EVALUATING THE ECONOMIC FEASIBILITY OF THERMAL SCREENS IN NEW ZEALAND USING A MATHEMATICAL MODEL

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ABSTRACT

A mathematical model of the greenhouse environment was developed to ascertain the annual savings in heating expenditure achieved by thermal screens. Thirteen materials with thermal screening potential were investigated. Each material was modelled within glass, *Agphane*, and twin skin *Agphane* covered greenhouses, 300m^2 and 1000m^2 in floor area, heated with diesel, coal, electricity, natural gas, or L.P.G., to set points of 15°C and 20°C, in Auckland and Christchurch.

The model consisted of two phases. Phase 1 was a steady state model of the greenhouse environment based on a series of energy and mass balances. The temperatures within the greenhouse and the quantity of heat required to hold the house at a specified set point were predicted by solving these balances simultaneously. This process enabled the average U-value for each greenhouse to be estimated.

In Phase 2 of the model the annual heat load for combinations of each house size and type, cover, screen, set point, and location were estimated using average U-values from Phase 1 and meterological data indicative of Auckland and Christchurch. Using current fuel prices, annual heat loads were converted into annual heating expenditures.

Using annual heating expenditure, screen life expectancy, and screen installation cost an economic analysis was conducted using internal rate of return as a measure of thermal screen feasibility.

In terms of savings in heating expenditure, Black Polythene, *Infrane*, and Clear Polythene recorded the highest internal rate of return. It was decided that before a formal recommendation could be made further research was required to evaluate screens as summer shading or photoperiod control devices and to consider the practical problems associated with some of the screens.

It was shown that returns from thermal screening were greater in Christchurch than Auckland, greater at a 20°C set point than at a 15°C set point, greater for a 1000m^2 house than a 300m^2 house, greatest with diesel heating in Auckland, and greatest with diesel and L.P.G. heating in Christchurch.

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LIST OF FREQUENTLY USED SYMBOLS

A	advective heat transfer (Wm^{-2})
Al	aluminium
AUX	auxiliary heating or cooling (Wm^{-2}floor)
C	cloud fraction, conductive heat flux density (Wm^{-2})
$^{\circ}$C	degrees Celsius
CAI	cover area index
Cp	specific heat capacity of dry air at 20°C (1.01Jg$_{DA}^{-1}$ $^{\circ}$C^{-1})
D	diffusive heat transfer (Wm^{-2})
e	water vapour pressure (Pa)
E	energy of one photon (J), evaporative heat transfer coefficient (Wm^{-2} $^{\circ}$K^{-1})
Eb	total emissive power of a blackbody (Wm^{-2})
EMF	evaporative cooling, misting, or fogging (g$_v$s^{-1}m^{-2})
EVA	ethylene vinyl acetate
ERR	external rate of return (%)
f	frequency (s^{-1})
F	FIR
FIR	far infra-red radiation
g	gram
h	convective heat transfer coefficient (Wm^{-2} $^{\circ}$K^{-1}), Plank's constant (6.63 × 10^{-34} Js^{-1})
H	rate of heat loss (Wm^{-2}), solar radiation (MJm^{-2}day^{-1}), convective heat flux density (Wm^{-2})
$\mathcal{H}$	enthalpy of moist air (Jg$_{DA}^{-1}$)
IR	infra-red (long wave) radiation
IRR	internal rate of return (%)
J	joule
k	thermal conductivity (Wm^{-1} $^{\circ}$K^{-1})
K	thermal conductance (Wm^{-2} $^{\circ}$K^{-1})
$^{\circ}$K	degrees Kelvin
$\mathcal{L}$	latent heat of vaporization of water at 20°C (2454Jg$_v^{-1}$)
L	latent heat loss (Wm^{-2})
LAI	leaf area index
m	metre
mm	millimetre
M	molecular mass (gmol^{-1}), mass transfer (g$_v$s^{-1}m^{-2})

N	NIR, number of air changes per second (s^{-1})
NIR	near infra-red radiation
ø	permeance ($g_v s^{-1} m^{-2} Pa^{-1}$)
P	PAR
PAR	photosynthetically active radiation
PE	polyethylene
PVC	polyvinyl chloride
q	conductive heat flux density (Wm^{-2})
r	resistance (sm^{-1})
R	Universal gas constant ($8.314 Jmol^{-1} {}^{\circ}K^{-1}$)
s	second
S	solar radiation (Wm^{-2})
T	temperature
U	overall heat loss coefficient, thermal transmittance, U-value ($Wm^{-2}floor^{\circ}C^{-1}$ or $Wm^{-2}floor^{\circ}K^{-1}$)
UV	ultra-violet
v	velocity of light in a vacuum (3×10^{6} ms^{-1})
V	greenhouse volume (m^{-3})
VA	vinyl acetate
W	watt
x	direction of heat flow (m)
Z	water vapour flux density ($g_v s^{-1} m^{-2}$)

GREEK ALPHABET

α	absorptivity
ϵ	emissivity
γ	slope of enthalpy lines on the psychometric chart ($Pa^{\circ}K^{-1}$)
δ	slope of the saturated vapour pressure curve ($Pa^{\circ}K^{-1}$)
Θ	equivalent temperature ($^{\circ}C$)
λ	wavelength (m)
μm	micrometre
ρ	reflectivity, density of gas (gm^{-3})
σ	Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2\circ}K^{-4}$)
τ	transmissivity
Φ	advective heat transfer coefficient ($Wm^{-2} {}^{\circ}K^{-1}$)

χ	water vapour density or absolute humidity ($g_v m_{DA}^{-3}$)
ω	humidity ratio ($g_v g_{DA}^{-1}$)
Ω	diffusive heat transfer coefficient ($Wm^{-2}\,{}^{\circ}K^{-1}$)

SUBSCRIPTS

a	inside air
c	cover
DA	dry air
f	floor
F	FIR
i	inside air
l	lower surface of thermal screen
N	NIR
o	outside air
p	plant
P	PAR
q	quiescent airspace
s	thermal screen
sky	sky
s1	soil layer 1
s2	soil layer 2
s3	soil layer 3
s4	soil layer 4
v	water vapour
vap	water vapour
u	upper surface of thermal screen
w	wet bulb

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

A greenhouse is a structure designed to facilitate the control or modification of environmental factors affecting plant growth. By controlling the environment, variations and hazards associated with weather are eliminated. Temperature, humidity, day length, gas composition (carbon dioxide and oxygen), and light can be regulated with varying degrees of precision; damage from wind and rain is avoided; and injury from plant diseases and insects is reduced. Growing media, moisture content, nutrition, and fertility levels can also be adjusted to meet plant requirements. Consequently crops can be produced for specific market dates; grown more rapidly with greater uniformity, and yield a product with less variation in quality.

Compared to field production, greenhouse crop culture is characterised by high capital, labour and fuel costs. The cost of erecting a manually controlled plastic covered house was around 40-55 $\$/m^2$ in 1990; the cost for a glass covered house was around 80-100 $\$/m^2$ (Faber, 1990; Tailor, 1990; Williams, 1990; and Young, 1990). To offset capital cost of this magnitude, efficient and intensive year round production are important management strategies.

As heating is a major component of greenhouse management (Burit et al, 1978), intensive production effectuates a high heating cost. It follows that price premiums arising from superior quality and timing production to coincide with the short or non-existent supplies from field sources, are intrinsic when justifying greenhouse heating cost (Breuer, 1985a).

Fuel cost in New Zealand stands out as the one economic factor which is expected to escalate at a rate higher than inflation (Breuer 1985a). The price of oil based fuels fluctuate depending on political action in oil producing countries. Recent events in the Middle East have caused the price of petrol in New Zealand to increase by about 20%. By improving both energy efficiency and independence, New Zealand's greenhouse industry will become increasingly cost competitive and more able to withstand shortfalls or discontinuity in energy supply.

Modern glass or plastic covered houses have been designed for maximum light transmission without particular regard for heat conservation. They are usually leaky structures, having thin walls with high U-value (overall heat loss). As a result they tend to be expensive to heat especially in windy conditions (Hurd and Sheard, 1981).

Measures which reduce the heating requirement of a greenhouse include:

a) Self-evident measures: The grower may delay planting or lower the heating set point of the greenhouse. Such measures however may cause reduced and later yields (Hurd and Sheard, 1981). Other options include converting to a more economic heating system, insulating heating pipe work, checking thermostats regularly for proper operation, using reflectors behind pipe work, regularly checking flue gas temperature and carbon dioxide to maintain combustion efficiency, and constant monitoring of temperature levels (Hurd and Sheard, 1981; and Winspear, 1978).

b) Greenhouse shape: Since heat loss is directly proportional to surface area, greenhouse geometry has a marked affect on heat loss. Small houses and houses rectangular in plan have relatively large surface to plan area ratios. Large houses domical in shape minimize heat loss. Paraboloid is the next best shape followed by square (Burit et al, 1978).

c) Shelter: The rate of heat loss from a glasshouse is given by:

$$H - U(T_i - T_o)$$

where H = rate of heat loss (Wm^{-2})

U = the overall heat loss coefficient for the glasshouse ($Wm^{-2}\,^{\circ}C^{-1}$)

T_i = air temperature inside the glasshouse ($^{\circ}C$)

T_o = air temperature outside the glasshouse ($^{\circ}C$)

(Burit et al, 1978)

Sheard (1978) investigated the effects of wind on greenhouse heat loss and came up with the following U-value relationships:

Glasshouses	$U - 4.04 + 0.65W$
Single skin plastic	$U - 4.76 + 0.52W$
Inflated two skin plastic	$U - 4.06 + 0.25W$

where W = wind speed (ms^{-1})

It follows that the heat loss of an exposed greenhouse is reduced be installing suitable windbreaks.

d) Alternative or renewable heat sources: Solar storage, geothermal energy sources, and waste heat recovery are possible approaches for achieving resilience to conventional fuel pricing and availability (Breuer 1985a).

Internationally, solar heat storage has been shown to reduce annual energy consumption by 5-20% (Breuer, 1985a). Bellamy and Ward (1984) examined the application of solar storage to New Zealand greenhouses and concluded that an attractive option was solar storage coupled with heat pumps.

Geothermal energy is a New Zealand resource which is well suited to greenhouse heating (Breuer 1985a). In general most geothermal bores produce water at 90-150°C. Although its use has been long-standing for water and space heating in the Taupo-Rotorua region, geothermal energy is now used to heat a number of commercial greenhouses in this region.

The use of recovered waste heat is an economic heating method. Many industries recover heat for internal re-use, but cannot easily accommodate an ancillary industry. Power generation stations however, provide an ideal host since land is often available in their buffer zone. More than half of the energy generated by a thermal power station is rejected as low grade heat in the condenser cooling water. Internationally most stations have large flows of cooling water available at temperatures from 22-80°C. In this country cooling water seldom exceeds ambient by 15°C. This combined with our mild climate highlights technical and economic shortcomings (Breuer, 1985a).

e) **Increasing thermal resistance:** Increasing the thermal resistance of a greenhouse reduces heat loss. The resistance must be increased in a controlled manner so that transmission of solar radiation is not impeded (White, 1980). Increased thermal resistance is achieved by reducing air leakage, layering the cladding, or installing a thermal screen.

Air leakage is a significant heat loss mechanisms in New Zealand greenhouses. Air leakage rates as high as 4 air changes per hour are not atypical (Breuer, 1985a). Up to 12% of the total heat loss may arise from air leakage (Burit et al, 1978). Mending torn plastic, erecting wind breaks, sealing glass laps with transparent adhesive sealing compounds, and restricting leakage around loose fitting doors and vents, are management strategies for reducing air leakage. Fuel saving from lap sealing alone range from 5% to 30%, depending on the original condition of the roof (Breuer, 1985a).

The use of twin covering materials offer energy savings of up to 40% (White, 1980; Winspear, 1978). Benefits are often offset by the loss in revenue from delayed or reduced cropping caused by light loss (Winspear, 1978). With the exception of shade-loving ornamental plants the benefits of twin-skinning are often not justified (White, 1980). Tests in New Zealand (Levin) show a 15% reduction in annual fuel consumption with minimal effects on greenhouse lighting and yields when a clear polyethylene sheet is attached to the interior end and side walls of a greenhouse. Attaching clear polyethylene to the ceiling gives a 24% reduction in annual heating but a 10% light transmission reduction (Breuer, 1985b).

The thermal screen; also known as thermal curtain, night curtain, thermal blanket or internal blind, is a relatively new technology aimed at increasing the thermal resistance of a greenhouse. The screen system consists of a flexible material constructed and supported so that it completely encloses the crop and heating system at night. The thermal screen is movable to enable storage during the day. The thermal effectiveness of a screen is related to the type of greenhouse used, the screen material, outside weather conditions, the way it is mechanised, the ratio of covered crop volume to unheated above screen volume, and the air tightness of the screen (Breuer, 1985b).

As 70-80% of the total heat loss occures at night, more is gained by insulating at night (Breuer, 1985b).

1.2 STATEMENT OF THE PROBLEM

Nocturnal heat loss is a problem facing many greenhouse growers. Although thermal screens are an accepted panacea in Europe, the United States, and Japan (Breuer, 1985b), their use has met much grower scepticism in New Zealand. As a rule New Zealand growers are reluctant to change from traditional practice until they have clear evidence of improved returns. Many continue to use relatively inefficient heating systems as they are not convinced the returns from thermal screens justify their installation. Unfortunately the environmental and economic conditions faced here prevent the application of overseas findings. At present thermal screen research in this country is sparse. As a result controversy over their economic effectiveness and the severity of their drawbacks limits widespread adoption. Under such conditions of uncertainty growers choose to minimise risk through inaction.

In short, as growers can not afford to experiment with new technologies, the heat saving potential of thermal screens in New Zealand will continue unnoticed unless research by a recognised institution for New Zealand conditions eventuates.

Conducting a real-life investigation of thermal screens in an actual greenhouse is both costly and time consuming. By modelling the greenhouse environment mathematically a large number of greenhouse, screen, and climate combinations can be simulated and evaluated without fitting screens to a actual greenhouses and running numerous trials. With this in mind a research programme was proposed aimed at developing a mathematical model to investigate the economic feasibility of thermal screens in New Zealand.

1.3 SCOPE OF THE STUDY

The economic feasibility of sixty two greenhouse and thermal screen combinations were assessed by performing an internal rate of return (IRR) analysis on thirteen materials with thermal screen potential within four different greenhouses. The greenhouses investigated were:

1. A small glasshouse (300m^2)
2. A large glasshouse (1000m^2)
3. A large single skin *Agphane* house (1000m^2)
4. A large double skin *Agphane* house (1000m^2)

Agphane is an ethylene vinyl acetate (EVA) film. In New Zealand EVA films are commonly used to cover greenhouses. In this study *Agphane* was assumed to be representative of EVA materials in general.

The screen materials investigated were:

1. ***LS 13***
2. ***LS 15*** (narrow strips of polyester and aluminised
3. ***LS 18*** polyester sewn together in varying ratios)
4. ***LS 18F***
5. ***Marix*** (spun bonded polyester fabric)
6. **Clear Polythene** (125µm)
7. **Black Polythene** (125µm)
8. ***Infrane X 30*** (a 80µm single layer extrusion of infra-red absorbing Polythene, commonly known as *Infrane*)
9. ***Infrasol*** (a 150µm three layer co-extrusion of infra-red absorbing Polythene, containing antifogging agents, antistatic additives, and ultra-violet stabilizers)
10. ***Durafilm*** (a 150µm EVA containing slip additives, condensation inhibitors, and a HALS ultra-violet stabilizer)
11. ***Duratherm*** (a 150µm EVA containing a CIL antifog agent)
12. ***Hyerlyte*** (400µm, Polyvinyl chloride)
13. ***Agphane*** (150µm EVA)

Each combination was analysed for Auckland and Christchurch climates, since the majority of greenhouses are in this region, at heating set points of 15°C and 20°C. Economic analysis was based solely on the fuel savings achieved when diesel, electricity, coal, natural gas and L.P.G. were used as heating fuels. The analysis did not make allowance for the value thermal screens have as shade cloth or photoperiod control. Nor did it penalise combinations based on practical problems associated with humidity buildup beneath impermeable screens.

Screen life expectancy was taken from manufacturers' data. It was assumed that the strength and durability of the material and its support system enabled it to fulfil its role throughout this period.