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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, 300m² and 1000m² 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 meteorological 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 1000m² house than a 300m² house, greatest with diesel heating in Auckland, and greatest with diesel and L.P.G. heating in Christchurch.

TABLE OF CONTENTS

	PAGE
TABLE OF CONTENTS	i
LIST OF FIGURES	vi
LIST OF TABLES	viii
LIST OF PLATES	xi
LIST OF FREQUENTLY USED SYMBOLS	xii
ACKNOWLEDGEMENTS	xv
I INTRODUCTION.....	1
1.1 BACKGROUND	1
1.2 STATEMENT OF THE PROBLEM	5
1.3 SCOPE OF THE STUDY	6
II LITERATURE REVIEW.....	9
2.1 HEAT MOVEMENT IN GREENHOUSES	10
2.2 SCREENING MATERIALS	14
2.2.1 Polyethylene	14
2.2.2 Polypropylene	15
2.2.3 Polyester	15
2.2.4 Acrylic	15
2.2.5 Ethylene Vinyl Acetate	16
2.2.6 Polyvinyl Chloride	16
2.2.7 Aluminium	16
2.3 MATERIAL CONSTRUCTION	17
2.3.1 Film	18
2.3.2 Fibre	18
2.3.2.1 Woven fabric	18
2.3.2.2 Non-woven fabric	18
2.3.2.3 Knitted fabric	19
2.4 SCREEN PROPERTIES	19
2.4.1 Flexibility	19

2.4.2	Durability and Life Expectancy	21
2.4.3	Long wave transmission	24
2.4.4	Permeability	27
2.5	OPERATION	28
2.5.1	Towing and Support	28
2.5.2	Control	32
2.6	EFFECTS IMPOSED BY THERMAL SCREENS	33
2.6.1	Light transmission and shading	34
2.6.2	Leaf temperature	35
2.6.3	Humidity and Condensation	36
2.6.4	Wind Speed and Heat Loss	37
2.6.5	Indirect Effects	39
2.7	ECONOMICS OF THERMAL SCREENS	40
2.8	REVIEW OF GREENHOUSE MODELS	41
2.8.1	Black-Box Models	42
2.8.2	Steady-State Single Component Models	43
2.8.3	Steady-State Multiple Component Models	44
2.8.4	Dynamic Models	46
2.8.5	Models Including Carbon Dioxide	48
2.9	CONCLUSIONS	49
III	OBJECTIVES	52
IV	THE MODEL	53
4.1	THE PHASE 1 MODEL	54
4.1.1	Phase 1 Equations for the Standard Greenhouse	62
4.1.1.1	Greenhouse cover energy balance	63
4.1.1.2	Plant energy balance	63
4.1.1.3	Floor energy balance	64
4.1.1.4	Soil layer 1 energy balance	65
4.1.1.5	Soil layer 2 energy balance	65
4.1.1.6	Soil layer 3 energy balance	66
4.1.1.7	Soil layer 4 energy balance	66
4.1.1.8	Inside airspace energy balance	67
4.1.1.9	Inside airspace mass balance	68
4.1.2	Phase 1 Equations for the Screened Greenhouse	69
4.1.2.1	Greenhouse cover energy balance	69

4.1.2.2	Thermal screen energy balance	70
4.1.2.3	Plant energy balance	71
4.1.2.4	Floor energy balance	72
4.1.2.5	Soil layer 1 energy balance	73
4.1.2.6	Soil layer 2 energy balance	73
4.1.2.7	Soil layer 3 energy balance	73
4.1.2.8	Soil layer 4 energy balance	73
4.1.2.9	Quiescent airspace energy balance	73
4.1.2.10	Greenhouse airspace energy balance	74
4.1.2.11	Quiescent airspace mass balance	76
4.1.2.12	Greenhouse airspace mass balance	77
4.2	THE PHASE 2 MODEL	78
4.2.1	Estimating the Overall Energy Need	78
4.2.1.1	Estimating the day and night-time temperature distribution	78
4.2.1.2	Estimating night-time energy need	80
4.2.1.3	Estimating daytime energy need	82
4.2.2	Estimating the Solar Contribution	83
4.2.2.1	Solar energy collected	83
4.2.2.2	Useful solar energy	84
4.2.3	Auxiliary Heating Loads	89
4.3	ECONOMIC ANALYSIS	90
4.3.1	Screen and Fuel Costs	92
4.3.2	Fuel Use and Cost Calculations	93
4.3.2.1	Diesel	93
4.3.2.2	Coal	94
4.3.2.3	Electricity	94
4.3.2.4	Natural gas	94
4.3.2.5	L.P.G.	94
V	RESULTS AND OBSERVATIONS	96
5.1	PHASE 1 RESULTS	96
5.2	PHASE 2 RESULTS	98
5.2.1	Annual Heating Loads	98
5.2.2	Fuel Usage and Cost	102
5.2.2.1	Diesel	102
5.2.2.2	Coal	103

5.2.2.3	Electricity	103
5.2.2.4	Natural gas	104
5.2.2.5	L.P.G.	104
5.2.3	Internal Rates of Return	115
VI	DISCUSSION	130
6.1	SCREEN TYPE	134
6.2	SECONDARY ISSUES	137
6.2.1	Cover Type	137
6.2.2	Greenhouse Size	138
6.2.3	Set Point	138
6.2.4	Location	138
6.2.5	Fuel Type	139
VII	SUMMARY AND CONCLUSIONS.....	140
VIII	RECOMMENDATIONS FOR FUTURE RESEARCH.....	143
	REFERENCES	144
	APPENDICES	156
	APPENDIX 1: HEAT TRANSFER	156
A1.1	Conduction	156
A1.2	Convection	157
A1.3	Radiation	161
	APPENDIX 2: RADIATION SOURCES	168
A2.1	Atmospheric Transmission of Solar Radiation	169
A2.2	Solar Transmission at the Ground	170
A2.3	Effects of Clouds	171
A2.4	Radiation from the Atmosphere	171
A2.5	Terrestrial Radiation	173
	APPENDIX 3: PHASE 1 DERIVATIONS	174
A3.1	Cover Energy Balance	174
A3.2	The Plant Energy Balance	190
A3.3	The Floor Energy Balance	192
A3.4	Soil Layer 1 Energy Balance	192

A3.5	Soil Layer 2 Energy Balance	193
A3.6	Soil Layer 3 Energy Balance	193
A3.7	Soil Layer 4 Energy Balance	193
A3.8	Inside Airspace Energy Balance	194
A3.9	Inside Airspace Mass Balance	203
APPENDIX 4:	PHASE 1 INPUTS	207
A4.1	Parameters	207
A4.2	Independent Variables	223
APPENDIX 5:	CALCULATED VALUES	224
A5.1	Convective Heat Transfer Coefficients	224
A5.2	Advective Heat Transfer Coefficients	224
A5.3	Evaporative Heat Transfer Coefficients	224
A5.4	Permeance	226
APPENDIX 6:	LONG WAVE TEST	227

LIST OF FIGURES

FIGURE	PAGE
2.1 Heat transfers of a screenless greenhouse at night	12
2.2 Heat transfers of a screened greenhouse at night	13
2.3 Strip structure of an aluminised polyester Ludvig Svensson screen (Ludvig Svensson International, 1989).	17
2.4 Tomato yields across a screened and unscreened house (Hurd and Sheard, 1981).	20
2.5 A track type thermal screen with side and end curtains (Badger and Poole, 1979).	29
2.6 Curtain system for a clear span greenhouse (Breuer, 1985a)	31
2.7 Details of the mechanical system (Mayer, 1981)	31
2.8a PAR transmission of a multi-span glasshouse (Bailey, 1981b)	35
2.8b PAR transmission of a single span glasshouse (Bailey, 1981b)	35
2.9 Influence of glass temperature on the dew point of glasshouse air (Bailey and Cotton, 1977)	37
2.10 Heat loss coefficient (U-value) of glasshouses at night (Bailey, 1979b)	38
4.1 Simplified representation of the standard greenhouse	56
4.2 Simplified representation of the screened greenhouse	56
4.3 Three cover shapes with a CAI of 1.6	57
4.4 A system with a LAI of 2.1	59
4.5 Variation in the stored energy as a function of collected solar energy in a tomato crop (Jolliet, 1988)	86
4.6 Daytime utilisation factor (UF^d) as a function of daytime GLR (Jolliet, 1988)	89
A1.1 Spectrum of electromagnetic radiation (Incropera and DeWitt, 1985).	163
A1.2 Spectral blackbody emissive power (Incropera and DeWitt, 1985) .	164
A1.3 Absorption, reflection, and transmission of radiation for a translucent medium	166
A2.1 Directional natural of solar radiation outside the atmosphere (Incropera and DeWitt, 1985)	168
A2.2a Estimated atmospheric emission downward at the earth's surface and ground emission upwards (Monteith and Unsworth, 1990) . . .	170

A2.2b	IR transmission of the earth's atmosphere (Monteith and Unsworth, 1990)	170
A3.1	1st order PAR absorption by the cover	175
A3.2	2nd order PAR absorption by the cover	175
A3.3	3rd order PAR absorption by the cover	176
A3.4	Diagrammatic representation of equation A3.2a	179
A3.5	Diagrammatic representation of equation A3.2b	180
A3.6	Diagrammatic representation of equation A3.2c	181
A3.7	Diagrammatic representation of equation A3.2d	182
A3.8	Penman-Monteith transformation I	188
A3.9	Equivalent Temperature	196
A3.10	Penman-Monteith Transformation II	200
A6.1	Radiative heat exchanges for the measurements of reflectivity and transmissivity	228
A6.2	Radiative heat exchanges for measurement of emissivity	228
A6.3	Equipment for measuring transmissivity and reflectivity of screen materials	232
A6.4	Equipment for emissivity measurement	233

LIST OF TABLES

TABLE	PAGE
2.1 Economic life in years of selected thermal screen materials (Meinders et al, 1984)	23
2.2 Effect of abrasion on emissivity of aluminised screen materials (Bailey, 1981a).	24
2.3 Long wave properties of selected screen and cover materials	26
2.4 Reported fuel savings by thermal screens	33
2.5 U-values for common greenhouse coverings (Breuer, 1985a)	38
2.6 Percentage reduction in U-value by thermal screening	39
4.1a Dependent variables for the standard greenhouse	60
4.1b Dependent variables for the screened greenhouse	60
4.2a T_x , T_m , and solar radiation (H) for Christchurch (from NZMS, 1980).	79
4.2b T_x , T_m , and solar radiation (H) for Auckland (from NZMS, 1980).	79
4.3 Economic life, screen cost, and complete cost (screen material + labour + fittings + hardware) in 1990 dollars	92
4.4 Fuels: cost (in 1990 dollars), calorific value and efficiency in 1990	93
5.1 Average U-values in $Wm^{-2}floor^{-1}K^{-1}$ for screen and cover combinations	97
5.2a Annual auxiliary heating loads for Auckland in $MJm^{-2}floor$	100
5.2b Annual auxiliary heating loads for Christchurch in $MJm^{-2}floor$. . .	101
5.3a Diesel usage (in l/m^2) and cost (in $\$/m^2$) for screened and non- screened greenhouses in Auckland at set points of $15^\circ C$ and $20^\circ C$	107
5.3b Coal usage (in kg/m^2) and cost (in $\$/m^2$) for screened and non- screened greenhouses in Auckland at set points of $15^\circ C$ and $20^\circ C$	108
5.3c Electricity cost (in $\$/m^2$) for screened and non-screened greenhouses in Auckland at set points of $15^\circ C$ and $20^\circ C$	109
5.3d Natural gas cost (in $\$/m^2$) for screened and non-screened greenhouses in Auckland at set points of $15^\circ C$ and $20^\circ C$	110
5.4a Diesel usage (in l/m^2) and cost (in $\$/m^2$) for screened and non- screened greenhouses in Christchurch at set points of $15^\circ C$ and	

	20 °C	111
5.4b	Coal usage (in kg/m ²) and cost (in \$/m ²) for screened and non-screened greenhouses in Christchurch at set points of 15 °C and 20 °C	112
5.4c	Electricity cost (in \$/m ²) for screened and non-screened greenhouses in Christchurch at set points of 15 °C and 20 °C	113
5.4d	L.P.G. usage (in kg/m ²) and cost (in \$/m ²) for screened and non-screened greenhouses in Christchurch at set points of 15 °C and 20 °C	114
5.5a	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for diesel heating, at T _a =15 °C	117
5.5b	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for coal heating, at T _a =15 °C	118
5.5c	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for electrical heating, at T _a =15 °C	119
5.5d	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for natural gas heating, at T _a =15 °C	120
5.6a	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for diesel heating, at T _a =20 °C	121
5.6b	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for coal heating, at T _a =20 °C	122
5.6c	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for electrical heating, at T _a =20 °C	123
5.6d	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Auckland, for natural gas heating, at T _a =20 °C	124
5.7a	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Christchurch, for diesel heating, at T _a =15 °C	125
5.7b	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Christchurch, for coal heating, at T _a =15 °C	126
5.7c	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Christchurch, for electrical heating, at T _a =15 °C	127
5.7d	AHC, AS, and IRR of 300m ² and 1000m ² screened greenhouse in Christchurch, for L.P.G. heating, at T _a =15 °C	128
6.1a	Investment feasibility of thermal screens in Auckland at 15 °C . . .	131
6.1b	Investment feasibility of thermal screens in Auckland at 20 °C . . .	132
6.1c	Investment feasibility of thermal screens in Christchurch at 15 °C .	133
A4.1a	PAR absorptivity	208

A4.1b	PAR transmissivity	209
A4.1c	PAR reflectivity	210
A4.2a	NIR absorptivity	212
A4.2b	NIR transmissivity	213
A4.2c	NIR reflectivity	214
A4.3a	FIR absorptivity	216
A4.3b	FIR transmissivity	217
A4.3c	FIR reflectivity	218
A4.4	Convective heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$	219
A4.5	Advective heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$ and symbolised Φ_{a_0} for advective heat transfer through standard greenhouse covers	219
A4.6a	Advective heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$ and symbolised Φ_{q_0} for advective heat transfer through screened greenhouse covers (with the screen in its drawn position)	219
A4.6b	Advective heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$ and symbolised Φ_{a_q} for advective heat transfer through thermal screens	220
A4.7	Evaporative heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$	220
A4.8	Conductive heat transfer coefficients in $\text{Wm}^{-2}\text{K}^{-1}$	220
A4.9	Permeance figures for cover and screen materials in $\text{g}_{\text{vap}}\text{s}^{-1}\text{m}^{-2}\text{Pa}^{-1}$ (symbolised ϕ)	221
A4.10	Phase 1 constants	222
A4.11	Known variables of Phase 1	223

LIST OF PLATES

PLATE		PAGE
2.1	Three aluminised polyester materials. From left to right: <i>LS 13</i> , <i>LS 15</i> , and <i>LS 18</i>	22
2.2	Aluminised Ludvig Svensson screen in parked position	22
2.3	Reversible electric motor, torque tube, and cable support system .	30

LIST OF FREQUENTLY USED SYMBOLS

A	advective heat transfer (Wm^{-2})
Al	aluminium
AUX	auxiliary heating or cooling ($\text{Wm}^{-2}\text{floor}$)
C	cloud fraction, conductive heat flux density (Wm^{-2})
$^{\circ}\text{C}$	degrees Celsius
CAI	cover area index
C_p	specific heat capacity of dry air at 20°C ($1.01\text{Jg}_{\text{DA}}^{-1}\text{C}^{-1}$)
D	diffusive heat transfer (Wm^{-2})
e	water vapour pressure (Pa)
E	energy of one photon (J), evaporative heat transfer coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)
E_b	total emissive power of a blackbody (Wm^{-2})
EMF	evaporative cooling, misting, or fogging ($\text{g},\text{s}^{-1}\text{m}^{-2}$)
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 ($\text{Wm}^{-2}\text{K}^{-1}$), Plank's constant ($6.63 \times 10^{-34}\text{Js}^{-1}$)
H	rate of heat loss (Wm^{-2}), solar radiation ($\text{MJm}^{-2}\text{day}^{-1}$), convective heat flux density (Wm^{-2})
\mathcal{H}	enthalpy of moist air ($\text{Jg}_{\text{DA}}^{-1}$)
IR	infra-red (long wave) radiation
IRR	internal rate of return (%)
J	joule
k	thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)
K	thermal conductance ($\text{Wm}^{-2}\text{K}^{-1}$)
$^{\circ}\text{K}$	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 ($\text{g},\text{s}^{-1}\text{m}^{-2}$)

N	NIR, number of air changes per second (s^{-1})
NIR	near infra-red radiation
ϕ	permeance ($g, s^{-1} m^{-2} Pa^{-1}$)
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 ($8.314 J mol^{-1} K^{-1}$)
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 ($3 \times 10^8 ms^{-1}$)
V	greenhouse volume (m^3)
VA	vinyl acetate
W	watt
x	direction of heat flow (m)
Z	water vapour flux density ($g, s^{-1} m^{-2}$)

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 ($5.67 \times 10^8 Wm^{-2} K^{-4}$)
τ	transmissivity
Φ	advective heat transfer coefficient ($Wm^{-2} K^{-1}$)

χ	water vapour density or absolute humidity ($\text{g}_v\text{m}_{\text{DA}}^{-3}$)
ω	humidity ratio ($\text{g}_v\text{g}_{\text{DA}}^{-1}$)
Ω	diffusive heat transfer coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)

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 \$/m² in 1990; the cost for a glass covered house was around 80-100 \$/m² (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 ($Wm^{-2} \text{ } ^\circ C^{-1}$)

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 by 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 occurs 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 (300m²)
2. A large glasshouse (1000m²)
3. A large single skin *Agphane* house (1000m²)
4. A large double skin *Agphane* house (1000m²)

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