CONSERVING ENERGY IN CONTAINER GREENHOUSES

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Abstract.--Energy conservation can significantly offset the escalating fuel cost of winter-grown container stock. Costs are discussed, and a procedure is presented for choosing among the many cultural and structural alternatives available with the aid of illustrative data from a computer model developed at the Maritimes Forest Research Centre. Future research needs and industry trends are suggested.

Résumé.--L'économie d'énergie peut contrer de facon importante l'augmentation du prix du combustible nécessaire pour chauffer les serres en hiver. On discute des prix et on présente, à l'aide de données explicatives obtenues avec un modèle informatisé mis au point au Centre de recherches forestières de Maritimes, une méthode permettant de choisir parmi les nombreuses possibilités offertes en matière de culture et de construction. On fait entrevoir les besoins à venir en matière de recherche et les tendances dans l'industrie.

INTRODUCTION

The greenhouse has a 2000-year-old history (Hanan et al. 1978). The energy-conscious designs of a century ago indicate that fuel consumption has been a concern in previous times (Fig. 1), and that the greenhouse industry has responded by producing efficient structures and improved growing methods. Similarly, there is much that the container nurseryman can do to conserve energy in the greenhouse.

Rising energy costs are stimulating rapid changes in containerized tree seedling culture methods. Alternatives to winter-grown crops produced for early summer planting are being investigated. The spring/summer period is being used for stock production, followed by overwintering and planting the next year. However, information is not available for determining if energy cost savings are sufficient to offset possible adverse effects on stock quality and survival. Overwintering and accelerated late spring/summer growth rob the nurseryman of a valuable asset--the use of the greenhouse to

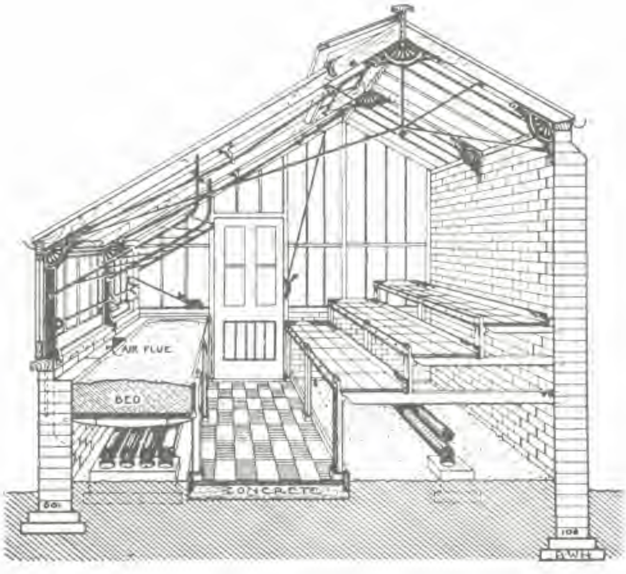

Figure 1. An energy-conserving greenhouse available as a kit from a 19th century manufacturer. Source: Clegg and Watkins 1978.

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tailor crops to the increasingly specific requirements of the field planting manager. In opposition to current trends, the winter container greenhouse may well remain a significant cultural tool. This parallels the experience of greenhouse vegetable and flower growers, who have realized that increasing the quantity and quality of products whose yields and quality are already high is accomplished by optimally fine-tuning the environment to the crop - a situation for which a greenhouse is ideally suited.

Various publications list in excess of 50 modifications applicable to container seedling greenhouses (see Appendix 1), some of which require substantial capital outlay. The problem is: where does the nurseryman start? Two risks immediately become apparent. Application of an inappropriate method (or combination of methods) may have negative effects or may simply be an investment wasted if the high cost of a modification is not offset by the fuel dollars saved over its lifetime. Every greenhouse operation differs and will require a different package of options to arrive at an optimal solution.

Methods for calculating approximate fuel requirements and the effects of a number of energy-saving strategies are available elsewhere (see Appendix 2). The intent of this presentation is to:

a) provide a perspective on the problem by examining current and projected crop cost data;

b) suggest a method by which the grower may choose among the many conservation alternatives available;

c) indicate the degree of savings that are reasonably possible; and

d) attempt to predict some future industry responses to increasing energy costs.

THE COMPUTER MODEL

As an aid in attempting to identify the important aspects of winter container growth, a computer model has been developed at the Maritimes Forest Research Centre (MFRC) to simulate a greenhouse under winter conditions.

Our objectives are to develop a combined research and consumer-oriented tool for both in-house use and distribution to outside agencies (if demand exists) to meet the following requirements:

a) the ability to predict the energy impacts of conservation alternatives applicable to containerized tree seedling greenhouses in the Maritimes and elsewhere;

b) sufficient simplicity (in a modular format for use with different greenhouse types) to run at low cost, yet with enough detail to allow minor structural and cultural details to be studied; and

c) the capability ultimately for use with a physiologically based tree seedling growth model.

Such models, though not routinely used by the forest nursery sector, are not new, and have been employed in various forms for a number of years (Takakura et al. 1971, Kimball 1973, Hallman 1974, Rotz 1977, Chandra 1979, Kindelan 1980).

The model consists of a series of conventional engineering equations which describe heat gain or loss through the various greenhouse components (cover, perimeter, side/endwalls, etc.). The mathematical analogue is run hourly, using 24-hour blocks of data, through the required portion of a computer weather file. Weather data of two types may be used: either Atmospheric Environment Service (AES) computer tape archives or output from a previously developed weather simulator (Degelman 1974). The latter format allows a greenhouse at any location to be used provided there is a weather station nearby which records mean monthly values, as opposed to AES hourly data files which are available for only a restricted number of weather stations. Although the computer language (APL) and format are substantially different, in concept the MFRC model resembles a similar program developed at the Pennsylvania State University (Rotz 1977).

Current improvements being attempted or planned are in the areas of perimeter heat loss, an improved solar radiation generator, incorporation of snowfall and wind direction, a radiant energy component in double PE (polyethylene) cover R-values, and humidity generation as a function of crop physiology.

The existing model runs specifically for single quonset and ridge-and-furrow double PE greenhouses. Future development plans include the addition of simple solar radiation models for glass and fibreglass structures, and, if demand warrants, translation into FORTRAN.

GROWING COSTS

Some winter crop costs (mid-January seeding) representative of those incurred in the Maritimes are shown in Figure 2. The sum of the six categories--fuel, container system (FH 408 paperpot), casual labor, electrical, peat and grit, and fertilizer--yields total direct growing costs of approximately $55.00 per thousand seedlings. Less direct costs--those of management salaries, equipment and structure depreciation, and nursery maintenance--would add $30 to $50 to such direct costs. Fuel oil constitutes slightly over 40% of direct growing costs, and probably represents 25% of total (direct + indirect) seedling costs at current Maritime prices. The recent Canadian oil pricing agreement will allow energy prices to rise rapidly in the coming years to approach more closely world prices. Clearly, if winter container crops are to remain a significant component of the planting schedule, there is ample incentive for energy conservation.

RANKING ALTERNATIVES

Generally, conservation methods may be weighted according to their implementation costs, which range from nil to many dollars per square metre of growing area. Fuel savings can be visualized as occurring incrementally: i.e., each time an energy-saving strategy is put in place, there is a reduction in fuel use, leaving a total to be affected by the next proposed method. Therefore, the ranking of alternatives will be on the basis of:

a) no cost
b) minimal to low cost
c) high cost, with substantial energy savings.

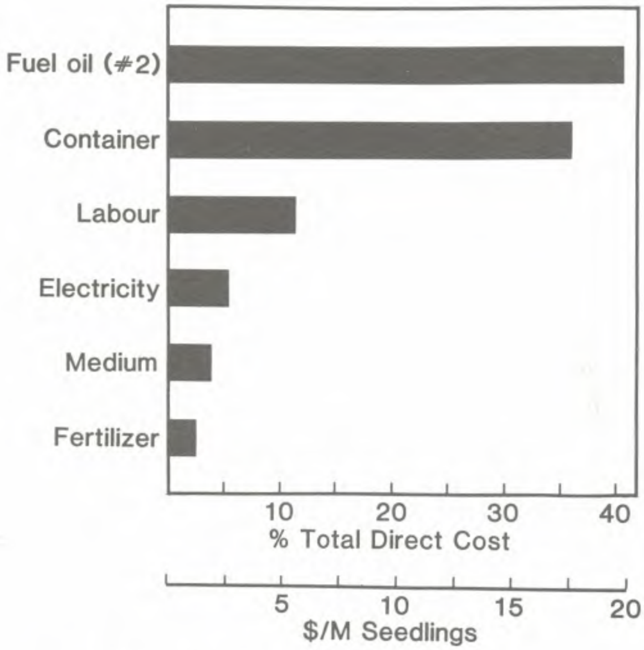

Figure 2. Representative direct winter container crop costs.

There is no simple way to order alternatives accurately within cost classes. However, as a general guideline, within a group of methods, those whose ratio of initial cost to amount of fuel saved is low are probably preferable.

A CASE EXAMPLE

The following greenhouse will serve as an illustration: a 9 x 29 m single quonset type, double-PE covered structure located in the Fredericton area (annual total of approximately 4700 18°C heating degree days). Endwalls are insulated to full height, and sidewalls to 1.22 m with R-10 to R-12[2]. A growing regime is implemented to produce a crop for early June planting. If stock is to meet size requirements, germination must commence at the end of the first week of January, although the boilers are on from 1 September to provide heat to the working area and prevent damage to pipes in the greenhouses. The heating regime can then be broken into four periods as shown in Table 1.

Table 1. A typical winter crop heating schedule.

Period	Inclusive date	Day/night temp (°C)	No. of days
Off-season	1 Sept - 6 Jan	7/7	128
Germination	7 Jan - 22 Jan	24/24	16
Growing	23 Jan - 31 Mar	21/18	68
Hardening	1 Apr - 30 Apr	4/4	30
Total	1 Sept - 30 Apr	-	242

During a typical year, this greenhouse would be predicted by the computer model to require a seasonal total of 352.1 million BTU, or, in terms of no. 2 fuel oil, 14,770 L at a service efficiency of 65%. (Service efficiency differs from combustion efficiency in that all boiler and piping losses are included.)

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[2] Refer to Appendix 3 for conversion factors.

Following the increasing-cost method previously outlined to rank the various energy conservation schemes results in a variety of options--by no means an inclusive list--which could be applied to this greenhouse. Each cost class may be further divided into structural and cultural components as is shown in Table 2.

No-cost Methods

Structural modifications are only a minor factor in an existing greenhouse, but can be applied effectively in planning a new facility. The cultural aspect of these modifications consists primarily of tailoring temperature requirements so as not to impair crop growth or quality, but to minimize energy use during the coldest periods.

The effect on energy use of varying the temperatures for each heating period throughout the model year for the Fredericton area greenhouse is shown in Tables 3 to 6.

Off-season

Heating requirements during the idle period prior to germination are substantial, as can be seen from monthly totals, only because of the length of time over which the heating system must maintain a minimal temperature to prevent freezing damage to water or heating lines.

During the off-season period, especially in early fall, boiler service efficiency, i.e., the ratio of the heat usefully delivered to where it is required to the amount of oil used at a given combustion efficiency is very low. Daytime requirements at the lower set temperatures are routinely supplied by the sun (data not shown). Even with lower boiler water temperature settings, there will be long idle periods when heat is not required, and large boiler and piping losses will result. Therefore, consideration should be given to partial or complete system draining, and boiler shutdown for at least part of the heating period.

If heat is not required for the headerhouse area, one interesting alternative, not currently in wide practice, to boiler draindown is the inclusion of ethylene glycol (antifreeze) in the heat transfer system, provided that it is compatible with the boiler used. The use of antifreeze allows shutdown well into the coldest part of the year until heating is required for snow removal.

Table 2. Ranking of some energy conservation methods according to cost.

Cost	Modification examples	
	Structural	Cultural
1. None	- few, if any, in an existing greenhouse (caulking, sealing cracks) - E-W siting, natural windbreak, choice of heating system (new complex only)	- lower off-season temperature or drain heating system - optimize germination temperatures - lower day/night temperatures - lower hardening temperatures
2. Low ($5.40/m^2)	- frequent boiler testing and tuning, retention burner head - side/endwall insulation	- supplementary CO$_2$ on time control - altered fertilization and watering with basic soil analysis (pH, salts)
3. High ($5.40-$54.00/m^2)	- thermal blanket - combined boiler insulation and stack draft damper - microprocessor control of greenhouse environment	- routine soil/plant nutrient analysis - supplementary CO$_2$ light-modulated, monitored by IR gas analysis
4. Very high (>$54.00/m^2)	- change to alternative fuels: wood, peat, solar, etc. - relocate nursery site to use waste heat	- select improved seedlots showing rapid growth - minicomputer environmental control at the plant level

Table 3. Heating requirements for the off-season period.

Date	Day/night temp. (°C) 7/7	4/4	2/2
	(BTU x 10^6)		
1 Sept - 30 Sept	2.0	1.5	1.5
1 Oct - 31 Oct	7.5	3.2	1.3
1 Nov - 30 Nov	22.1	13.6	6.8
1 Dec - 31 Dec	50.9	40.1	28.8
1 Jan - 6 Jan	9.3	7.4	5.4
1 Sept - 22 Jan	91.8	65.8	43.8

Germination

Optimal germination temperatures provide cultural benefits as well as energy savings. Temperatures too high or too low are inhibitory, and at less extreme values, necessitate the use of greatly lengthened time periods to complete emergence, especially in species such as white spruce (*Picea glauca* [Moench] Voss) which are slow to germinate (Fraser 1970, 1971).

The energy necessary for germination at different times and temperatures is indicated in Table 4. The data used are for black spruce (*Picea mariana* [Mill.] B.S.P.) (Fraser 1970, Hallett, unpubl. data[3]).

Table 4. Energy requirements for germination at different temperatures.

From 7 Jan to	Germination Day/night temp. (°C)	Days	Energy	Days[b] at 18/16 °C	19-day energy total
			(BTUx10^6)		(BTUx10^6)
16 Jan	29/29[a]	10	51.5	9	81.1
18 Jan	27/27	12	56.6	7	79.9
22 Jan	24/24	16	69.9	3	79.3
25 Jan	21/21	19	75.0	0	75.0

[a] May be inhibitory to some provenances.
[b] Additional days required to compare all germination temperatures over an equal time.

It is evident that energy requirements for germination vary greatly because of the lengthened time at lowered temperatures. However, overall heating demand corrected to the same time-base by adding growing day contributions (last two columns, Table 4) differs less, except at the lowest temperature used. Germinating at the highest non-inhibitory temperature (in this example 27 °C) would be more cost-effective than using the lowest value, as the crop would be advanced by one week in development, and total growing time would be shortened accordingly.

Growing

It has been suggested that controlled diurnal temperature fluctuation during the growing period is beneficial for growth (Pollard and Logan 1975).

The impact on energy use of different day temperatures during the growing period, with a common night temperature, is shown in Table 5.

The high and low temperature values in Table 5 are generally considered to be outside the optimal growing range for most species. Of the less extreme values, the lowest, 18 °C, represents an optimal choice. During long overcast periods in mid-winter a low day set point temperature ensures that seedling "legginess" is minimized, yet is adequately high to maintain a good photosynthetic rate (D'Aoust 1980). Further, higher daily temperatures are rapidly attained if clearing occurs.

Similar data (Table 6) can be presented to describe the effect of varying night temperatures.

Table 5. Energy requirements at different day temperatures during the growing period from 19 Jan to 31 Mar.

Day/night temp.	Seasonal energy required Day[a]	Night[b]	Total
(°C)	(BTU x 10^6)		
27/16	47.0	148.0	194.9
24/16	39.9	147.5	187.4
21/16	33.4	147.1	180.5
18/16	27.5	146.7	174.3
16/16	22.1	146.4	168.5

[a] Day is defined as the period when light outside the greenhouse exceeds 8 BTU$h^{-1}ft^{-2}$ (2500 lux).
[b] Slight differences in nightly totals are due to thermal lag effects of day temperature on ground heat losses.

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[3] R.D. Hallett, Dep. Environ., Can. For. Serv., Maritimes Forest Research Centre, Fredericton, N.B.

Table 6. Energy requirements at different night temperatures during the growing period from 19 Jan to 31 Mar.

Day/night temp.	Seasonal energy required		
	Day[a]	Night[b]	Total[b]
(°C)	(BTU x 10^6)		
18/18	27.8	163.5	191.3
18/16	27.5	146.7	174.2
18/13	27.2	130.0	157.1
18/10	26.8	113.2	140.0

[a] Day defined as in Table 5.

[b] Daily totals are slightly influenced by thermal lag in ground losses.

Lower night temperatures promote favorable shoot:root ratios (Larson 1974, Pollard and Logan 1975). Data for black spruce are lacking, although a general recommendation for temperatures as low as 10°C has been given (Armson and Sadreika 1979) and some Maritime growers have used this temperature in the past without ill effect although results are undocumented. Therefore, the more conservative estimate of 16°C given for white spruce might be applicable, though not as energy efficient.

Hardening

The spring hardening period has, because of the lateness of season, minimal impact on total fuel use. Total energy demand for the model month of April at day/night temperatures of 7/7, 4/4 and 2/2°C is 13.9, 8.3, and 4.0 million BTU, respectively. Because of its energy efficiency value and favorable effects on hardening, the lowest above-freezing temperature would be preferable.

The low-energy growing schedule

Combining the four phases in the schedule summarized in Table 7 has dramatic effects on fuel consumption.

Each period of both the typical and the energy-conserving regimes, and seasonal totals, are shown in Figure 3.

The total fueling necessary with slightly lowered temperatures is reduced to 278.5 million BTU per season, or 11,680 L of oil at 65% efficiency, a saving of 21%.

Table 7. An energy-efficient winter crop heating schedule.

Period	Inclusive date	Day/night temp (°C)	No. of days
Off-season	1 Sept - 6 Jan	2/2	128
Germination	7 Jan - 18 Jan	27/27	12
Growing	19 Jan - 31 Mar	18/16	72
Hardening	1 Apr - 30 Apr	2/2	30
Total	1 Sept - 30 Apr	-	242

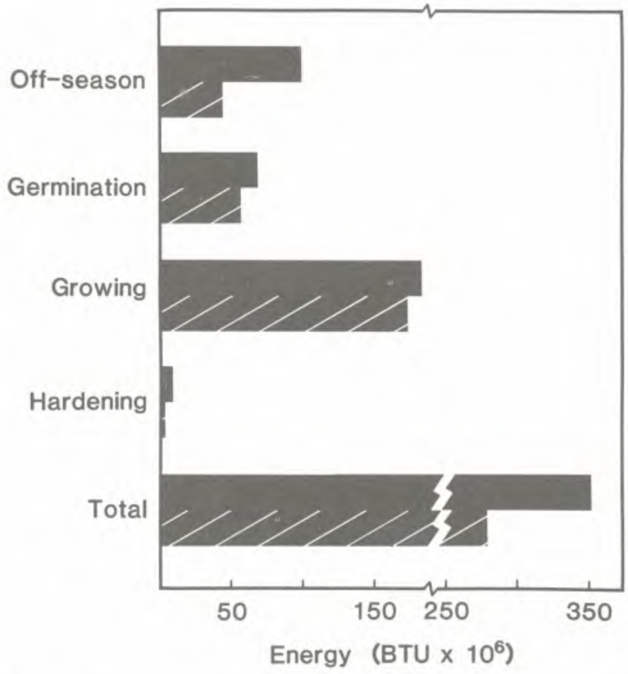

Figure 3. Comparison of the typical and energy-conserving cultural regimes for winter stock. Solid bars: typical regime; hatched bars: energy-conserving regime.

Low-cost Methods

Aside from the arbitrary capital cost limit of $5.40/m^2, low cost options as defined here also recover their initial cost in one, or at most two, growing seasons. According to Table 2 (and Appendix 1), a variety of measures of moderate cost can be implemented to lower fuel consumption, depending upon the state of existing structure and cultural conditions.

Structural modifications

One of the most important, yet often forgotten, components of the greenhouse system is the boiler and piping network. For the sake of simplicity, the current example --the Fredericton area greenhouse--is considered to be a well insulated structure containing modern boilers equipped with fuel retention nozzles providing an 85% combustion efficiency. If the boiler system is serviced twice yearly--prior to and at the end of the heating season--a drop in combustion efficiency of 5% or more is possible. Extra service calls and routine efficiency testing incur only moderate costs. If seasonal average combustion efficiency can be increased by 3-5%, fuel savings will pay for the extra service costs. For the example greenhouse, an increase in service efficiency to 70% reduces fuel requirements from 11,680 L to 10,870 L.

Cultural modification

Routine on-site soil nutrient testing is performed at most Maritime nurseries. However, the use of supplementary CO2 as a winter cultural method has yet to be exploited, although the benefits are adequately documented (Tinus and McDonald 1979). Since supplementary CO2 can cause nutrient deficiency under a standard fertilization schedule, the addition of slow-release fertilizer to the growing medium represents a moderate cost item which, in the absence of detailed nutrient analysis, would provide a safety margin. (This fertilization method used alone has been shown at Maritime nurseries to accelerate significantly the growth of winter spruce crops.) For the purpose of energy modelling, the impact of these two methods, taken either separately or in combination, can be conservatively estimated by assuming that germination can be delayed by two weeks.

Low-cost summary

As a consequence of implementing low-cost methods, the cultural schedule and energy requirements would be altered as shown in Table 8.

Structural and cultural improvements taken singly or in combination would save significant amounts of energy. As previously indicated, an increase in boiler service efficiency from 65 to 70% would reduce fuel requirements (using the 11,680 L of the energy efficient regime shown in Table 7 as the base) by 7% to 10,870 L; cultural modification alone (assuming 65% service efficiency) would reduce fuel requirements to 10,590 L, and the combination would lower fuel requirements by 16% to 9,820 L.

Table 8. The cultural regime and energy requirements resulting from low-cost modification.

Period	Inclusive date	Day/ night temp.	Days	Energy
		(°C)		($BTUx10^6$)
Off-season	1 Sept - 20 Jan	2/2	142	63.5
Germination	21 Jan - 1 Feb	27/27	12	50.9
Growing	2 Feb - 31 Mar	18/16	58	133.4
hardening	1 Apr - 30 Apr.	2/2	30	4.0
Total	1 Sept - 30 Apr	-	242	251.9

High-cost Methods

The third class of alternatives has high capital outlay, and initial cost recovery routinely requires a number of years. If funding limits the number of methods which can be implemented yearly, standard capital costing and discounting methods are used to choose among options. Straight or discounted payback is *not* sufficient to make the choice (see Capital Costing).

Structural modification

Choice of the second building modification is based on the thermal properties of a greenhouse. Using the combined low-cost regime (Table 8, 70% service efficiency), modelled heating data may be broken down according to structural component (Fig. 4).

As expected, most of the energy loss (75%) occurs through the double PE cover, and even a small improvement in the overall cover R-value, especially at night, would be of benefit. To reduce such losses, the 300-year-old technology (Hix 1974) of thermal screens or blankets drawn at night is being reintroduced. A variety of blanket materials (Fig. 5) and tracking systems are available.

Strictly from an energy conservation viewpoint (and ignoring problems such as frost accumulation and drip), the most efficient material appears to be the aluminized/ white, non-porous type, installed so that the

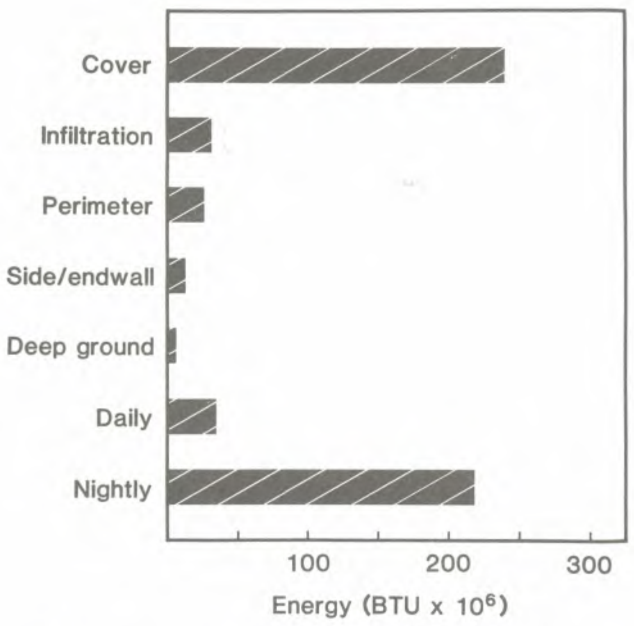

Figure 4. Energy losses through each of the major structural components, and by day and night (as defined in Table 5).

aluminized surface faces outward (Simpkins et al. 1976, Chandra and Albright 1980). If care is taken to install the system so that air leakage around the edges is minimized, considerable seasonal fuel savings in the range of 30 to 35% are possible (White 1978). The timing of blanket deployment is equally important. The model defines the day period as those hours when outside illumination (prior to interception of the double PE cover) exceeds 2500 lux because, below this level, light reaching the crop is insufficient to be usable for growth (Seginer and Albright 1980). Therefore, retracting a curtain after dawn or deploying it prior to dusk represents a reasonable compromise between crop needs and fuel reduction.

Cultural modification

Unfortunately, the energy impact of cultural alternatives in the high-cost classification is difficult to predict because our knowledge of container stock physiology is still incomplete. The "upper limit to seedling growth" (Larson 1974) has yet to be defined.

Current state-of-the-art cultural improvements centre around the optimal tailoring of the environment to the crop. Recent developments in microprocessor technology allow much more than simply the precise control of temperature and humidity. Elevated CO2 levels (measured by infrared gas analysis) modulated with venting temperature according to light intensity, variable lowering of rates (ramping) to night set temperatures whose levels can also be set according to previous day conditions, and even the modulation of nutrition by means of constant fertilization are all being practised either operationally or on an experimental basis with crops whose requirements are well defined (Mulder and Bot 1980). For container seedlings, the use of microprocessor control would necessarily be coupled, in the absence of a crop growth model, with frequent detailed soil and foliar analysis at considerable expense.

If we speculate, then, on the energy impact of growth acceleration due to a well controlled environment, a conservative estimate for the example greenhouse might have two components. First, the one month hardening period could be decreased by one week by improved cultural control. Second, the growing period might be decreased by one week by the combined influence of an improved CO2/nutritional regime.

High-cost summary

Using a thermal blanket (R2.0) coupled with the low-cost cultural regime (see Table 8) for the whole of the heating period, the model predicts a seasonal heat loss of 159.7 million BTU, a 6,230 L requirement (at 70% service efficiency). The saving--37%--is substantial, though undoubtedly an overestimate, since factors such as snowfall and imperfect curtain edge seals are not included. (If the curtain were used only during the active growing period to prolong its service life, heat loss would rise to 186.2 million BTU, consumption would increase to 7,270, and savings would diminish to 26%.)

As previously mentioned, the estimated net effect of high-cost cultural methods is to delay germination by two weeks and hardening by one week, resulting in the growing schedule shown in Table 9. This delay is only slightly less efficient than that which would result if a thermal blanket were used. The 170.4 million BTU demand is equivalent to seasonal fuel use of 6,640 L. It is notable that off-season heating under this growing regime accounts for almost one-half of the total fuel use. Boiler and piping draining, or antifreeze addition, if feasible, could reduce costs still further.

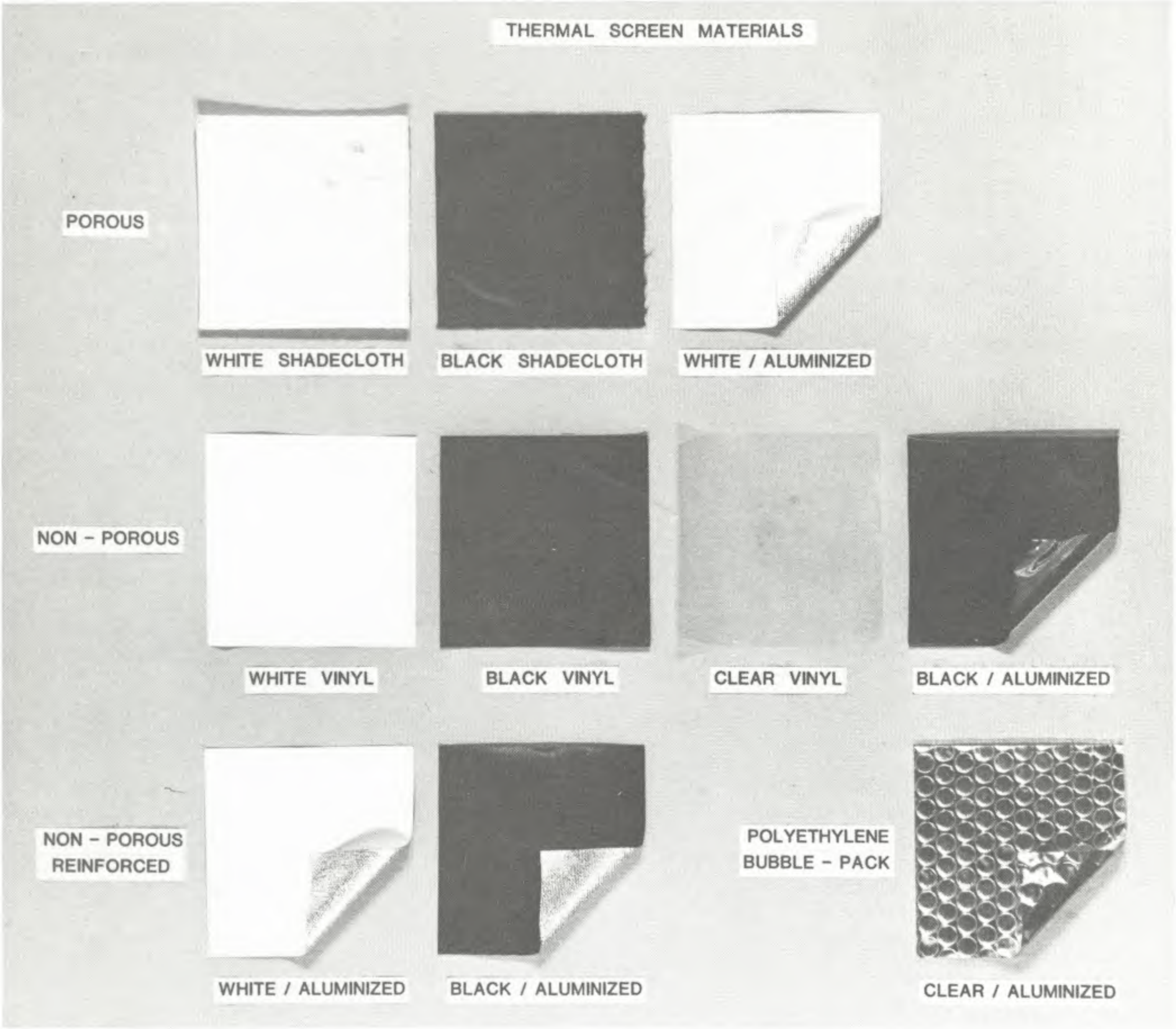

Figure 5. Some thermal screen materials used for energy conservation.

The combination of the two energy-conserving methods reduces heating use significantly. Off-season, germination, growing, hardening and total heating requirements are reduced to 45.9, 33.1, 63.8, 2.3, and 145.0 million BTU, respectively, for an annual projected fuel consumption (70% service efficiency) of 5,650 L. If we recall that the initial fuel requirement for the greenhouse with neither cultural nor structural improvements is 14,770 L, such methods are very significant.

Very High-cost Modification

Highly capital-intensive methods are not yet routinely considered viable even at current energy prices. Most of these options will not reduce fuel consumption sufficiently to justify their high cost (especially if the other methods previously described have been applied incrementally).

Where exploitable waste heat sources already exist, there is excellent potential for placement of new facilities to defray heating

Table 9. A proposed cultural regime resulting from high-cost modifications.

Period	Inclusive date	Day/ night temp	Days	Energy
		(°C)		(BTUx10⁶)
Off-season	1 Sept - 3 Feb	2/2	157	79.1
Germination	4 Feb - 15 Feb	27/27	12	51.7
Growing	16 Feb - 7 Apr	18/16	51	36.4
Hardening	8 Apr - 30 Apr	2/2	22	3.1
Total	1 Sept - 30 Apr	-	242	170.4

costs (Ball 1981), but the transfer of preexisting complexes to such sites remains questionable. Of course, should conventional energy sources cease to be readily available at any cost, either alternative fuels and/or waste heat sources have immediate value if winter growing is to continue.

Cultural methods in this cost category are not ordinarily considered for container seedling production facilities. The use of such methods requires that the crop have a high per unit value, and that increased crop costs are either passed on to the buyer, compensated by the resulting increase in product quality, or returned in some measure through crop production increases which cannot be achieved by any other method (e.g., growing a September-seeded crop under HID lighting).

Overall Heating Reduction

Each cost category outlined previously affects overall energy use, as has been demonstrated. Putting the various options together in different combinations is an important step in defining which package to use. Not every greenhouse operation will be the same as the Fredericton example. One method of indicating all the combinations is to tabulate all the options as shown in Table 10, on the assumption that they are applied in order of ascending cost.

The summary for the Fredericton example indicates that potential fuel savings can range over a very wide spectrum from a low of 7% up to 62%.

Table 10. Possible combinations of energy-saving strategies used in the Fredericton greenhouse. (It is assumed that methods are applied incrementally according to cost.)

	Structural Options[a]				
Cultural options	No change	+	Low cost	+	High cost
			(L)		
No change +	14,480 (100%)		13,730 (93%)		8,460 (57%)
No cost +	11,680 (79%)		10,870 (74%)		7,290 (49%)
Low cost +	10,590 (72%)		9,820 (66%)		6,230 (42%)
High cost	7,290[b] (49%)		6,640 (45%)		5,640 (38%)

[a] The no-cost option is omitted because of its inapplicability.

[b] This specific combination, though calculated, has not been discussed in the text.

Such ordering facilitates choosing between alternatives, and may be used either between or within cost groups. Although choosing rigorously among the no-cost and low-cost options may initially be trivial, eventually, after a series of such choices, energy costs will he reduced to a low level. Then, even low-cost methods become significant because of the length of time taken for cost recovery.

Capital Costing

As was noted previously, every greenhouse operation differs culturally, structurally, and climatically. The lack of a common starting point makes a universally applicable package of energy-conserving recommendations impractical. Further, since many energy-saving methods require high initial investment (or alternatively may never justify their expense on the basis of savings regardless of the first cost), and since in any business the supply of money is not unlimited, some measures must be chosen while others are excluded. In an attempt to apply a simple common denominator for all situations, the "payback method" is commonly--and incorrectly--used to determine which of a group of energy-reducing options is best.

Figure 6. Some different lighting systems used for photoperiodic lighting: a) static incandescent; b) mobile incandescent; c) mobile VHO fluorescent.

A discussion of the mechanics of capital costing is beyond the scope of this paper. It is a powerful tool for assessment of the real costs and profits associated with the various combinations of alternatives which comprise energy conservation packages. The use of capital costing methods allows the nurseryman to select which package is best tailored to his objectives. The spectrum of such objectives may legitimately range from lowering oil use maximally on a cost-recovery-only basis--i.e., investment sufficient to equal the oil dollars saved (applicable to a restricted energy supply situation) --to maximizing the profitability of a commercial nursery operation. A thorough treatment of capital costing is contained in many standard references such as Fleischer (1969).

ELECTRICITY: A FORGOTTEN COST

The topic of energy conservation is incomplete if electrical consumption is not considered. Winter-growing electrical costs (see Fig. 2) result primarily from the running of the heating system and the use of lighting to prevent dormancy.

Most nurseries are classed by the power utility as industrial users, and therefore are subject to a different billing calculation than the residential user. In its simplest form, the monthly bill has two components. A "peak demand" charge is levied for the highest number of kilowatt-hours (KWH) used at any one time, and a total use or "energy" charge, similar to that levied on a homeowner, is added to account for the total number of KWH used over the month.

Reduction of greenhouse heating requirements can directly influence electrical costs. The decreased demand for hot water (or steam) results in less running time for the various pumps and valves associated with the boiler and heat distribution network.

The type of supplementary lighting used (Fig. 6) may also result in widely different power consumption.

The three systems (static incandescent, mobile incandescent, and mobile fluorescent) have power requirements (including the irrigation cart motor in the latter two) of 7.7, 1.2, and 0.9 KW, respectively. If these systems are active for an average of two hours per night for the months of January through March, seasonal costs at current New Brunswick rates[4] would be approximately $60, $9, and $7, respectively, on the basis of KWH consumption alone, or $204, $32, and $24, respectively, if demand is assumed to be directly increased by their use.

FUTURE TRENDS

As was noted earlier, greenhouse energy consumption can be greatly lessened. Currently, the extent of the reduction is limited more by a lack of knowledge of seedling growth processes and quality indices than by technical restraints. However, because energy use can still be significantly cut, the large number of options available using a winter growing schedule for growth and conditioning will remain too attractive to be ignored.

In the Maritimes, current levels of winter container stock production will probably be maintained or even expanded for several reasons: first, the predicted future

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[4] 1981 rates are $6.25 per KW demand and $0.0434 per KWH.

wood shortage in some regions; second, the more intensive use of genetically superior seedlings for both seed orchards and outplanting, where a relatively small decrease in time to rotation or flowering more than compensates for the extra front-end costs; and third, the high capital and labor cost penalty incurred by not making year-round use of existing facilities.

Substantial innovation in planning for expanded production is likely in the future. Large-scale contracting-out of nursery functions will increase, where centralized companies or cooperatives, set up specifically for the purpose, will be given responsibility for providing seedlings for outplanting. The economies of scale would allow such groups to research growth and quality improvements intensively in addition to monitoring and producing stock. Also, a large operation would permit allocation of the substantial capital associated with, for instance, locating near and using waste heat sources. (Such an installation on a small scale exists already at a heavy water plant in Nova Scotia, and another demonstration unit has been proposed by the electrical utility in New Brunswick for installation near a thermal generating station.) Indeed, should energy availability, as opposed to cost, become critical to the extent that "non-essential" energy users are actively discouraged from operating, such a facility might be the only alternative available to the grower for winter-grown stock.

It appears that, even in the midst of an on-going energy crisis, current winter container culture systems are unlikely to disappear. Because large-scale containerized seedling production is a relatively recent phenomenon, the container nurseryman is at an advantage or disadvantage, depending upon one's point of view. Unlike the horticulturalist, he potentially can effect greater energy savings because there is much greater scope for cultural improvement arising from a better understanding of basic physiology. However, fuel cost and/or availability may limit the allowable time for development of optimized cultural systems. Energy conservation may just allow the grower an extended period of grace.

LITERATURE CITED

Armson, K.A. and Sadreika, V.
1979. Forest tree nursery soil management and related practices. Ont. Min. Nat. Resour., Toronto, Ont.

Ball, V.
1981. Exhaust heat-Saskatchewan-exciting! Grower Talks 44:1-13.

Chandra, P.
1979. A time-dependent analysis of thermal energy and moisture exchanges for greenhouses. Ph.D. Thesis, Cornell Univ., Ithaca, N.Y.

Chandra, P. and Albright, L.D.
1980. Analytical determination of the effect on greenhouse heating requirements of using night curtains. Trans. Am. Soc. Agric. Eng. 23:994-1000.

Clegg, P. and Watkins, D.
1978. The Complete Greenhouse Book. Garden Way, Charlotte, Vt.

D'Aoust, A.L.
1980. La physiologie des semis d'épinette noire *Picea mariana* (Mill.) B.S.P. en contenants. Dep. Environn., Serv. Can. For., Ste-Foy, Que. Inf. Rep. LAU-X-35.

Degelman, L.O.
1974. A weather simulation model for building energy analyses. Dep. Agric. Eng., Penn. State Univ., University Park, Pa.

Fleischer, G.A.
1969. Capital Allocation Theory: the Study of Investment Decisions. Appelton-Century-Crofts, New York, N.Y.

Fraser, J.W.
1970. Cardinal temperatures for germination of six provenances of black spruce seed. Dep. Environ., Can. For. Serv., Chalk River, Ont. Inf. Rep. PS-X-23.

Fraser, J.W.
1971. Cardinal temperatures for germination of six provenances of white spruce seed. Dep. Environ., Can. For. Serv., Ottawa, Ont. Publ. No. 1290.

Hallman, R.G.
1974. Cost of raising containerized trees in the United States. Part A: A computer program. p. 412-427 *in* R.W. Tinus, W.I. Stein and W.E. Balmer, *Ed.* Proc. North American Containerized Forest Tree Seedling Symposium. Great Plains Agric. Counc. Publ. 68.

Hanan, J.J., Holley, W.D., and Goldsberry, K.L.
1978. Greenhouse Management. Springer-Verlag, New York, N.Y.

Hix, J.
1974. The Glasshouse. MIT Press, Cambridge, Mass.

Kimball, B.A.
1973. Simulation of the energy balance of a greenhouse. Agric. Meteorol. 11:243-260.

Kindelan, M.
1980. Dynamic modeling of a greenhouse environment. Trans. Am. Soc. Agric. Eng. 23:1232-1239.

Larson, P.R.
1974. The upper limit of seedling growth. p. 62-76 in Tinus, R.W., Stein, W.I. and Balmer, W.E., *Ed.* Proc. North American Containerized Forest Tree Seedling Symposium. Great Plains Agric. Counc. Publ. 68.

Mulder, W.P. and Bot, G.P.A., *Ed.*
1980. Symposium on Computers in Greenhouse Climate Control. Wageningen, The Netherlands. Acta Hort. 106.

Pollard, D.F.W. and Logan, K.T.
1975. Prescriptions for the aerial environment of a plastic greenhouse nursery. p. 181-191 in Proc. 12th Great Lake States For. Tree Improvement Conf. USDA For. Serv., Gen. Tech. Rep. N6-26.

Rotz, C.A.
1977. Computer simulation to predict energy use and system costs for greenhouse environmental control. Ph.D. Thesis, Dep. Agric. Eng., Penn. State Univ., University Park, Penn.

Seginer, I. and Albright, L.D.
1980. Rational operation of greenhouse thermal—curtains. Trans. Am. Soc. Agric. Eng. 23:1240-1245.

Simpkins, J.C., Mears, D.R. and Roberts, W.J.
1976. Reducing heat losses in polyethylene covered greenhouses. Trans. Am. Soc. Agric. Eng. 19:714-719.

Takakura, T., Jordan, K.A. and Boyd, L.L.
1971. Dynamic simulation of plant growth and environment in the greenhouse. Trans. Am. Soc. Agric. Eng. 14:964-971.

Tinus, R.W. and McDonald, S.E.
1979. How to grow tree seedlings in containers in greenhouses. USDA For. Serv., Rocky Mt. For. Range Exp. Stn., Gen. Tech. Rep. RM-60.

White, J.W.
1978. Energy research program at Penn State. Penn. Flower Growers Bull. 305:1-10.

APPENDIX 1

A Checklist of Energy Conservation Measures Potentially[a] Applicable to Container Greenhouses

	Method	Cost/savings[b]	Comments
1.	Lower off-season temperatures, drain heating system, or adding antifreeze	N-M/L-M	c
2.	Germination at an optimal high temperature for the least number of days	N/L	
3.	Pregermination of seed for several days prior to sowing to shorten germination period in the greenhouse	L-H/M	d
4.	Germination in a separate well insulated heated area, lit if necessary	H/H	d
5.	Lowering day and (more importantly) night temperature set points during the growing period	N/L	e
6.	Split-night temperature regime during the growing period	N/M-H	d,f
7.	Supplementary CO_2 on timer control during the growing period	L/M	
8.	Supplementary CO_2 controlled by gas analysis (IRGA) to maintain optimally high daily concentration(s)	H/H	g,h
9.	Elementary soil analysis (salts, pH) and attention to soil moisture by weighing the containers	L/M	h
10.	Frequent soil and foliar nutrient analysis and/or constant-feed fertilization methods (requiring close soil moisture control)	H/H	h
11.	Microprocessor control of greenhouse temperature, humidity, and CO_2	H/H	h,i
12.	Minicomputer control of the greenhouse total environment at the plant level	VH/H-VH	d,h,i
13.	HID (high intensity discharge) lighting for accelerated crop growth	VH/L	j
14.	Mobile boom-mounted lighting (or other type) on a night-break regime for dormancy prevention	L/M	
15.	Ridge-and-furrow (gutter-connected) complexes as opposed to single greenhouses	H/H	k
16.	An E-W greenhouse ridgeline as opposed to a N-S aligned structure	N(?)/L	k,l
17.	Wind-sheltered site and/or carefully designed natural windbreak	N-L/L-M	k,m
18.	Artificial windbreak using posts and snowfence or 50% porous netting/shade material	L/L-M	
19.	Single or double PE over a glass or FRP (fibreglass-reinforced polyester) greenhouse	L/H	
20.	Caulking between glasshouse panes with clear compound (Lapseal)	L/M	n

APPENDIX 1 cont'd.

	Method	Cost/savings[b]	Comments
21.	Replacement of glasshouse cover with double skin or double layer materials of higher R-values	H-VH/H	
22.	Use of longer-lived (3-5 yr) types of film plastics	L/L	o
23.	Use of infrared-reflective plastic films in place of PE for a double cover	L/L-M	p
24.	Insulate side/end walls to R10-12 with moisture-insensitive insulation	L/M	q
25.	Use of rigid sheet materials for perimeter subsoil insulation	L-H/L	r
26.	Seal between the bottom of the side/endwall and the foundation or soil	N-L/L	s
27.	Seal off all unused fan-openings, louvres, and vents, and insulate the openings, if possible	L/L	s
28.	Weatherstrip/seal large access doors to shipping/holding area	L/L	s
29.	White paint or reflective foil on interior side/endwall surfaces to reflect light to the crop	L/N-L	t
30.	Reflective surface behind finned pipe	L/L	t
31.	Forced air recirculation in the greenhouse to promote growth and minimize temperature stratification	L/L-M	
32.	Raise the crop level by use of benches or elevated pallets	L/N-L	h,u
33.	Under-bench polytube heating from unit heaters lowered to floor level	L/L-M	h,v
34.	Routine check of thermostat calibration, and use of an aspirated, shaded thermostat enclosure	N/L-M	
35.	Installation of a thermal screen (blanket) with care being taken to seal all edges and gaps	H/H	w
36.	Thermal screen deployment/retraction with a photocell in place of a timer	L/L	x
37.	Use of a snow-sensor for blanket retraction during snowstorms	L/L	y
38.	Central heating (boiler) system as opposed to individually fired unit heaters	H/L-M	z
39.	Regular boiler service, frequent efficiency testing and adjustment (if required) during the growing period	L/M	aa
40.	Installation of heat-retention burner nozzles to increase combustion efficiency of older units	L/M	
41.	Lower boiler water temperature as weather moderates in spring and fall	N/L	

APPENDIX 1 cont'd.

	Method	Cost/savings[b]	Comments
42.	Additional boiler jacket insulation to prevent boiler room or headerhouse overheating		
43.	Motorized stack draft damper installation in the boiler flue	H/L-M	bb
44.	Secondary heat recovery with an air-water flue heat exchanger or similar device	H/L	
45.	Turbulator installation in heat exchanger tubes to equalize flows and aid heat transfer	L-H/L(?)	d,cc
46.	Adequate combustion air intake ducting in an enclosed boiler room	L/L-M	dd
47.	Annual inspection of all pipes, valves, and circulating pumps	N/L	
48.	Insulation of all pipes and flanges where heat is not required (including underground lines)	L/L-M	
49.	Devise (and use) a written maintenance schedule, including a checklist	N/L-H	
50.	Use of an infrared internally fired heater in conjunction with lowered air temperatures	H/M-H	d,ee
51.	Solar-assisted or alternative fuel (coal, wood, peat, propane, etc.) heating system	VH/M-H	
52.	Movable benching (roller benches) or mobile pallet systems to increase effective growing area	H/N	ff

COMMENTS

a. All these methods have been proven effective to some degree. However, some are experimental while others may not justify their initial capital or annual maintanance costs solely on the basis of the annual energy savings in a particular growing regime and/or climate.

b. These are guidelines only. N - Nil; L - Low; M - Moderate; H - High; VH - Very High

c. The necessity for replacement of corrosion and scale inhibitors will add an annual maintenance cost to boiler service if draindown is used. Boiler manufacturer should be consulted to determine system compatibility with antifreeze.

d. Experimental technique whose cultural and/or conservation effects have not been well established.

e. Temperatures are lowered only to the point at which crop growth and/or quality remain unaffected.

f. The split-night temperature technique uses a moderately high set point for a short period, followed by a much lower temperature for the remainder of the night.

g. An infrared gas analyzer coupled with a photocell measuring greenhouse light levels is used to maintain high, optimal levels of CO_2 during the day.

APPENDIX 1 cont'd.

h. Energy conserving in the sense that crop cultural conditions are optimized, resulting in a delayed seeding time to achieve equal or better crop size and/or quality.

i. Microcomputer control may have substantial effects on quality and perhaps survival, but only if there is adequate information about the physiological requirements of the species grown.

j. HID lighting is, at present, used only for special crops.

k. This option is usually restricted to the planning of new nursery sites.

l. An E-W single greenhouse has better winter light interception than a N-S greenhouse. Alignment is not as critical in gutter-connected structures.

m. Savings vary according to average windspeed, type of greenhouse cover, how tight the greenhouse is (infiltration rate), and whether a shelterbelt is maintained (pruned, trimmed) as it matures.

n. Infiltration will be reduced more in older, looser glasshouses.

o. 3- to 5-year plastics are sometimes thicker (e.g., 10 mil) and may result in unacceptable light loss. Nonetheless, buying PE (or other plastics) is still buying oil, only in a different form.

p. PE is transparent to infrared (radiant) energy, and a significant component of nightly losses can be attributed to radiation to a clear sky on cold nights.

q. Fibreglass, cellulosic and certain types of foam insulation degrade when exposed to high humidity. Use of rigid sheet materials impermeable to water vapor is recommended.

r. Initial cost is variable depending upon the amount of labor associated With installation. Sites with a high water table require vertical installation, and perhaps even drain tile below the insulation. Well drained gravelly sites may have the insulation laid horizontally just below the surface, perhaps inside the greenhouse. Savings diminish with the use of raised benches, good snowcover (which acts as an insulator) and the size of the greenhouse (perimeter:floor area ratio).

s. CO2 is depleted more quickly in a tightly sealed greenhouse. Minimal ventilation or (preferably) supplementary CO2 will be required, especially on sunny days.

t. If foil-backed building paper is used, periodic replacement will be necessary, as the surface dulls (oxidizes) in high-humidity areas.

u. Removing the crop from the floor warms the root zone.

v. Under-bench heating warms the soil, promotes air-pruning and drying.

w. Of the wide variety of thin blanket materials available, a non-porous white/aluminized material (or one with a reflecting surface on both sides) is the most thermally efficient. The aluminized surface should face the coldest region, i.e., the outside. Condensation may be a problem if the blanket cannot be sloped to allow runoff. Fabrics with an internal mesh or scrim are probably more durable. Good edge and gap sealing are imperative for maximum efficiency. Thick materials (R 6-10) are available but are difficult to deploy and store.

x. Using a photocell ensures that morning retraction and nightly deployment do not occur until light conditions based on crop needs are correct. This minimizes loss of usable light to the crop, and increases thermal screen "on-time" since the material is in place during part of the day (for a brief period both after sunrise and before sunset).

APPENDIX 1 concl'd.

y. Use of a snow sensor permits the blanket to be retracted only during and after a storm to allow melting, rather than for the whole night period when snow is expected.

z. Depending upon the size of the complex, and relative costs of different fuels. Heating efficiency is easier to maintain in a centralized system and fuel change-over costs are lower.

aa. During long periods of low heating demand, boiler on-cycles occur infrequently, resulting in soot accumulation, and decreased overall service efficiency.

bb. This unit increases service efficiency during low heating demand periods by preventing the flow of draft air up the flue when the boiler is not firing, and the resultant cooling of internal heat exchange surfaces. It is less effective during times of almost continuous firing.

cc. Although the method is not new, its effectiveness in newer boiler models has been questioned.

dd. Size of the free opening required can be obtained from the boiler manufacturer.

ee. A highly experimental system which uses low-level radiant heat to warm plant surfaces rather than the greenhouse air. Effects on soil temperature when container stock is used are not known. Could perhaps be used with soil bed heating and flats on low pallets.

ff. No energy reduction, but rather a more efficient use of space to reduce unit crop cost.

APPENDIX 2

Useful References

Manuals:

Badger, P.C. and Poole, H.A. 1979. Conserving energy in Ohio greenhouses. O.A.R.D.C. Spec. Circ. 102. Ohio Coop. Ext. Serv., Ohio State Univ., Wooster, Ohio, 44691. ($2.00)

Blom, T., Hughes, J. and Ingratta, F. 1978. Energy conservation in Ontario greenhouses. Ont. Min. Food Agric., Publ. 65.

Correll, P.G. and Pepper, J.G. 1977. Energy conservation in greenhouses. Agric. Ed. Off., Agric. Hall, Univ. Delaware, Newark, Del, 19711. ($3.75).

Poole, H.A. and Badger, P.C. 1980. Management practices to conserve energy in Ohio greenhouses. O.A.R.D.C. Spec. Circ. 104. Ohio Coop. Ext. Serv., Ohio State Univ., Wooster, Ohio, 44691. ($2.50).

Ross, D.S., Roberts, W.J., Parsons, R.A., Bartok, J.W. and Aldrich, R.A. 1979. Energy conservation and solar heating for greenhouses. Northeast Reg. Agric. Eng. Serv. Publ. NRAES-3 Ext. Agric. Eng., Univ. Conn., Storrs, Conn., 06268. ($1.50)

White, J.W. and Aldrich, J.W. 1980. Greenhouse energy conservation-Penn State 1980. Ind. Res. Innov., 225 Pond Lab., University Park, Penn., 16802. ($2.50).

Periodicals:

Connecticut Greenhouse Newsletter. Conn. Coop. Ext. Serv., Univ. Conn., Storrs, Conn., 06268.

Colorado Greenhouse Growers Assoc. Bulletin. Colorado Greenhouse Growers Assoc. Inc., 2785 N. Speer Blvd., Suite 230, Denver, Colo., 80211.

Grower Talks. Geo. J. Ball Inc., P.O. Box P800, West Chicago, Ill., 60185.

Pennsylvania Flower Growers Bulletin. Pennsylvania Flower Growers, P.O. Box 384, Bloomsburg, Penn., 17815.

APPENDIX 3

Conversion Factors

Thermal resistance (R-value):
1 h ft^2 °F BTU^{-1} = 0.17611 m^2 $°\mathrm{C}^{-1}\mathrm{W}^{-1}$

Conductance (U-value = 1/R-value):
1 BTU h^{-1} ft^{-2} $°\mathrm{F}^{-1}$ = 5.6783 W m^{-2} $°\mathrm{C}^{-1}$

Energy:
1 BTUh^{-1} = 0.2930W
1 BTU = 1.055 kJ

Electric:
1 KWh = 3,413 BTU
1 hp = 745.6 W

Boiler horsepower:
1 BHP = 33,742 BTU

Fuel:
1 gal = 4.546 L
1 gal no. 2 oil = 166,600 BTU at 100% efficiency.

Windpseed:
1 mph = 0.447 m s^{-1} = 1.609 km h^{-1}

Radiation:
1 BTU ft^{-2} = 0.01135 MJ m^{-2}