some insect pests such as spider mites.

Air circulation, then, can control excessive humidity. In attached greenhouses, good air circulation benefits the occupants of both the greenhouse and the parent building through an equalization of humidity levels and an interchange of carbon dioxide and oxygen between house and greenhouse.

2.5 Greenhouse Soils

In simplistic terms, soil is made up of solid matter interspersed with voids or pores. Its function is to provide mechanical support for the plant and to make water air and nutrients available to the roots.

Soil in nature is not, however, a static system of inert components, but rather a dynamic community in which energy and matter are continually being converted from one form to another. These conversions are carried out by a variety of soil organisms, from microscopic viruses, bacteria, and fungi, to nematodes, earthworms, and insects.[29]

Generally speaking, soils that can sustain plants outdoors are often unsuitable for use in greenhouses culture. This is because in a greenhouse, soil volumes are limited and plant culture is usually much more intense than outdoors. As a result, there are greater demands for water, nutrients, and air placed on a given volume of soil. Greenhouse soils also tend to be less self-maintaining and more prone to imbalances because they are not totally natural systems as are outdoor soils.

In fact, in commercial greenhouse operations, soils are routinely sterilized in order to prevent disease and insect problems from arising. Because of the large scale and typically monoculture crops, great care must be taken to ensure that offending organisms are completely eliminated. This is accomplished either through the use of chemical fumigants or heat. Most commonly, greenhouse soils are sterilized using steam. (Some writers prefer the word "pasteurized" since the soils are not completely sterile, but still contain lower life forms such as bacteria).[30] The common practice in commercial greenhouses is to introduce steam through 10 cm tiles buried at the bottom of the soil beds. The soil is heated to 80 degrees C. and held at that temperature for 30 minutes to four hours. Thirty minutes will kill most of the common pathogens,[31] while four hours is needed to kill all disease-causing organisms in plant debris.[32] Soils are usually sterilized whenever there is a crop turnover.

Lately, as an offshoot of the organic gardening movement, a trend towards living soil in hobby greenhouses has developed. The rational is that a living soil system is a less intrusive and more self-regulating approach in that organic material is continuously being broken down by soil organisms, thereby replenishing soil nutrients. Insect pests that start causing problems are controlled through such organic methods as predator insects (ladybugs, parasitic wasps, etc.) organic pesticides, or even hand-removal of the offending insects. Diseases are prevented from occuring or spreading through careful sanitation and good cultural practices - removing dead or diseased plant parts, and isolating and quickly dealing with infected plants.

Another more recent approach to controlling or preventing disease in the greenhouse environment is the use of soil-less mixes or sterile plant growing media. The advantages in using such media are that they do not require steam sterilization (which can be expensive and complicated for the inexperienced grower), they offer a greater degree of standardization, and they are lighter in weight.[33]

Because they are based on such non-nutritive substances as sphagnum moss, soil-less mixes require more care in their formulation. Nutrient supplements can be home-made or can be purchased ready-to-use. Since plant nutrition is entirely dependent upon added nutrients, defficencies are more likely to show up in soil less media than in mixes which include soil. Control in supplemental feeding is therefore more critical.

Materials and proportions of these mixes can vary with local availability. For example regions with logging operations and sawmills could use sawdust or shredded bark, while another area's best choice might be sphagnum moss and sand. Other components of soil-less media are man-modified products such as vermiculite or perlite. While costing more than the natural products, these materials are lighter in weight and are more consistant in their physical structure.

An example of a soil-less mix is:

75% sphagnum moss
25% fine sand

Other examples, formulated at Cornell University and referred to as the Cornell Peat-Lite mixes, include:

50% sphagnum moss
50% vermiculite
or
50% sphagnum moss
50% perlite [34]

(Note that these formulae also require the addition of plant nutrients - including micro-nutrients and trace elements)

At the far end of the root medium spectrum is the hydroponics approach to plant growth where plant roots are bathed in controlled nutrient solutions. Hydroponics usually takes the form of either water or aggregate culture. In aggregate culture, which is generally simpler to set up and operate and thus more appropriate to the home greenhouse, plants are supported in inert aggregates such as sand, gravel, or perlite. Hydroponic systems are quite compatible with greenhouse operations and offer the advantages of increased sterility, lower volumes of rooting media, and the potential for complete automation. Nutrient solutions must be monitored carefully, however, since imbalances can occur as nutrients are used up. Hydroponics is the most "intrusive" system, requiring man-made chemicals as well as more specific equipment such as containers, pumps, and timers.

This concludes a discussion of plant requirements as they might apply to greenhouse design in terms of defining the conditions sought in the controlled environment. The next section will introduce the topic of solar design through a review of some basic thermodynamic principles as a means of attaining the goals of climate control.

PART 3 THERMODYNAMICS AND PLANT GROWTH

Part 3 Thermodynamics And Plant Growth

An understanding of some basic principles of the movement, and interaction of energy and heat is essential in any discussion of energy-efficiency. In greenhouse design we are concerned specifically with the energy flows which work together to optimize the conversion of solar energy into the chemical energy of plant parts, in this case food. Between sun and food are a number of intermediate steps and interactions. This section traces energy pathways relevant to the creation of an "artificial climate" and to the production of food in such an environment.

3.1 Solar Energy

The source of virtually all energy on earth is the sun. It is in reality a giant nuclear fusion reactor in which hydrogen nuclei are fused to form helium, a process whereby mass is converted to energy. The vast energy release is "contained" by the tremendous gravitational force of the sun itself. The radiant energy create arrives at the earth 8.3 minutes later in many different wavelengths.[35]

The greatest proportion (51%) of the radiation is in the high frequency (short wavelength) region. This consists of visible light with 46% of the total output, and ultraviolet with 5%. The remaining 49% is the longer wavelength infra red radiation which is invisible but can be felt as sensible heat.[36]

Of all the solar radiation incident upon the earth and its atmosphere, as much as 35% is reflected back into space. The amount of radiation that does reach the earth is dependent upon how much atmosphere it has to pass through, since the atmosphere not only reflects but absorbs and scatters radiation as well. Thus when the sun is low in the sky, radiation must pass through more atmosphere and less actually reaches the earth. (Fig. 9).

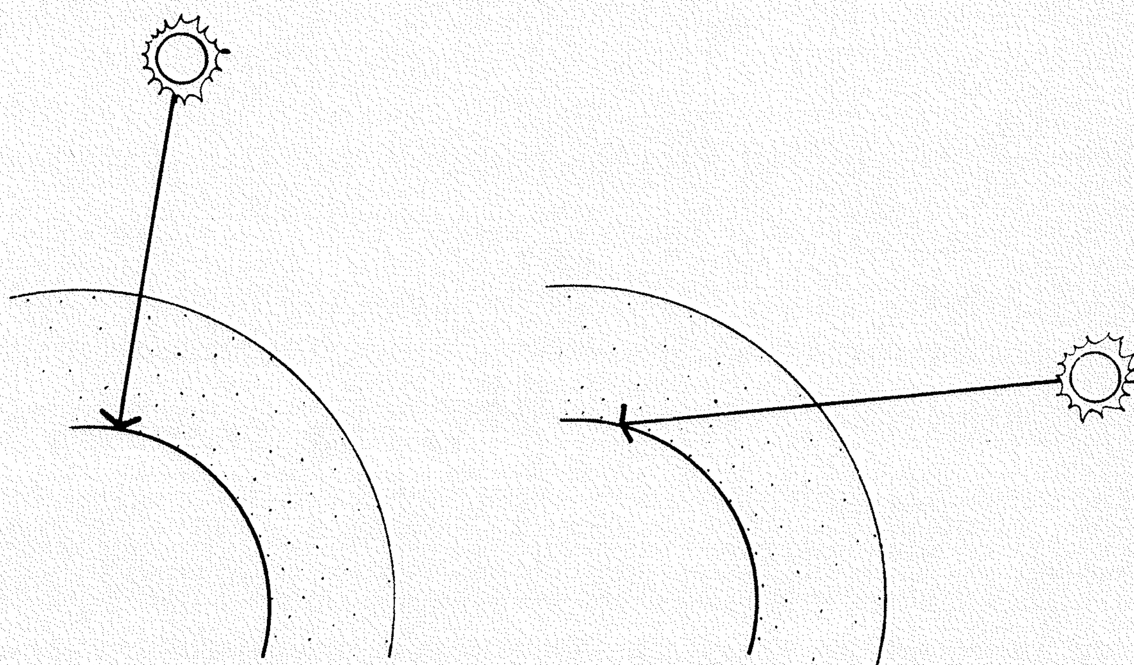
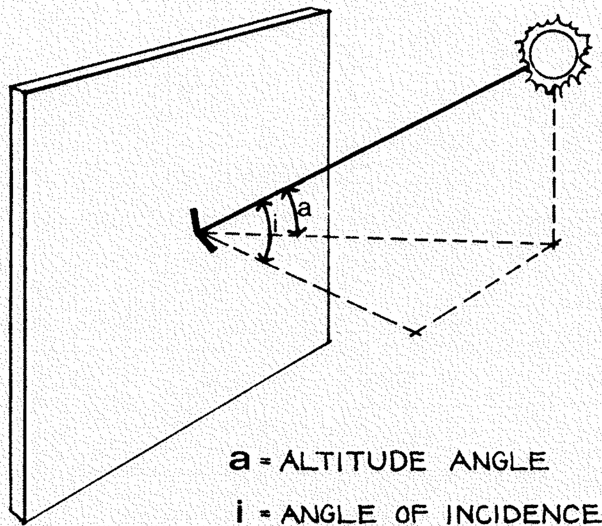


Figure 9. Light penetration through the atmosphere

Similarly, the angle of incidence of the sun's rays on a surface will determine how much energy the surface actually receives. A surface perpendicular to the sun's rays will receive the most energy; the further from perpendicular, the less energy received. (Fig. 10)



Incident Angle Angle (degrees)	Radiation Intercepted (percent)
0	100.0
5	99.6
10	98.5
15	96.5
20	94.0
25	90.6
30	86.6
35	81.9
40	76.6
45	70.7
50	64.3
55	57.4
60	50.0
65	42.3
70	34.2
75	25.8
80	17.4
85	8.7
90	0.0

Figure 10. Intensity of radiation and angle of incidence (Mazria).

Note that a surface can be as much as 25° away from perpendicular to the sun and still intercept over 90% of the direct radiation.

Basic information such as this is important in determining optimum angles for glazed surfaces as well as absorptive or reflective surfaces in a greenhouse.

3.2 Solar Energy Transfer

It should be re-stated that the radiation reaching the earth's surface is composed primarily of visible light and infra red radiation. The distinction is made because both types of radiation do not behave exactly the same. Both types of radiation, upon reaching the earth can be either reflected transmitted or absorbed, depending upon the type of material they intercept.

For example, polished chrome and white plaster are both highly reflective to visible light. The chrome is referred to as specularly reflective because the angle of reflection of the light equals it's angle of incidence, while the plaster reflects light in a diffuse or scattered manner. However, the infra red part of the sun's radiant energy, while being reflected by the chrome will be absorbed by the plaster. In general, most surfaces will absorb infra red radiation unless they have a highly polished or specularly reflective appearance.

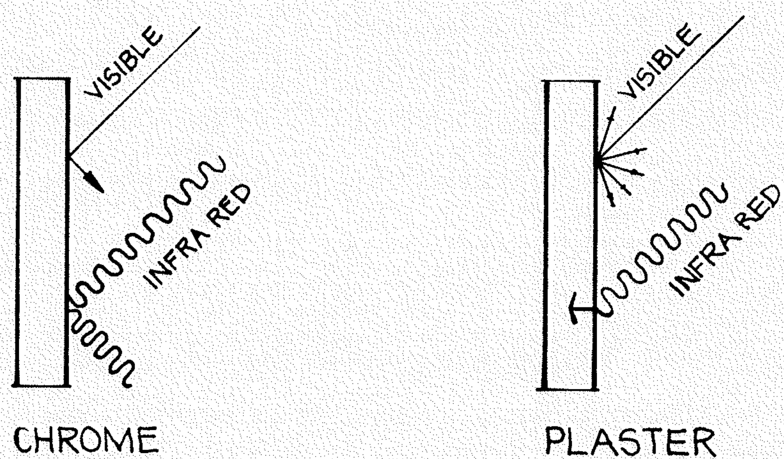


Figure 11. Reflection of infra red and visible radiation.

Radiant energy that is not reflected will either be transmitted or absorbed. Visible radiation is mostly transmitted through glass. Glass is therefore referred to as being transparent. A material that diffuses the light it transmitts is called translucent.

Materials which transmit light do not necessarily transmit thermal radiation. Thus while glass is transparent to visible radiation, it transmits almost no thermal radiation. (fig. 12)

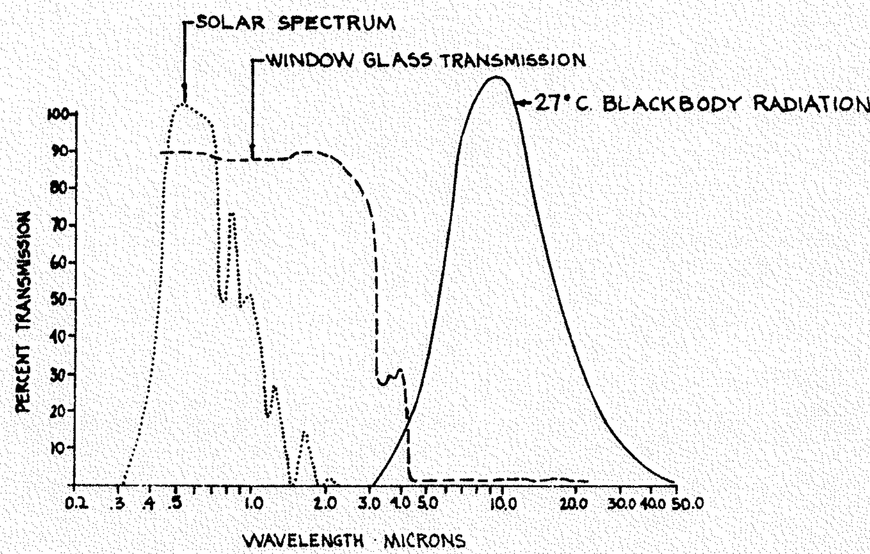


Figure 12. Transmittance of glass and radiation curves (Lebens).

Finally, radiation that is neither reflected or transmitted is absorbed. Solar radiation that is absorbed by a material is converted to thermal energy or heat. This explains why glass is highly suited to gathering solar energy. Sunlight is transmitted by the glass, absorbed by objects in the space, and converted to heat, which cannot pass back out through the glass. This process of trapping heat is commonly referred to as the greenhouse effect and is the very basis of energy-efficient greenhouse design.

3.3 Thermal Energy Transfer

Heat is thermal energy and temperature is the measure of this energy. As more heat is added to a material, its temperature will increase. Thus the same amount of heat energy can be stored in a small volume of hot water or in a larger volume of cool water.[37] In other words, a fixed amount of heat energy causes less of a temperature increase when absorbed by a greater volume of material.

Objects tend towards temperature equilibrium with their surroundings. Whenever a temperature difference exists, the object at the higher temperature acts as an energy source, and heat energy will move from hot to cold. The greater the temperature difference, the more quickly the heat energy will move. Heat energy moves by one of three processes: conduction, convection, and radiation.

Conduction is heat flow through a solid mass. (fig. 13). The rate of heat flow through a substance is called thermal conductivity. Generally, metals are good conductors of heat energy, while air is quite poor. Thus good insulation materials are those that trap air.

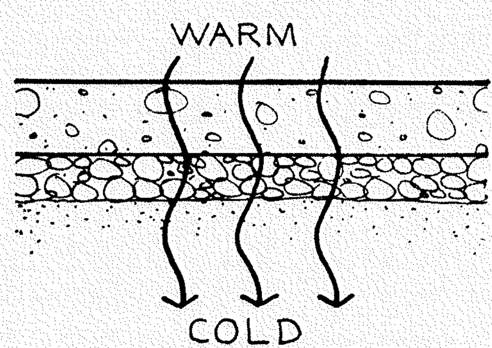


Figure 13. Conduction through a solid.

Convection is heat movement via currents in a fluid (liquid or gas). For example, as a warm object warms the air surrounding it, the air becomes lighter and rises away from the object. Cooler air then moves in to replace the warm air. The same process can occur in a liquid in a container which is being warmed (fig. 14).

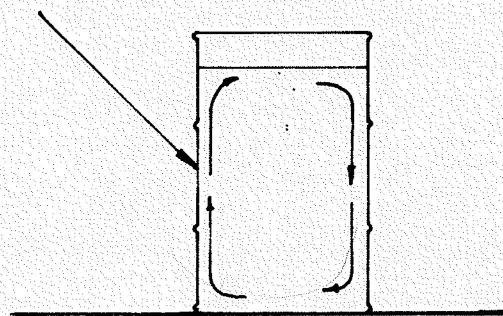


Figure 14. Convection in a liquid.

Radiation is the flow of heat in the form of electromagnetic waves from a high temperature body to one at a lower temperature. Radiant energy does not need a medium through which to move and can flow even in a vacuum, just as the sun's radiant heat reaches earth through the vacuum of space. The amount of energy flow through radiation is dependent upon the temperature of the radiating surface.

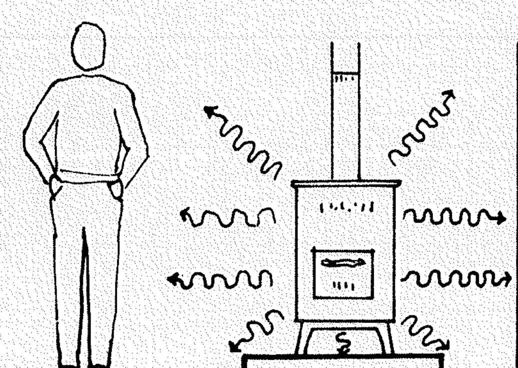


Figure 15. Radiation.

3.4 Thermal Principles in Greenhouse Design

As stated in the discussion of solar energy, the fundamental principle underlying the function of a greenhouse is the so-called greenhouse effect where visible light, after passing through glass, is absorbed by materials in the greenhouse, converted to heat, and prevented from escaping because of the opacity of the glass to longwave radiation. The greenhouse effect is summarized in fig. 16.

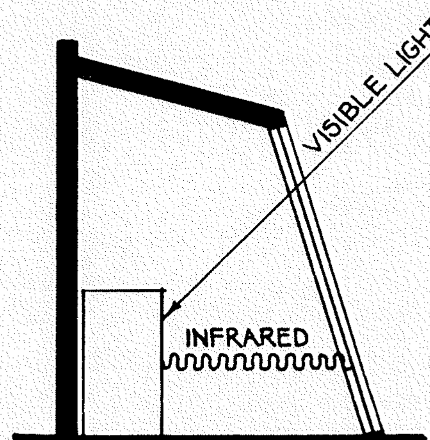


Figure 16. The greenhouse effect

It must be pointed out that while glass is opaque to longwave radiation, it is still not a good insulator because it absorbs heat and conducts it to the outside. Thus while glass is responsible for large temperature gains, it is also the source of major heat losses when the sun is not shining. Because they have large areas of glass, greenhouses, are subject to wide temperature variations. In conventional greenhouses, these potentially damaging temperature swings are eliminated by mechanical intervention: removal of excess heat and addition of supplemented heat when required.

In passive solar design, attempts are made to store the excess heat within the space until it can be used later when it is needed. The usual approach is to incorporate materials which have a high heat storage capacity. Such materials are referred to as "thermal mass". Thermal mass performs two functions:

1. It prevents overheating of the space as it absorbs heat and

2. It stores this energy for release later when temperatures in the space drop.

Thermal mass can be any material that absorbs and releases heat. However, not all materials undergo the same temperature rise when they absorb a given amount of heat. For example, to raise each cubic meter of the air in a greenhouse by one degree C., requires only about .37 Kcal. which explains why a greenhouse can overheat so easily. By way of contrast, a cubic meter of concrete at room temperature needs 516 Kcal. to gain one degree, and a cubic meter of water needs 997 Kcal.

By placing massive materials such as concrete and/or water in the greenhouse, peak temperatures are lowered since these materials absorb a great deal of the sun's energy that normally goes into warming the air. As these materials absorb energy, they increase in temperature. At night, when air temperatures in the greenhouse drop below that of the thermal mass, the heat is radiated back to the greenhouse. This stored warmth prevents the temperature from dropping as low as it otherwise would.[38]

Water is a common choice for thermal storage because it stores the most heat per unit volume of any commonly available material. This measure of a material's ability to store heat is called its volumetric heat capacity and is a product of its specific heat and density. The following is a list of some common materials along with their specific heats, densities, and heat capacities.

	Specific Heat (cal/g °C)	Density (Kg/M^3)	Volumetric Heat Capacity (Kcal/m^3 °C)
Water	0.999	998	997
Mild Steel	0.12	7830	940
Rock, typical	0.21	2640	550
Concrete	0.23	2240	516
White oak	0.57	750	429
Brick, building	0.20	1974	395
Clay	0.22	1010	222
Gypsum	0.26	802	209

Heat capacities of some common materials at room temperature (from Howell & Bereny).

Specific heat is a measure of how much heat a substance can hold (relative to water at 15°C). While concrete and clay have roughly the same specific heat, concrete can store more than twice as much heat per unit volume because of its much higher density.

Besides having a high heat capacity, a good storage material must have good conductivity. Wood is not a very good choice for thermal mass, even though it has about the same heat capacity as brick, because it has poor conductivity and cannot effectively move the heat from its surface to its interior.[39]

Another class of heat storage materials used in passive solar design are "phase change" materials such as sodium sulfate decahydrate, calcium chloride hexahydrate, and sodium thiosulfate. These materials can store much more heat than any conventional material because they store latent heat rather than sensible heat. This is the heat of fusion that is stored in molecular bonds as a substance undergoes a reversible phase change. To be effective these materials must change state within the "low-grade" temperature range of the greenhouse. These phase change materials can store from five to ten times as much heat as a given volume of water,[40] depending upon the water temperatures being considered. Earlier problems with phase-change materials, including limited lifetime, container corrosion, segregation of the salt mixtures into their separate components, and high cost have been resolved, and a variety of phase change products is now entering the marketplace. Cost-effectiveness is beginning to approach that of more common materials [41] and commercialization will likely bring costs down further in the future.

Whatever the material, thermal mass should be placed where it will receive as much direct sunlight as possible, since shortwave radiation that is absorbed is converted to heat energy. Dark-coloured, non-reflective materials absorb the most shortwave radiation and are therefore the best for heat storage containers or materials. This can be in direct conflict with the need to reflect light from non-glazed surfaces and a compromise must often be struck in the design of the greenhouse.

Absorption of radiant heat energy, however, is not dependent on colour, but rather on surface composition and density. Polished or "shiny" surfaces reflect heat radiation, while most other surfaces absorb heat energy regardless of colour.[42] This means that interior surfaces not in direct illumination can be light in colour. Since they can absorb heat energy, they should be of a relatively high heat capacity.

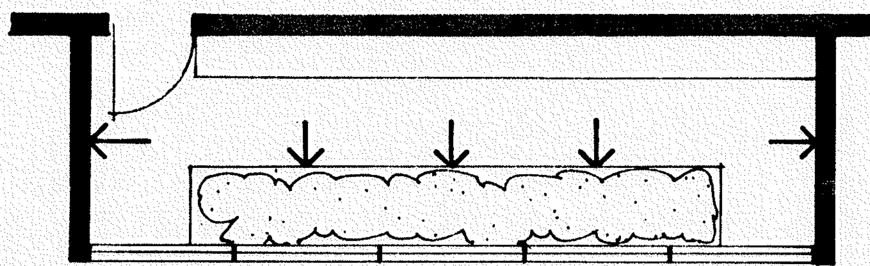


Figure 17. Surfaces not in direct sun.

Conventional storage materials such as water and concrete are bulky and occupy valuable growing space in a greenhouse. Another strategy in heat storage is to remove the excess heat from the greenhouse and store it remotely. This is usually accomplished in one of two ways:

1. Storage or use in the parent building;
2. Storage in a rockbed.

Both of these approaches are somewhat more complicated than direct gain storage (ie: the storage of heat within the greenhouse itself) since they involve mechanical air movement. Systems using fans in conjunction with passive solar techniques are commonly called "hybrid" systems.

Moving the heat to the parent building can only be successful if the home can use the excess heat produced by the greenhouse without itself overheating. Since most homes are of wood frame construction and contain relatively little thermal mass, overheating could be a problem. Because the heat is not stored within the greenhouse, the heating system of the house must supply heat to the greenhouse at night in order to maintain minimum temperatures. The extra ductwork required to move heat to and from the greenhouse could be fairly complex and expensive.

Rock bed storage is a system often used in solaria and greenhouses. In this approach, warm air is forced through a bed of rocks just below the floor. Heat moves back to the space by direct radiation.

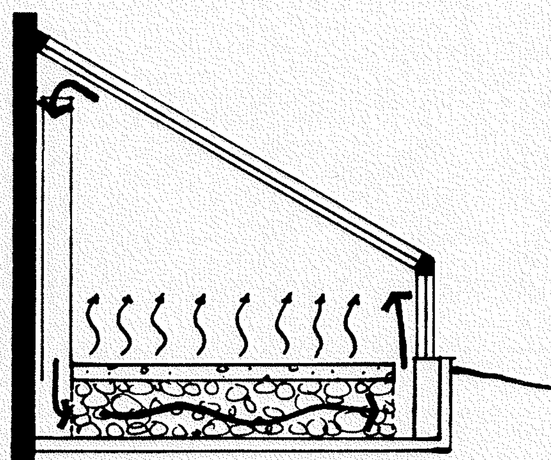


Figure 18. Heat storage in a rock bed

A rock bed, while being more complicated and expensive than direct-gain mass, can be justified in a greenhouse where thermal mass can often be shaded by plants, containers, or benches. Also, because greenhouses have a high ratio of south-facing glazing to interior volume, the large heat gain can often be too high to be absorbed by adjoining spaces and direct-gain mass combined.[43] Thus the rock bed can act as reserve thermal capacity when needed (which could be a substantial part of the year). Finally, the thermal mass embodied in a rock bed does not occupy growing space in the greenhouse itself. In any case, some experts feel that the heat removed to a rock bed should not amount to more than 1/3 of the net heat gain of the space, both to ensure optimum operating efficiency, and to prevent the system from being totally dependent upon external power for reliable operation.[44]

PART 4 GREENHOUSE DESIGN

PART 4 Greenhouse Design

4.1 Site

The primary objective in siting any greenhouse is to maximize the exposure to sunlight throughout the year and particularly in winter. This requirement was easily satisfied in conventional greenhouses which were typically free-standing and glazed on all sides. Traditionally, these greenhouses were usually oriented north-south for even light distribution throughout the day. However, it has been shown that in latitudes above 40 degrees N., illumination and temperature levels are higher in greenhouses oriented along an east-west axis.[45] Furthermore, because little or no appreciable solar radiation comes from the northern sky in winter, a solid north wall will eliminate considerable heat loss while reducing light levels only slightly.[46] Only during summer do significant amounts of solar radiation come from the north. In attached "lean-to" greenhouses the solid north wall becomes the common wall between house and greenhouse, with the facing wall glazed and open to the southern sky.

The optimum orientation of the glazed wall is due south, although some authorities contend that an orientation slightly east of south is more beneficial since plants get a boost in temperature earlier in the day when both indoor and outdoor temperatures are low from the night before. An orientation west of south, on the other hand, receives less morning radiation and more exposure to direct radiation in mid-afternoon - a time when outside temperatures are highest and the sun is low enough to penetrate the glazing and contribute to overheating, especially in summer.

In any case, the orientation and site considerations of the existing house will impose the most significant constraints on the greenhouse location. Many existing houses are not oriented along primary compass (north-south, east-west) axes, although this situation will undoubtedly change as neighbourhood planning for solar access becomes a more important issue. In such situations, McCullagh recommends locating the addition on the southeast face, provided it is not greater than 45 degrees from due south.[47] Gough also recommends limiting main solar apertures to within ± 45 degrees of south, since beyond these limits:

1) solar transmission (of glazing) declines rapidly, and
2) the amount of radiation received by a given surface declines rapidly.[48]

The National Research Council of Canada advocates limiting glazing orientations to ± 30 degrees of due south, pointing out that beyond these limits, glazed surfaces will lose more energy than they collect between October and March.[49] Mazria similarly advises ± 30 degrees as a limit. This along with the fact that maximization of direct sunlight is also of prime concern in greenhouse location in terms of plant growth suggests that it is reasonable to limit the orientation to within ± 30 degrees of due south, with southeast orientations being preferred over southwest.

Another important site factor is the amount of shade on the proposed site, particularly in winter when the sun is low in the sky, and when solar gain is most important. While maximum sun exposure is desireable, it is not reasonable to attempt to eliminate shading on the south facing glazing for the entire day. This is because shadows are of infinite length at sunrise and sunset, and again because beyond incident angles of approximately 50 degrees, light transmission of most glazing materials declines rapidly. It is therefore useful to define a shade-free zone within 50 degrees in either direction of the glazed surface and to restrict planting in this zone to low-growing plants which will not cause shading in the future. (fig. 19)

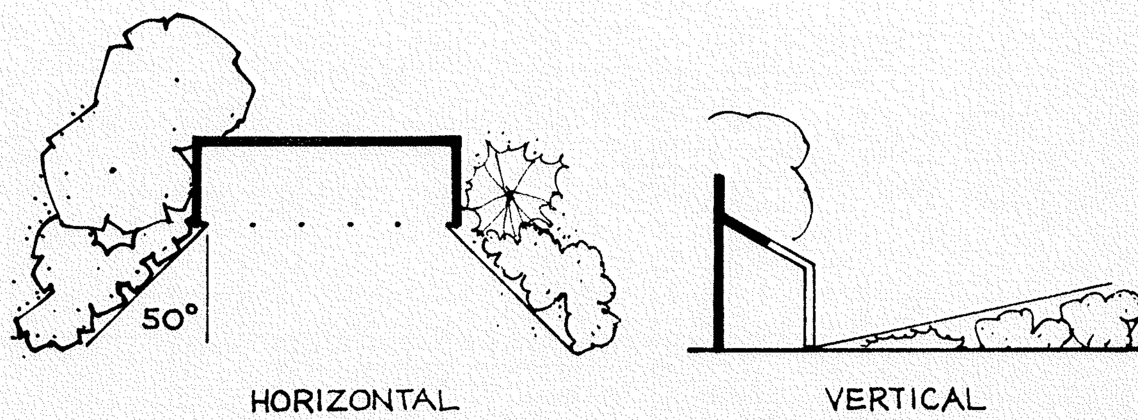


Figure 19. Shade free zone.

Even deciduous trees in winter will block from 30% to 70% of the sun's radiation, depending upon the species. While some shading of the greenhouse addition may not significantly affect greenhouse plant growth, it will result in reduced solar gain with a corresponding increase in auxilliary heating costs.

Before finalizing the greenhouse location, potential obstructions and shade patterns should be plotted on the site plan. A sun path diagram for Winnipeg's latitude (50 degrees) will be useful in determining exposure to the sun at different times throughout the year.

A final site factor in locating the greenhouse is exposure to winds, which influence a building's energy consumption through increased air infiltration and increased conductive losses. While the problem of air infiltration is minimized in modern air-tight construction, conductive and radiative heat losses are especially significant in a greenhouse due to the large areas of glazing (the principal site of such heat losses). Control of winter winds should therefore be a goal of a greenhouse site design. Winds during the heating season in Winnipeg are most prevalent from the south, northwest and north (in that order) and plantings, fences, and other wind control strategies should be designed to obstruct, deflect, or filter winds without interfering with winter insolation.

4.2 Greenhouse Planning: Initial Considerations

After the site constraints have been evaluated, initial planning should address the function of the proposed greenhouse. For example, the size of the greenhouse will depend not only upon the limitations of the existing dwelling and site, but also upon the expectations of the potential users. Expectations may range from growing a few leaf vegetables and herbs in winter to a major commitment to produce all of a family's vegetable needs.

Other factors can influence greenhouse size as well. Generally speaking, the smaller the greenhouse, the more likely it is to experience extremes in temperature fluctuation due to the smaller contained volume, and to the higher exposed surface area relative to interior volume. It is easier to maintain a more constant air temperature in a larger space.

Some authors suggest a starting point for good thermal performance would be a minimum interior area of 7.5 square meters, while 14 m^2 might be an adequate size to supply a family of four with vegetables throughout the year.[50] Personal experience suggests that this figure is a reasonable estimate. What is important, in any case, is the net useable growing space (both horizontal and vertical) after such components as thermal mass and circulation space have been taken into account. A greenhouse that is too small may be very difficult to plan efficiently.

While a conventional all-glass greenhouse can be virtually any size and shape, the configuration of an energy-efficient design is a function of a tradeoff between light admission and heat retention. The width (east-west) of the greenhouse can be essentially unlimited: however the maximum depth is limited and is largely a function of the slope and exact configuration of the south wall. For any given sun angle, the more steeply sloped the south wall, the less light penetration there will be, and the less effective depth the greenhouse can have. (Fig.20).

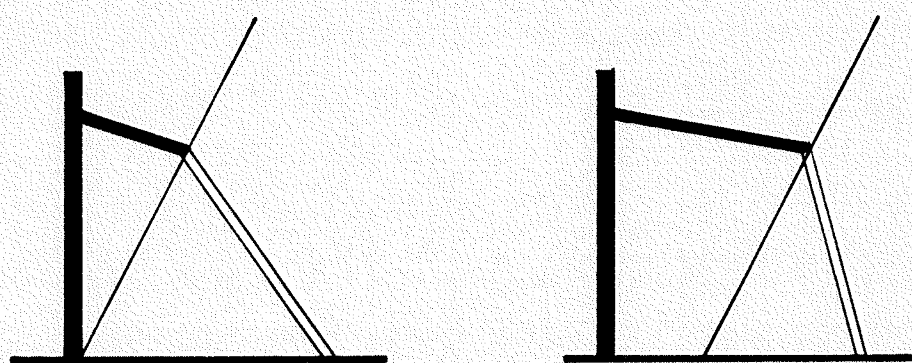


Figure 20. South wall angle and light penetration.

(The design of the south wall will be discussed in greater detail in the next section)

The depth of the greenhouse should be such that no significant shading will occur during the anticipated seasons of use. Unless the greenhouse will not be used in the summer, the critical design angle will be the sun's highest altitude of the year, on June 21, 12 noon. In Winnipeg, this will be 63.7 degrees. (Summer use of the greenhouse should not be discounted, especially in cooler climates.

Excellent yields can be had with vegetables such as peppers, eggplant and melons which require high temperatures and/or a long season for optimum results. Depending upon the summer, these vegetables can be only marginally successful outdoors because of cool weather or an early fall).

Note that the maximum sun angle is suggested as a general guideline in spite of the fact that photosynthesis in most plants may be saturated by the high summer irradiance levels. It is assumed that some form of shading will be employed to reduce heat gain in summer, providing a general reduction in illumination over the entire floor area rather than extremes of bright sun and full shade (shading is discussed in section 4.8). A greenhouse with too great a north-south dimension may cause problems with phototropism (leaning of plants towards light) due to high contrast levels.

For maximum thermal efficiency, end walls (east and west) should be opaque and insulated, since an east or west window loses more heat than it gains over the heating season. However, opaque end walls will cause shading and will render the back corners of the greenhouse unuseable for much of the year.

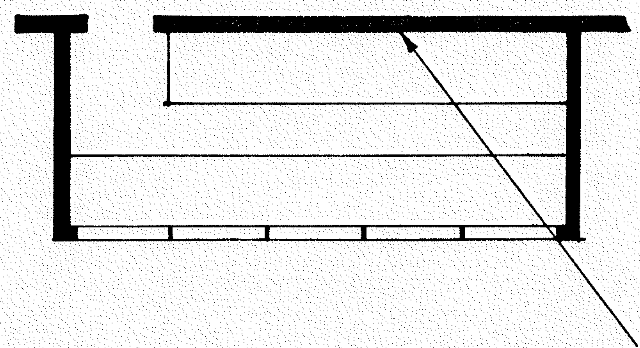


Figure 21. Shading from end walls.

For this reason, east and west walls should be at least partially glazed. If the greenhouse is relatively long in relation to its depth, the end wall losses will be proportionately smaller (fig 22).

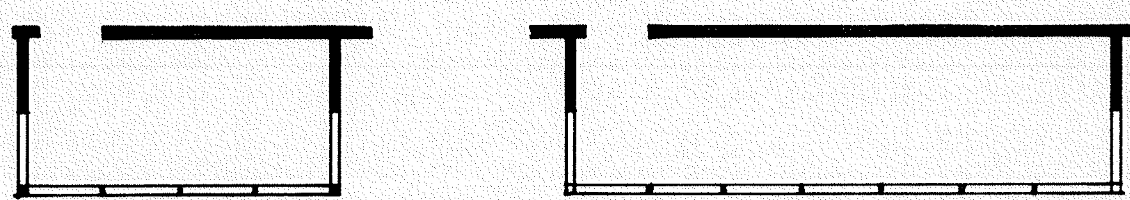


Figure 22. Proportions of east/west glazing to south glazing

The end wall glazing could be made seasonally adaptive by covering it with insulating panels during the most severe weather, thereby significantly reducing heat losses. Removing the panels in the spring would increase the useable growing area.

A door from the greenhouse to the outside should be considered a necessity, particularly in light of the bulky materials such as soil, peat moss, sand, and tubs and planters that are associated with a greenhouse. The outside door should be large enough to accommodate large objects such as wheelbarrows, planters etc., and should ideally be located on the most sheltered side of the greenhouse. A double entry or air-lock arrangement will prevent large amounts of warm air from escaping and plants from being blasted with frigid outdoor air each time the door is opened. The heat losses from opening the outside door could represent a large portion of the air in the greenhouse space, and a double entry should be considered if this door will be used in the winter. The entry could perform other functions as well, acting as a storage area, potting table, or as a "cool room" for growth of cool varieties or for root storage (fig. 23).

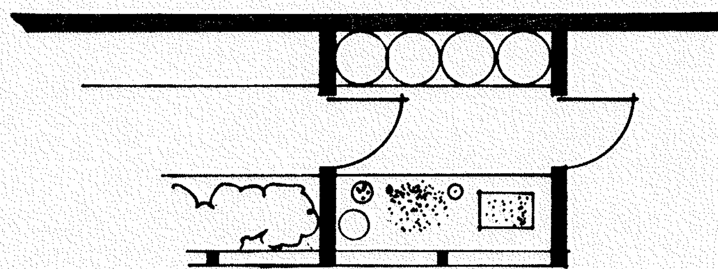


Figure 23. Double entry

A door between the house and greenhouse, while not absolutely necessary, is highly recommended, since having to go outside to gain access to the greenhouse could discourage its use, particularly in winter. Furthermore, a greenhouse that is highly accessible and integrated with the parent dwelling will probably add a great deal to the enjoyment of both the greenhouse and the associated spaces. By the same token, it is important that the greenhouse be capable of being thermally isolated from the house both to prevent overheating in the summer, and to allow for a winter "shutdown", if desired.

4.3 Foundation Design

In the design of greenhouse foundations special attention must be paid to minimizing differential movement of the support, since glazed structures are highly susceptible to damage in this way.[51] In attached structures especially, it is important that the greenhouse remain stable in relation to the existing dwelling.

The two main causes of foundation movement in Winnipeg's clay soils are soil settlement and frost heave. Soil settlement occurs after lens formation and adfreezing common to the fine-textured clays of the prairies. Traditionally, uninsulated foundations ensured little or no freezing in adjacent soils due to heat losses from the foundations themselves. However, today's higher thermal standards for foundations can result in greater depths of frost penetration. To prevent damage from frost heave, foundations should rest on footings below the maximum depth of frost penetration, or on friction piles that extend significantly beyond the depth of frost penetration. Back-filling with less susceptible materials such as well-drained crushed rock is also helpful in that it prevents the formation and adfreezing of ice lenses near the foundation surfaces. 52 Figure 24 describes some foundation systems recommended by the City of Winnipeg for attached greenhouses.

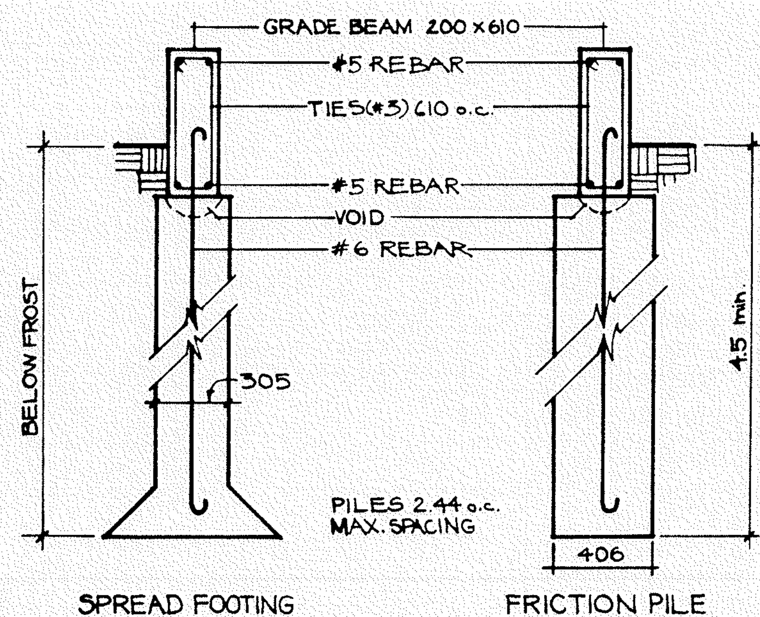


Figure 24. Suggested foundations.

Maximum frost presentation in Winnipeg ranges from 1.5 m. under snow cover to 1.9 m. under clear pavement.

Another approach to the problem of frost heave employs in-ground insulation to prevent freezing of the soil adjacent to the foundation.(fig. 25)

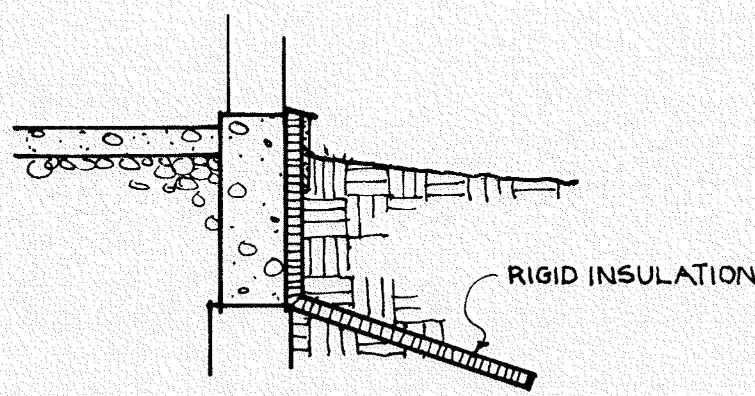


Figure 25. Insulation in soil mass.

Besides controlling frost heave, such insulation is also thought to improve thermal performance in both winter and summer; enhancing summer cooling benefits by enclosing a larger mass within the insulated envelope, while still insulating the building from the surface to limit heat loss in winter. While sound in theory, the benefit of summer cooling has a substantial cost in increased winter heat loss. Furthermore, this approach generally requires more insulation, and the insulation is more susceptible to damage in backfilling and soil settlement, leading to thermal "short circuits". [53]

Insulation will be most effective and lead to fewer problems if it is placed adjacent to and outside the structure. In this way, the concrete foundation is available as thermal mass within the system. The most appropriate insulation material for underground applications is extruded polystyrene, since it is resistant to moisture absorption and retains its insulative properties well in underground situations. Fig. 26 shows one possible configuration for insulation of the foundation. However, final placement of foundation insulation will also depend upon other aspects of the overall design, including configuration of growing beds and heat storage strategies.

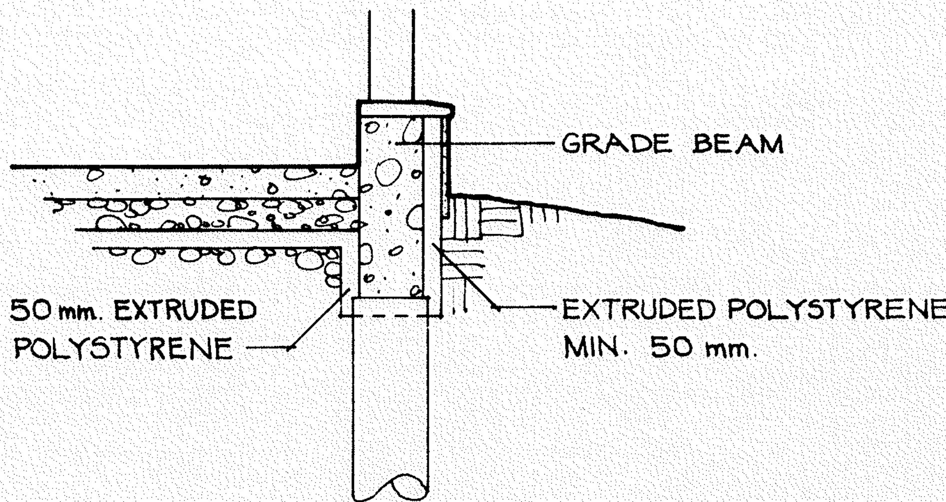


Figure 26. Foundation insulation.

4.4 The South Wall

In determining the configuration of the south glazed wall, a prime objective is to maximize solar gains throughout the season(s) of anticipated use. However, other factors such as site limitations, interior planning, and microclimate can also have an influence on the final design. Ideally, to maximize heat and light collection, the south wall should be as near perpendicular to the sun's radiation as possible, since the angle of incident radiation determines not only how much radiation the surface will intercept, but also what proportion of the radiation is transmitted through the glazing. (fig. 27).

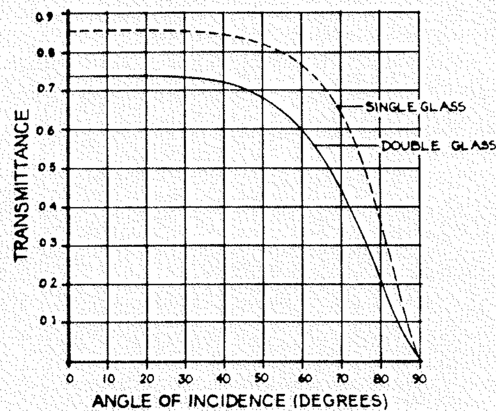


Figure 27. Transmittance of glazing vs. angle of incidence (Mazria).

The goal, then in choosing a glazing angle is to have as ideal an angle (normal to the sun) for as long a period each day as possible, and for as much of the chosen season as possible. If radiation is to be maximized, the angle should be optimized for solar noon, when radiation is most intense (except perhaps in summer when overheating could be a problem). Some of the most general rules of thumb recommend south glazing angles of latitude + 20 degrees (Mazria) or latitude + 15 degrees (Clegg). In Winnipeg at latitude 49.9 degrees, this would result in angles of approximately 65 to 70 degrees above horizontal. If winter heat collection were the only objective, these angles could be considered ideal. However, if the greenhouse is to be used during the spring and fall as well as winter, or if it will be used all year, then obviously some sort of compromise must be reached. Based upon National Research Council guidelines (Solar Technical Series No. 2) optimized angles for various seasons in Winnipeg would be:

Winter	72°
Spring/Fall	50°
Summer	26°

These recommendations are derived from sun angles at noon for December 21st, March/September 21st, and June 21st, and should be considered as general guidelines only. It is perhaps inappropriate to consider solar gain as the sole form determinant. In fact the determination of an optimum angle may not be as important as other considerations. Early research at the Brace Institute indicated that the angle of south glazing was not as critical as many had predicted. [54] This is because most glazing materials will admit a high percentage of direct sunlight over a wide range of incident angles (fig.). Losses from reflection often are over-emphasized, [55] and, as seen in figure 27, until the angle of incidence reaches 50 degrees, solar penetration of the glazing is still quite significant. [56]

Diffuse radiation is also important to the growth of plants in a greenhouse, whether originating from an overcast sky or reflected from snow on the ground. A uniformly overcast sky is normally 2 1/2 to 3 times as bright overhead as it is near the horizon and over 80 percent of the overall available illumination comes from that part of the sky above an altitude of 30 degrees from the horizon. [57] Thus overhead glazing becomes important during overcast periods. Similarly, the diffuse light reflected from snow can significantly increase the light (and heat) in the greenhouse. [58] In this case, vertical glazing would intercept more of this reflected light.

Perhaps even more important in the design of the south wall are such practical considerations as the amount of useable interior space in the greenhouse, ease of layout and circulation, and relative ease of construction.

It is a mistake to think of growing space in terms of floor area only. As in initial planning of greenhouse spaces, the full size of the particular crops must be taken into account when working with sun angles and considering areas of potential shade. (fig. 28) It is useful in greenhouse design to think in terms of useable volume, rather than just floor area.

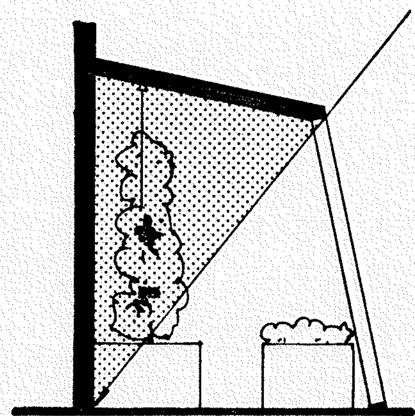


Figure 28. Useable space in the greenhouse.

Conversely, the desired depth of the greenhouse can influence the angle of the south wall; the more depth desired, the lower the angle of the wall.

At steep angles, greenhouse heights become impractical and will have to be modified in most situations where the existing house form will impose limitations.

In greenhouses for northern climates, vertical glazing is increasingly being seen as the most efficient overall proposal for a number of reasons. [59] As stated, the angle of incident radiation does not become a serious limitation until approximately 50 degrees. At Winnipeg's latitude this would limit light transmission only during the summer months. The chief advantages of vertical glazing are its ease of construction and efficient use of space. A wall that is even a few degrees off vertical can limit headroom and growing space. Vertical glazing is often easier to integrate with conventional house aesthetics, and offers greater flexibility in the location of doors as well as operable windows and vents. Vertical glazing can make better use of the light reflected from snow, which can add 40 percent to winter light and heat. [60] In spite of these advantages, vertical glazing on its own may limit light penetration to a significant degree. A combination of glazing angles could combine greater light penetration with the advantages of vertical glazing. (Fig. 29).

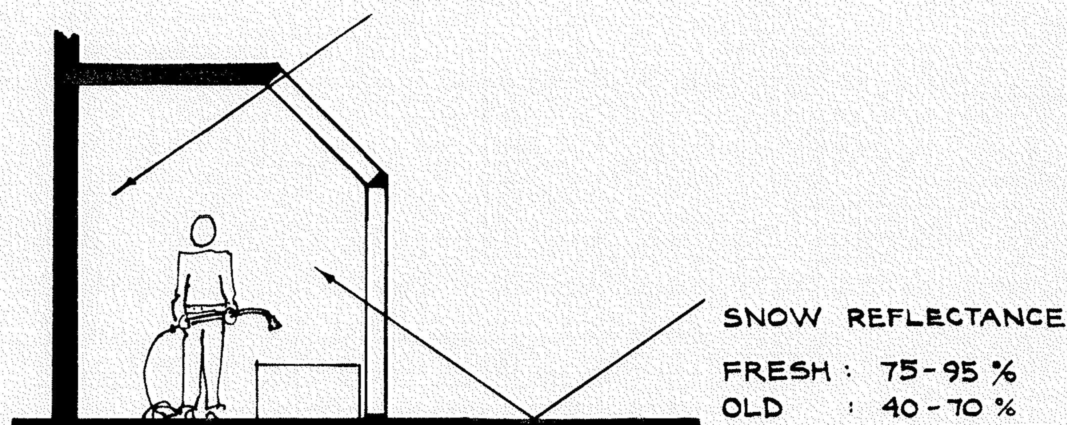


Figure 29. Combination of glazing angles

Snow and ice can also influence the choice of a glazing angle. Gently sloping glazing will collect snow, and with double glazing it will be slow to melt, making that portion of the glazing unuseable until the snow is cleared. Traditional greenhouses, with a single layer of glazing relied on escaping heat to melt snow from shallow roofs. Shallow-sloped glazing is also more prone to damage from hail and falling ice from overhead eaves, and may have to be glazed with impact-resistant tempered glass or plastics.

In a location where any amount of snow accumulation is likely, glazing should not extend too close to grade. This will prevent snow buildup from blocking the sunlight. An insulated solid knee wall of appropriate height above grade (based on microclimate observations) will allow space for snow to accumulate without obscuring the glazing. (Fig.30) A vertical knee wall can also provide extra headroom in a design with sloping glazing.

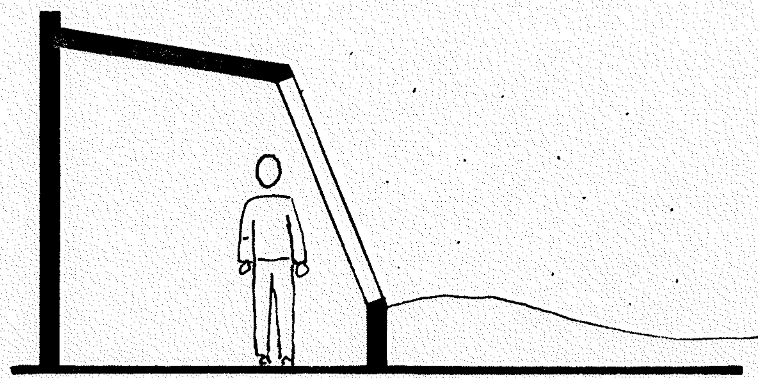


Figure 30. Knee wall for snow accumulation and headroom.

An easily overlooked but important factor in the design of the south wall is the relationship of the glazing to planting beds. The bottom of the glazing should not be at a higher level than the soil surface. A sill which is even a few centimeters higher than the soil surface can shade a large proportion of the potential growing area, especially at the low sun angles of winter. (Fig. 31).

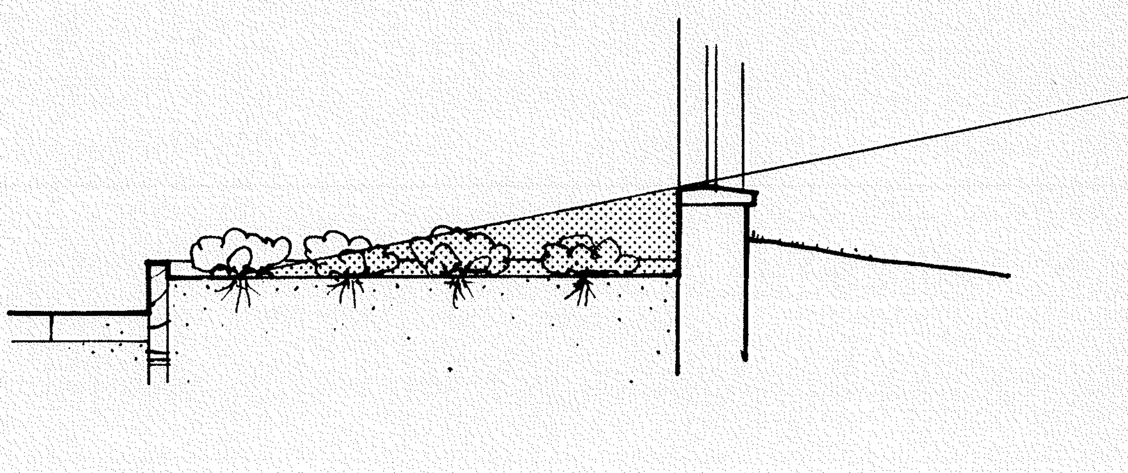


Figure 31 Soil surface and glazing.

From this discussion, it becomes apparent that there is no single ideal choice in south wall angles, that any given angle has advantages and disadvantages, and that perhaps the importance of finding an ideal angle has been somewhat overemphasized. While defining suitable angles for maximized insolation is one goal, other factors such as greenhouse plan and layout, site limitations, and microclimate are at least as important. As long as angles are kept within the broadest limits with respect to solar collection, and provided the greenhouse is sited properly for maximum exposure, there should be little effect on efficency. While a particular angle may provide slightly more heat gain on a given day, it is important to keep in mind the importance of light availability (both direct and diffuse) throughout the year for acceptable plant growth. Ultimately the final configuration must remain a compromise between thermal efficiency, light penetration, and practical considerations of layout and construction.

4.5 Glazing

Glazing is any material that is used to transmit radiant energy (especially light). It is the simplest solar collector in that light striking objects in glazed spaces is converted to heat which is trapped by the glazing material. Historically a variety of materials from talc, soapstone, and mica, to oiled skins and paper have been used as glazing materials. However, these served only a limited role in admitting light, and it was not until the development of glass that significant light and heat could be admitted to interior spaces. Glass has been in use since the seventeenth century and is today the most familiar, widely used, and in many respects the best glazing material. Within the last few years however, a wide variety of new materials - mostly based on petroleum products - has been developed. While glazing was traditionally designed to admit light, the development of solar glazing specifically for the control and use of the sun's energy for heat is increasingly becoming a priority. In spite of all the new materials available, some feel that glass is still the material most ideally suited to greenhouse design.[61]

Before discussing various specific glazing materials, the criteria for evaluating a greenhouse glazing system must be examined.

While glazing can be a source of heat gain, it is also a major source of potential heat loss in any building. The prime determinants of heat gain and loss are transmittance and thermal conductivity which are primary physical properties of glazing materials themselves. Two other factors affecting heat loss, convection and infiltration, relate more to the glazing system as a whole, rather than a particular glazing material.

Transmittance is the amount of energy that passes through a material relative to the amount that reaches its surface. Transmittance varies with incident angle, and values are expressed assuming perpendicular incident radiation. While this may not provide an accurate indication of performance over a wide range of conditions, it does provide a basis for comparison. Different glazing materials have different surface reflectance which can influence transmission at incident angles other than perpendicular.

Transmittance is also affected by the thickness of the glazing material and by the number of layers. For example, 3 mm glass has a transmittance of .84 (84%) while transmittance for 5 mm glass is about .81. The transmittance of multiple glazing is found by multiplying the transmittance values of the individual layers (eg 2 panes of single strength glass = .84 x .84 = .7056 or about 71%). Similarly three layers of glass will have a transmittance of .590 (.84 x .84 x .84) which can result in a significant reduction in solar gain.

Transmittance through glazing can be either diffuse (translucent glazing) or specular (transparent glazing). Translucent glazing provides a more scattered and even distribution of light throughout the greenhouse, while transparent glazing provides a more directional light pattern as well as unobstructed view to outdoor spaces.

The transmittance characteristics of a glazing material can influence heat loss as well as heat gain. As noted, the greenhouse effect results from the fact that glass and other glazings transmit visible radiation but do not transmit the infrared radiation emitted after the light is absorbed by an object. Thus the degree to which a material transmits infrared radiation can be a factor in the material's suitability for greenhouse glazing applications. Glass has very good performance in terms of infrared radiation, transmitting less than 2%, while polyethylene, by way of comparison transmits about 80%. Many of the thicker plastic glazings come close to, but do not equal the resistance of glass to thermal transmittance. Ideally, the best solar glazing would reflect the heat radiation back into the space. This can be accomplished only with special coatings. Instead, glass and other glazings with low infrared transmittance actually absorb this radiation and reradiate it from both sides. Thus, in structures with large areas of glazing such as greenhouses, these losses through absorption and reradiation are a major factor in heat loss.

While thermal conductivity is a major source of heat loss in glazing, it is not a factor in comparing and selecting individual glazing materials, since conductivities of these materials do not vary significantly. Compared to other building materials, however, heat losses through glazing are very high. The conductivity of a material is not directly proportional to its thickness, but it is influenced by other factors such as the presence or absence of a dead air film at its surface.

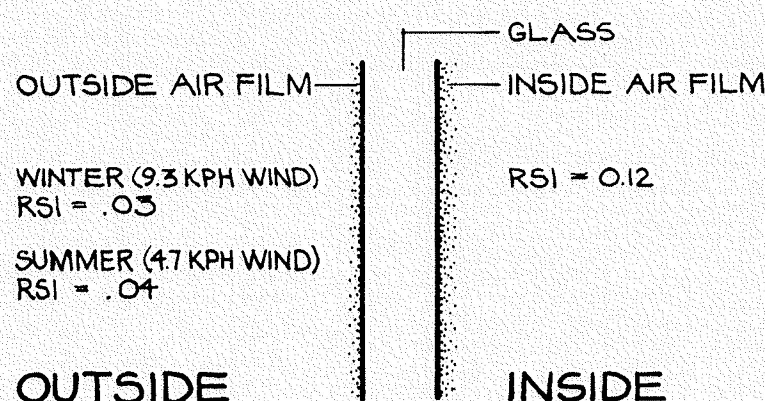


Figure 32. Single glazing and air films.

This air film is a function of surface texture and air movement across the surface. Thus, two sheets of glazing material with an enclosed space between have a much lower conductivity than the same two panes sandwiched together. This is due to the added surface-to-air resistance at each face as well as the actual enclosed air which is a relatively poor conductor of heat. Thus, double glazing has approximately 50% less conductive loss than a single glazing. Beyond two layers there are diminishing returns in the ratio of reduced conductivity to decreased solar transmittance and thus double glazing is the most feasible choice in a greenhouse.[62]

Convection and infiltration are two other sources of heat loss associated with glazing systems. Convection, as it applies to glazing systems, is the movement of air as a result of temperature differences. Warm air next to a cold window will lose heat to the glazing through conduction. The air, once cooled, will descend and displace other air in the greenhouse, starting a cycle or convective loop.

Convection can also occur between two layers of glazing if the air space between panes is wide enough. This results in increased heat loss because air currents assist in moving heat from warm to cool zones (Fig. 33). The air movement is driven by the temperature difference between the inner and outer glazing.

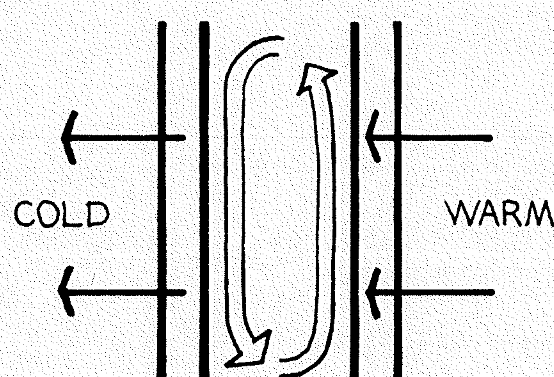


Figure 33. Convection between glazings

Theoretically, the more air space between the panes, the greater the insulating effect, but convective losses increase significantly as the air gap increases, thereby negating any reduction in conductivity. An optimum spacing between panes of double glazing is 12 mm.[63] For triple glazing, a spacing of 19 mm has been found to be optimum, but to date, glazing manufacturers in Canada are still using a 12 mm spacing in their triple-glazed units. Thermal resistance could be improved by 25% with the increase in air space.[64]

Air infiltration is a final source of heat loss associated with glazing systems. The rate of air infiltration in a space is usually expressed in terms of air changes per hour. For example, in a traditional overlapped-glass greenhouse, the air infiltration rate might be around four air-changes per hour; possibly higher with a wind. This means that every 15 minutes, the warm air of the greenhouse is completely replaced with cold air from outside. A carefully constructed and sealed greenhouse could have an infiltration rate of .5 air changes per hour.[65] Good design and construction techniques can virtually eliminate heat losses due to infiltration.

Care must be taken in designing glazing systems to allow for thermal expansion, since glazing materials expand and contract as they undergo temperature changes. Movement of glazing as a result of these daily and seasonal temperature swings can put stress on seals, leading to air and moisture leakage. A material's coefficient of expansion is an expression of its tendency to expand (or contract) as a function of temperature and dimension. Glass has the lowest coefficient of expansion of any commonly-used glazing material. Some plastics have coefficients of from 2.5 to 6 times that of glass. Because thermal expansion is a function of sheet size, large sheets will undergo a greater dimensional change than smaller sheets given the same temperature rise. Thus, some plastics may undergo excessive expansion and contraction when used in large, uniterrupted sheet sizes.

Even though glass undergoes less dimensional change, failure to allow for expansion and contraction due to temperature fluctuations will result in breakage.

Other factors influencing glazing choice relate to safety. For example, glazing in overhead installations dictates that the glazing material be impact resistant enough to withstand damage from hail and falling objects such as ice from overhead eaves. Tempered or wired glass, or a more resistant material such as rigid plastic would be required. Similarly, fire safety might dictate the use of glass rather than plastic in overhead situations. Most plastics will burn and should not be used in any situation involving high levels of heat exposure. A viable solution in overhead glazing installations is a combination glazing of rigid plastic outside with standard glass inside.

There are a variety of glazing materials appropriate for greenhouse applications, each having certain limitations and advantages. Many greenhouse designers feel that glass is unmatched in its suitability as a solar glazing material. It is the most durable material, highly resistant to abrasion and ultraviolet degradation, with a virtually unlimited lifespan. Glass is also relatively inexpensive and has very good thermal and light transmittance characteristics. For these reasons, it is still used extensively in direct-gain solar applications, in spite of the variety of new materials available. The major disadvantage of glass is its very low impact resistance.

Higher strength (tempered) glass can be used where standard glass would be unacceptable. Tempered glass is about five times stronger than standard glass and breaks into small blunt pieces rather than dangerous fragments. Because tempered glass cannot be cut and is ordinarily made in a few stock sizes, local availability should be checked before designing framing members. Custom sizes can be ordered, but this will add considerably to the cost.

Tempered glass should not be confused with heat-strengthened glass. While heat-strengthened glass is stronger than standard glass, it still can break into dangerous sharp-edged pieces.

A special high-transmission grade of glass is available which is able to transmit more visible light due to its lower iron-oxide content. Because of its substantially higher cost, this low-iron glass is more appropriate for use in high temperature solar collectors where the need for maximum light transmittance, along with proportionately smaller glazing area justifies its use. Low-iron glass is not yet readily available from glazing suppliers in Winnipeg. Transmittance of low-iron glass compares with standard glass as follows:

	Double Glazing	Triple Glazing
Standard Glass (3 mm)	71%	60.5%
Standard Glass (5 mm)	65%	53%
Low-Iron Glass (5 mm)	77.8%	69.3%

Several types of plastics are available for use as greenhouse glazing. Plastics in general are more impact resistant and lighter in weight than glass. They also generally require more structural support, are less resistant to weathering, and have higher co-efficients of expansion, in comparison to glass. Almost all of the plastic glazings will eventually decrease in light transmission and structural strength as a result of weathering, particularly from ultraviolet light.

Acrylic sheeting (Plexiglass and others) is perhaps the most well known of the plastic glazings and it is the most resistant to weathering. With a life expectancy of 25 years, acrylic has been shown to retain a significant amount of its transmissivity after many years of exposure to the elements.[66] Compared to glass, acrylic has slightly better transmission of visible light (89%) while it is less opaque than glass to infrared radiation. This can be significant in greenhouse installation.[67] Acrylic sheeting is generally more expensive than glass, but its high transmissivity, and long life make it a good choice amongst plastics, especially in applications where greater impact resistance is needed. A disadvantage of acrylic is its susceptibility to surface abrasion.

Acrylic glazing is also available as a double-walled extruded glazing (Fig. 34) which is less expensive than factory-sealed double glass units. Double-walled acrylic is not completely transparent and provides an obscured view. This may be a drawback especially where a view is desired.

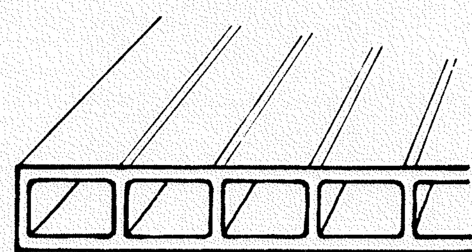


Figure 34. Double-walled extruded acrylic glazing

Polycarbonate is similar to acrylic but is more impact resistant and more resistant to higher temperatures. However polycarbonate has lower transmittance (74 - 85%) and less resistance to weathering. After prolonged exposure to outdoor conditions, it is prone to surface cracking and discolouration leading to reduced light transmission. It is most often used where high resistance to breakage is a priority as in areas of potential vandalism. However, polycarbonate has been shown to lose considerable impact strength due to surface cracking resulting from weathering.[68] Polycarbonate is also available as a double-wall extrusion, similar to acrylic double-wall, and a triple-walled version has been introduced.

Fiberglass-reinforced plastic (FRP) is a semi-rigid material made from thermoset polyester resins and 25-33% glass fibre. FRP is popular with amateur builders and solar enthusiasts as it can be cut, handled and installed more easily than other glazing materials. It is more susceptible to ultraviolet degradation and weathering in general, and requires periodic renewal of the ultraviolet-inhibiting coating. Deterioration from weathering results in discolouration, fibre popout, surface microcracking, reduced light transmission, and increased brittleness. Because of its semi-rigid nature and high coefficient of thermal expansion, it is difficult to maintain a tight, flat, architectural appearance unless using double-glazed pre-manufactured panels. Light transmission through FRP is very good (85% for the 1 mm thickness) but is diffuse and not specular, thus obscuring vision.

Of a variety of thin plastic films available, polyethylene is the most widely used in greenhouse applications. This is because it is relatively inexpensive. However, even the U.V. stabilized greenhouse grade will provide only 1-3 years of service in outdoor conditions. Commercial greenhouse operators still find polyethylene to be economically viable, however, even with annual replacement. In a home greenhouse, where time may not be computed as an operating cost, polyethylene can be considered a practical choice, although most people would question its acceptability from an aesthetic standpoint. The chief disadvantages of polyethylene are its very high level of infrared transmittance and its susceptibility to tears and punctures. Recently a much stronger fiberglass-reinforced polyethylene has been made available specifically for greenhouse use.

Weatherable polyester is another thin film which may have greenhouse applications. Because of an integral U.V. stabilizer (as opposed to a surface coating) its life span is much greater than polyethylene. Like most of the thin films, it has very good light transmission, but can be easily punctured.

Two other films with possible applications as greenhouse glazings are polyvinyl-fluoride (PVF) and acrylic/polyester thin film laminate. PVF (Dupont Tedlar) was developed for solar applications and has good transmittance of visible light (90%). It too is susceptible to tearing and puncture, which can be a disadvantage. Life expectancy is up to 10 years. Acrylic/polyester laminate has similar life expectancy and light transmittance. Resistance to infrared transmittance is better than most films (less than 10%).

When considering any of the thin films for a greenhouse, permanence is an important consideration, in terms of weathering and especially mechanical damage. Weatherability can be greatly improved if a susceptible material is used as an inner glazing behind a U.V. - stable material such as glass or acrylic, since most of the ultraviolet radiation will be filtered out. Many of the thin films have applications as inner glazings in prefabricated multiple-layered arrays, and are perhaps most appropriate for these uses as opposed to exposed applications. The most thermally resistant glazing system commercially available consists of two thin-film layers between two layers of glass. Such a system has been shown to have better thermal resistance than triple glazing while having equal or better light transmittance.[69] Research in the area of energy-efficient glazing systems is ongoing, and will undoubtedly lead to widely available superior materials and systems in the future.

4.6 Window Insulation

While glazing can admit large quantities of solar heat it can also lose a lot of heat - many times more than an insulated wall or ceiling - due to its low thermal resistance. If the greenhouse is to operate primarily on incoming solar gains, some form of moveable window insulation will be necessary to reduce the outflow of heat at night.

When window insulation is used at night, heat loss through double glazing can be cut by 45-50%.[70]

There are a variety of window insulating systems from simple to complex, with new products entering the market at a rapid rate. In evaluating any insulation system the primary criteria are thermal resistance, air infiltration, ease of operation, and durability.

As the fundamental purpose of window insulation is to reduce heat flow, thermal resistance (R) values are of prime importance.

The greatest proportional savings in heat loss can occur at the lower end of the scale of R values, since insulation tends to follow the law of diminishing returns. For example, adding RSI.88 insulation to a double glazing reduces heat loss by 38%, while doubling the R value to RSI 1.76 will increase the savings by only 10% more to 48%. [71] These figures are based on use of the insulation for 14 hours per day.

A low infiltration rate is important in any window insulation system, and especially on an interior system. A good edge seal on window insulation is important for a number of reasons. First, it will decrease or eliminate convection at the window surface, which can make the insulation almost useless, regardless of R value. Secondly, reduced infiltration and convection means reduced condensation at the window surface which, in a greenhouse can be a serious problem. Finally, well sealed window insulation will reduce infiltration from outdoors, although this should not be an issue in a well-constructed greenhouse. (If there is infiltration however, it is better stopped at the source using caulking or sealant).

Because window insulation must be used consistently to be effective, operating convenience is an extremely important aspect. As one author writes: "A low-R thermally lined curtain used regularly will outperform a high-R panel left in the closet". [72] Operating a window insulation system twice daily throughout the heating system can represent a significant investment in time and effort. Minimizing this effort should be prime consideration. Completely automated systems are available, but will add considerably to the cost of a system.

Finally, durability and consistently reliable performance of a system over time will be in important factor in system choice.

Window insulation systems can be located outside, between, or inside the glazing.

The main disadvantage of exterior insulation systems is that they are exposed to the elements and as such they must be capable of withstanding the effects of snow, ice, rain, wind, and sun, while still remaining operable. Unless they are operable from the inside, operating them involves going outdoors twice daily - regardless of weather. Remote operation will add complexity and cost, as controls will have to be strong, maintenance-free, and extremely well-sealed against the outdoors. Systems with top-hinged panels will have fewer problems with snow load. In spite of these drawbacks, some feel that outdoor insulation is the only realistic and safe solution when all options are considered.[73]

Between-glazing systems are perhaps the least common, but have fewer operational problems, since the insulation is protected both from the exterior climate and the human element. This means also that the insulation makes the glazings immune to interior and exterior convection, which results in higher R values. There is also less of a condensation problem with glazing insulated in this way. The best known is the "Beadwall" system, in which polystyrene beads are blown between two layers of glazing. Advantages of the system are that it provides a consistently higher R value and is totally automated. Disadvantages are that it is expensive and can take up a lot of space for equipment and storage of the bead insulation.

Other systems offer operable venetian-blind mechanisms between glazings, which can also serve to precisely control insolation and heat gain. Still others employ multiple layers of aluminized fabric or plastic film which expand to enclose dead air spaces between layers. These materials are effective because they not only add thermal resistance, but reduce convection between glazings and also reflect heat radiation back to the inner glazing. Such units should have tightly sealed inner glazings and removable outer glazings for cleaning and servicing.

Interior window insulation systems are the most widely available commercially, and much of the new product development is concentrated in this area. Interior systems are the easiest to install and, depending on the system, can be the least expensive. As stated, the edge seal is especially important with interior systems due to the potential condensation problem, which could damage wooden glazing bars and the insulation itself.

Interior insulation can take many forms. The most effective are the rigid panels or shutters. While hinged shutters are considered the best choice for smaller, single windows (as in a conventional room) removeable panels are more appropriate for the larger, closely spaced glazing of a greenhouse. These panels are often custom built from rigid-foam insulation and can be covered with reflective foil and backed with board for support. They are best connected directly to the glazing by magnetic strips. These panels can be very efficient due in part to the high R value of the foam board itself, and to the fact that there is essentially no air space between glazing and panel which can lead to convection and greater heat loss. The problems associated with rigid panels are the time involved in installation and removal, as well as the need for a relatively large amount of storage space.

Flexible shades, while less efficient than rigid panels, are more convenient to use in conjunction with the large expanses of glazing in a greenhouse. These can be roll-up or folding in nature, and many variations exist. They usually consist of an insulating fabric, a vapour barrier, and often a reflective layer (which may be one in the same with the vapour barrier). Because much of their thermal value derives from enclosing a dead air space between insulation and glazing, good edge seals are, once again, very important.[74]

Other types of fold-up or roll-up shades are of the thin-walled, multi-cell type used in between-glazing systems. Many new schemes are being developed, based on new materials and combinations such as laminated thin foam materials and aluminized mylar and polyester reflective vapour barriers.

There is one serious problem with tightly-fitting interior insulation systems which has come to light. That is the danger of broken windows due to thermal shock which can occur when the morning sun warms the cool interior glazing of double-pane units.[75] In fact, manufacturers of sealed double-glazing warn against the use of even heavy drapes and advise good air circulation between drapes and windows.[76] It may be some time before such issues are resolved and a clear concensus evolves in this relatively new area.

A final point to consider is whether or not window insulation is worth the investment in light of the new developments in solar glazing systems. Current thinking is that fixed insulation (ie. highly resistive glazing systems), which operates around the clock is more effective. For example, triple glazing, used 24 hours a day is just as effective as a good window insulation, over double glazing, for 12 hours per day.[77] This, too will have to be studied further as new glazing systems become readily available.

4.7 Heat Collection and Storage

As previously discussed, the function of thermal storage in solar design is 1) to prevent overheating and 2) to store excess heat energy for release when heat is needed. Heat storage is a very important component in an energy-efficient greenhouse because of the large glazing area relative to floor area. In standard passive solar design, south-facing glazing can be limited to reduce solar gain, but in a greenhouse, the large areas of glazing necessary for adequate light levels can admit many times the amount of heat energy required to maintain minimum temperatures. If this excess energy cannot be stored in some way, and if the parent building cannot use it, it will have to be vented outside and therefore wasted, if reasonable temperatures are to be maintained. Overheating is probably the most common problem associated with the energy efficient greenhouse.

Generally, heat storage strategies in a greenhouse can be classed as either direct gain or hybrid in nature.

Direct Gain Storage

Direct gain systems refer to those in which the collector, storage, and distribution system are one in the same (thermal mass) and operate primarily through radiation and convection. Such systems are generally the most simple and efficient, because heat radiation is one of the stongest forms of heat transfer in the greenhouse. Johnson states that the fastest way to pump heat into storage is to flood it in sunshine.[78] Thermal mass which is exposed to direct sunlight is referred to as primary mass. While primary mass will be heated with the greatest efficiency, it is not necessary to have all storage materials in direct sun in order to be effective. This is because as objects absorb energy and heat up, they in turn radiate energy which is absorbed by other objects in the space. This absorption and re-radiation of energy will continue until a temperature equilibrium is reached. Thus, storage materials not in direct sunlight can also absorb and store thermal energy. Such materials are referred to as secondary mass.

Whatever the type, the thermal mass must be located in the greenhouse in such a way that it can transfer its heat directly to the plants at night by radiation as well as convection, since the relatively low operating temperature which thermal mass typically attains would not be sufficient to heat the greenhouse by natural convection alone. [79] Thus, any interior surface exposed to planting areas is a potential location for thermal mass. Lebens [80] found that different interior surfaces will have different proportions of radiative and convective heat transfer as follows:

Surface	% Convection	% Radiation
Floor	46	54
Wall	40	60
Ceiling	30	70

These figures indicate that no matter where the mass is located, radiation is an important factor in heat transfer from thermal mass.

Because direct gain storage must occupy the greenhouse interior where plants are to be grown, efficient use of space is of prime importance. Since water is the common material capable of storing the greatest amount of heat per unit volume, it is the usual choice for direct gain storage. Containers for water can be of any material, but preferably one with good conductance such as metal. Containers made from materials with relatively poor heat transfer (such as plastic) should be thin-walled. If opaque containers are used they are most effective painted flat black. Other dark colours such as dark blue have been shown to be only 5% less efficient than black [81] with the added possible benefit that the small amounts of blue light reflected could play a role in counteracting the bending of plants towards the glazing as a result of the strongly directional light.

Transparent or translucent containers are most efficient when the water is coloured using black dye or any other dark colouring agent, since the molecules of dye can absorb the light energy and transfer it directly to the water. Computer simulations comparing opaque and transparent containers show the transparent to be slightly more efficient at collecting incident solar radiation. [82] This is because the water in the transparent container absorbs heat throughout its volume while an opaque container absorbs at its surface and then must transmit it to the water. As such, some heat can be lost to the air before the water absorbs it.

Containers can be anything that is readily (and cheaply) available, but should use space efficiently. A number of types have been used, the most common being the 209 l. oil drum. However, due to its cylindrical shape, the oil drum wastes storage space. Another problem with cylindrical containers such as drums is the large surface area on the sides, back and top which lead to high radiant losses in directions which do not strike the plants. [83]

Other cylindrical containers commonly used are steel culverts and fiberglass reinforced plastic cylinders, available in various diameters and lengths. A further problem with these taller containers is stratification: the tendancy for warm water to rise to the top of the container and stay there, while the lower portion remains cool. This is less efficient because the warm upper section will lose heat faster than if the same heat were dispersed throughout the volume. [89] (Fig. 35). Similarly, radiation and convection at the top of the greenhouse does not benefit the plants down below.

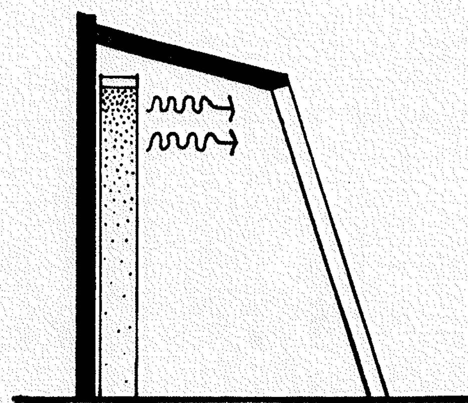


Figure 35. Thermal stratification in tall water containers

Smaller, right-angled containers would eliminate most of the problems associated with oil drums and other such containers as they would use space more efficiently and not be prone to heat stratification. While seemingly easier to install, smaller stacked containers would require some type of bracing for additional support to prevent crushing from containers above.

A water container that appears to have few problems is the modular steel tank. While not commercially available such a container could easily be locally fabricated and installed. Tank size could vary according to the space limitations of the particular greenhouse, but module size should be limited to enable easy moving and installation. (e.g. .5 x 1 x 1.5 m.). Note that unlike solid storage materials, the thickness of such a "water wall" is not crucial because convection within the container ensures that all of the water participates in heat storage. Modular plastic "blocks" and panels specifically designed for water storage are available commercially.

The obvious location for any primary thermal mass will be against the north wall. Exact placement depends upon the individual greenhouse and such factors as the south wall configuration, window placement, etc. End walls could be another potential location for directly illuminated mass, especially the east wall since this is the surface which will intercept the low west sun which could cause overheating from late spring to early fall. Anywhere the sun strikes is a potential location for primary thermal mass.

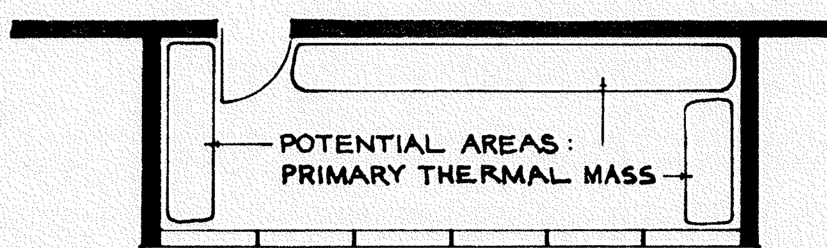


Figure 36. Locating primary thermal mass

The exact amount of primary thermal mass required is subject to a number of variables and is discussed in more depth in Part 5. As a general guideline, allow from .25 to .5 cubic meter of water storage for every square meter of south glazing.

Other materials commonly used for thermal storage are concrete, masonry, or stone. Concrete, being the most massive, has the highest heat capacity of all three. However, these materials, besides being able to store much less heat than water, have low conductivity which means they are less able to conduct the heat from the surface to the interior of their mass. Because heat cannot move into the material fast enough, the surface temperature rises, and the surrounding air is heated. For this reason, directly-illuminated masonry materials should not be dark in colour, since the dark surface will heat up more quickly, leading to increased convection to the air. If masonry is being considered for primary mass, it must be used in thin, large area slabs. Johnson states that 135 mm. is the maximum useful thickness, and that from 5 to 7 times the window area will be necessary if such mass is to absorb all the incident radiation. [85] This indicates that concrete and related masonry materials are not appropriate materials for directly illuminated thermal mass in a greenhouse.

These materials are more appropriate as secondary mass, i.e. mass which is not in direct sunlight, since secondary mass does not heat as quickly or store as much heat as primary mass. Secondary mass should always be considered in conjunction with primary mass because as primary mass absorbs energy and heats up, it emits radiant heat which is intercepted by other surfaces in the greenhouse. If these surfaces are of low heat capacity or very low in conductivity (such as wood) they quickly heat up and convect heat to the air.

Because absorption of radiant heat is independent of colour, secondary mass should be light in colour to reflect visible light back to plants and other surfaces. While water is the best storage material, there are problems in using it against sloping walls and ceilings. For this reason, dense masonry materials such as concrete or stucco are reasonable alternatives for secondary mass, their lower conductivity posing less of a problem in absorbing the smaller amounts of radiation. Thickness recommendations of secondary mass vary, depending upon the mode of heating and the area ratio of secondary mass to primary mass. Lebens [86] suggests 95 mm. for a 1:1 ratio, and 70 mm. for 2:1. Note that since infrared radiation is emitted in all directions, any interior surface exposed to primary mass is a potential location for secondary mass.

Hybrid Systems: Hot Air Collection and Storage

Even when large amounts of direct gain mass are incorporated into the greenhouse, the sun will inevitably strike objects and surfaces of low heat capacity (such as plants, soil, wood mullions, etc.) which will result in increases in air temperature. In fact, some writers feel that overheating in a greenhouse is unavoidable. [87] This warm air need not be "dumped" as it can still be stored in a rockbed. This is usually accomplished by ducting hot air from the highest point in the greenhouse through a bed of rocks where it gives up its heat. Because of the mechanical input (fans) such a scheme is considered at least partly "active" and this active/passive combination is often referred to as a "hybrid" system. While not as efficient as direct gain system and generally more complex and expensive, active rockbed storage can be justified in a greenhouse where:

1) extensive night-time use of the space is the norm;
2) plants limit the exposure of direct thermal mass; or
3) the parent building and greenhouse thermal mass combined cannot absorb all the incoming heat. [88]

Active storage of hot air offers some advantages over direct gain storage. First, because a rockbed can be located anywhere (usually beneath the floor) it does not occupy valuable growing space, and thus is not in competition with plants for direct light. Furthermore, the rock storage is not limited by the floorplan of the space. Secondly, there is less heat stratification in the air of the greenhouse as the warmest air is constantly being pulled down and through the rockbed. This heat stratification can be quite dramatic in a greenhouse and can result in significant increases in heat loss. (Fig. 37).

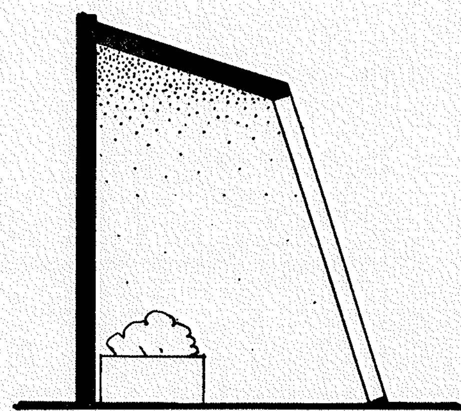


Figure 37. Heat stratification in greenhouse air

Third, the constant movement of air during the day can benefit plants both in increased CO_2 uptake, and in preventing diseases associated with humidity and stagnant air. Air movement can also be an aid in pollination of many plant varieties. Finally, hot air storage is flexible, it can be used to more closely control air temperature without resorting to venting during the heating season. Similarly, it can also provide extra cooling during the hottest parts of the year.

Because of the relatively low storage temperatures, rockbeds, like direct gain mass must be in radiant contact with the space if they are to work at all. [89] This can be accomplished most effectively by placing the rockbed directly under a concrete floor. Thus, heat is actively pumped through the rockbed where it heats the rocks and is released back to the greenhouse through radiation and natural convection.

For specific information on sizing and design of rockbeds, refer to

Passive Solar Design Handbook, Vol II and "Passive Principles: Rockbeds", Solar Age, March, 1982.

A problem associated with rockbeds in greenhouses is mildew resulting from charging a cold rockbed with warm moisture-laden air. This can result in problems ranging from odors to the rendering of the rockbed completely inoperable. Another disadvantage of the rockbed is the difficulty in construction because of the large volume of rocks.

Recently, an alternative to rockbeds has become increasingly popular. This is the so-called "radiant slab", a derivative of the rockbed. Besides having none of the problems associated with rockbeds, the radiant slab has been proving to be less expensive, making use of more conventional construction skills. 90 Instead of forcing warm air through rocks with spaces, the radiant slab system forces the warm air under or through a concrete slab by way of air channels preformed in the concrete. These channels can be formed in a number of ways, using metal decking, concrete block, flexible tubing or proprietary systems. (Fig. 38)

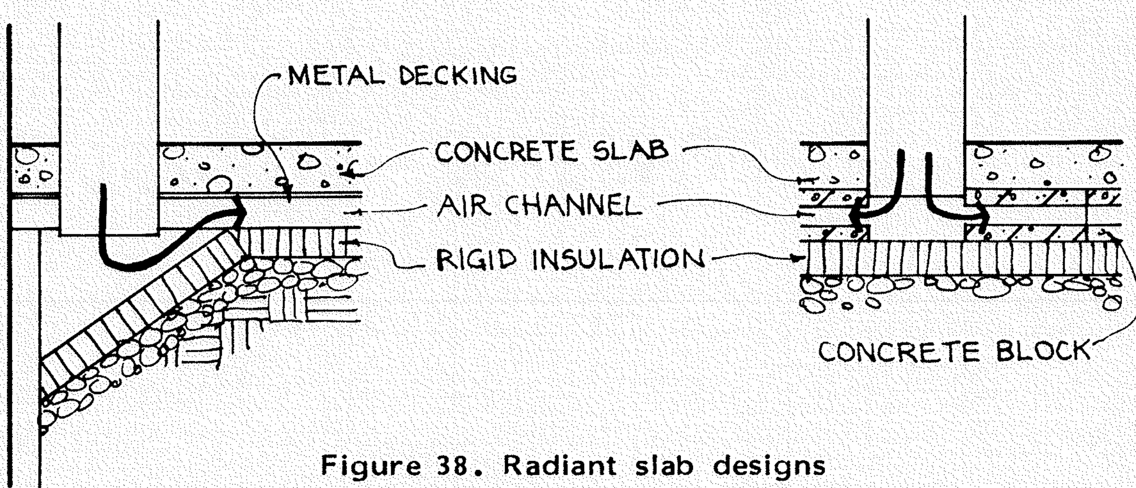


Figure 38. Radiant slab designs

A 100 mm. depth of concrete is recommended for optimum performance. A thinner slab cycles the heat out too quickly, while a thicker one prevents all the heat from escaping. 91

4.8 Cooling and Ventilation

While much discussion has been directed to solar gains and heat management within the greenhouse, there will be periods during the year when keeping heat out and temperatures down will be an important concern.

One way to deal with overheating in summer is to prevent some of the solar radiation from entering the greenhouse in the first place. This is best accomplished by partially blocking the sun outside the glazing. Traditionally, paint-on sun screens have been applied to outside glazings, although these are not recommended for fiberglass and other plastics, due to the difficulty in removal and potential damage which could result. A home-made paint-on shading compound often recommended is white latex paint mixed with 8 parts water. A more logical approach would be to shade only those wavelengths which plants do not use efficiently - green and yellow - resulting in a mauve or pink shade colour. Another option is neutral density shading material which is available in a variety of densities for precise control of insolation.

Perhaps the simplest and most automatic shading devices are decidious vines which can be trained up mullions and across eaves to provide shade in summer. Recommended for the prairies are various grape varieties, bittersweet, and climbing honeysuckle which will all require support of some kind, and Engleman's ivy, which is self supporting and therefore highly appropriate in this situation. Vines are undoubtedly the most appealing shading device from an aesthetic standpoint, and can be the least effort over the years.

If for some reason exterior shading is not practical, material such as cheesecloth can be hung inside the glazing to diffuse and partially block direct sun.

If some form of shading is used to reduce insolation, it may be desireable to cover dark-coloured thermal mass with white or reflective materials such as roll-up shades in order to compensate for reduced light levels. This would have the further advantage of effectively removing the thermal mass from the system. This way the thermal mass would not store heat which could have the effect of keeping night temperatures too high.

Once the greenhouse air is overheated, good ventilation is necessary to expel the hot air and draw in cooler outside air thereby keeping greenhouse air temperatures close to those outside. Some solar purists advocate totally passive ventilation whereby air is vented by natural convection alone. This is less practical than forced ventilation, since recommended vent sizes are from 1/6 to 1/5 the floor area for the ridge (roof) vents and the same again for the lower intake vents. Furthermore, roof vents, which must be well sealed against air infiltration and moisture, can be difficult to construct.

The most realistic option is forced cross-ventilation, with an exhaust fan and intake vent on opposite end walls. The exhaust fan could be located opposite the door to the outside, with a screened door serving as an inlet vent. However, a separate inlet vent (smaller and high up) would be better for security reasons, since the screened opening will have to be open at all times during hot weather.

Recommended ventilation rates range from 1/4 air change per minute to a maximum of 1 air change per minute. [92] This compares with a rate of 1.5 air changes per minute recommended for conventional greenhouses, due to the proportionately larger areas of glazing and lack of thermal mass. In a well designed greenhouse, an exhaust fan rated to provide 3/4 of an air change per minute will most likely be sufficient to handle any situation. A rheostat control on the fan switch will allow fan speeds to be adjusted to the degree of overheating. The exhaust fan should be regulated by an adjustable thermostat.

If the greenhouse is to be used extensively throughout the summer, it may be necessary to cool the intake air with an evaporative cooler. This is a system used extensively in commercial greenhouses where hot intake air is drawn through water-soaked fibrous pads. The air causes water in the pads to evaporate, which removes heat from the air. It is possible to reduce air temperatures by 8 - 11 degrees C., depending upon the original moisture content of the air and the size of the unit. Smaller units are available for home greenhouses, or a system could be fabricated on-site with readily available components. In the end, though, it may be most economical to grow only warm season varieties in the summer greenhouse, and forgo the added expense of an evaporative cooling unit.

4.9 Interior Design

The arrangement of the interior spaces of a food-producing greenhouse will be determined to a large extent by the type of cultural system employed. While soils and growing media were discussed specifically in Part 2, it is necessary here to define the various methods of physically arranging the soils and plants within the greenhouse.

The traditional approach uses the raised bench in which plants are grown either in pots or directly in the shallow benches. Benches are constructed from treated wood or asbestos board, usually on bases of metal pipe or tubing.

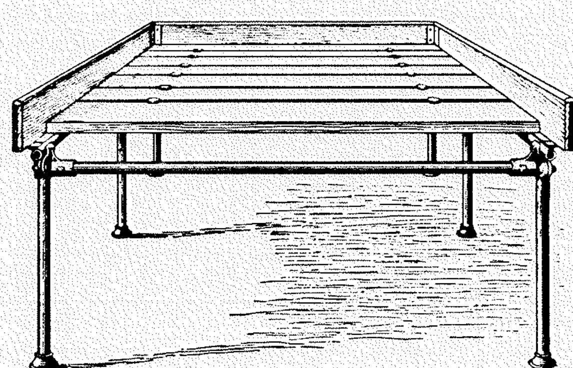


Figure 39. Bench with pipe-frame support

A simple, moveable bench system can be made from snow fencing over a concrete block base. Bench systems are typically used in commercial greenhouses for growth of foliage plants, cut flower production, as well as some vegetable produce. The stated advantage of this system is a more precise control of soil moisture and temperature. Raised bench systems can be quite flexible, accommodating pot plants, direct planting, bedding plants, etc. Soil depths in direct planting are usually limited to around 18cm. and as such, soil nutrition and moisture must be carefully monitored. This may be a disadvantage to the home greenhouse operator. Benches also tend to waste vertical growing space, since the area under the benches is too shady to support vegetable crops. In the energy efficient greenhouse, this space could be used for thermal mass.

Ground beds have become popular in more recent home greenhouse literature. This system is also used in larger commercial greenhouses, where the entire floor area of the greenhouse is cultivated in much the same manner as outdoor agriculture. In the smaller home greenhouse, the usual approach is to have ground level planting areas serviced by permanent, hard-surfaced walkways.

Ground beds can be very space-efficient, allowing maximum height for vertically-trained plants. The larger soil volumes are less prone to temperature fluctuations and nutrient or moisture deficiencies under the less precisely controlled conditions of the home greenhouse. Soil depth should be as deep as practicality allows; a minimum of 30cm. and preferably 45 to 60 cm. [93] Some greenhouse source books state that ground beds can suffer from poor drainage and cold temperatures especially during cool, cloudy winter conditions. Drainage should not be a problem if the soil has been properly prepared and is of good structure. A layer of crushed rock over weeping tile is used by commercial operators to ensure good drainage in ground beds. (Fig. 40). This drain tile system can also serve to conduct steam for soil pasteurization. To prevent pooling of cold air, the soil level should be at a somewhat higher elevation than the greenhouse floor.

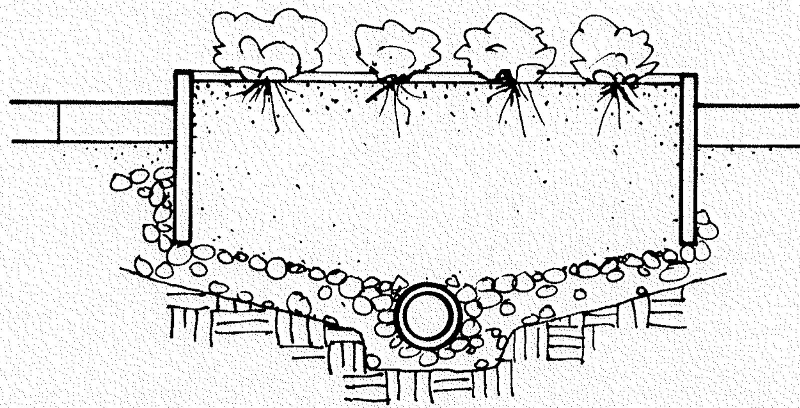


Figure 40. Ground bed with drainage tile

There are, however, some drawbacks to using ground beds in an energy-efficient greenhouse design. Ground beds will preclude the use of sub-floor thermal mass such as that in a rockbed or radiant slab. Also, water that drains through a ground bed and out to the ground beneath will take with it heat that was once a part of the greenhouse system. This form of heat loss can occur even though the sub floor area is insulated. Finally, ground beds with permanent walkways can be difficult to construct properly, and are relatively inflexible.

A final option in greenhouse plant culture is containers on grade. This system is more flexible, partly because any number of different container types can be used and, depending on container size, plants can be moved to take advantage of different microclimates (i.e. variences in light and temperature) which may occur. There is further flexibility in that a variety of rooting media or soil types can be used at the same time. This is an advantage since not every plant variety has exactly the same nutritional or moisture requirement. Greenhouse cucumbers, for example, require higher levels of nutrients and of a different balance than most other vegetable varieties, and would therefore be difficult to grow in the same soil bed with other vegetables. Containers on grade would also allow experimentation with alternate cultural systems such as hydroponics and soil-less culture. This system is also the most conducive to flexible greenhouse planning, allowing the layout to be changed for the addition of a sitting area, or the eventual conversion of the entire space to a heat-producing solarium or living space by a future owner. A final advantage of containers on grade is that it allows for the use of a sub-floor heat storage system if desired.

This system could be considered somewhere between raised benches and ground beds in terms of efficiency of space utilization. Large, right-angled containers are prefered over smaller, round pots. Containers could be recycled items such as wooden boxes and crates, or constructed specifically for the greenhouse in modular sizes to facilitate arrangement and rearrangement. New wood containers, unless of rot-resistant wood such as cedar, should be coated inside with fiberglass resin or lined with a heavy grade of polyethylene. Wood preservatives and treated lumber are of questionable safety in a food-producing greenhouse and are not recommended.[94]

Whatever system is decided upon, the final plan should maximize the growing area and have all planting areas within easy reach of pathways.

When the cultural system has been decided, the design of the south wall should be checked and adjusted if necessary so that shading does not occur on any potential soil surface. (See Fig 31).

Connections

Recently, there has been a move towards a more complete integration of the greenhouse and living areas in passive solar dwellings. While such "green rooms" may be desireable for the nurture and display of ornamental foliage plants, a greenhouse which is designed primarily for food production should be capable of being isolated from the main living areas of the house for a number of reasons. Intensive food production is prone to outbreaks of insects which could migrate to other parts of the house. If chemical controls are resorted to, it is desireable to be able to use these in a contained, controlled environment. This could also apply to safer, but often equally oderous substances such as compost, manures, and other organic fertilizers. Furthermore, temperatures both higher and lower than are acceptable for human comfort are likely to be experienced in growing areas due to the requirements of some vegetable crops. Finally, the greenhouse should be capable of being thermally isolated for a complete mid-winter (or mid-summer) shutdown in which extreme temperatures could be a part of a general sanitation program.

It should be noted that in much of the literature on attached greenhouses, the common wall between the house and greenhouse is assumed to be massive and uninsulated and therefore both a component of heat storage and a means of heat transfer to adjoining spaces. This does not apply to the bulk of Winnipeg's housing stock where most existing houses are of insulated wood-frame construction.

Because there will be inevitably some increase in air temperature during the heating season beyond those considered optimum for plant growth, a small thermostatically-controlled fan in the common wall will most effectively transfer any excess heat to the house.

Finishes

Interior finishes should be chosen with consideration for durability and ease of maintenance. Porous materials such as drywall are inappropriate due to potential water damage. Painted surfaces in general should be minimized as they will require more frequent maintenance in the high humidity and light levels of the greenhouse.

All interior surfaces other than direct-gain mass should be matt white or similar in colour and preferably of relatively high heat capacity. In enclosed environments the diffuse light reflected from matt surface textures has been shown to be better for plant growth than specular reflection from glossy surfaces.[95]

Given the requirements of high heat capacity, resistance to moisture, and light colour, appropriate choices for interior finishes are such materials as concrete, stucco, and light-coloured masonry materials such as quarry tile, stone, brick, and (matt finish) ceramic tile.

The use of reflective finishes could even extend to mulching soil beds with white polyethelene to reflect light up to plants. Clear polyethylene has been shown to boost soil temperatures, [96] and would thus be useful in winter growing, since warmer soil can compensate for lower air temperatures. [97] White mulch would prevent sunlight from striking dark soil surfaces and would thus help keep air temperatures down in summer.

Auxilliary Equipment

Because water for plants should be at a minimum of 21 degrees C., a tap which mixes hot and cold water should be installed unless other provisions are made. An alternative would be a water pre-heat tank which would use the sun's energy to warm cold tap water to acceptable levels. Such a tank should be located to intercept direct sun (especially morning sun for early warming) and should be of a low horizontal configuration rather than vertical to avoid problems with thermal stratification. A large water pre-heat tank could be located on top of a water wall. (Fig. 41)

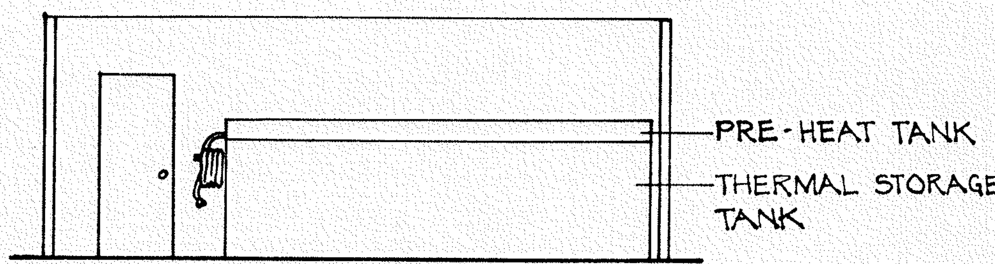


Figure 41. Water pre-heat tank

Auxilliary backup heating will probably be necessary if operating throughout the winter, even in the best-designed greenhouse, since a continued period of overcast weather with little insolation will depleat storage reserves. Depending upon the location and type of heating system in the parent building, it may be practical to extend that heating system into the greenhouse.

A much simpler and more precise method would be to locate an auxilliary radiant heater within the greenhouse. Radiant heaters are preferred since they heat the plants directly, without first heating the air. As such, lower air temperatures result in less heat loss.

Auxilliary lighting is another accessory worth considering if it is anticipated that warm-season crops will be grown throughout the winter. Lights can also augment daylight on cloudy days, and the added heat can be a significant supplement as well. [98] Fluorescent lighting should be used only at relatively short distances from plants, as intensity drops off rapidly with distance. Fluorescents could be used for example, under raised benches. For more general illumination, a more concentrated light source such as low pressure sodium is recommended. These lights have been shown to be over

50% more efficient than fluorescent at providing light useable to plants. [99] Another advantage is that they do not have special wiring or voltage requirements as do high-intensity discharge types such as mercury vapour or metal halide. Supplemental lighting could be considered in a small portion of the greenhouse which could be maintained as a "warm room" for special crops in winter.

This concludes a discussion of energy-efficient greenhouse design principles, from initial planning to specifics of interior layout. In Part 5, the design of a greenhouse addition for a typical suburban house in Winnipeg illustrates how these principles can be applied in a specific situation.

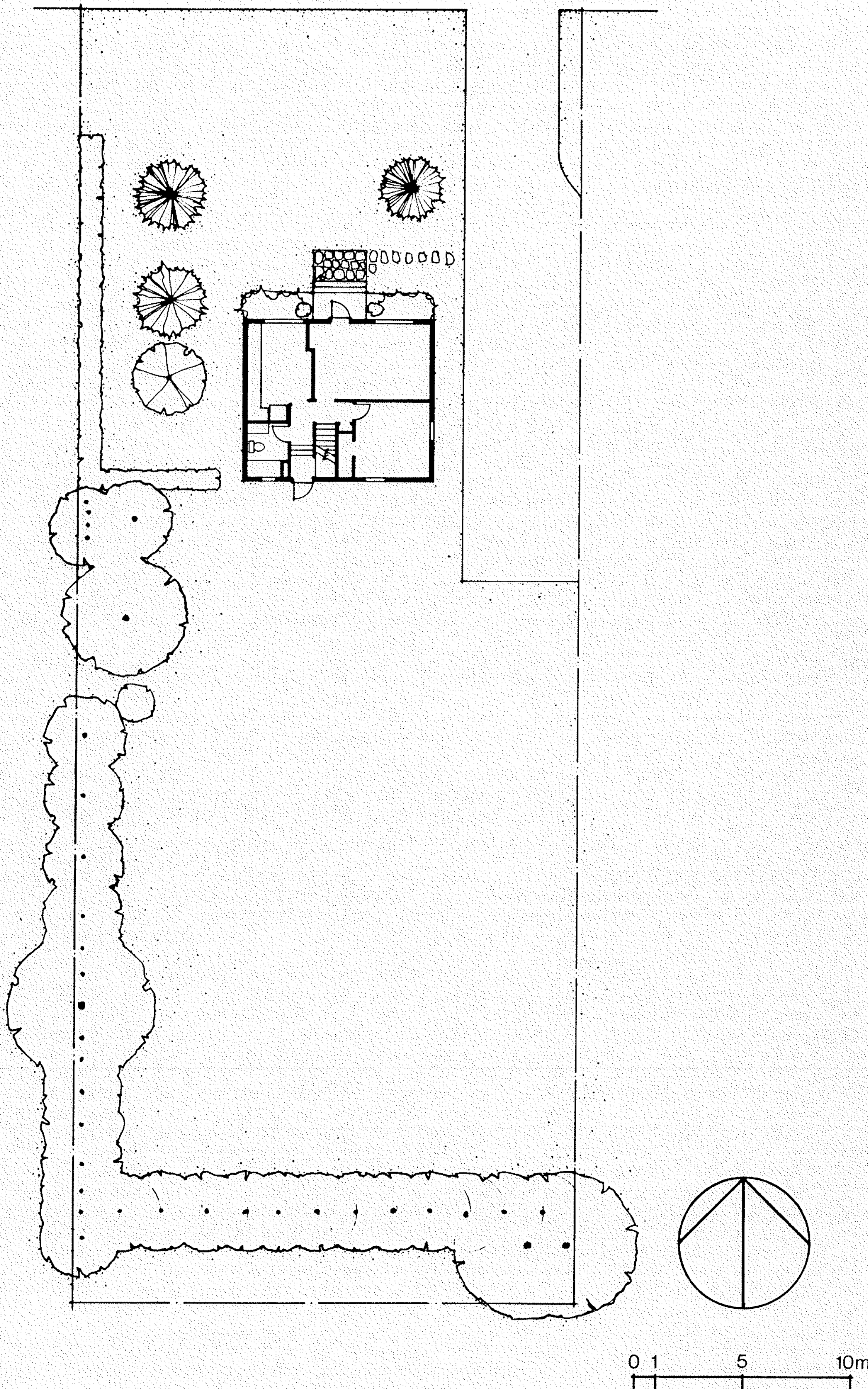
PART 5 CASE STUDY

Part 5 Case Study: A Greenhouse Addition

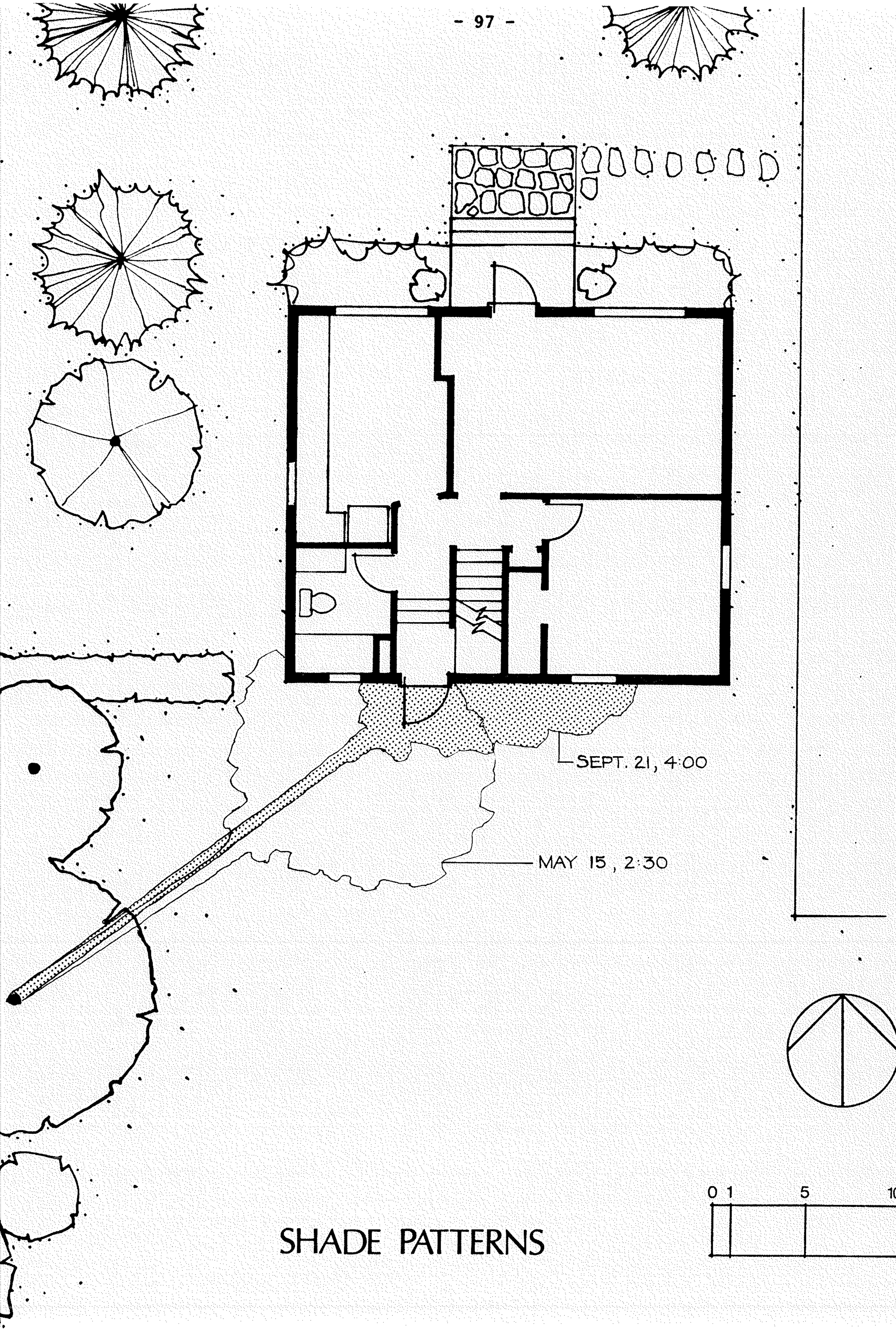
In this section, a specific design for an energy-efficient greenhouse is presented. The design of such a greenhouse addition must take into consideration not only the principles relative to solar gain and the needs of plants, but also the needs of people in a broader program involving the design of comfortable living spaces and the integration of these new spaces with existing ones (inside and out) in an orderly and aesthetically satisfying fashion. While every case is unique, it is hoped that an example will serve to illustrate the decisions (and compromises) which often must be made along the way.

5.1 Existing Conditions

The subject of this study is a small 1 1/2 storey house of post-war vintage, located in southwest suburban Winnipeg. The house proved to be very well suited to a greenhouse addition since its back faces due south and looks out over a large open backyard and park beyond. An analysis of the proposed greenhouse site indicated some shading in the afternoon from deciduous trees to the west, however this was not considered a serious problem since shading would be minimal from fall through until springtime due to the absence of leaves. The shade in summer could prove to be an asset by reducing solar gain during late afternoon - a time when overheating can be a problem. In any case, it is felt that judicious pruning of any trees causing excessive shading would be a viable solution.



EXISTING CONDITIONS



SHADE PATTERNS

5.2 Design Program

In conjunction with the greenhouse addition, a general renovation of existing spaces was to be undertaken as well, and a number of overall objectives was identified:

1) Generally open up the small, compartmentalized spaces within the house;
2) Increase south glazing areas to take advantage of solar gain as well as views to the south;
3) Connect the greenhouse with living spaces in the house, while still allowing for thermal isolation of the greenhouse;
4) Incorporate a new entry near the driveway;
5) Allow for a work/storage area within the greenhouse;
6) Maximize planting area in the greenhouse while allowing space for a sitting area;
7) Establish connections and a flow of living space from house to greenhouse to outside.

5.3 Design Development

After identifying these objectives, several specific decisions were made which would begin to define initial greenhouse form.

An existing bedroom at the southeast of the main floor would be converted to a dining room to become a major visual and physical link with the new greenhouse. As such, the two floor levels at this point were to be as close as possible.

Upstairs, the stairwell dormer was to be extended to open the bedrooms to the south. A balcony serving the bedrooms would form the greenhouse roof.

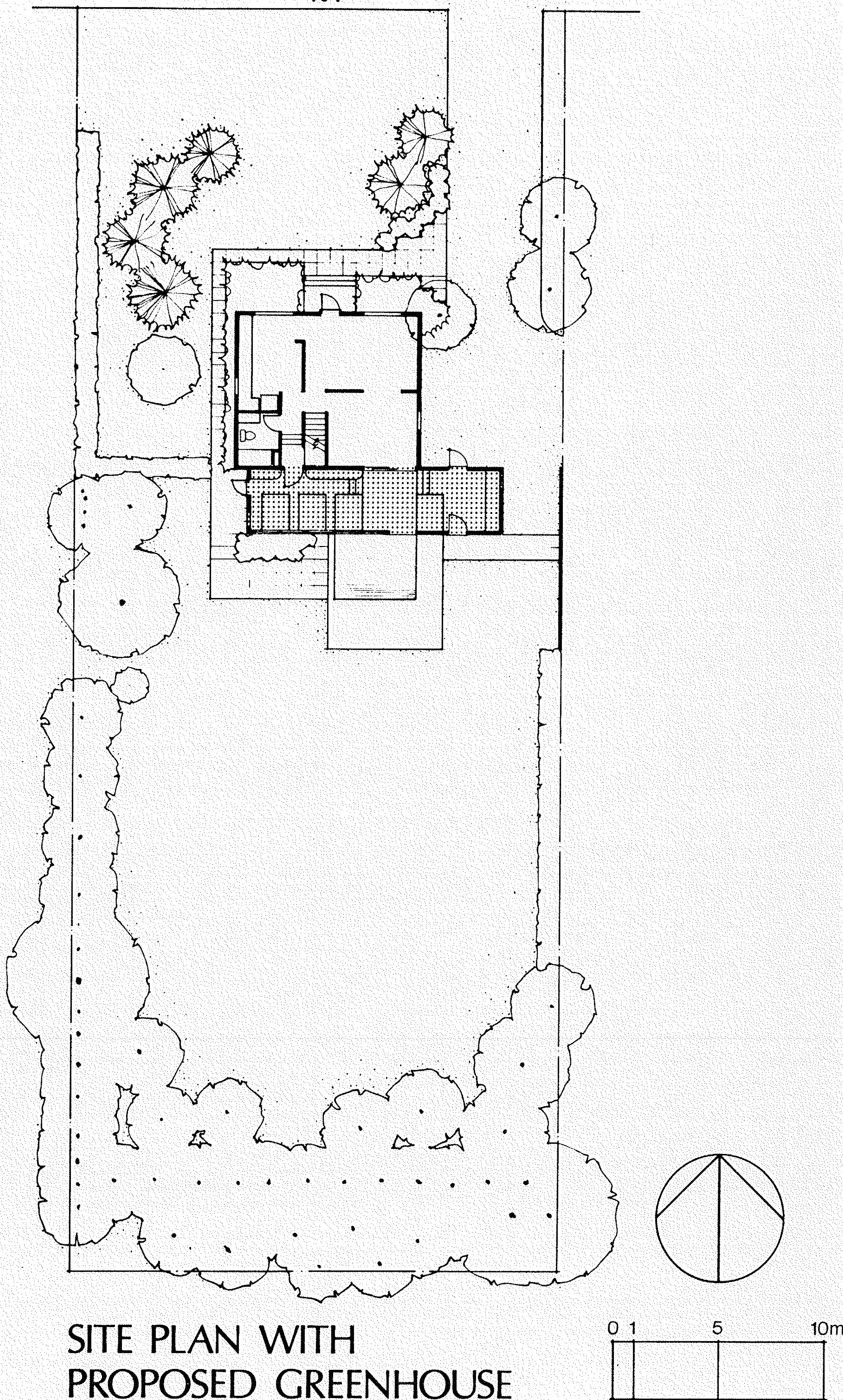
With the roof height and upper floor level set, a series of trials was undertaken to determine a south wall configuration, which in turn would influence the north-south dimension. A combination of vertical and angled glazing was decided upon to provide headroom at the upper floor level. The height of the vertical glazing was not without constraints since it influenced the angle of the overhead glazing - the higher the vertical wall, the lower was the angle of overhead glazing. The 30 degree angle arrived at is considered a compromise, since lower glazing angles result in increased summer heat gains.

After the south wall was more or less defined, the greenhouse plan evolved through further refinement of the objectives. For example, the plan was extended to the east to provide an entry and work/storage area. Level changes within the greenhouse serve not only to connect the different levels within the house, but also as a cold-air dam at the main entry. The level change also dictated refinement of the south wall, determining the lower extent of the glazing and in turn the height of the planters.

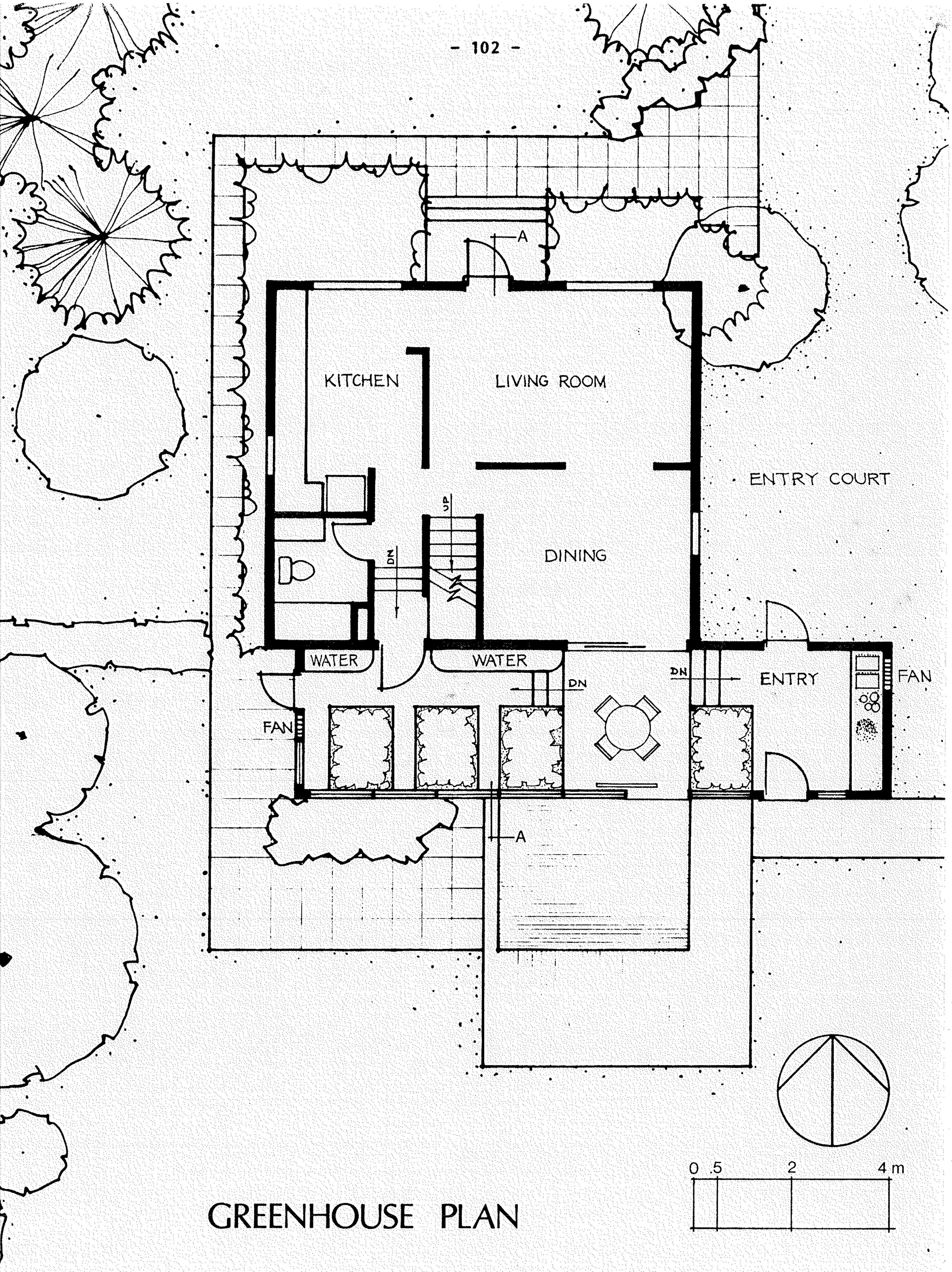
A sliding glass door establishes the main physical and visual link between the house and greenhouse, while allowing for thermal isolation of the greenhouse from the house. The greenhouse space at this connection point is essentially a continuation of the household living spaces. This central raised area of the greenhouse serves also as a transition space, not only to the rest of the greenhouse to the east and west, but also to the outdoor decks and grounds beyond. This north-south link is particularly important in establishing a clear flow of space, visually and physically, from the living room at the north of the house, right through to the outdoor spaces of the back yard.

Glass was chosen as a glazing material not only for its favourable transmittance and thermal characteristics, but also for the unobstructed view it provides compared with most of the common plastic glazing material. The relative merits of double and triple glazing are compared in the heat-loss calculations.

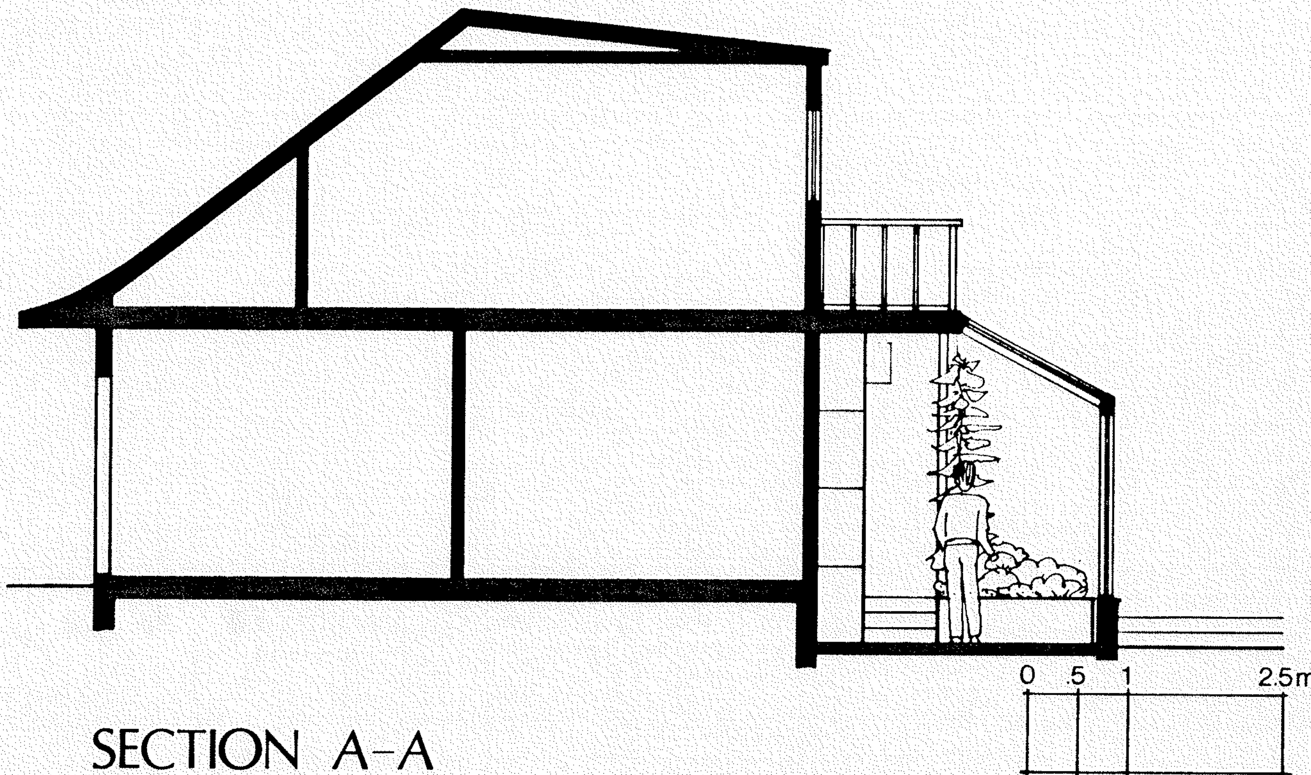
Water in modular steel containers is the main heat storage, and was chosen for its high heat capacity compared to other common materials. Interior finishes, including smooth white stucco on walls and ceiling, and quarry tile on a 100mm concrete slab floor function also as secondary thermal mass. (The benefits of an actively-charged radiant floor slab are examined in the calculations as well).



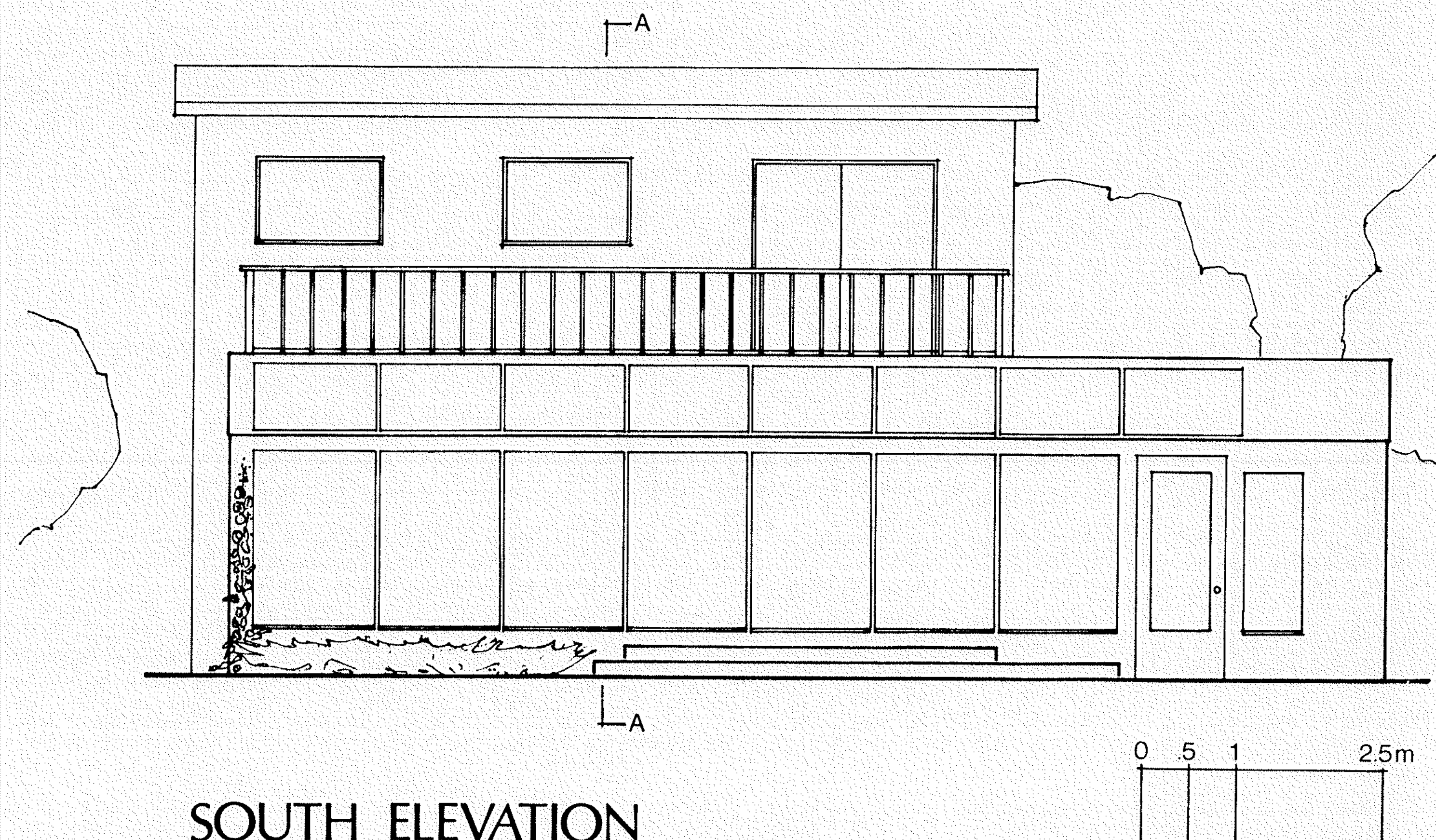
SITE PLAN WITH
PROPOSED GREENHOUSE



GREENHOUSE PLAN



SECTION A–A



SOUTH ELEVATION

5.4 Greenhouse Data

The final design is 2.74m deep by 11.43m wide and ranges in height from 2.29m at the eaves to 3.05 at its high point. Total floor area is 31.32 m^2, with a net planting area of 7.4m^2. Glazing areas are: 17.6m^2 south vertical, 15.8m^2 south 30 degrees, and 1.7m^2 east vertical.

The foundation is a grade beam on piles insulated with 50mm of extruded polystyrene on the outside of the grade beam and beneath the concrete floor slab, providing an RSI value of 1.7. Walls are assumed to be RSI 3.3, the ceiling RSI 3.7.

5.5 Predicting Performance

To predict the thermal performance of the greenhouse, heat flow calculations were undertaken to investigate heat defficiencies, the relative merits of double and triple glazing, sizing of heat storage, and temperature ranges.

Calculations are based on mean monthly temperature and radiation data. The operating temperature range is to be limited to 8 degrees C., from 17 degrees to 25 degrees C., for an average daily temperature of 21 degrees C.

Because foundation heat loss is maximized at or above ground level with below-grade losses diminishing rapidly with increasing depth, conductive losses are assumed to be .86 Watt for every meter of foundation length for each degree difference between average indoor temperature (21 degrees C.) and average outdoor temperature.

Air infiltration is assumed to be kept to within one air change per hour and is calculated at 0.355 $W/m^3 \cdot {}^oC$. Sample calculations are presented for January and March. January has the lowest mean daily temperature of the year and is modelled to determine how much (if any) auxilliary heat will be required to maintain the minimum greenhouse temperature (17 degrees C.) as well as the heat saved with triple glazing as opposed to double glazing.

March is a month with high solar gains and relatively low mean daily temperatures, and as such a time when storing incoming heat is important. This month is therefore used to check whether the thermal mass in the greenhouse is adequate to keep temperatures within the specified limit of 25 degrees C.

Calculations for January: Double Glazing

Gross Gains

Glazing Orientation and Inclination	Incident Radiation (W h/m^2.day)		Area (m^2)		Trasmittance		Gain (W hr/day)
South 90°(Vert.)	3630	x	17.6	x	.71	=	45 360
South 30°	2911	x	15.8	x	.71	=	32 656
West 90°	1364	x	1.7	x	.71	=	1646

Gross Gain = 79 662 W hr/day

Losses

	Area (m^2)		Conductance, U (W/m^2.°C.)		A•U (W/°C.)
Roof	16.3	x	.27	=	4.4
Walls	37.1	x	.30	=	11.1
Doors	2.9	x	1.00	=	2.9
Glazing	35.1	x	2.90	=	101.8
Foundation	17m	x	.86W/m.°C.	=	14.6
Air Infiltration	84m^3	x	0.335 W/m^3•°C.	=	28.1
			Total:	=	162.9W/°C.

Temperature difference (T inside - T outside) = 21° - (-17°) = 38°C.

162.9 W/°C. x 38°C. = 6190 W

6190 W/ x 24h/day = 148 560 W h/day

January daily gross gain	79 662 W h/day
Losses	148 560 W h/day
Net Deficit, Double Glazing	68 898 W h/day

January: Triple Glazing

For triple glazing, a glazing transmittance value of .59 is substituted under "gross gains", and a U value of 1.9 is substituted under "losses", resulting in the following figures:

January daily gross gain	66 198 W h/day
Losses	116 462 W h/day
Net Deficit, Triple Glazing	50 264 W h/day

Calculations for March: Double Glazing

Gross Gains

Glazing Orientation and Inclination	Incident Radiation (W h/m^2· day)		Area (m^2)	Transmittance		Gain (W h/day)
South 90^o(Vert.)	4419	x	17.6	x .71	=	55 220
South 30^o	5181	x	15.8	x .71	=	58 120
West 90^o	3071	x	1.7	x .71	=	3707
				Gross Gain =		117 047 W h/day

Losses: 162.9 W/^{o}C

Temperature difference (T inside - T outside) = 21^o - (-7^o) = 28^{o}C.

162.9 W/^{o}C. x 28^{o}C. = 4561 W

4561 W x 24h/day = 109 469 W h/day

March daily gross gain	117 047 W h/day
Losses	109 469 W h/day
Net Gain	7578 W h/day

March: Triple Glazing

March daily gross gain	97 264 W h/day
Losses	85 881 W h/day
Net Gain	11 383 W h/day

Heat Storage Performance for March

Gross gain figures for double glazing are used to test the sizing of heat storage, and to predict temperature ranges in the greenhouse assuming 5.5m^3 of water storage. For the sake of simplicity and clarity, only primary thermal mass will be considered for these particular calculations. The heat capacity of water is 4.18 MJ/m^3·°C., or 4.18 million Joules per cubic meter for every degree of temperature increase. Solar gain units of Watt-hours are converted to MJ on the basis of 1W h = .0036 MJ.

Gross Gain: 117 047 W h x .0036 = 421 MJ

Water Storage Capacity: 4.18 MJ/m^3·°C. x 5.5m^3 = 22.9 MJ/°C.

In the example greenhouse, a one degree increase in the water storage temperature will account for 22.9 MJ of the heat gain. To store all of the solar gain (421 MJ), the 5.5m^3 of water will have to increase by:

$$\frac{421 \text{ MJ}}{22.9 \text{ MJ/}^{\circ}\text{C.}} = 18.3^{\circ}\text{C.}$$

Since this is beyond the specified increase of 8°C., some heat will have to be vented to the house, assuming more thermal storage cannot be added.

The amount of heat that can actually be stored in the given volume of $5.5m^3$ over an $8^oC.$ temperature range is:

$$4.18\ MJ/m^3 \cdot {}^oC. \times 5.5\ m^3 \times 8^oC = 183.9\ MJ$$

To determine whether this amount of stored heat will maintain minimum temperatures throughout the night, the rate of heat flow is first converted to J/h as follows:

$$\text{Rate of heat loss} = 4561\ W = 4561\ J/sec. \times \frac{3600}{10^6} = 16.42\ MJ/h$$

At this rate, the stored heat (183.9 MJ) will last

$$\frac{183.9\ MJ}{16.42\ MJ/h} = 11.2\ h$$

In March, the average length of night is 12.4 hours, and the storage capacity is therefore defficient by 1.2 hours. Without auxilliary heat, the temperature will drop below 17^oC.

To determine the relative benefit of an active-charge radiant slab floor design some final calculations were undertaken. Because such a system operates on heat transfer from air to mass rather than by direct radiation, the projected temperature rise of the concrete is considered as one-half the change in air temperature, or in this case 4 degrees C. The volume of concrete is $31.4m^2 \times .1m$ thick or $3.14m^3$. The heat capacity of concrete is $2.157\ MJ/m^3 \cdot {}^oC$, therefore the heat capacity of the slab is:

$$2.157\ MJ/m^3 \cdot {}^oC \times 3.14\ m^3 \times 4^oC = 27.09\ MJ.$$

Another area of heat storage is in the stucco finish which contributes secondary mass on interior walls and ceiling. Assuming a thickness of 50mm, the volume of stucco will be 2.1 cubic meters. With a heat capacity of 1.96 $MJ/m^3 \cdot {}^oC$, the amount of heat that can be stored in the stucco is:

$$1.96\ MJ/m^3 \cdot {}^oC \times 2.1\ m^3 \times 8^oC = 33.0\ MJ.$$

5.6 Discussion of Heat Flow Data

As revealed by the heat-flow analysis, a net deficit of 68.90 kWh per day can be expected with double glazing under average January conditions. This can be reduced by 27% to 50.26 KW.hr. per day with triple glazing. In March, an average daily net heat gain of 7.58 kW h is increased by 50% to 11.38 kWh per day when triple glazing is substituted. The benefits of triple glazing must be weighed against an increased cost of 60% over double glazing. For a more accurate picture of the relative benefits of these and other options, life cycle costing , involving anticipated energy costs and inflation rates should be developed in conjunction with a more extensive and detailed thermal analysis, both of which are beyond the scope of this study.* The intent here is primarily to present a method of predicting heat deficits or surpluses in order to anticipate the amount of auxilliary heat (and therefore heating system) required, the amount of heat storage needed, and the temperature ranges which can be expected.

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* For a detailed discussion of life-cycle costing, refer to National Research Council of Canada, Solar Technical Series No. 2, The Solarium Workbook, P.63.

Based on data for March, the example demonstrates a method for checking storage capacity to determine whether temperatures will stay within the specified range of 8 degrees C. It is apparent from this exercise that the $5.5m^3$ of water is not enough thermal mass for this greenhouse, either to prevent overheating, or to store enough heat to last through the night.

Since heat storage is a function of volume and temperature as well as specific heat, storage in the greenhouse can be increased either by increasing the storage volume, by widening the acceptable temperature range, or by switching to a material with a higher volumetric heat capacity. If none of these is possible, the house itself can be used as storage, accepting excess heat during the day and returning heat at night by way of a reversible fan between the two spaces.

In the example, the volume of water required to maintain an 8^oC. temperature range in March is $12.6m^3$. While there are other areas along the north wall for more storage, this figure is more than double the storage volume already present, and accommodating this volume may pose problems.

The only realistic alternative to water as a storage material is a phase change material (PCM) such as calcium chloride hexahydrate, which is now commercially available. This material can store 298 MJ per cubic meter. To store the 421 MJ gain for March would require only 1.4 cubic meters of this PCM.

From the investigation of heat storage in the concrete floor slab, it was found that the 3.14 cubic meters of concrete in the floor will store less heat than one cubic meter of water, partly because of the lower heat capacity, but also due to the lower range in temperature. However, this heat storage should not be considered impractical, especially if the greenhouse floor is to be concrete slab in the first place, since the modifications are relatively minor. Furthermore, any exposed portions of a slab floor, whether actively-charged or not, will act as secondary thermal mass and absorb reradiated energy from other surfaces in the greenhouse. PCM pellets are also being developed for use as aggregate in concrete, and offer tremendous potential in increasing heat capacity in radiant floor slabs and other building elements.

A final potential area of heat storage - the greenhouse soil - was not included in the calculations due to the difficulty of predicting not only the actual heat capacity of the soil, but also its conductivity, both of which are dependent upon the relative amounts of water and air in the soil. For example, the heat capacity of soil can range from 1.58 $MJ/m^3 \cdot {}^oC$ (dry) to 3.69 $MJ/m^3 \cdot {}^oC$ (wet). Greenhouse soils, with a relatively high proportion of air spaces, will not only be less massive, but will have lower conductivity. As such, heat will not effectively move into the soil mass. A final problem in predicting heat storage in soil is that heat is lost quickly from moist soil due to evaporation.

5.7 Conculsions

A number of conclusions can be drawn from this discussion. The most obvious is the importance of storage and heat management. Because efficient use of space is so important in a greenhouse of this type, priority should be given to water storage in direct sun. Even with water storage, the required storage volumes are exceedingly high, and could present major logistical problems in containment and placement. As such, the present trend in the refinement and marketing of PCM's is most welcome and could be one of the most significant developments in the evolution of energy-efficient greenhouses. (According to one manufacturer's advertisement, their PCM module is already less expensive per unit of stored energy than any other material, including water).

Other common materials such as concrete and masonry are feasible as heat storage only when they can double as building elements such as walls or floors or as interior finishes (e.g. ceramic tile, brick, stucco), thereby contributing to secondary thermal storage.

Active heat storage is similarly feasible only if combined with an existing or proposed building element, especially a floor slab since the floor will have little direct gain due to shading from plants and other elements.

A final aspect of heat management and storage that is apparent from the analysis is the importance of the specified temperature range, as it has a direct bearing on the amount of energy stored and therefore on the size of storage. Temperature requirements of plants can vary considerably and a thorough understanding of the requirements of the particular plants under consideration is fundamental to the design of an energy-efficient greenhouse.

One qualification must accompany the preceeding discussion; the model has assumed a static, closed environment and has not taken into account certain variables, one of which is internal shading. When the greenhouse is full of plants, much of the sunlight will strike leaf surfaces and other objects of low thermal mass, and will thus not be directly absorbed by thermal storage as assumed. Even more significant is the substantial heat that is "lost" through evaporation of water. Water absorbs approximately 2.5 MJ for every litre that is evaporated. This is the principle behind evaporative cooling and it is the method by which plants cool themselves in direct sun and/or hot weather (through water evaporation from leaf tissue). As noted, water can also evaporate from soil surfaces in the greenhouse. While this evaporation is beneficial to both plants and people in maintaining humidity levels, it nonetheless represents energy which is lost from the system and difficult to account for.

Regarding the choice of glazing, it is generally accepted that south-facing double glazing will produce a net gain over the course of the heating season. Triple glazing is recommended for orientations other than south. However, the benefits of triple glazing will be even more significant if and when glazing manfuacturers incorporate 19mm air spaces as discussed in section 4.5. Furthermore, new glazing systems under development may eclipse triple glazing in both cost and performance in the near future.

In terms of more general conclusions, for a greenhouse of this type in Winnipeg, it is not possible to maintain an environment conducive to the growth of food crops throughout the year without auxilliary heating and cooling. A net heat deficit can be expected for at least three months of the year from mid-November to mid-February. This is assuming that temperatures are maintained sufficiently high so that crop choice is not limited. Similarily, there will be a three to four month period in summer where greenhouse temperatures will be too high for many crops. Without heating and cooling during these periods, gardening will not be impossible but it will be limited. However, it is during the remainder of the year that the greenhouse can provide not only an ideal plant environment, but a net solar heat gain to supplement the heating of attached spaces.

Much of the discussion has had to do with heat storage and management, since this is the very essence of a successful greenhouse design. However it should be remembered that a greenhouse is a system of many sub-components; from the foundation which supports the structure, to the glazing which is the solar collector, to the soil, air, and water which support and nurture the plant. Together these components function to sustain an environment identified as being the optimum for a particular group of plants. What is different about a greenhouse designed for energy-efficiency (in comparison to a conventional greenhouse) is that so much of the function and control is integral with the very form and structure rather than being added on after the fact. As such, a clear understanding of climate, energy flows, and plant requirements is required at the very outset of the design process.

There is, however, more to greenhouse design than energy flows and thermal modelling. A greenhouse of this type can and should become very much a part of the building to which it is attached, rather than remain a separate entity for the production of edible plants. While the properly-designed greenhouse will function in this capacity, there is also great potential for the creation of amenable living spaces.

It should be stressed in retrospect that, while this study has dealt with small-scale residential greenhouses, and specifically with food production, there is no reason why the same principles could not be applied either to larger-scale structures as in community greenhouses and commercial concerns, or to greenhouses designed for functions other than food production. The same principles, for example, could be applied to create greenhouses more suited to raising orchids, cut flowers, alpine bonsai, or any other exotic plant culture, as long as the specific plant requirements are understood. The fact that any of these can be undertaken with less energy use than conventional technology makes them worthy ventures.

The future looks very promising for the energy-efficient greenhouse, no matter what the specific application. New technological advances, which have already started to emerge, particularly in glazing systems and thermal storage, are being intensely researched and will inevitably have a profound impact upon greenhouse design as they are refined.

For those people who believe that their actions can have an effect in shaping a different world, and those who want to take an active role in supplying more of their own needs, an energy-efficient greenhouse can be an effective tool.

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