THE AIR GASIFICATION OF WOODY BIOMASS FROM SHORT ROTATION FORESTS

Opportunities for small scale biomass-electricity systems

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ABSTRACT

Downdraft gasification of short rotation forestry (SRF) biomass was investigated to identify opportunities for small scale biomass-electricity systems. Case studies were conducted in Kenya to identify these opportunities by (i) defining the energy demand and supply structure to identify markets; (ii) evaluating the biomass resources available; and (iii) identifying the availability of other facilities required for such a system. At the same time, the yield potential of 12 SRF species, planted in Palmerston North, New Zealand in small plots at 3470 stems/ha and harvested after 2, 3, 4 and 5 years was evaluated. Samples were collected from each species to determine their energy properties. Data on tree growth, yield, and biomass properties were used to develop two multi-objective indices - the relative yield index (RYI) and the fuelwood value index (FVI) for evaluating SRF species. Biomass from the 4 year rotation harvest was used as feedstock to fuel a downdraft air gasifier rated 35 kW (electric). Feedstock gasification processes, gas quantity and quality were correlated with the biomass properties to define the characteristics of a good fuelwood species for gasification purposes.

The Kenyan studies highlighted constraints in the energy sector and identified opportunities for new bioenergy technologies. Small scale biomass gasification systems showed potential but suitable sites were restricted to sawmills where processing residues could be used as gasifier feedstock. Field trials of SRF systems were recommended to evaluate tree species over different silvicultural treatments, and to intensify biomass production. A demonstration plant at one of the bigger sawmills was recommended to stimulate interest among investors.

Species yields of the trial plantings in New Zealand in the 12 species assessed ranged from 6 ODt/ha/y for *Alnus glutinosa* to 73 ODt/ha/y for *Eucalyptus globulus* at 5 year rotations. A stocking density trial of *E.saligna* showed that 3,500 stems/ha managed on 4-5 year rotations provided the highest yields. Though these yields may not be achieved in field plantings or in Kenya, the study demonstrated the feasibility and methodology that could be applied.

Like yield, the bioenergy properties varied between species. Higher heating values ranged from 19.6-20.5 MJ/kg for wood, 17.8-20.6 MJ/kg for bark, and 19.5-24.1 MJ/kg for leaves. Gas yields varied between 1.88-2.89 g/g dry wood due mainly to moisture content variations which also affected the composition of the gas. Gas heating values varied from 4.602 to 6.112 MJ/Nm^3, and were considered to be of sufficient quality to fuel internal combustion engines.

Both RYI and FVI showed that yield factors outweighed bioenergy properties when identifying a good fuelwood species. The large differences in yields indicated the benefits that could be achieved by selecting appropriate species for a specific region. Although feedstock properties affected the gasification processes and products, their overall influence was not statistically significant. The inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock.

EXECUTIVE SUMMARY

The energy supply and utilisation structure of many developing countries is constrained. Since the development of national economies is linked to the availability of appropriate energy resources, it is important that alternative energy supplies to fossil fuels that are environmentally friendly, economically sound, and those that will blend with the existing energy supply and utilisation technologies are identified. One such energy option is biomass when converted by thermal gasification for electricity generation. A successful application of this option requires (i) the identification of appropriate biomass energy applications and technologies; (ii) the identification of biomass resources to be supplied on a sustainable basis; (iii) the definition of biomass feedstock quality requirements for the selected technology; and (iv) the determination of the optimum operating conditions for high quality products. These were all covered in this research programme.

A case study was conducted in Kenya to identify the opportunities for modern biomass energy technologies like gasification for small scale biomass-electricity systems. At the same time, field trials of short rotation forestry (SRF) at Massey University, New Zealand were conducted to evaluate a selected range of tree species and silvicultural treatments (based on growth and yield). Samples were collected from each of the species grown under a range of silvicultural treatments and tested in the laboratory to characterise their energy properties. The data on growth, yield, and energy properties obtained were used to develop two multi-objective indices used to evaluate SRF species - the relative yield index (RYI) and the fuelwood value index (FVI). Samples of biomass harvested at the age of four years from nine of the twelve SRF species were processed and used as feedstock in a 35 kW (electric) downdraft gasifier. The gas produced under a controlled set of conditions was analysed and correlated with the laboratory feedstock characteristics to determine any differences in the fuelwood species.

In Kenya, fuelwood supplies more than 70% of the total national energy requirements. Oil provides 22-26%; coal 1%; and electricity (hydro, thermal, geothermal and imports) 2-4%, being 821 and 672 MW (installed and effective capacity, respectively). Recommendations for the development and use of more renewable energy sources were made based on economic, environmental and feasibility considerations, and favoured sustainable utilisation of biomass in modern conversion technologies like gasification for electricity production. However, the standing tree stock as assessed on private farms in the densely populated rural areas (0.7-4.6 m^3/household) would be insufficient to supply such technologies for rural areas. The location of such plants is therefore limited to sawmills processing more than 720 t/y of round wood and generating more than 1 t/day of solid residues (including slabs and offcuts but excluding sawdust). This quantity of residues could be supplied to a gasifier to generate on an annual basis more than 0.3 GWh (electric) and almost 0.6 GWh of heat in a co-generation plant. The 73 medium to large scale sawmills in Kenya have the potential to generate more than 100,000 t of solid residues per year with a producer gas potential of 221 x 10^6 normal cubic metres per year (Nm^3/y), equivalent to 24,000 t of oil. This gas could be used to generate up to 76 GWh (electric) plus another 141 GWh of heat per year.

A demonstration plant at any of the 73 sawmills was recommended to illustrate the potential of the technology. Also, field trials were recommended to (i) evaluate a range of high yielding SRF species suited to specific regions; (ii) evaluate a range of silvicultural treatments suited to the production of large quantities of high quality woody biomass; and (iii) intensify woody biomass production to supply gasifier installations in rural communities.

Of the 12 SRF species evaluated in New Zealand, being planted at 3470 stems/ha in small plots and harvested at 3, 4 and 5 year rotations, *Eucalyptus globulus* had the highest yields of 73 oven dry tonnes per hectare per year (ODt/ha/y), while *E.nitens* and *Acacia dealbata* had 59 and 49 ODt/ha/y respectively in the 5 year rotations. The lowest yielding were *Eucalyptus saligna* (< 12 ODt/ha/y); *Salix matsudana* x *alba* (1002), (< 10 ODt/ha/y); *Alnus glutinosa*, (< 6 ODt/ha/y); and *Paulownia tomentosa*, (< 7 ODt/ha/y) in all three rotations. Although the longer rotations had higher yields, the current annual increment (CAI) for most species was decreasing and approaching the mean annual increment (MAI) for the 5 year rotation. This indicated that the plots were nearing the optimum rotation length. In a "Nelder" radial design trial of *E.saligna*, the 4-5 year rotations at a stocking density of about 3500 stem/ha provided the optimum growing conditions for SRF systems in the Manawatu region of New Zealand. Results of the coppicing trial were not conclusive.

A series of biomass properties were recorded - the harvest index, proportion of bark on the stem, basic density, fixed carbon content, extractives content and heating values. These varied significantly between species, and among the tree components tested (wood, bark and leaves). Most properties did not vary significantly with different silvicultural treatments except for the proportion of bark which declined with cutting age, and the wood basic density which increased. Biomass properties did not vary significantly with sampling height up the stem.

Higher heating values (HHV) ranged from 19.6-20.5 MJ/kg for wood, 17.8-20.6 MJ/kg for bark, and 19.5-24.1 MJ/kg for leaves. The highest HHV (20.5 MJ/kg for wood and 20.6 MJ/kg for bark) was obtained from *Pinus radiata*, the only softwood tested. The different properties were correlated indicating that the quality of biomass used as feedstock was defined by most of the properties. Therefore, each property of the potential feedstock must be considered when formulating guidelines for the design of biomass energy conversion equipment.

Multi-objective techniques incorporating measured yields and energy properties for the range of species showed that yield factors outweighed the energy characteristics when identifying a good fuelwood species. The large differences in species yield indicated the large gains in terms of GJ/ha/y to be made by selecting the most appropriate species for a specific region. Assuming that the average yields (27-39 and 41-55 ODt/ha/y of stemwood and total biomass respectively) from the 4 best species over the three rotations would be achievable under Kenyan growing conditions, it was estimated that a gasifier suitable to produce electricity and hot water for a village community would require a minimum of 10 hectares of SRF harvested (2.5 ha/year), to produce about 0.5 t of dry feedstock per day.

The processes and products of downdraft air gasification were influenced by (i) gasification temperature (ii) the equivalence ratio (ER) defined by the quantity of air used; and (iii) the feedstock moisture content. High temperatures (above 1000°C) produced larger quantities of gas with high heating values. The ER values of 0.195-0.328 (with an average of 0.250) were less than the optimum value of 0.275 and indicated that air flow was not optimum for most runs, resulting in insufficient gasification reactions (tending towards pyrolysis), and lower gas yields. High feedstock moisture contents reduced the reaction temperatures; altered the optimum temperature profiles; reduced the available feedstock substrate through hydrolysis, thereby reducing the quantity of gas achievable; and produced a gas with high moisture content, high CO_2 and N_2

content, but reduced CO and CH_4 content with consequently lower heating value. Although feedstock properties affected the gasification processes and products, their overall influence was not statistically significant. Similarly, the inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock when compared to samples without bark.

Downdraft air gasification of biomass produced 1.88-2.89 grams of gas per gram of feedstock (equivalent to 2.1-3.0 m^3/kg of dry feedstock). The gas composition varied but typically contained 51-62% nitrogen; 19-26% carbon monoxide; 8-13% hydrogen; 7.5-10.6% carbon dioxide; and 1.8-2.5% methane. The gas heating value varied from 4.602 to 6.112 MJ/Nm^3, and the heating value of the stoichiometric gas-air mixture ranged from 2.241 to 2.524 MJ/Nm^3 for air dry and oven dry feedstocks. The gas composition and heating values were considered to be of sufficient quality to fuel internal combustion engines.

The quantity of solid residues (and ash particulates) produced was not sensitive to the species or feedstock properties, reaction temperature, equivalence ratio (air supply) or the feedstock moisture content. The quantity of liquid residues (condensate) generated being 20-80 g/kg of dry gas from air dry feedstock and oven dry feedstock decreased with increasing gasification temperatures and increased with increasing feedstock moisture contents. The quantity of condensate was however not sensitive to the species or to the equivalence ratio. The pH, COD, electrical conductivity and turbidity of the condensate showed that it would be unsafe to dispose of the residue into water-ways or onto land without pre-disposal treatment. An initial step would be to filter the residue through the solid residues collected from both the ash port and from the cyclone.

The study demonstrated methodologies for (i) identifying and evaluating opportunities for biomass to electricity systems in developing countries, and in isolated remote regions of developed countries; and (ii) evaluating SRF species for fuelwood requirements using multi-objective indices - the relative yield index (RYI) and the fuelwood value index (FVI). The methodologies may be applied to other regions of the world. In particular, the indices could be used to evaluate SRF species grown under Kenyan conditions. The species which performed well under the Manawatu conditions, (*E.globulus*, *E.nitens*, *A.dealbata* and *E.ovata*), and others which are known to grow well under tropical conditions should be evaluated alongside high yielding local species.

Commercial gasifiers need to be compared and one selected for a demonstration to stimulate the concept in Kenya. A financial and economic evaluation of the demonstration plant would not necessarily indicate the true economic and environmental values of the venture as a learning process will be involved. However, given that the project would be in the experimental / demonstration stages, it would enable a full cost - benefit analysis to be undertaken to provide useful data which would be accurate enough to be used when comparing electricity generation from SRF crops and sawmill residues with other electricity generating technologies such as traditional fossil fuel fired power plants, or even photovoltaic, solar, wind, or diesel generator sets.

DEDICATION

This Thesis is dedicated to my mother, posthumously,

The Late

†

MAMA PAULINE MUHONJA KINGIRI

†

You got so close, yet

(i) a few weeks shy of realising your own work
(ii) many years shy of reaping the full benefits of your long, hard and painful struggle
(iii) capable of much more, had you had the opportunities you gave us

"……the long hours of sleep after finishing school will never have the meaning you meant".

Gona vulahi

Nyasaye nakutumikiyi
kulikaaganili mwigulu

†

May the almighty God rest her soul in eternal peace

†

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The economic development of most countries with intermediate technologies that are energy intensive has been linked to adequate availability, supply and use of energy (Leach *et al*, 1986; Ang, 1987; Dunkerley, 1986; Desai, 1986; Pearson, 1987; Arima, 1994). Ebohon (1996) concluded that the relationship between energy and economic growth is complementary. In Kenya, Senga and Mwendandu (1980) and Okech (1986) demonstrated strong positive relationships between the growth rates of modern energy consumption and monetary GDP. Firstly, the availability of appropriate energy resources determines the level of manufacturing; and secondly, imports and trade in oil (the world's major traded energy resource) determines a country's trade balance. In the case of oil importing countries therefore, development and utilisation of available indigenous fuel resources would save foreign exchange and thus provide the funds for alternative uses, and consequently foster development. In this context, energy development could be regarded as the prerequisite of social and economic development. Growth strategies must therefore be validated against the attendant energy requirements (Ebohon, 1996).

Burning fossil fuels in the transport sector, for generating electric power, to supply industrial heat and power demand, as well as for agricultural production has had a significant effect on air quality. The resulting "green-house gas" effect has recently become more apparent. Further, the increasing cumulative imbalances of payment of most developing countries which import oil, and the effect of the huge foreign debt on their economies can not be over-emphasised. Even with the predicament of the present difficulties in acquiring fossil resources, the possibility of increased oil prices can not be ruled out, particularly in view of the possible incorporation of a carbon tax in fossil fuels pricing. If this happens, it could further reduce the level of energy dependent manufacturing in developing countries - though at present it is the developed countries who are obliged to reduce their carbon emissions. Accordingly, every effort to find alternatives to fossil fuels to reduce CO_2 emissions, and stabilise the Third World economies need to be sought.

The search for alternative forms of energy from modern biomass has been the subject of debate for a long time. The driving forces in the 1970's were the uncertainties in the energy reserves; the oil shortages of 1973 and 1979; the associated escalating energy costs; and the finite nature of the fossil fuels reserves. The current concerns and the renewed research efforts in the biomass option are centred on environmental issues and the potential for biomass energy systems to address the problems of land surplus to requirements for food production in the developed nations. Short rotation forestry (SRF) systems are environmentally benign; have the proven ability to contain the current levels of CO_2 in the atmosphere when sustainably managed; are renewable and have widespread global distribution. In certain countries, SRF systems have the potential to provide energy at lower relative costs than imported fossil fuels.

Although traditional direct combustion of biomass to provide heat has been used since the discovery of fire, and will continue to be used by the majority of the world population for a long time yet, the process is inefficient and environmentally unsustainable. It does not easily permit direct retrofitting or alterations of the combustion systems to give higher efficiencies. Other technologies like thermal gasification are being developed to convert biomass into gaseous and liquid fuels which may lend greater versatility, and provide a more efficient, sustainable and therefore acceptable use of the biomass resource.

Thermal gasification of biomass offers a number of advantages over the direct combustion technologies. The resulting gaseous fuels can be burnt more efficiently with less toxic emissions, and lend themselves to easy distribution for industrial and domestic uses. The gas can also be used in internal combustion engines for transport, or may be coupled to alternators for electricity generation. The gas could also be used for chemical synthesis of liquid fuels and chemicals. However, there is insufficient biomass feedstock in some regions, and a poor understanding of the variability in biomass properties which influence the conversion processes like gasification. World-wide studies by the FAO (1981) indicated that most regions in developing countries were facing fuelwood scarcity problems, partly due to (i) increasing population and hence increasing demands; and (ii) more stringent environmental regulations and conservation policies to protect native forests and vegetation. SRF has a strong basis to supply fuelwood under such conditions.

The thesis of this study is that a successful biomass energy option depends on the ability to (i) identify appropriate biomass energy applications; (ii) identify the availability of, and or the ability to produce biomass in sufficient quantities; (iii) determine and define the quality and the suitability of fuelwood feedstock from different sources for a particular conversion technology; and (iv) utilise the available biomass most appropriately.

Remote regions of developing countries with high population concentrations were emphasised with a view to identify possibilities of supplying electricity to villages and small scale industries in rural areas that are either too far from the national grid or where connection would be uneconomic, on a decentralised basis; saving on the scarce foreign exchange used to import fossil fuel for electricity generation; and providing employment opportunities in the electric power producing and consuming outlets.

1.2 OBJECTIVES

The objectives of the study were to:

1. define the national energy profile of Kenya and identify the opportunities for the application of small scale biomass-electricity systems, being a case study of a developing country;

2. develop a methodology for evaluating short rotation forestry (SRF) fuelwood species;

3. analyse biomass feedstock characteristics for a range of SRF species and identify the main parameters defining fuelwood quality;

4. evaluate the downdraft air gasification process on a range of SRF fuelwood species by measuring the quantity and quality of gas produced; and

5. relate biomass yield and feedstock energy characteristics data of a range of fuelwood species to the gasification behaviour, gas yield and quality data in a methodology of selecting SRF fuelwood species for biomass production in small-scale biomass-electricity systems for remote power supplies.

1.3 JUSTIFICATION

Implementation of a sustainable biomass-electricity system for remote rural areas in developing countries requires a clear understanding of the forces determining energy procurement and its utilisation. Relationships between optimisation of yield of different species used for fuelwood and their feedstock quality is useful in the determination of optimal methods of biomass production, and may assist in the scheduling of biomass production and harvesting operations.

The methodologies used in the evaluation of the potential of small-scale biomass-electricity systems in Kenya, and of evaluating the species may be applied to other regions in developing countries where similar technologies are envisaged.

1.4 PREVIEW OF CHAPTERS

Having provided the rationale and an overview of the study in this chapter, the energy profile of Kenya is outlined in chapter two to show the dependence of many developing countries, particularly the rural areas, on biomass energy. Thermal gasification of biomass is investigated to demonstrate the opportunities of sustainable biomass use in the provision of small scale electricity.

Chapter three evaluated a range of short rotation forestry (SRF) species for fuelwood production, incorporating the effects of rotation length, stocking density, and coppicing on yield, while chapter four investigated the energy characteristics of the feedstock produced from the different species. These two chapters developed indices - the relative yield index (RYI) and the fuelwood value index (FVI), respectively, to be used in evaluating species for fuelwood requirements. The air gasification behaviour of SRF woody biomass harvest from chapter three, and characterised in chapter four is reported in chapter five. Both gas yield and quality is related to biomass characteristics and yield to define a good SRF fuelwood species for gasification. Chapter six provides a general overview and conclusions of the study.

Each of the research chapters (2 - 5) are organised as independent topics of investigation having sub-chapters: introduction and objectives; review of literature; materials and methods; results; discussion; and conclusion.

CHAPTER TWO

SMALL-SCALE BIOMASS ELECTRICITY SYSTEMS IN KENYA

2.1 INTRODUCTION

Kenya covers an area of 582,646 km^2 of land bordering five nations and the Indian Ocean. There are considerable variations in climatic conditions - from hot to humid, through temperate to cold with permanent snow on Mt. Kenya. Two thirds of the land area is either arid or semi-arid, but the central highlands which fall between 1370 m and 3000 m enjoy good rainfall for agriculture and forestry, resulting in regions of population concentration. The vegetation types include lowland savannah woodlands, montane semi-evergreen forests, and lowland and equatorial rain forests (ETC, 1991).

The Kenyan economy is based on agriculture providing about 30% of the national GDP, relying on one or two major export crops, and supporting almost 80% of the population that lives in the rural areas. Other contributors to GDP include the manufacturing sector, 15%; and the trade, restaurants and hotels sector including tourism, 12% (Central Bank of Kenya, 1997).

Kenya has no known fossil fuel resources (coal, oil or natural gas). The level of manufacturing is low and relies on imported commercial energy particularly oil. This reliance makes the country vulnerable to international energy shocks (Dick *et al*, 1984; Semboja, 1993; Semboja, 1994; Singh, 1991), which in turn affects the economic structures (Central Bureau of Statistics, CBS 1994a,b; Mureithi *et al,* 1982). The limited availability of cheap conventional energy in agriculture and manufacturing sectors has been blamed for the low manufacturing levels and therefore the under-development of industries. Kenya must therefore continue to develop new sources of cheap commercial energy to be available to both industry and households in order to uplift the levels and standards of manufacturing and living, respectively.

2.1.1 THE ENERGY SECTOR

Kenya's total annual energy demand has fluctuated between 6.7 to 9.6 million tonnes of oil equivalent (Mtoe) during the period 1980-1994, but overall show a gradual increase of 2.9%

per annum, which was similar to the growth in fuelwood demand as shown in figure 2.1 (Okech and Nyoike, 1989; Okech and Nyoike, 1994; Senelwa and Hall, 1993; Nyoike and Okech, 1992). Since 1984, growth rate in energy demand was greatest for electricity averaging 5.6% per year. Growth rate in oil utilisation was 3.2% per year which equalled the growth in the national economy during the same period (Okech and Nyoike, 1994; CBS, 1994a,b). The increase in electricity and fuelwood use resulted partly from the population growing from 19 million in 1980 to 25 million in 1994 (Okech and Nyoike, 1994), and partly from the growth in infrastructure and socio-economic conditions. There is likely to be no diminution in rates of growth in demand, unless the growth is constrained by supply.

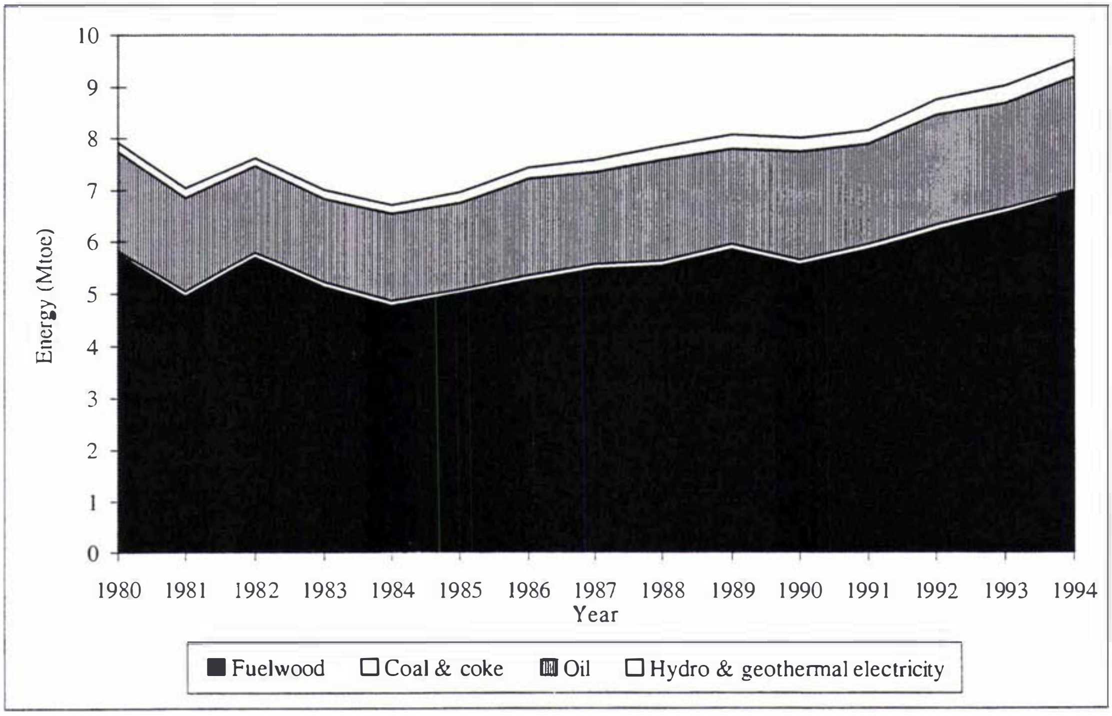

Figure 2.1 **Trends in total energy supply in Kenya (Mtoe)**

Fuelwood constituted more than 70% of the national energy demand, while oil, part of which was used to generate electricity, provided 22-26%. Hydro and geothermal electricity provided 2-4%, and coal provided only 1%. In addition, the use of dung, agricultural and forest residues (not included in Figure 2.1) were earlier estimated to supply more than 1.2 Mtoe annually (approximately 15%), predominantly in the rural areas (Senelwa and Hall, 1993).

Between 1980 and 1992, up to 60% of the energy supplied was used by the domestic sector, 95% coming from fuelwood (Table 2.1) (Okech and Nyoike, 1989; Senelwa and Hall, 1993; Nyoike and Okech, 1992; CBS, 1994a,b). The commercial and industrial sectors accounted for 17%, followed by the transport sector with 12-15%. The agricultural sector which involves 75% of the population, and contributes up to 70% of the foreign exchange earnings (CBS, 1994a,b) used only 8-10% of the total energy supplied, most of which (80%) was biomass based. All the oil was imported, utilising up to 45% of total export earnings, and accounting for 23% of the total import bill (Nyoike and Okech, 1992; Okech and Nyoike, 1994; CBS, 1994a,b,c). Reliance on imported oil and coal without commensurate expansion in exports is economically unsustainable (Dick *et al*, 1984; Semboja, 1993; Semboja 1994; Mureithi *et al*, 1982). There is a need to develop local energy resources to reduce reliance on expensive oil imports.

Table 2.1. **Energy end-use by sector and source for selected years ('000 toe)**

Source	Year	Domestic	Agriculture	Commercial & industrial	Transport & communication	Others*	Total
Fuelwood (Biomass)	1980	4540	539	687			5766
	1989	4519	704	646			5869
	1992	4811	719	679			6209
Coal & coke	1980			60			60
	1989			92			92
	1992			99			99
Petroleum	1980	107	69	497	999	248	1920
	1989	208	64	460	968	143	1843
	1992	203	65	454	1272	157	2151
Electricity	1980	45	3	87	7	14	155
	1989	67	13	134	13	31	258
	1992	77	27	145	15	35	296
Total	1980	4692	611	1331	1006	258	7902
	1989	4794	781	1332	981	130	8062
	1992	5091	811	1377	1287	118	8758

* - Others include the energy used in oil refinery, power generation and street lighting

2.1.2 ELECTRICITY POTENTIAL, GENERATION AND USE IN KENYA

ACRES (1986) and the United Nations Development Programme and World Bank (UNDP/WB, 1987) estimated that there was an untapped hydro-electricity potential of 1400

MW with an annual generating capacity of 6000 GWh. The geothermal potential was estimated to exceed 2200 MW capable of generating 16000 GWh/year. These resources are under-developed due to the high capital investment costs of development in spite of the increasing power demand.

Table 2.2 presents details of electricity generation and consumption in Kenya (KP&LC 1995). The table shows that up to 77% of total installed capacity was hydro, 5.5% was geothermal, and the remainder mainly thermal. The differences between installed and effective capacities were attributed to priority generation levels, normal maintenance shutdowns and general failures. System losses, (the percentage of power put into the distribution system which never reaches the final consumers as recorded by electricity sales) averaged 15% for the period of analysis and were attributed to the long transmission distances combined with low consumer demand; poor quality and undersized transmission lines and distribution transformers giving large resistance losses. These proportion of losses is high and expensive for a nation where power demand outstrips supply, necessitating rationing and outage as a tool for managing demand.

Table 2.2. **Generation and utilisation of electricity for selected periods**

	Capacity (MW)		Energy (GWh)					
Source	Installed	Effective	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94
Total hydro (local)	599	569	2449	2517	2713	2831	3069	3132
Thermal (Kipevu)	93	55	25	97	74	75	59	140
Geothermal (Olkaria)	45	30	322	336	298	272	272	261
Gas turbine	44	12	21	10	21	3	2.1	1.6
Diesel (Grid connected)	4	2	2	2	0.4	3	0.3	0.4
Wind turbine (Ngong)	0.4	0.4	-	-	-	0.8	-	-
Imports (Hydro, Uganda)	30	-	112	174	181	185	177	180
Total national grid	814	668	2931	3136	3288	3369	3580	3715
Isolated diesel	6	4	11	12	14	16	20	17
Total capacity	821	672						
Gross generation			2943	3148	3302	3385	3600	3732
Auxilary consumption			27	33	33	30	29	38
System losses			448	453	484	510	566	560
System peak demand (MW)			480	520	550	566	596	612
System load factor (%)			70	69	68	68	69	69
Losses as % of generation			15	15	15	15	16	15
% annual growth in generation			4	7	5	3	6	4
% annual growth in demand			4	8	6	3	5	3

In the period of analysis (1980-1994), 49-56% of the total electricity was used in the commercial and industrial sectors. The domestic sector used 26-29%, mostly in the cities

(KP & LC, 1995). Based on current demand and utilisation levels, it has been projected that the country will require an additional generating capacity of 1,256 MW (204 MW hydro; 450 MW base load thermal; 431 MW geothermal; and 150 MW, standby thermal) by the year 2010 in order to meet future energy requirements (Karekezi *et al*, 1995).

The national grid connects major urban centres traversing the high potential, and densely populated areas (figure 2.2). Other urban centres including Lodwar, Marsabit and Lamu are supplied by thermal stations. Sugar and pulp & paper industries have power co-generation systems with installed generating capacities of up to 25 and 12.5 MW electric, respectively.

Figure 2.2 **The Kenyan grid network (and the rural household survey region**Insert)

Although major urban areas of the country were connected to the grid by 1995, more than 80% of the population had no access to electricity, and in rural areas where 75% of the population lives, only 1% of the population was estimated to have access to the grid network (Kenya News, 1996). There were only 0.351 million consumers by 1994, 0.272 million being domestic users concentrated in the cities (KP & LC, 1995). The low proportion of electricity use in the domestic sector particularly in rural areas was attributed to lack of accessibility to the grid, high installation costs, and low income levels among rural inhabitants. In these rural areas, electricity could be used for lighting, water pumping, food processing, and sterilisation and refrigeration at health centres. Lack of electricity could be seen to inhibit economic and social development by limiting the quantity and extent of social services, quality of residential life through forced dependence on low quality lighting systems, and have a direct impact on the levels of literacy. Like electricity, the production and distribution systems of other traded energy in rural areas are poorly developed.

Since Kenya is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), it has an obligation to support and participate in international efforts to minimise human impacts on the climate systems, while promoting efforts that support sustainable social and economic development. Development of electric power generation from fossil fuel sources and the associated impacts on the environment is not only expensive, but is also limiting, and contravenes the UNFCCC obligations. Supplies from further large hydro and geothermal systems are limited. Therefore, other sources must be developed.

2.1.3 THE RURAL ELECTRIFICATION PROGRAMME IN KENYA

The Rural Electrification (RE) programme in Kenya was started in 1973 by the Government of Kenya (GoK) to bridge the gap between the rural and urban areas in a bid to decentralise some government services. The RE programme was also a strategy by the GoK to control urban migration designed to proceed in phases corresponding to the following specific objectives (i) to electrify all district headquarters; (ii) to provide electricity to rural industries formerly dependent on diesel; (iii) to provide market centres of rural areas with electricity; and (iv) to provide domestic consumers with electricity.

Besides the stated objectives, RE programmes have broader objectives including the control of deforestation activities by providing alternative energy sources; stimulating economic activities particularly the small to medium agricultural industries; improving social life in the rural areas; improving refrigeration and sterilisation at health centres; and elevating literacy standards. Although all district headquarters had been electrified by 1995, the RE programme fell short of its objectives due to the high cost involved of implementing the programme; and effective utilisation of the power and the generation of income to sustain the programme.

Schramm (1993a) concluded that RE was a potentially desirable investment in many countries but indicated that low-cost electrification designs be sought, and that rural towns in agricultural provinces be considered as part of RE as they are often important demand centres and sources of growth. Mariam (1992) argued that the benefits that accrue from RE programmes are by and large different from those derived from a large electrification schemes that are intended to supply concentrated loads in urban centres. However, Pearce and Webb (1987) rejected the social benefit arguments, asserting that the non-monetary benefits of rural electrification are neither as widespread nor as strong as to warrant a side stepping of the conventional rate of return criterion. This arguments suggest that the cost-benefit analysis commonly used to determine the viability of projects should not be the only yard stick in evaluating RE projects except for ranking purposes only. Thus, the government of Kenya is still committed to the extension of electricity services to these areas.

2.1.4 BIOMASS ENERGY OPTIONS FOR KENYA

Michaelis (1987) evaluated wood-based energy technologies and options for Kenya and indicated that the efficiencies of biomass use were low. Senelwa and Hall (1993) assessed the country's total biomass energy potential incorporating agriculture, forestry and grasslands, and mapped out a flow chart detailing the biomass use in different forms. They recommended the use of more efficient conversion systems such as improved charcoal stoves, and increasing the use of dung, together with harvesting and processing wastes from agriculture and forestry to provide an extra 2.4 Mtoe.

Laichena (1993) surveyed the availability, use, ease of gathering and suitability of various biomass fuels from forest industries and the agricultural sector for thermal gasification. He concluded there existed a potential for biomass gasification in Kenya, but failed to nominate possible sites for such a plant. Karekezi *et al*, (1995) stated that gasification activities in Kenya were yet to be instigated. Elsewhere, ETSU (1993) demonstrated the economic viability of small scale plants (up to 200 kWe) using an illustrative example from the Enniskillen Plant, Northern Ireland, but stressed that the viability was sensitive to fuel price and to the electricity sale value. In India, Talib *et al*, (1989) outlined the successful development and testing of small biomass gasifier engine systems, but in the Philippines, Bernardo and Kilayko (1990) showed that gasification technology did not achieve its objectives due to institutional and management problems, and illustrated the importance of adequate planning prior to project implementation.

Stassen (1993) proposed a “decision tree” for small-scale biomass gasifier projects and emphasised the need for a reliable supply of cheap biomass relative to petroleum. Small scale capacities up to 500 kW electric were recommended, being commercially proven. Cort’e (1989) suggested that biomass gasifier demonstration programmes should give preferences to sites where adequate technical skills, sufficient fuel resources of uniform quality, and skilled operator availability coincide with direct economic interests. Thus, a major pre-requisite of the scale and long term viability of biomass gasifier programmes depends on the availability of fuelwood feedstock, and is therefore location specific.

Other renewable energy alternatives include draft animals, biogas, ethanol and methanol derived from crops, and external combustion engines such as Stirling engines running on any combustible material which can provide heat. Briquetting characteristics of sawdust, wood shavings and wheat straw were studied to enhance utilisation for energy (Wamukonya and Jenkins, 1995). For the generation of electricity under specific application conditions, other options include photovoltaics (not economically feasible using current technology); wind and hydro (site specific); production of methanol and ethanol from biomass (still energy inefficient and capital intensive); small steam engines (low efficiencies, <10%) and Stirling engines (need a major development effort to make them cost effective) (Datta and Dutt, 1981).

2.1.5 OBJECTIVES

The objective of this part of the study was to identify the opportunities for small scale biomass-electricity systems in Kenya by defining the technical requirements for the use of biomass gasification for rural electric power supply. The following aspects were examined in this study:

i) availability and geographical distribution of woody biomass including the forestry resource, farm woody biomass production and wood industry processing residues; and

ii) the potential markets or outlets for the expected electricity and heat.

The study identified possible sites for small-scale gasifier demonstration plants with technical abilities for operating the plants, and strategies for encouraging replication in rural areas.

2.2 METHODOLOGY

2.2.1 THE FORESTRY RESOURCE

The forestry resource base data were gathered from Government records.

2.2.2 THE HOUSEHOLD SURVEY

The Vihiga and Kakamega districts region in Western Kenya (Figure 2.2), were chosen for a survey of rural households to assess domestic tree growing and energy utilisation activities. The region with an area of about 3,521 km^2 (0.5% of the national area), was considered one of the most densely populated rural areas in the country with a population of up to 1000 persons per km^2 in places. The 1994 population was estimated to exceed 1 million (GoK, 1994).

The region was divided into 7 parts to cover localised variations in socio-economic and population activities. In each part, one sub-location (the smallest administrative unit in Kenya, with 900-2000 households) was selected. Two of the sub-locations (Ebusikhale and Kegoye) are located in the densely populated southern parts, while Chekalini, the most sparsely populated was in the north (Figure 2.2). The selected sub-locations were used in a previous survey (Senelwa, 1988), and had also been targeted by the Kenya Woodfuel Development Programme.

One in 200 households in each sub-location were randomly identified for the survey. A total of forty two households were surveyed. The selected households were visited and oral interviews conducted with the senior householder to complete a questionnaire (Appendix 2.1).

The objectives of the questionnaire were:

i) to define the socio-economic activities of a densely populated rural area;
ii) to determine land use activities, and appraise tree growing and utilisation activities;
iii) to evaluate energy demand, procurement and utilisation activities in rural areas of Kenya; and

iv) to establish the potential, feasibility and the general responses by the rural population towards the introduction of biomass gasification technology for generation of electricity.

The quantity of fuelwood used was assessed by the number of headloads consumed and sample measurements of the fuelwood bundles together with the quantity of charcoal (either by stove-full or bags), used daily or weekly. Physical counts and tree size measurements on individual farms were attempted, but later abandoned as the trees were of widely different species, sizes and age. Besides, different farms were characterised by different tree/forestry configurations. Only the proportion of land occupied by tree cultivation was therefore determined, while taking note of the different tree configurations and common species.

2.2.3 WOOD PROCESSING RESIDUES

A census of the wood processing industries was undertaken to categorise the industries by type and size to indicate the location and concentration of major wood processing residues on a national basis. For each industry, annual raw material requirements were established from recorded raw material sales (logging licenses) from Forest Department (FD) forests. The nature of residues from the pulp and paper mill, and from the reconstituted wood panel mills precluded their possible application as fuel for a downdraft gasifier as originally envisaged in the project. Only sawmill residues were therefore thought to be suitable. Besides, the pulp and paper mill utilised all its bark and wood waste on-site for generation of low pressure steam for industrial process heat requirements. In future, a wood-fired co-generation plant could be warranted.

Several saw mills were visited as part of the project to gain an understanding of the general processes, and to undertake some measurements of recovery factors and residues generation. It was assumed that 1.4 m^3 solid roundwood volume is equivalent to 1 tonne of air dry wood (15% moisture content, dry basis). Recovery rates for harvesting operations were taken as 70%, while a sawmill recovery factor of 37% was assumed based on sample measurements, and the nature of machinery used in most sawmills.

2.3 **RESULTS AND DISCUSSION**

2.3.1 WOODY BIOMASS RESOURCES

Inventory of the forest resource

Forests in Kenya cover an area of about 14,000 km^2 (2.4% of the national land area), of which 12,200 km^2 is gazetted (KIFCON, 1994). Apart from 800 km^2 of mangroves in the coastal region, the forests are located in the highlands. About 1,640 km^2 was under commercial plantations in blocks dominated by exotic species (cypress 45%, pines 31%, eucalypts and other hardwoods, 10%), and indigenous species, 14%.

The standing stock in gazetted forests was estimated to be about 230.6 million m^3 (Mm^3) or 176 m^3/ha on average (KFMP, 1994). There was about 57.4 Mm^3 in plantations at 350 m^3/ha; and 75.4 Mm^3 in farm/settlement lands at only 7.9 m^3/ha. More than 50% of the total national standing tree stock, estimated to be about 571 Mm^3, was in woodlands and bushlands at 15.2 m^3/ha. Since the standing volume of woody biomass outside conventional forests was greater than the volumes found in them, the forest resource should be interpreted in a broad sense to include all growing woody biomass regardless of land classification (Holmgren *et al*, 1994).

Procurement and utilisation of biomass in rural areas

Table 2.3 presents features of the rural economy in relation to energy use in Vihiga and Kakamega districts. Although the sample size was limited, being only 0.5% of the population since resources to undertake a more intensive survey were not available, the results are characteristic of the densely populated rural areas of Kenya with population densities ranging from 220-1100 persons/km^2. The economy was mostly subsistence with maize and beans being the main food crops. Tea, coffee, sugarcane and sunflower were the major cash crops.

The rural inhabitants had a high demand for bioenergy, as all households surveyed used fuelwood (charcoal and firewood) and crop residues for cooking and minimal heating. Although charcoal was not used on an all year round basis like firewood, 69% of the households used it. Kinyanjui (1987) and Karekezi *et al*, (1995) had previously estimated that charcoal provided up to 6% and 26% of the total and domestic energy requirements respectively. The annual growth rate in charcoal use was about 6.7%.

Table 2.3 **The rural household economy[*] and energy use in Vihiga/Kakamega region**

Sub-location	No. of h/holds	Farm size, ha.	Persons per ha.	Land use activity**	Land under trees (%)	Tree stock (m^3)***	Biomass use (kg/person/y)		Charcoal use (% h/holds)
							Firewood	Charcoal	
Ebusikhale	6	0.66	11.2	S	11.0	0.7	750	88	83
Eshianda	7	1.35	6.3	C+S	15.4	1.9	938	28	57
Mayoni	5	1.80	4.3	C+S	5.1	0.9	672	24	60
Kegoye	7	0.94	9.3	C+S	23.1	2.0	990	82	86
Murhanda	6	1.06	7.4	S	12.8	1.3	530	56	50
Lukume	6	4.50	2.3	C+S	11.0	4.6	580	51	67
Chekalini	5	6.88	2.2	C+S	5.3	3.3	532	38	80

* The minimum monthly wage in urban areas in 1995 was about KShs 1500.00, but most people in the rural areas were not in formal paid employment (Central Bank of Kenya, 1997).

** S = Subsistence; C = Cash crops

*** Calculations based on national mean standing stocks of 9.3 m^3/ha (KFMP, 1994).

Other energy sources used by all households included illuminating kerosene (for lighting), solar power for farm produce and fuelwood drying; and animal power (oxen, donkeys and humans) for farming and transport. Petrol and diesel were used in vehicles and stationary engines for water pumps by 14% and 5% of the households, respectively. In addition, diesel was used in 5 out of the 9 flour (grinding) mills, and as fuel for the 12 tractors in the region. Domestic use of petroleum products was limited to illuminating kerosene, being expensive and with most retail outlets located 10-20 km from the households. The published retail prices for a litre of kerosene, diesel and petrol were US $[a] 0.40, 0.50 and 0.60 respectively. There tended to be a gradual upward price differential with increasing distance from the nearest major kerosene/petrol outlets. Traditional water wheels were used at a flour mill (not operational at the time of the survey), while dry cells and car batteries were used for lighting (85% of households), and in portable radios, cassette recorders and televisions, (70%). Although Vihiga/Kakamega region is supplied by the national grid, none of the households sampled were connected, and electricity was used at only 4 of the 17 shopping centres in the 7 sub-locations. There was a reticence to admit to burning animal dung for heating and cooking, as dung was considered inferior to fuelwood, and seen to reflect poverty. The

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[a] Unless otherwise stated, reference to monetary values in US $ assumes the June-December 1995 mean US $ to Kenya shillings exchange rate of US $ 1 = KShs 56.5.

potential to use dung in anaerobic digesters was high as all households surveyed had cattle, sheep, goats or poultry, but no biogas plants were in evidence.

There were variations in the quantities and patterns of fuelwood used from one sub-location to another, with per capita biomass energy use ranging from 8.6-18.3 GJ/person per year, equivalent to 0.54 - 1.1 tonnes of wood per year (Table 2.3). The consumption of illuminating kerosene ranged from 4 - 8 litres/household per month. The variation in the quantities of energy used was not influenced by farm size or the proportion of land under woodlots, but by the local availability, family size, season of the year (festive, wet seasons etc.), lifestyles and income levels (see minimum monthly wages above), types and number of meals served per day, and the availability of alternative energy sources (Senelwa, 1988). The limited use of charcoal was associated with the higher costs of the fuel, being US $ 2-3 per 40 kg bag of charcoal (US $ 1.6-2.4/GJ), and the capital investment necessary for a charcoal stove, being US $ 1.50 for a medium size (8 kW) metallic stove with estimated energy efficiencies of 20%. An improved Kenya ceramic stove with measured efficiencies of up to 35% was retailing at about US $ 4.0, equivalent to 15% of the minimum monthly wage. A 5-10 kg firewood bundle was retailing at US $ 0.20 (≈ US $1.7/GJ), but the open fire stoves were "free" although inefficient.

Most firewood was gathered locally from family farms or nearby bushes by women, and warranted little attention by men. None of the households gathered fuelwood directly from Forest Department (FD) forests, partly because most of the villages were far from the nearest forests, but mainly because the state forests are protected against subsistence fuelwood harvesting. It is however possible that most of the charcoal, and part of the fuelwood sold at market places was obtained from FD forests. Out of the 42 households surveyed, 12 purchased some firewood although it was not possible to determine the proportion of total consumed or the average expenditure on firewood procurement. All the charcoal, petroleum based energy, and dry cells were purchased. Crop residues were used when available, mostly in the harvest season, and none of the households purchased crop residues.

The cost of conventional commercial energy supplies in Kenya was considered high in relation to income levels as real wages and salaries remain below the 1976 levels (Okech and Nyoike, 1994; World Bank, 1994). The high commercial energy costs, coupled with increasing regional fuelwood scarcity, indicate a supply deficit which has stimulated the need for self sufficiency in fuelwood supplies. This desire has in turn intensified farm forestry activities by most rural householders. It has also injected an element of commercialisation in the rural fuelwood procurement sector which has in turn intensified the awareness and need to use fuelwood more efficiently. This has also created employment for an increasing number of fuelwood vendors in the region. An earlier survey showed that only 19.1% of all charcoal consumers used the more efficient Kenya ceramic stove (Senelwa, 1988). This proportion had risen to 24% by 1995. Further, in 1988 bundles of firewood for sale were evident only at market places in the southern parts of the region whereas by 1995, all the markets visited had bundles of firewood on sale.

Socio-cultural factors in tree growing and utilisation activities

All households sampled were actively growing trees. The drive for tree planting was derived from a desire for self sufficiency in fuelwood supplies; a well established private land tenure system; and the customary values attached to land, and to trees. It is believed that if a woman plants a tree, she will become barren - a factor associated with marriage break-up; if a woman plants a tree on her husband's land, the husband will die; and tree planting by women is a direct challenge to the husband's supremacy in the household. People plant trees on their land because trees are inheritable assets, and since women do not own land, and do not inherit it, they do not plant any. Most trees planted are used for house construction and since women do not construct houses, using material raised by a woman is a taboo. Certain trees and tree species such as *Erythrina abysinica* are considered sacred and therefore protected, and used as sites for customary rituals like burial and circumcision ceremonies which are performed by men. Women are prohibited from felling trees on farms, a prerogative of the men. Although the cultural beliefs in the region were seen to enhance the art of tree growing, and to restrict rampant tree felling, they are also constraining active involvement of women.

The wood supply sector was linked to the subsistence nature of agriculture since it directly affects the majority of people. However, since the role of fuelwood collection is played by women, the problems associated with procurement are often overlooked. Consequently, fuelwood has not been ranked as a major product of farm forestry, its procurement being regarded as a female task. Other than fuelwood, other tree uses stated in the survey included production of timber, poles, fruits and medicines; to provide windbreaks and shade on farms and in homesteads; soil conservation; land demarcation; fences and hedges; ornamental benefits; and to identify social gathering sites for traditional rituals.

Farm and short rotation forestry configurations

The concept of short rotation forestry (SRF) was not apparent even to the forestry professionals, although it was evident in a range of configurations such as rural forestry, woodlots, farm forestry, agroforestry, hedgerows and shelterbelts. Konuche (Pers. Comm, 1995), the Director of the Kenya Forestry Research Institute, indicated that the trend was moving away from growing SRF, apparently in favour of industrial plantation forestry (IPF). Since SRF and IPF target different major product markets, they should be treated differently.

In the Vihiga/Kakamega districts, 95% of the households had trees around the homestead, including shrubs and fruit trees; 92% had hedgerows around the homesteads; 93% had intercropped trees on their land; 78% grew woodlots ; and 25% had bushes commonly of mixed species and growing wildly. Most woodlots were composed of a range of *Eucalyptus* species while species like *Sesbania sesbans*, *Markhamia lutea*, and *Leucaena leucocephala* were most commonly found inter-cropped on farmland. The hedgerows were characterised by *Cupressus lucitanica*, and *Lantana camara*. Bushes (associated with large farms and absent in the south where farms were smaller) were a mixture of many different species with some landowners having up to 50 tree species and shrubs on a 0.5 ha plot. On many farms, marginal land (swamps, steep slopes and rocky portions) were devoted to tree growing.

The proportion of land for growing trees on a private farm increased as the plot size decreased (Table 2.3). Holmgren *et al*, (1994) found similar relationships between population density and standing planted volumes on a district wide basis (correlation, $r^2 = 0.64$). Although it would have been most desirable to assess the quantity of standing stock on the farms surveyed in the region, the study constraints precluded the task. On a national scale, the Kenya Forestry Master Plan (KFMP, 1994) survey of woody biomass indicated that about 40% of the woody biomass outside closed canopy indigenous forests are from planted trees and that the total volume of trees planted by farmers equals that of closed canopy indigenous forests and government forest plantations combined. It was estimated that farmlands and settlements contain on average 9.3 m^3/ha of woody biomass, totalling 74 Mm^3

on 9.54 million hectares. The woody biomass quantities were assessed to be increasing at a rate of about 0.5 m^3/ha/y.

Using the national average of the woody biomass standing stock in farmlands and settlements (9.3 m^3/ha) (KFMP, 1994), the average household woody biomass stock was calculated based on the farm size, and the proportion of land under tree cultivation (Table 2.3). Households in the region were estimated to own 0.7-4.6 m^3 of standing tree stocks, the quantities being limited by the farm size. Although such values show general trends, they underestimated the quantities on farms in some of the sub-locations such as Kegoye, Ebusikhale, and Murhanda where woodlots were dominated by mature trees of *Eucalyptus* species, and where farms appeared heavily forested.

Wood processing residues

Residues constituted 63% of the total roundwood including off-cuts, slabs, trimmings, bark and sawdust. The remainder 37% was solid sawn timber. Of the residues, sawdust constituted about 10% of the total roundwood weight.

In 1994, 325 sawmills obtained licenses to log in the FD forests, extracting about 349,438 m^3 of solid roundwood. Of these, only 73 mills had licenses to extract more than 1000 m^3 of solid round-wood per year (Appendix 2.2). Assuming 70% harvesting recovery of the total aboveground standing stock, and 37% processing recovery rates from the roundwood delivered to sawmills, up to 150,000 m^3 of material was calculated to be left in the field as forest arisings. A total of 129,500 m^3 (92,500 t) was recovered as solid timber during that period. Thus, up to 158,000 t of primary wood processing residues were generated, 132,000 t being solid residues including off-cuts, slabs, trimmings and bark.

2.3.2 PRODUCER GAS POTENTIAL

The principles and technology of air gasification, including products, products distribution and quality is presented in chapter 5. The air gasification of 1 kg of air dry (up to 15% moisture content, wet basis) wood with bark in a downdraft gasifier yields between 2.1 to 3.0 Nm^3 of dry dust free product gas. The gas is composed of 9.5-12% H_2, 53.8-60.2% N_2, 18.9-22.8% CO, 1.8-2.3% CH_4 and 7.9-10.3% CO_2, and has a gross heat value of 4.6-5.5

MJ/Nm^3. The gross heat value of the stoichiometric product gas air mixture before combustion in an internal combustion engines is 2.2-2.4 MJ/Nm^3. ESMAP (1990) used a factor of 2.185 m^3/kg of dry wood. Assuming these lower factors and using the lower heat values of the gas (4.6 MJ/m^3) from direct firing of the gas, then 10 MJ (or 2.73 kWh) thermal can be generated from 1 kg of wood. Assuming a 27% conversion efficiency, the electric power potential from 1 kg of wood was taken as 0.754 kWh. In a co-generation system (electricity/heat) with overall efficiency of 80%, another 1.4 kWh of heat could further be generated for every 1 kg of wood used.

Potential from gazetted forests and from farm forestry activities

Gazetted forests in Kenya were restricted with limited primary firewood harvesting activities. The extent of the gazetted forest was considered limiting for the day to day operation of gasifiers for electricity production. Besides, most forests were far from major village clusters. It was considered that gazetted forests were not a potential source of primary feedstock for decentralised gasifier operations during the time of the study, and into the near future.

Although the householders interviewed were actively involved in tree growing and utilisation activities, the 0.7-4.6 m^3 average tree standing stock on the farms (table 2.3) was considered inadequate for continuous operation of a privately owned small scale downdraft gasifier. The limited biomass stocks on the farms require other intervention measures to encourage biomass production such as from short rotation forestry (SRF). However, this would be limited by the farm sizes, being an average of 0.66-6.88 ha/household.

Potential from wood processing residues

Appendix 2.2 lists the 73 largest sawmills in Kenya, each of which extracted more than 1000 m^3 (720 tonnes) of logs per year. Each of these sawmills generated more than 72 t and 390 t of sawdust and solid residues per year respectively. These mills were considered suitable sites for installing a small to medium sized gasifier, having the minimum quantity requirements of biomass feedstock to supply it. Of interest to this project was the large particle size of the solid residues totalling over 100,000 t/y, and at sawmills producing at least 1 tonne of material per day.

The potential from sawdust was not included being limited by minimum fuel particle size requirements for current designs of downdraft gasifiers. Similarly, the potential from forest harvesting residues were not considered as the present harvesting technologies and policy structures would not result in significant changes in harvesting and collection of this material.

The total gas yield from gasifying residues from the 73 major sawmills (Appendix 2.2), was 221 x 10^6 m^3 every year, equivalent to 24,000 tonnes of oil per year. Although the gas could be used for direct heating, the main focus was for electricity production on a decentralised basis. A typical mill would have sufficient annual feedstock to generate up to 300 x 10^3 kWh electric (total 76.166 GWh/y), plus another 581 x 10^3 kWh thermal (total 141.422 GWh/y) in a co-generation system. To put it into perspective, the total potential of 76 GWh (electric) from the 73 sawmills is equivalent to 12-16% of total national domestic load; or 133-282% of the total irrigation load. The power could supply the total annual domestic load for West Kenya, Mt. Kenya, and the North Rift regions (KP & LC, 1995). Given maximum overall efficiencies of a biomass gasification system in the order of 17%, and operating efficiencies of 7-10%, it was concluded that all the mills listed in appendix 2.2 could meet the feedstock requirements of a small scale gasifier, utilising a minimum of 1 air dry tonne of solid wood residues per day. Each of the sawmills listed provides a potential site for a demonstration unit.

2.3.3 SMALL-SCALE BIOMASS ELECTRICITY SYSTEMS

The national energy profile analysis above demonstrated growing trends in energy consumption, and a reliance on biomass. The use of, and future growth of conventional commercial energy supplies were assessed to be limited at least in the foreseeable future, being expensive to import. The largest supply growth was for electricity which does not yet match the demand, and the gap is widening (Kenya News, 1996). This reality has been appreciated by the Kenyan government which opened up the generation sector, under the Independent Power Producers (IPP) project. This was expected to increase the capacity by up to 88 MW by 1997, and up to 499 MW by the year 2002 (Economic Review, 1997). The IPP scheme provides an opportunity for biomass electricity systems to be demonstrated.

Although farm forestry is common practice in densely populated regions in Kenya, the nature of configurations using different types of species, the concentration and quantities of tree stocks on any one farm (averaging 0.7-4.6 m^3 per household) were considered inadequate for the continuous operation of a biomass gasifier-electricity system. Farm sizes were small, and only able to support subsistence fuelwood and wood product needs. Utilisation of purpose produced biomass from SRF schemes was in doubt at the present time as the concept was poorly understood.

The 42 householders interviewed and the sawmills visited were enthusiastic about the technology (based on photographs of a prototype set-up and explanations of how it works). Although a financial and economic assessment of gasifier systems was not undertaken, the ability of the majority of households to support such an installation on an individual basis was not feasible since families in the rural areas had an average annual paid income of less than US $ 400. This income supplemented the on-farm subsistence activities whose value was not established.

In the absence of actual income levels, the willingness and ability of the householders to pay for electricity was evaluated based on the estimated expenditure on alternative energy to supplement biomass, particularly for lighting and entertainment - illuminating kerosene, US $ 3 - 5; and dry cells, US $ 3 - 6 per month. This total expenditure (US $ 6-11, equivalent to KShs. 340-620 per household per month) was considered adequate, as most households could then afford the services of electricity for basic requirements (lighting and entertainment). Further, households with television sets required an extra US $ 3-5 for charging batteries per month.

Market conditions for the power generated were assessed to be good. The population is concentrated in rural areas which were not connected to the grid, and where demand was high for activities requiring electric power. Other community-based activities that could provide markets for the power included water pumping, rural industries, food processing facilities, and isolated health centres requiring basic sterilisation and refrigeration facilities. The wood processing plants where the gas would be generated are accessible, and well-placed to provide markets for the electricity produced, either for industrial or residential use. The waste heat could be utilised in some installations such as timber kilns. Thus, there are opportunities to displace some of the energy used currently (diesel, petrol, and grid electricity) with locally generated heat and electric power.

The greatest opportunities for wood gasification in terms of resources were thought to be in the wood processing industries which have large quantities of wood wastes, coupled with the desire to obtain a more reliable power supply to counter frequent power cuts. Low feedstock delivery costs, reduced wood waste disposal costs, and the guaranteed markets for the power generated are significant reasons for siting such plants at wood processing facilities. The distribution of the mills throughout the country implies that the power generated would be decentralised and generated at points of use, thereby mitigating transmission losses.

The capital costs of gasifiers may currently appear high, but could be significantly reduced if the plants could be locally manufactured. It was felt that a change in government policy regarding generation, marketing and use of electricity; construction of a demonstration plant to show the potential and opportunities offered by biomass gasification; and availability of external support in the form of financial resources to support the scheme, would enhance adoption of the technology.

Demonstration unit requirements

Figure 2.3 illustrates the factors that may determine the feasibility of biomass-electricity systems emphasising demonstration unit requirements including (i) the identification of opportunities; (ii) identification of policy structures favourable for private generation, distribution, and the marketing and sale electricity generated from decentralised sustainable systems; (iii) assessment of the market for the power generated; (iv) assessment of the biomass feedstock supply; (v) choice and development of the physical facilities; and (vi) the assessment of technical labour requirements.

Although the figure demonstrates the many factors influencing the siting, and the success of a biomass gasification system for electricity production, the present analysis emphasised wood supply strategies. Thus, the study recommended installations at sawmills processing more than 720 tonnes of logs per year and generating more than 1 tonne of solid residues (slabs, offcuts, trimming etc., but excluding sawdust) per day which could be used as feedstock. This has the potential to supply a gasifier to generate more than 0.3 GWh (electric) and another 0.558 GWh (thermal) in a co-generation system. Since many rural households are characterised by low loads, this electric power would be adequate to supply up to 160 domestic consumers (assuming that each household falls within the national average consumption of 1820 kWh/y). A village installation could be smaller than installations at sawmills, and therefore require less feedstock. The importance of biomass supply was also demonstrated by Durst (1986), by Stassen (1993), and by Cort'e (1989), while ETSU (1993) and ESMAP (1990) showed that the economics of gasifier installations depended on the capital cost, in particular per kW of capacity; electricity value, heat value, fuel cost, and the plant viability (i.e. operation hours per year).

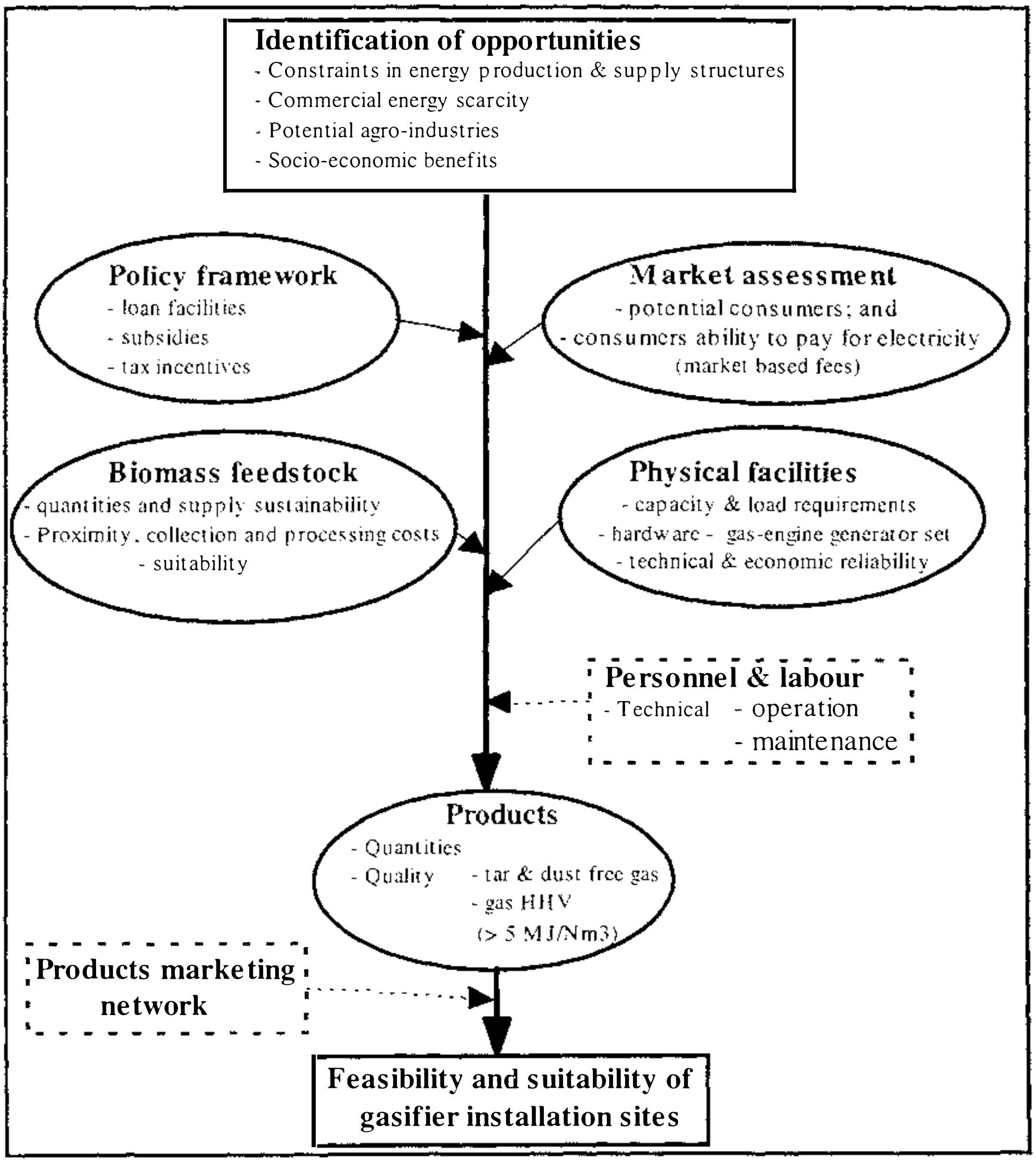

Figure 2.3 **Biomass-electricity systems demonstration unit requirements**

For demonstration purposes, the physical facilities required include the actual gasifier (with the associated gas cleaning attachments), an internal combustion engine modified to utilise the low calorific value product gas, and an alternator coupled to the engine to generate electricity. Other requirements include the availability of personnel with the operation and maintenance skills to run the plant; an electricity distribution network to the consumers, and policy structures favourable for the introduction of new electricity generating technologies. There must be markets to absorb the electricity generated, and availability of subsidies or tax relief on capital investment. The possibility of loan facilities for the pioneering plants may be added incentives that the Government could offer, while a market based fees (user pays) system could be put in place following successful demonstration to phase out any subsidies.

The high costs and the erratic nature of distribution of fossil fuels and grid electricity in Kenya, and the abundant nature of woody biomass material at sawmill sites makes gasification a possible contender to supplement the conventional energy supplies used by sawmills. Once the wood gasification technology is better understood and becomes more widely accepted, the expensive polluting diesel generating plants could be phased out, being replaced by locally grown cheap woody biomass and locally manufactured gasifiers for stand alone remote area power generation. The Government of Kenya should consider sponsoring technical expertise to advise on the operation and maintenance of gasifier plants. Also, commercial gasifiers need to be compared and one selected for the gasifier demonstration. Although a financial and economic evaluation of such a scheme would form an important aspect, it may not indicate the true economic and environmental value of the venture, given that the project would be in the experimentation/demonstration stages. It would enable a complete life cycle analysis to be undertaken to provide accurate data when evaluating other potential installations.

2.4. CONCLUSIONS

The commercial energy sector of Kenya is under-developed, being constrained by primary energy supply, availability and costs. Electricity supply reliability problems, particularly in rural areas, result from the centralised generation facilities giving priority to urban areas, and also the long distribution distances leading to high system losses from an already inadequate supply. The cost of line erection and maintenance does not warrant the relatively small demand for power in many rural areas, which are therefore not connected to the national grid.

Generation of electricity from biomass on a decentralised basis in Kenya is considered technically feasible, and has good potential as a means of developing local energy resources. The greatest opportunities are dictated by the availability of quality feedstock and financial investment backup, and are coupled with the need to diversify power supplies. Wood processing plants with annual log intakes exceeding 720 t/year were the most suitable potential users to develop bioenergy systems. A survey showed that there is potential fuelwood available mainly from sawmill residues to generate up to 76 GWh (electric) annually, equivalent to 12-16% of the total national domestic load. If co-generation systems could be used, an additional 141 GWh of heat could be generated and used for steam raising or industrial process drying of timber etc.

Use of purpose grown biomass from farm forestry plantations in rural areas to supply a gasification system is not practical due to a lack of available land and limited knowledge. It however holds potential for the future. In the longer term, SRF schemes may intensify biomass production by farmers, thereby improving the possibilities for village scale gasifier projects and community based power plants on a scale smaller than the sawmill installations might be. Ideally, a village or community gasifier to supply about 80 households with electricity would require about 0.5 tonne of air dry biomass feedstock daily.

Financial support from the government for a demonstration plant based at one of the larger sawmills is recommended to raise the awareness of biomass gasification, and to encourage investment in other plants. With careful management, small-scale electric power generation from biomass could provide an efficient use of this renewable natural resource, and be an alternative to expensive (by Kenyan standards) and polluting fossil fuels. Intensifying the use of the biomass resource would provide a stable economic base for the forestry and agricultural sectors. It would also generate employment (Sims *et al*, 1991) while at the same time reducing the country's dependence on imported oil, with consequent savings of foreign exchange

CHAPTER THREE

SHORT ROTATION FORESTRY SPECIES EVALUATION

PREAMBLE

Chapter 2 demonstrated the feasibility of small-scale biomass-electricity systems on a decentralised basis in Kenya. The country was used as an illustrative example of a developing country. Although there is good potential for bioenergy, the location and siting of a gasifier system was constrained by the availability of biomass feedstock in sufficient quantities and quality. Since there was a lack of understanding of the potential of short rotation forestry (SRF) systems by the rural inhabitants, suitable sites were limited to sawmills where large quantities of processing residues were potentially available. This chapter investigates methods of intensifying biomass production from SRF systems to supply isolated gasifier installations in rural areas. Chapter 4 will investigate the properties of biomass from a range of SRF species, while chapter 5 will evaluate the suitability of SRF biomass as feedstock for downdraft gasification.

3.1 INTRODUCTION

The concept of biomass production from SRF entails planting fast growing trees at higher stocking densities (>3000 stems/ha) than used in conventional plantation forestry practices; harvesting the trees at relatively short intervals of 1 to 10 years; and either replanting or allowing the trees to coppice (resprout) into the next crop. The objective of the high stocking density is to achieve rapid canopy closure and high productivity (Senelwa and Sims, 1997a) to optimise the quantity of solar energy stored (GJ/ha/y).

As an energy resource, the advantages of SRF systems over conventional forestry practices include:

i) higher above-ground biomass yields per unit of land area, which suits more densely populated areas where demand for fuelwood often exceeds supply;
ii) early amortisation of plantation establishment costs;
iii) increased efficiency of cultural operations due to the possibility of complete mechanisation;
iv) if using a coppice regime, SRF systems involve reduced plantation regeneration costs after each rotation (relative to seedling planting); and
v) easy selection of the characteristics of the biomass produced giving uniform feedstock quality to suit specific biomass conversion systems after minimal preparation.

SRF systems also have significant drawbacks:

i) the initial plantation establishment costs per hectare are very high due to the number of seedlings required which increases the financial risk involved;
ii) potential planting sites for SRF systems tend to be limited in that steep country is unacceptable where complete mechanisation is envisaged;
iii) the relatively uniform genetic make-up of the trees grown in mono-culture stands increases the risks of epidemic diseases and insect hazards;
iv) research on optimising yields with regard to species choice, stocking densities, rotation length and other silvicultural requirements is limited, often inconclusive, and tends to be site specific.

For SRF systems to be economically sustainable, their performance in providing a reliable source of energy should be gauged on the gains to be made in terms of optimizing the yields obtainable. Where practical, only the highest yielding species should be considered for SRF. For a particular region, emphasis should be placed on the yield potential which requires a system of grading performance of a range of species. Selection and suitability of a species could thus be based on its relative advantages over a range of parameters incorporated into a relative yield index (RYI). The RYI methodology shows the comparative potential of a range of species for a specified region, and may also be tailored to provide a rating of suitability for defined applications.

3.1.1 **OBJECTIVES**

The objectives of this chapter were to:

1. establish a method for comparing the relative suitability of a range of short rotation forestry species for biomass production (in this instance grown in a temperate climate);

2. develop a methodology for the evaluation and selection of species for biomass production, using relative yield indices (RYI); and

3. demonstrate SRF biomass production requirements for a village gasifier system.

3.2 BIOMASS YIELDS AND ASSESSMENTS

Five aspects of biomass production were considered: (i) short rotation forestry (SRF) species and yield; (ii) the influence of silvicultural treatments; (iii) yield equations and tree biomass estimation in SRF systems; (iv) yield optimisation; and (v) relative yield indices and species selection.

3.2.1 YIELD IN SHORT ROTATION FORESTRY (SRF)

Biomass yield defines the net primary production of a biological system, but Schmidt (1973) designated conventional forestry yield as the potential of using given space. The focus in conventional forestry systems is on round wood yield (volume basis), with little emphasis on dry matter production. In SRF energy systems, emphasis is placed on above ground dry matter production, although Verma and Misra (1989) expressed the biomass produced in terms of energy production (MJ/ha/y). The distinction between yield measurement units in both conventional and SRF systems emphasises the different product types, and shows that the two systems may not be in direct competition with each other.

Forestry yield differs among different climatic conditions; among species and even among clones of the same species; and also among different growing (localised stand and silvicultural) conditions. Such differences are illustrated in figure 3.1 which presents a comparison of the highest biomass yield data from different regions of the world. The data was based on a range of assumptions including (i) the yield include stemwood, branches, and foliage, and that the stems were not debarked; (ii) all weights reported are dry weights, and where otherwise stated, the data was converted to dry weight; (iii) the unit of measure was assumed to be the imperial tonne.

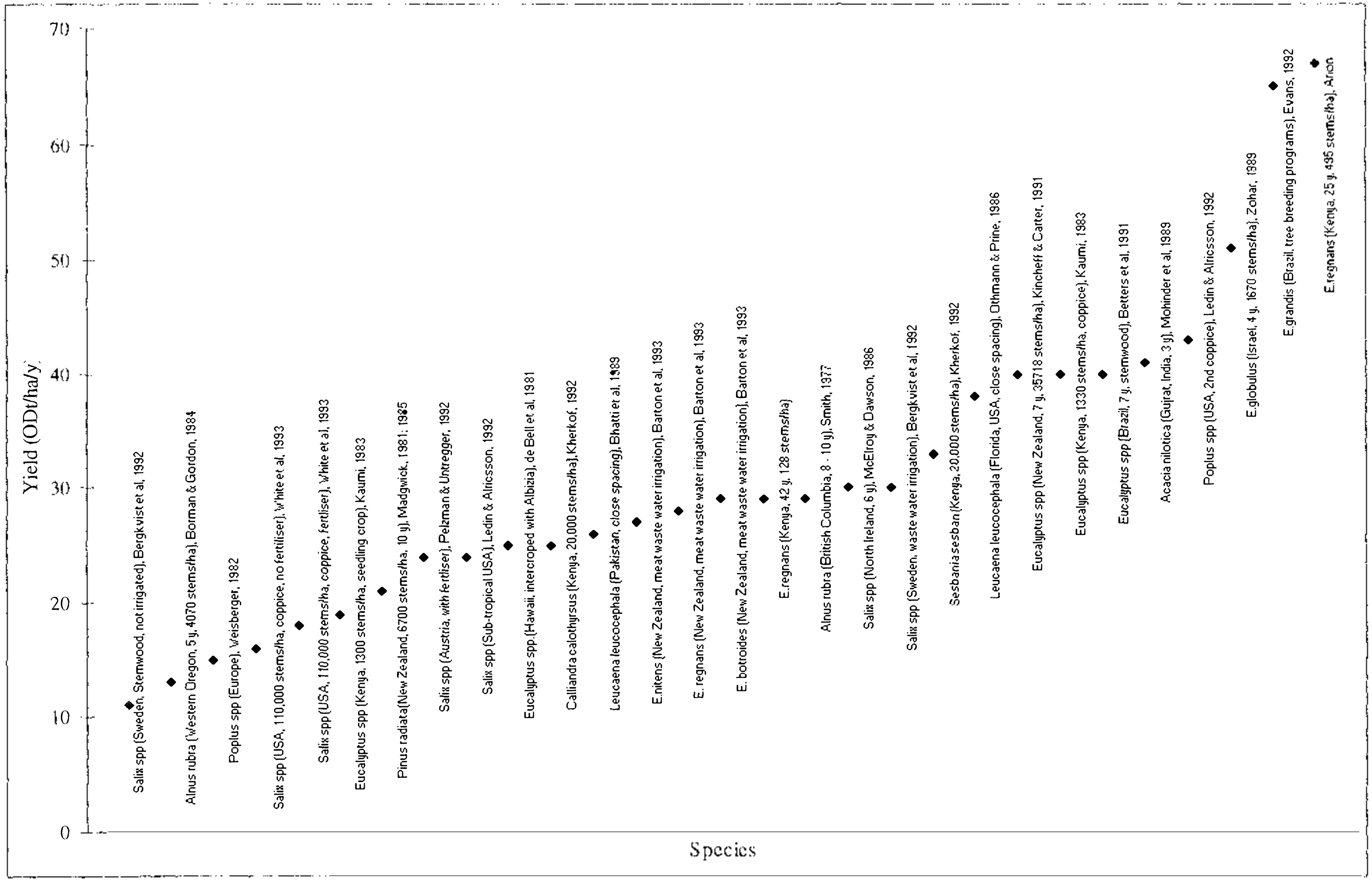

Figure 3.1 **Reported maximum yields data of different tree species from different regions of the world**

Although Cannel and Smith (1980) indicated similarities in many studies when they reviewed different yield studies using "yield-age-planting density relationships", figure 3.1 highlights striking differences obtained among regions; between intensively and non intensively managed crops; among different species; and even among clones of the same species. The differences suggest that successful cultivation of different crops in different regions may occur if the silvicultural requirements are identified and defined. Eucalypts were the most widely planted species; had the widest global distribution being planted in the tropics and sub-tropics; and had the highest recorded yields (up to 65 ODt/ha/y). *Salix* species and *Populus* species have been planted in the temperate regions.

3.2.2 INFLUENCE OF SILVICULTURAL TREATMENTS ON BIOMASS PRODUCTION

The production systems used in short rotation forestry can be divided into single stem or coppice (Mitchell *et al*, 1991). The former utilises conventional forestry species, both hardwoods and softwoods while the coppice system utilises hardwood genera such as *Populus*, *Eucalyptus* and *Salix*. Once the first rotation of establishment cycle or primary crop in a coppice system is harvested, the cut stumps resprout to provide another harvest and can continue to do so for several rotations depending on the life of most of the plants comprising the plantation. The sprouting shoots grow rapidly after harvest because the roots already have established access to soil water and nutrients, and also contain stored carbohydrates which help sustain rapid regrowth rates (Steinbeck, 1981). Other silvicultural considerations in biomass production include stocking density and rotation length.

Stocking density

The stocking density of a plantation defines the spacing among specific trees, and the number of trees planted per unit area of land (stems/ha). In theory, it shows the space available for the growth of each tree, understood to determine the nutrients availability, light interception etc. by the plant in relation to neighbouring plants. Therefore, stocking density determines the net primary production of the tree. However, the effect of spacing varies with species (Geyer *et al*, 1985).

Many assessments of the influence of stocking density have been made with a wide range of variables. Kincheff and Carter (1991) used a "Nelder" experimental design (Nelder, 1962) to show that yield (MAI) in *Eucalyptus nitens* increases with stocking density up to a peak for each population before starting to decline. Other studies have reported near linear relationships between stocking density and yield for a range of species (Sennerby-Forsse, 1992; Kincheff and Carter, 1991; Parrotta, 1989; Geyer *et al*, 1987; McElroy and Dawson, 1986); while Harrington and Fownes (1996) demonstrated that the time the stand takes to reach peak MAI decreases curvilinearly with increasing planting density.

Kincheff and Carter (1991) reported yields of 32 and 40 ODt/ha/y at 5861 and 17,414 stems/ha respectively for 7 year rotations in *E.nitens* in Northland New Zealand. Parrotta (1989) found yields of 22, 30 and 19 ODt/ha at stocking densities of 2500, 10000, and 40000 stems/ha respectively in *Albizia lebeck* in Puerto Rico, while Tomovic (1989) reported yields of 11.9, 20.4, and 26.3 m^3/ha/y at 320, 682 and 1310 stems/ha respectively in a *Poplus* species trial in Yugoslavia. Kherkof (1990) reported yields of 34 and 62 t/ha/y fresh weight at 10,000 and 40,000 stems/ha in *Calliandra calothyrsus,* and 62 and 81 t/ha/y at similar stocking densities in *Sesbania sesbans* in Kenya, while Frison *et al* (1990) reported yields of 14.5 and 9.5 ODt/ha/y at 6500 and 2770 stems/ha respectively in a poplar plantation in Italy.

Other recent stocking density trials involved the "Woodgrass" concept in which trees are planted at very close spacing (up to 440,000 stems/ha), and targeted for harvest every year by mowing (DeBell *et al*, 1989; DeBell *et al*, 1993; White et al, 1993; Hielman *et al*, 1972). Though the concept allows easy harvest by mowing (i) the yields reported are low, ranging from 6-16.6 ODt/ha/y (DeBell *et al,* 1989; DeBell *et al*, 1993; White, 1993; Hielman *et al*, 1972); (ii) the establishment and production costs are high; and (iii) the plantation life-span is reduced following continuous annual harvests placing stress on the stools (without providing for adequate recovery time) resulting in exhaustion and high mortality of the stools with a subsequent decline in growth and yields (Kaupi *et al*, 1984). Hielman *et al*, (1972) showed that except for the first harvest, very close spacing (111,100 stems/ha) was not necessary for maximum production. This suggests that the "woodgrass" concept involves stem numbers which are far above the optimal peak for most species and thus less productive. Thus, the woodgrass system has been regarded as unsustainable, and will not be discussed further.

As well as yield, plantation stocking density influences individual plant size and tree dimensions. Maclaren *et al* (1995) reported marked differences in mean tree height with stocking density (25.4, 27.6, 30.1 and 33.5 m at stocking densities of 47, 95, 193 and 385 stems/ha) in a 20 year old *Pinus radiata* agroforestry plantation in New Zealand. Kincheff and Carter (1991) showed that tree size (total dry weight per individual tree) in closely spaced plantations was lower than trees from widely spaced plantations as would be expected from the increased competition.

Figure 3.2 provides a generalisation of the influence of stocking density on tree dimensional properties and yield in short rotation forestry.

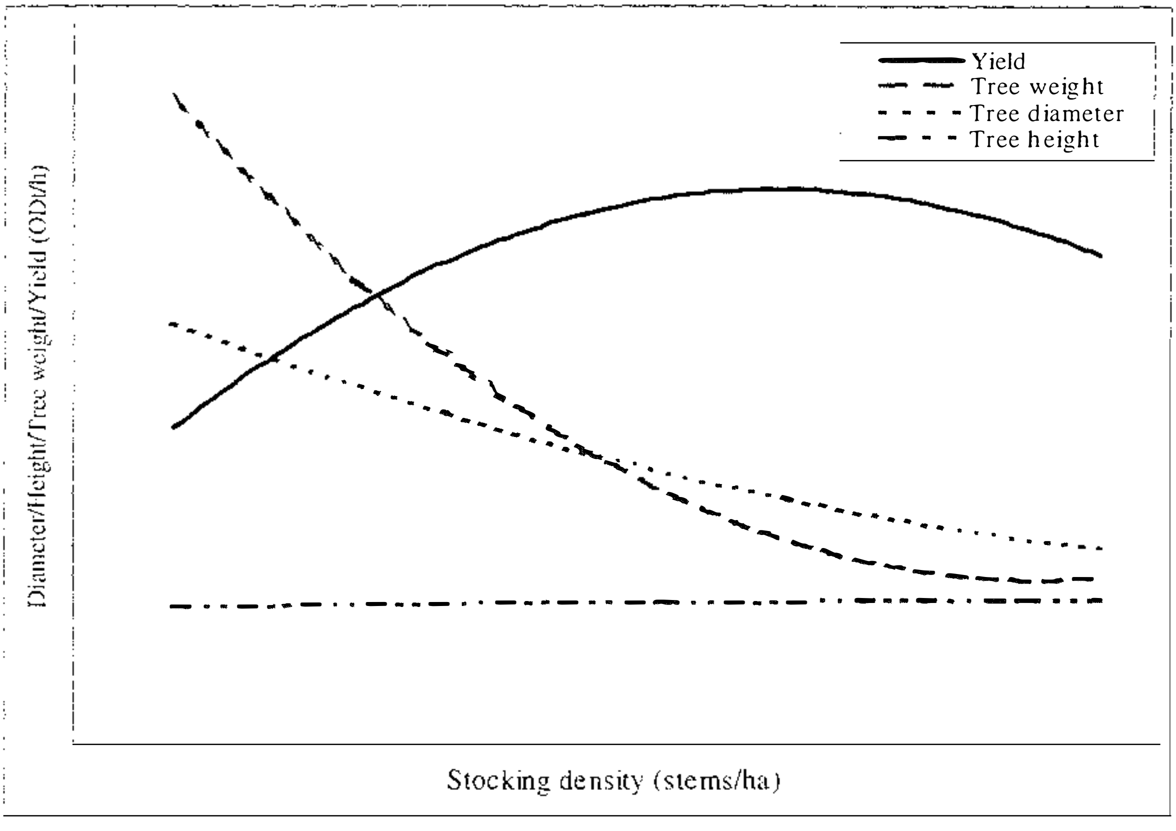

Figure 3.2 **Illustration of the influence of stocking density on tree size and yield in SRF**

In conventional forestry where stem form and maximisation of the individual tree size are the primary goals, the practice is to start with close spacing (1000-2500 stems/ha) which encourages rapid height increase, minimal branching in the juvenile stages of stand development, and reduced weed problem due to rapid site capture and canopy closure. For biomass energy crops where rapid canopy closure to control weeds is a requirement, and where the aim is to maximise total biomass yield (ODt/ha/y), and not necessarily stemwood volume, close spacing is essential. It is essential to examine outputs at different densities to determine optimal situations for different species, products, and regions. Although many conflicting results have been reported, it could be concluded that decisions on the number of trees or stems planted per hectare (stocking density) depend on species, site, type of product desired, rotation length, type and level of mechanisation, and the cost/revenue relationships.

Rotation length and periodic growth pattern in trees

Rotation length is the time (y) the crop of trees is allowed to grow before harvesting. There are many types of rotations but in SRF schemes, the more relevant rotations include the technical and financial rotations, and the rotation of maximum volume production. The technical rotation yields the most product of a specified size and type of biomass to satisfy a particular end user; the financial rotation yields the highest financial return under a particular set of conditions, while the maximum volume production rotation yields the greatest average annual product (Evans, 1992). Most rotations overlap to optimise on the different types. In practice, the type of product desired, being that which fetches the highest economic return, overrides most other decisions. Thus, an economic generalisation applicable to any crop nearing the end of the rotation is to fell it once the current value increment (the increase in stand value due to each year's new growth) falls below the maximum mean annual income of the stand. This is the financial equivalent of the point at which the current annual increment (CAI) falls below the mean annual increment (MAI) (figure 3.3). This also coincides with the point of the greatest total physical product from the site over time. It also signifies a point where the site's ability to provide nutrients to the crop starts declining, and where competition sets in, reducing the plant's growth vigour, and leading to excessive mortality.

The rotation length has a significant influence on the yield on forestry plantations. In Ireland, McElroy and Dawson (1986) reported mean annual increments of 9.0, 12.0, 14.6, 16.0. 20.5 and 30.7 ODt/ha/y for 1- 6 year rotations of willows planted at stocking densities of 20,000 stems/ha. Strause *et al*, (1990) found the period taken to attain maximum MAI in *Populus* hybrids planted at a stocking of 20,800 stems/ha varied with different rotations, and depended on whether fertiliser had been used or not.

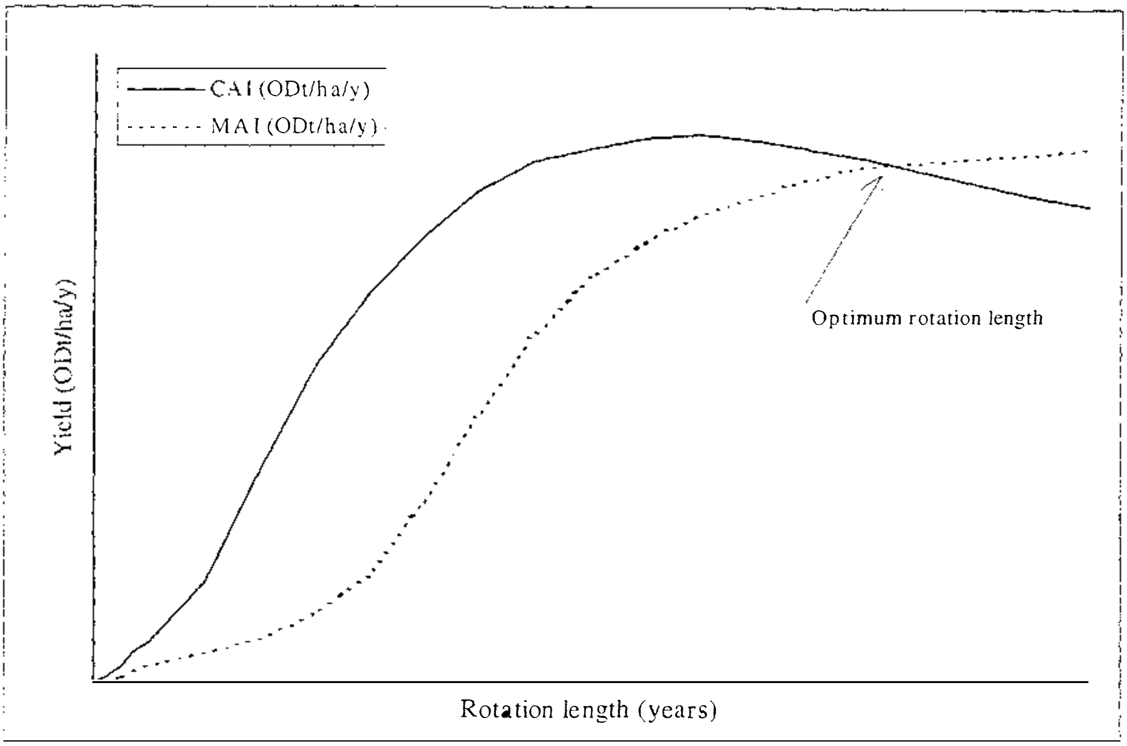

Figure 3.3 **Determination of optimum rotation age (MAI/CAI curves)**

Tree growth follows a defined pattern which can be expressed as a sigmoid (S-shaped) yield function which indicates that (i) the growth of plants is time dependent; (ii) the yield of a stand signifies the cumulative yield of the trees that comprise the stand; (iii) the longer the rotation, the higher the harvestable total yield; and (iv) the mean annual increment (MAI) of the stand increases over time to a maximum and then decreases over the remaining years (Geyer *et al*, 1985; Fraser *et al*, 1981; McElroy and Dawson, 1986; Hielman and Peabody, 1981; Strause *et al*, 1990). The age of the tree when maximum annual productivity is reached, and therefore the choice of optimum rotation length which may vary with species can also be influenced by other silvicultural factors and site quality. In dense plantations, the maximal yield is reached much earlier in the rotation cycle (Sennerby-Forsse *et al*, 1992). The choice of optimum rotation is particularly critical for close spacing generally associated with SRF systems because the average productivity decreases significantly once the optimum rotation is exceeded (Fraser *et al*, 1981).

The economic solution derived by determination of net present value (NPV) of the site may be different from the more traditional approach that determines the maximum physical output capability of the production site. The maximum MAI approach does not ensure an economic solution since the revenue and cost parameters of the proposal are ignored including the invested cost of the money over time (Strause *et al*, 1990). Besides, economic rotations for most stands tend to be shorter than the maximum MAI rotations due to the discount effect on future revenue earnings. The maximum product criteria (figure 3.3) can be used as a first guide of rotation estimation.

Coppicing

Coppicing describes a physiological feature in some plants where shoots may resprout from dormant buds on the stool, from adventitious buds in the cambial layer around the edge of the cut stem surface, or from ligno-tubers in some species (Evans, 1992; Sennerby-Forsse *et al*, 1992). The ability to coppice, and to withstand repeated harvesting is widely variable among different species, and is influenced by both internal and external factors. While most broad leaved species (angiosperms) coppice well, most gymnosperms do not coppice at all. This poor or zero coppicing ability could be associated with the lack of one or all of the coppicing physiological requirements. For instance, the lack of ligno-tubers in *E.delgupta* and *E.nitens* has been used to explain their poor coppicing ability among the eucalypts (Evans, 1992).

Coppice yields vary with species, stocking density, rotation length, age of the root stock, and may be higher than the yields from the first rotation harvests. In Sweden, yields of up to 12 and 36 ODt/ha/y have been achieved in willow coppice regrowth in field and research plantings respectively (Christersson, 1986; Sennerby-Forsse *et al*, 1986). In Kenya, Kaumi (1983) found that the first coppice rotation of a *Eucalyptus* species yielded about 200% of the establishment rotation; the second coppice rotation yielded about 150%, while the third crop was similar to the establishment rotation. Dyson (1974) reported yields of 11 ODt/ha/y in the establishment rotation of *E.saligna* and *E.grandis* compared to 17-23 in the first coppice rotation, but declined to 13-15 in the second coppice over 5 year rotations in Kenya.

In Poplar clones, yield of the coppice rotation was found to increase at each harvest reaching a ceiling yield in the fourth coppice rotation (14.92 ODt/ha/y) before starting to decline to the first rotation yield (8.1 ODt/ha/y) in the ninth rotation (Frison *et al*, 1990). Yield in subsequent crops decline following stump mortality due to increased risk of pests and disease infection; internal disturbances which reduce the stocking density; production of coppice stems which `mature' earlier, and the exhaustion of the site requiring nutrient replenishment.

The length of coppice rotation is governed by the size of roundwood required. However, longer harvesting cycles are favoured due to increased total biomass yields. The overall age of the stand before replanting depends on the stool mortality and the resprout vigour. Three to four coppice rotations have been found workable with most species even though some exceptions have been reported (Jacobs, 1981; Pawlick, 1989). Stump mortality has also been found to vary with species (Sims, 1996; Stubbings and Schonau, 1979; Kaumi, 1983).

3.2.3 SRF SPECIES EVALUATION - A MULTI-OBJECTIVE APPROACH

The choice of species in conventional forestry is normally based on the intended purpose of the wood products and the species that will grow best under the prevailing conditions of the site (Evans, 1992). Though these factors are important in SRF schemes, there are two short-comings which require attention (i) the consideration of one objective only in conventional forestry i.e. merchantable volume yield; and (ii) the species range in conventional forestry practice is narrow due to strict requirements of specific tree form, emphasising merchantable volume only.

Although maximum biomass production (MAI, yield/ha/y) is the most desirable characteristic when selecting tree species for a biomass energy system, there are other important consideration including i) availability of seed and ease of propagation; ii) good survival under adverse conditions; iii) multiple use potential; iv) ability to coppice if intended; and v) biomass fuel value and suitability for combustion and or other conversion processes. In evaluating a species for planting, it is therefore useful to incorporate as many attributes of the species as much as possible, including the best and worst characteristics. The use of the many facets in evaluating a species against competing species constitutes the "multi-objective approach" in defining the suitability of the species for planting.

Multi-objective approach techniques have been used to evaluate alternative energy resources. Ramanathan and Ganesh (1993, 1995) provided multi-objective evaluations for energy resources to meet household needs, and for water pumping. Chetty and Subramanian (1988) considered rural energy consumption patterns, while Kambo *et al*, (1990/1991) analysed the urban energy-economy-environment interaction. Cocklin *et al*, (1986) used the techniques to assess options in resource use with respect to establishment of forest energy plantations in

Eastern Ontario, Canada, and demonstrated the applicability of the system to natural resource problems. The methodology has not been applied in forestry / tree species evaluation even though it may provide a strong basis for species evaluation based on optimisation of preferred attributes. Senelwa and Sims (1997b) used the technique to evaluate the performance of a range of short rotation forestry species.

3.2.4 TREE WEIGHT EQUATIONS IN SHORT ROTATION FORESTRY

Short rotation forestry trees are often multiple stemmed and low branching. The techniques used to estimate conventional forestry products from standing crop have been found inadequate when applied to SRF trees as they do not consider the total biomass availability which is often the objective in SRF schemes (Tietema, 1993; Gwaze and Stewart; 1990; Senelwa and Sims 1997a). Thus, Verjwist and Nordh (1992), and Tietema (1993) found height to be less suitable for indirect determination of tree dry weight, and associated it to the non-linear relationship between the two variables. Wang *et al*, (1991), Mitchell and MacBrayne (1981), and Young and Francombe (1991) found that above ground biomass yield of a tree was more closely related to its basal area.

Senelwa and Sims (1997a) developed tree biomass equations to estimate total tree dry weight for five *Eucalyptus* species and also for *Acacia dealbata* and *Pinus radiata* trees grown under SRF schemes (Appendix R.1). The best model tested to estimate the tree dry weights of the five eucalypts (pooled model) incorporated the square of the stump diameter (D^2) and height (H). Thus, tree biomass could be predicted with reasonable accuracy from basal area and height measurements. Further, this study established the possibility of utilising one model to predict the tree biomass weights of a variety of species.

3.3 MATERIALS AND METHODS

Field trials were established at Massey University, Palmerston North, New Zealand to (i) evaluate the suitability of; and (ii) to define the effects of a range of silvicultural treatments on the growth and yield of a range of short rotation forestry (SRF) species.

Based on 35 years of data, the Palmerston North climate has about 50 days of frost per year, with average and gross minimum temperatures of 17.3°C and 9.1°C, respectively. The region receives about 970 mm of rain per year, and about 1740 sunshine hours. The soils are recent belonging to the Rangitikei soils series made up of well to excessively drained and gravely soils. The soil profiles are weakly developed, and variable in both depth and texture. Soil analysis on planting of the main species trial (August-December 1990) had a pH of 5.5-6.2; Olsen P of 6-17 mg/g; SO_4 of 2.8-8.5 mg/g; exchangeable K of 0.09 -1.37 mg/g; exchangeable Ca of 4.0-8.2; exchangeable Mg of 1.14-1.65; exchangeable Na of <0.1-0.32 mg/g; and a cation exchange capacity (CEC) of 14-16 meq/100 g air dry weight

Three trials were established:

1. species trial to investigate yield in 14 SRF species harvested at 3, 4, and 5 year rotations;
2. juvenile tree growth trial (to 2 years old) to investigate growth patterns and the influence on yield in 4 species planted at 2 stocking densities (6,940 and 16,440 stems/ha); and
3. "Nelder" (radial) design trial to investigate the influence of stocking density, rotation length, and coppicing on yield.

Both the species trial and the Nelder radial trial also provided materials for laboratory analysis of biomass energy properties (Chapter 4), while the 4 year old harvest of the species trial provided the feedstock for gasification experiments (Chapter 5). The trials did not involve the use of irrigation, fertilisers, or agricultural chemicals other than herbicides when first established. The trees were not pruned.

3.3.1 EVALUATION OF SRF SPECIES FOR BIOMASS PRODUCTION

Fourteen fuelwood species-*Eucalyptus ovata, E.saligna, E.nitens, E.globulus, Acacia dealbata, Paulownia tomentosa, Salix kinuyanagi, S.matsudana x alba* (1148), *S.matsudana* *x alba* (1002), *Alnus glutinosa*, *Pinus radiata*, *Poplus eridiano*, *Melicytus ramiflorus* (a New Zealand native species) and *Robinia pseudoacacia* were planted in 1990 in four separate blocks with each replicated plot of 46 m^2 containing 16 trees. The trees were planted at a spacing of 1.2 x 2.4 m to give a stocking density equivalent to 3470 stems per hectare. The replicate blocks for the species were located at 3 sites spread over 1 km of a river valley. Figure 3.4 shows one of the blocks of the different species when the trees were 3 years old, and ready for the 3 year rotation sampling.

Figure 3.4 **Species trials plots before the 3 year rotation sampling**

In November 1993, all plots were measured to establish the survival, growth vigour, stump diameter and tree height distribution by species. The selection of species and plots for sampling were based on survival rates, and biomass volume estimates of each plot. Where practical, plot evaluations, based on student t-tests to determine similarity in the selected plots were carried out using these non-destructive measurements. Diameter and height measurements were used to rank the performance of plots for different species. The two plots of each species with the highest survival rates, and depicting the highest quantity of standing stock were selected.

The plots selected were divided into four sub-plots, each containing 25% of the trees. One sub-plot was randomly identified and marked for harvesting at the age of 3 years in November 1993, leaving the other 75% of trees. In November/December 1994, another 25% was harvested and constituted the 4 year rotation yield. The remainder of the trees were harvested in December 1995, to give the 5 year rotation results. Thus both non-destructive and destructive measurements of the species trials were performed at the end of 1993, 1994, and 1995 (being the end of the growth year) to give three test rotations of 3, 4 and 5 years. The sampling technique was chosen because of the limited number of plots and plot sizes available.

3.3.2 GROWTH PATTERNS IN JUVENILE TREES

Four eucalypts - *Eucalyptus globulus*, *E.regnans*, *E.nitens* (NSW) and *E.nitens* (V) were planted in November 1993 at two stocking densities of 6,940 and 16,440 stems/ha (i.e. 1.2 m x 1.2 m and 0.78 m x 0.78 m respectively) in a randomised block design with 2 replicates of each plot. The tree height, stump diameter and crown diameter were measured every 3 months from 6 months to 2 years to determine growth variability of the four species at the two stocking densities. The plots were harvested in December 1995 when the trees were 2 years old.

3.3.3 SILVICULTURAL TREATMENTS - "NELDER" (RADIAL) TRIAL

A "Nelder" radial design trial (Nelder, 1962) was planted in October 1987 with *E.saligna* as part of a series of trials at Massey University investigating optimum rotation length and stocking density requirements for short rotation forestry for fuelwood and pulpwood production. The radial planting was divided into 12 segment blocks of 5 rows each, being three rows to measure with a guard row on either side. Each rotation period (2, 3, 4 and 5 years) was assigned three repetition segment blocks spaced equally round the circle as shown in Figure 3.5. Each intersection point between either the columns (C-1, C-2 etc.) and the arcs (1640, 3770, etc.) represent a tree. The arcs 1,640 - 16,260 represent the stocking densities (stems/ha), while the columns represent the replications for given stocking densities.

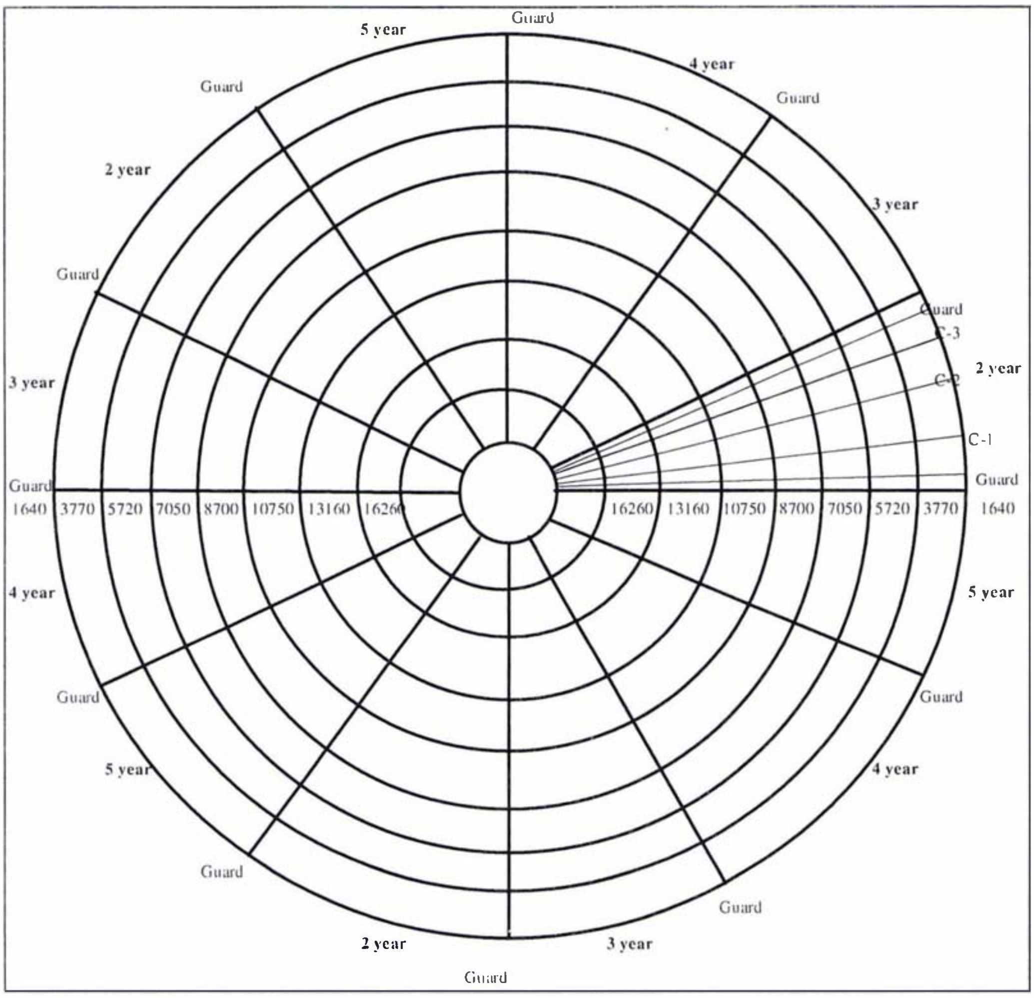

Figure 3.5 **The "Nelder" (radial) design trial showing sub-plots of 2-5 year rotations**

Figure 3.6 shows the aerial view of the "Nelder" radial trial after one of the harvests.

Figure 3.6 **The "Nelder" radial trial after the first harvest**

The blocks were harvested at the same time for any one rotation length. Sampling was conducted in November of every year with the 2 year rotation being harvested every 2 years, the 3 year rotation every 3 years and so on. Thus, three parameters were evaluated in the trial (i) stocking density - 1640, 3770, 5720, 7050, 8700, 10750, 13160, and 16260 stems/ha; (ii) cutting age (rotation length) every 2, 3, 4 and 5 years; and (iii) influence of coppicing - a comparison between the establishment stock and coppice rotations.

Rotation length (years) was also investigated in the 14 SRF species (3, 4, and 5 years, see section 3.3.1), while the influence of stocking density was also investigated in another 4 species trial that involved monitoring height and diameter growth at intervals of three months (see section 3.3.2).

3.3.4 SAMPLING AND TREE MEASUREMENTS

For each tree, the stump diameter (0.15 m above the ground) was measured to the nearest mm. In the case of multiple stem trees, all the stems were measured and the combined diameter calculated as the square root of the sum of squares of individual stem diameters ($\sqrt{\sum d^2}$), (MacDicken *et al*, 1991). The height (m) of each tree (or the tallest shoot when more than one) was measured.

On harvesting, trees were cut at 0.15 m above the ground, (referred to as stump height) using a power chainsaw, delimbed and cross cut at the 40 mm top diameter height to obtain the quantity of stemwood material. Trees with a stump diameter less than 40 mm were regarded as having no stemwood, and were therefore grouped as "other" material. Green weights of (i) total biomass (whole tree); (ii) stemwood (to 40 mm tdh); and (iii) "Others" (tops, twigs and foliage) were determined in the field to the nearest 0.1 kg using a calibrated load cell within a weighing frame (Figure 3.7). From each tree, representative samples of the stem, branches, twigs and foliage were collected for subsequent dry matter determination.

The laboratory stemwood samples were debarked and the different components weighed separately. The samples were oven dried at 80°C to constant weight, from which the green moisture content (dry weight basis), and dry matter were determined. Total yield and also stemwood yield in oven dry tonnes per hectare (ODt/ha) for each plot/species, the mean annual increment (MAI, ODt/ha/y), and the current annual increment (CAI, ODt/ha/y), were determined for each harvest. The harvest index (ratio of stem dry weight to total above-ground dry weight) shows the proportion of above ground dry weight that may be removed from the site.

Figure 3.7 **Sampling of fresh weight in the field**

3.3.5 ANALYSIS OF RESULTS

The General Linear Model and regression procedures of the SAS System were used in the analysis to indicate the correlation between various non-destructive and destructive measurements. Duncan's multiple range test was used to rank the performance of species, rotation length, stocking density and coppicing in all parameters investigated. Unless otherwise stated, tests of significance were performed at the 95% confidence level.

3.3.6 MULTI-OBJECTIVE EVALUATION OF SRF SPECIES FOR BIOMASS PRODUCTION

A species comparative evaluation was defined by measured attributes - age, height, diameter, tree size, stemwood yield, total biomass yield, and the harvest index. The aim of the evaluation was to select the "optimum combination" of measured attributes of such species.

The objectives incorporated into the model included:

a) total yield (ODt/ha) - maximisation;
b) rotation length (years) - minimisation;
c) piece size (average tree dry weight) - maximisation;
d) average stump diameter - maximisation;
e) average tree height - maximisation;
f) harvest index (stemwood to total above ground biomass ratio) - maximisation; and
g) stocking density (stems/ha) - minimisation.

All the objectives were quantifiable, being derived from the species sampling (destructive and non-destructive) results. The programme model optimising each objective was described by:

$$\text{Maximise } Z = \sum_{i=1}^{m} (m_1(x), m_2(x), \ldots\ldots m_k(x))$$

$$\text{subject to } x \in S$$

where $m_1, m_2, \ldots m_k$ are weights of the measured objectives derived as the exponential of the P-values obtained by regressing the total yield of all species and rotations against each of the other objectives; $x = (x_1, x_2, \ldots x_n)$, where x_j is an objective decision variable representing the net amount of source j; and S represents the constraints set, i.e., the limits within which the measured attributes or properties may lie. The objectives are expressed as targets, representing real values for individual species.

Z defines the species index factor which indicates the yield and suitability potential as identified in the trials given the specific growth conditions. It incorporates components for handling (piece size), harvestability and recovery potentials if machine harvesting is envisaged (harvest index factors), and the actual yield. Multiplying the index factor (Z) with MAI and the harvest index for each species harvest provides the non discounted relative yield index (RYI). The RYI may then be discounted at a suitable rate (10%) to account for the costs of investment, and provides the discounted relative yield index (RYI^{D}).

The general equations that constitute the objectives may be outlined as follows:

a) **Resource constraints**

- Land availability

  It was assumed that the amount of land available a_{ij} for production of all the species under different rotation managements was not a limiting factor in the SRF scheme. Land rent, site preparation and other costs in the species trials was assumed to be uniform to all species, the stocking density having been the same (3470 stems/ha). All uniform cost items were taken as unity (i.e. 1), and therefore did not influence the model.

- Biomass production, also defined as the mean annual increment (MAI, ODt/ha/y) for each species and harvest, taking into consideration the harvesting recovery factors was described by:

$$(\Sigma y_{ij} a_{ij} / I_j) h_i$$

  where y_{ij} is the amount of biomass yield (ODt/ha); a_{ij} is land (unity); I_j is the rotation length for each harvest; and h_i is the harvest index.

The harvest index of the different species and different rotations indicates the actual removable material given the possibility of reliance on machine harvesting utilising currently available machines developed for conventional forestry systems.

b) **Goal constraints**

- Economic efficiency in biomass production for a species X_i was described by:

$$\Sigma \{ [\sum_{t=o}^{I_j} \frac{R_{ijt} - C_{ijt}}{(1+r)^t}] I_j^{-1} \} a_{ij}$$

  where R_{ijt} is the per hectare return to species x_i and rotation system in year t (product of yield and price factors of the produce); C_{ijt} is the cost for producing a unit quantity for species x_i; per hectare; r is the rate of discount taken as 10% per year; t is time in years, I_j is the rotation length in years.

The assumptions underlying economic efficiency considerations are listed below.

1. The cost of time and money in the species trial for any one harvest rotation or similar year were constant having had the same stocking density. This was based on the assumption that the price of seedlings of different species was the same, though in reality this is not the case for *Salix* species and *Poplus* species cuttings.

2. The costs of site preparation, and plantation management were the same for the different species, and that the costs of harvesting a unit yield were similar.
3. Cost differentials resulted from the rotation lengths, most of which were assumed to be adequately addressed by monetary discount rates.
4. In defining the index for the "Nelder" radial trial, other costs besides the costs of money (taken as 10%/y) resulted from differences in stocking densities leading to higher establishment costs in denser spacing, and on whether the crop was establishment or coppice. One approach in the coppice management could be to spread the cost of seedlings by a factor through the life span of rootstocks, but the life of this coppiced crop is unknown.

It was assumed that all costs of production (C_{ijt}) for all species within the same harvest rotation (and spacing) were similar, and that the unit price of the produce (i.e. price/ODt corrected for the harvest index factor) was uniform. All pricing components were therefore considered unity.

The resultant economic efficiency model was therefore written as:

$$\Sigma \{ [\sum_{t=0}^{I_j} \frac{R_{ijt}}{(1+r)^t}] I_j^{-1} \} a_{ij}$$

Although the rate of discount "r" varies with region and time, a rate of 10% was used.

- Piece size optimisation

Piece size was defined by the average species total tree dry weight, mean tree diameter, and mean tree height in any defined species/rotation length combination. The programme aimed to optimise returns per species by maximising total yield, stemwood yield, and harvest index from the different rotations. Piece size requirements could in reality be restricted by harvesting machinery constraints.

- Harvest index maximisation

The need to maximise the ratio between stemwood and total above ground biomass was borne out of the assumption that machine harvesting was employed. High proportions of stemwood in relation to total biomass was therefore considered desirable.

- Stocking density minimisation

The influence of stocking density in the species trials was not considered having been similar in all the plots. It was therefore assumed that the costs of establishment (seedlings and site preparation) were uniform. Differences observed were therefore attributed only to species yield differences, and rotation lengths.

Unlike in the species trial, stocking density formed a major basis of evaluation in the "Nelder" (radial) trial as it influenced the tree growth and yield characteristics.

- Rotation length minimisation

The effect of time as a cost item was accounted for in the cost of capital as a rate of discount.

The return due to the species was based on the assumption that the material - species and piece sizes - had equal value. The harvest index corrects for the non merchantable material that may not immediately command market. Parameters which were uniform for all the species were taken to have unity value, and did not therefore influence the model.

c) **Weighting of goals**

The goal programme model required information on the relative preferences associated with respective goals. The preferences were incorporated as numerical weights (*m*) determined by the coefficient of correlation (R^2) in the regression between total yield and the goals. The weights were the exponential of the P-values from the regression analyses.

The best or optimal species was defined by optimising the objectives. The programme assumed that the best species for SRF systems was (i) high yielding; (ii) had a high harvest index; (iii) had a large piece size; and (iv) was grown in a relatively short time to reduce the costs of money over time. The numerical value obtained for each species and rotation length was the species **relative yield index (RYI)**, defined for different rotations, and which was used to rank the species and management system performance. The model was later extended to include the species energy characteristics (Chapter 4).

3.4 RESULTS

The results were distinguished under four sub-sections (i) short rotation forestry species - variability in growth and in biomass production; (ii) effects of silvicultural treatments on growth and yield in SRF systems, and yield optimisation; (iii) yield estimation in short rotation forestry; and (iv) short rotation forestry species evaluation.

3.4.1 SHORT ROTATION FORESTRY SPECIES GROWTH AND YIELD

Species evaluation

Out of the 14 species planted, only 12 species had survival rates of 75% and above when the reconnaissance survey was undertaken at the age of 3 years. Of these, only 10 were replicated in different blocks. *Eucalyptus saligna* and *Eucalyptus globulus* were not replicated and their results were based on one plot. *Melicytus ramiflorus* and *Robinia pseudoacacia* were abandoned as they had poor survival (up to 100% mortality in most plots). The low number restricted the value that can be placed on the statistical analysis.

All plots identified for continued monitoring at the age of 3 years had survival rates above 75%. Thus, the effective stocking density exceeded 2600 stems/ha, and since the plots were adjacent to each other, the need for guard rows was minimised even though Adams *et al*, (1973), Hühn (1974) and Tauer (1975) indicated that competitive interactions among neighbouring genotypes lead to serious overestimates of yields of the more competitive genotypes. Due to the variability in establishment and survival rates, experimental replication and blocking were not used to analyse the variability among different species, treatments, and plots. Data from the replicated plots were grouped to provide mean values used to evaluate the species. The results should therefore only be taken as broadly indicative of the species potential and performance under different cutting cycles.

Table 3.1 shows (i) the species survival rate when the trees were 3 years old and before the first harvest; (ii) average stump diameter (mm); (iii) height (m); and (iv) oven dry weights of the stem and whole tree (kg) for each of the 3, 4, and 5 year rotations. Although the tree diameter at breast height (dbh, ≈ 1.3 m from the ground), and the height of the trees to 40 mm top diameter (td) were measured, the results are not presented here since:

i. some species were low branching, while others were multi-stemmed such that a breast height diameter was not a good measure of growth for many of the trees;

ii. due to the age bracket and stocking densities considered in SRF systems, many trees had a dbh of less than 40 mm; and most did not have a (top diameter) td of >40 mm; and

iii. dbh and td measurements were found to be poorly correlated to SRF system yields (Senelwa and Sims, 1997a; Tietema, 1993).

Table 3.1 **Mean plot and tree characteristics at 3, 4 and 5 years old**[*]

	% survival	Stump diameter (mm)			Height (m)			Stemwood dry wt. (kg)			Whole tree dry wt (kg)		
Species	at 3 y	3 y	4 y	5 y	3 y	4 y	5 y	3 y	4 y	5 y	3 y	4 y	5 y
E.globulus	94	145	198	249 ^{a}	8.7	12.3	15.6 ^{a}	20.3	44.5	87.2 ^{a}	33.3	69.5	119.4 ^{a}
E.nitens	81	149	180	250 ^{a}	8.3	11.3	13.8 ^{a}	15.8	38.6	84.5 ^{a,b}	25.2	53.3	113.5 ^{a,b}
A.dealbata	88	122	158	223 ^{a,b}	7.1	9.1	11.3 ^{b}	13.7	27.1	50.4 ^{b,c}	24.1	40.6	78.9 ^{b,c}
E.ovata	81	98	162	202 ^{b}	6.3	10.0	11.5 ^{b}	5.9	22.0	43.4 ^{c,d}	11.2	35.3	64.2 ^{c,d}
S.mats x alba 1148	97	125	165	223 ^{a,b}	6.9	7.9	11.0 ^{b}	6.6	15.7	34.5 ^{c,d}	15.1	27.7	52.9 ^{c,d,e}
S.kinuyanagi	100	117	164	177 ^{b}	6.2	8.1	8.6 ^{b,c}	8.2	18.7	26.5 ^{c,d}	19.8	33.6	47.9 ^{c,d,e}
P.radiata	94	100	148	207 ^{b}	4.3	6.9	8.9 ^{b,c}	3.6	10.4	26.5 ^{c,d}	9.9	22.1	48.8 ^{c,d,e}
P.eridiano	88	117	145	216 ^{b}	5.4	7.7	10.4 ^{c,d}	4.7	7.3	31.0 ^{d}	10.6	12.7	48.1 ^{c,d,e}
E.saligna	75	98	122	117 ^{c}	4.7	6.2	5.7 ^{d,e}	6.0	5.7	13.5 ^{d}	13.3	11.4	21.7 ^{d,e}
S.mats x alba 1002	100	39	49	139 ^{d}	2.6	3.1	7.7 ^{e}	1.2	1.4	9.2 ^{d}	2.5	2.8	15.4 ^{e}
A.glutinosa	88	85	108	128 ^{c,d}	3.7	5.0	6.5 ^{d,e}	1.0	2.9	5.7 ^{d}	3.6	5.7	10.8 ^{e}
P.tomentosa	100	77	106	127 ^{c,d}	3.6	5.5	6.4 ^{d,e}	2.0	3.5	6.9 ^{d}	4.7	5.6	11.8 ^{e}
Mean	90	^{c} 106	^{b} 142	^{a} 188	^{c} 5.7	^{b} 7.8	^{a} 9.8	^{b} 7.4	^{b} 16.5	^{a} 34.9	^{b} 14.4	^{b} 26.7	^{a} 52.8
Std deviation	8	29	39	47	1.8	2.5	2.9	5.9	13.7	26.5	9.1	19.9	35.1

* - Average values with the same letter are not significantly different

The mean tree dry weight data in table 3.1 were multiplied by the stocking density (stems/ha) to show the total yield (oven dry tonnes per hectare, ODt/ha) for each species and respective cutting age. These data were divided by the rotation length (cutting age, years) to give the mean annual increment (MAI, ODt/ha/y). The current annual increments (CAI) between the 3rd and 4th years, and between the 4th and 5th years were calculated as the difference between the 4th and 3rd year and between the 5th and 4th year total harvests respectively. The proportion of stemwood weight (to 40 mm top diameter) to the total above ground tree biomass weight defined the harvest index (%). These total yield, MAI and harvest index results are presented in table 3.2 while Figure 3.8 provides a comparison of the mean annual increment (MAI) and the current annual increment (CAI) for the 12 species over the three rotations.

Table 3.2 **Short rotation forestry species biomass production in age series plots***

	Stem yield, ODt/ha				Total yield, ODt/ha				Stem MAI, ODt/ha/y				Total MAI, ODt/ha/y				Harvest index (%)			
Species	3 y	4 y	5 y		3 y	4 y	5 y		3 y	4 y	5 y		3 y	4 y	5 y		3 y	4 y	5 y	
E.globulus	71	154	265	a	116	242	363	a	24	39	53	a	39	60	73	a	61	64	73	a
E.nitens	41	134	220	a,b	66	185	295	a,b	14	34	44	a	22	46	59	b	62	72	75	a,b
A.dealbata	36	84	151	b,c	63	126	236	b,c	12	21	30	b	21	31	47	b,c	57	67	64	a,b
E.ovata	15	70	137	c,d	29	113	203	c,d	5	17	27	b,c	10	28	41	c,d	53	62	68	b,c
S.mats alba 1148	23	54	112	c,d,e	52	96	172	c,d,e	8	14	22	b,c,d	17	24	34	c,d	44	56	65	c,d
S.kinuyanagi	29	65	92	c,d,e	69	117	166	c,d,e	10	16	18	b,c,d	23	29	33	c,d	41	56	55	c,d
P.radiata	12	36	76	c,d,e	34	76	139	c,d,e	4	9	15	c,d,e	11	19	28	d,e,f	36	47	55	c,d
P.eridiano	14	25	88	c,d,e	32	44	137	c,d,e	5	6	18	c,d e	11	11	27	d,e	44	58	64	d,e
E.saligna	16	15	35	d,e	35	30	57	d,e	5	4	7	d,e	12	7	11	e,f	45	50	62	d,e
S.mats alba 1002	4	5	29	e	8	10	49	e	1	1	6	e	3	2	10	f	46	47	60	d,e
A.glutinosa	3	10	16	e	11	21	31	e	1	2	3	e	4	5	6	f	26	47	52	e,f
P.tomentosa	6	11	20	e	14	17	34	e	2	3	4	e	5	4	7	f	42	63	58	f
	c	b	a		c	b	a		c	b	a		c	b	a		c	b	a	
Mean	22	55	103		44	90	157		7	14	21		15	22	31		46	58	63	
Std deviation	19	47	76		29	69	102		6	12	15		10	17	20		10	8	7	

* - Average values with the same letter are not significantly different

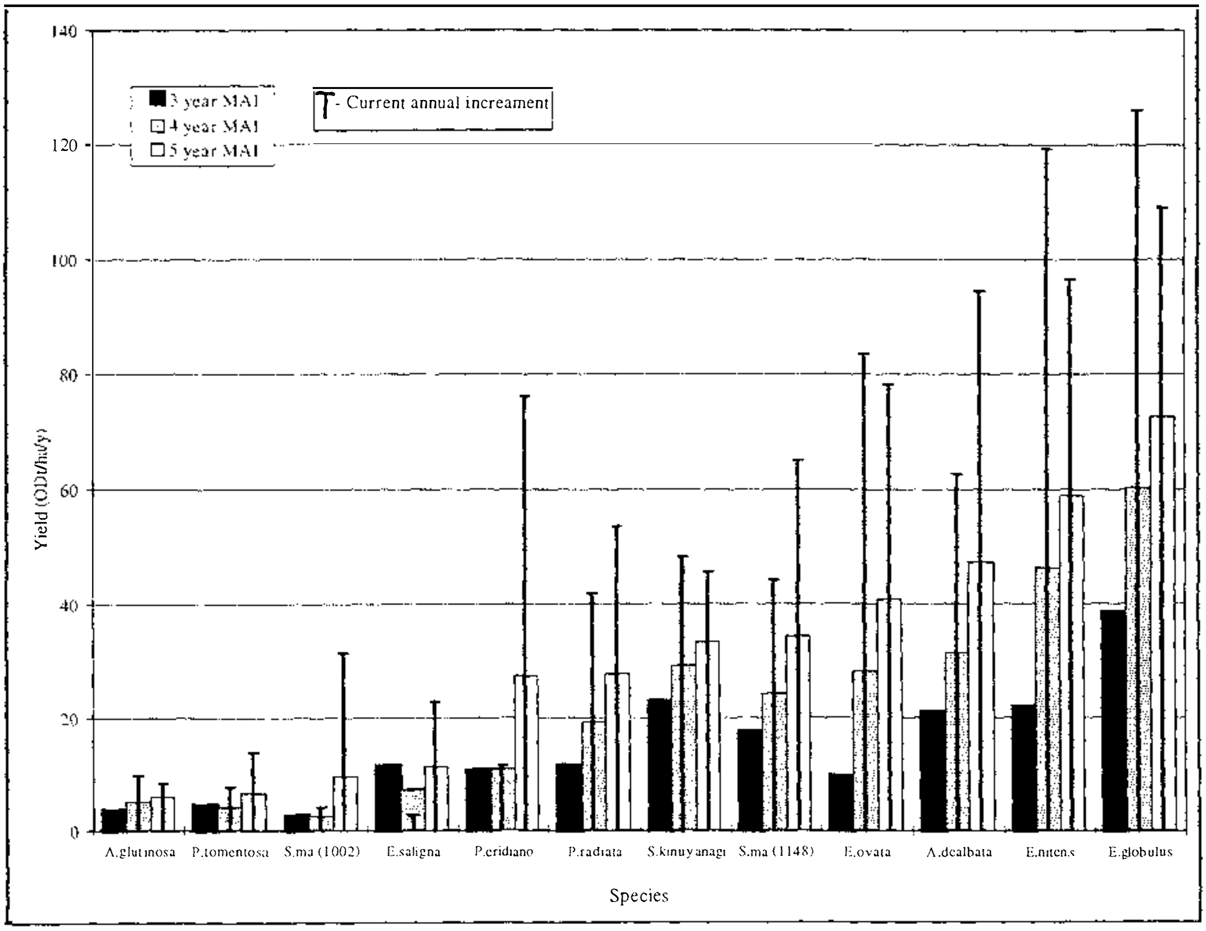

Figure 3.8 **Comparison of yields (MAI and CAI) in 12 SRF species over 3 rotations**

From the two tables (3.1 and 3.2), and from figure 3.8, it is observed that:

1. There were significant differences in tree dimensions, and in biomass yields among the 12 SRF species evaluated. Stump diameters, tree heights and tree dry weights were high for *E.globulus* and *E.nitens* but were low for *Alnus glutinosa* and *Paulownia tomentosa.* Consequently, yields of *E.globulus* were distinctly higher than yields from the other species at all the rotations. The lowest yields were obtained from *A.glutinosa* and *P.tomentosa.*
2. The three rotations evaluated had significantly different yields. Yield increased with increasing cutting age.
3. The harvest index which measures the recoverable potential, and indicates the proportion of the material removed (using conventional forestry machinery), also varied significantly in the different species, and increased with both cutting age and average tree size.
4. Except *E.saligna*, CAI (for 4 and 5 year rotation lengths) was greater than MAI.
5. The CAI at the 5 year rotation was less than that at the 4 year rotation in 5 of the species, but higher in the other seven species.

Growth patterns in juvenile trees

Figure 3.9 presents height and stump diameter growth curves of 4 eucalypts - *E.nitens* (V); *E.regnans*; *E.globulus*; and *E.nitens* (NSW) between 6 months to 2 years and shows that the growth rates in the 12 months were relatively lower than those in subsequent months. The overall growth rates in height and diameter up to 2 years when the trees were harvested are presented in table 3.3.

A gradual variation and differentiation in early tree growth occurred between both species and stocking densities. *E.globulus* and *E.nitens* grew faster than *E.regnans* at both stocking densities - an advantage maintained at least to the age of 2 years when the trees were harvested. The divergence of the height and diameter curves indicate that species and stocking density effects on the rate of growth became more apparent after the first 12 months of growth. However, the differences in height were not significant over the 24 months of the trial. The increase in diameter among different species, and among the different stocking densities became statistically different after the first 12 months of growth when the wider spaced trees showed much higher rates of diameter change which translated into higher tree yields.

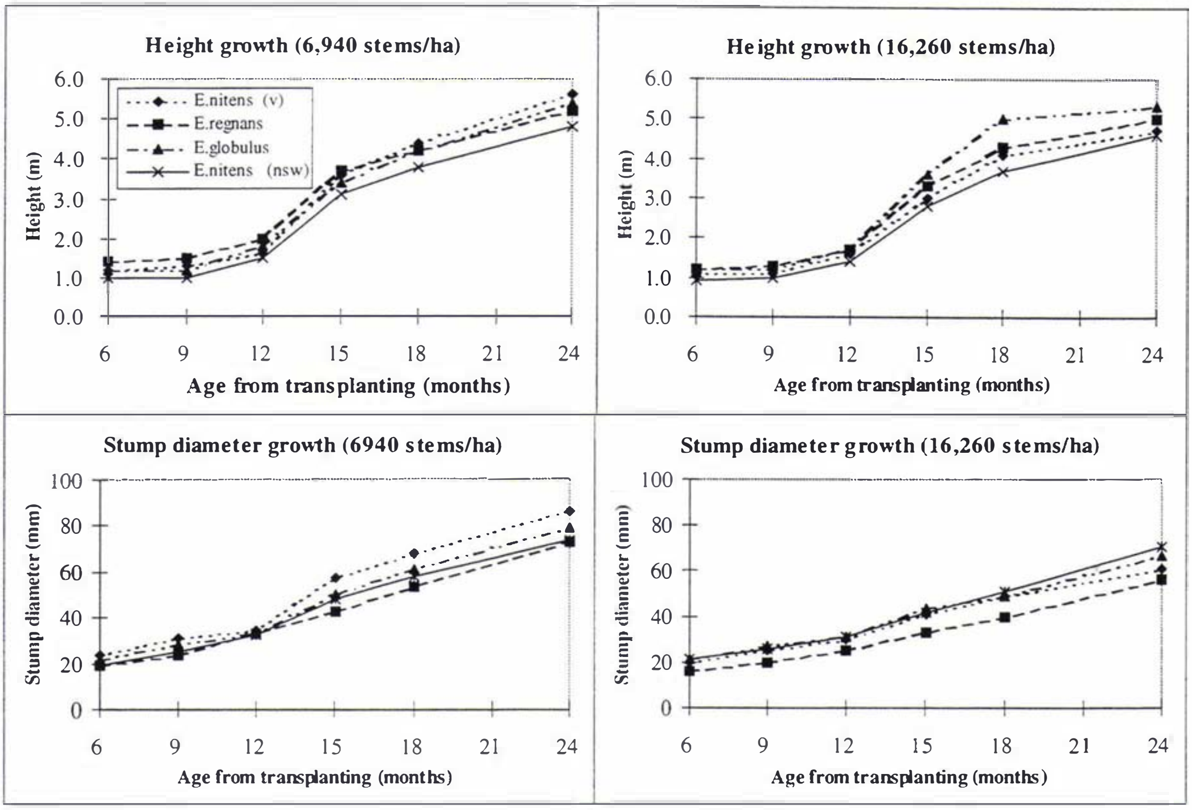

Figure 3.9 **SRF species height and diameter growths at 6,940 and 16,260 stems/ha**

The higher tree growth rates, (particularly in diameter) at the lower stocking density (6,940 stems/ha), resulted in bigger tree sizes (higher diameter and oven dry tree weight) than those planted at 16,260 stems/ha. However, the overall biomass yield was higher in the closely spaced plots, reflecting the greater number of stems constituting the stocking density.

Table 3.3 **Influence of stocking density on tree growth and yield in 4 species to 2 years**

Species	Stems per ha	Growth rates (R) Ht (R_H)	Dia (R_D)	R_H*R_D	Height (m)	Diameter (mm)	OD wt (kg)	Yield (ODt/ha)	MAI (ODt/ha/y) Stem	Total	Harvest index
E.nitens (V)	6940	0.276	3.685	1.016	5.6	86	7.2	50	13.8	25.0	56
E.globulus	6940	0.262	3.343	0.876	5.4	79	6.4	42	10.7	20.8	51
E.nitens (NSW)	6940	0.240	3.233	0.774	4.8	74	4.9	32	7.5	15.8	45
E.regnans	6940	0.237	3.081	0.731	5.2	73	4.7	28	7.0	14.1	50
E.nitens (V)	16440	0.233	2.391	0.557	4.7	61	2.8	41	11.0	20.6	54
E.globulus	16440	0.274	2.595	0.712	5.3	67	4.7	65	16.6	32.6	51
E.nitens (NSW)	16440	0.231	2.838	0.657	4.6	71	4.2	65	14.2	32.4	44
E.regnans	16440	0.243	2.262	0.549	5.0	56	2.6	40	8.0	20.1	40

3.4.2 EFFECT OF SILVICULTURAL TREATMENTS

Tables 3.1 and 3.2, and figure 3.3 showed the variation in growth and in yield in 12 SRF species at 3, 4 and 5 year rotation lengths. Figure 3.9 and table 3.3 showed the variation in growth rates, and in yield of 4 species planted at 2 stocking densities. In the "Nelder" radial trial where both stocking density and rotation lengths were tested concurrently, there were a total of 4 harvests for the 2 year rotation (lestablishment + 3 coppice); 3 for the 3 year rotation (1 establishment + 2 coppice); and 2 for the 4 year rotation (1 establishment + 1 coppice). Only 1 harvest was achieved at the 5 year rotation when these measurements were analysed. Figure 3.10 presents the results of stump diameter, tree height, tree dry weight and harvest index from the "Nelder" radial trial of *E.saligna*.

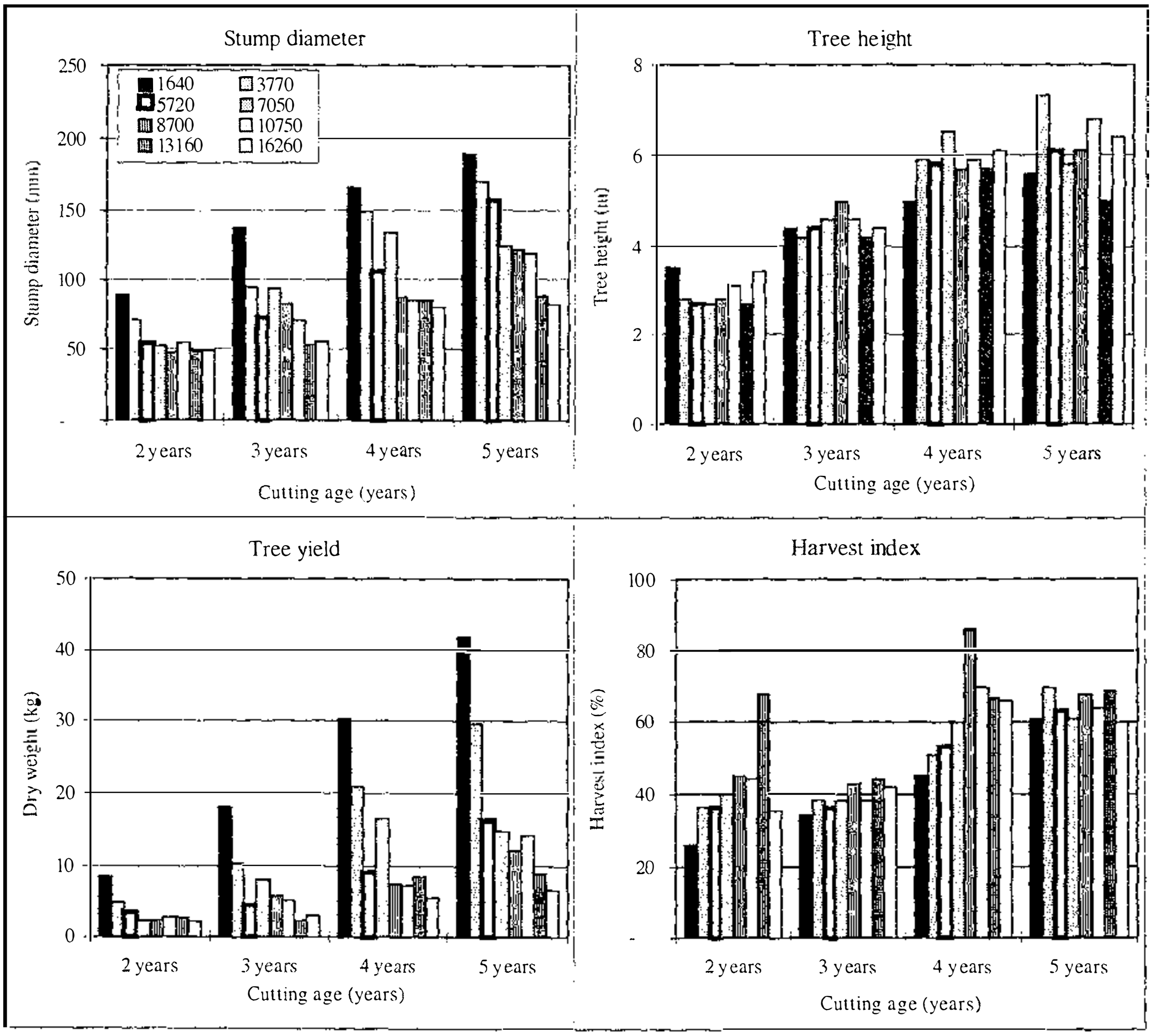

Figure 3.10 **Tree characteristics in the establishment rotation of "Nelder" trial of *Eucalyptus saligna***

The average stump diameter, tree dry weight, and harvest index were significantly different among different stocking densities, and among different rotation lengths (Figure 3.10; see also Appendix 3.1). Height of trees was significantly influenced by cutting age, but not with stocking density. The plots depict curvilinear trends with stocking density against stump diameter, tree dry weight and harvest index, and also with rotation length in stump diameter, tree height, tree dry weight and harvest index. Older trees had larger diameters, were taller, and were heavier with a higher proportion of total biomass being stemwood (greater harvest index). Stump diameter, dry weight and the harvest index declined with increasing stocking density but the tree height did not appear to be influenced by stocking density.

Tree oven dry weights were multiplied by the stocking density (stems/ha) to give the total above ground biomass production (yield ODt/ha). The results were divided by the rotation length to provide the mean annual increment (MAI, ODt/ha/y). The current annual increment was also calculated (as described above). The results of both MAI and CAI for the different stocking densities and rotation lengths for the establishment (first) crop are presented in Figure 3.11. Mean annual increment is shown as bar graphs, while current annual increment is presented as additional bars over MAI bar graphs of the respective rotations.

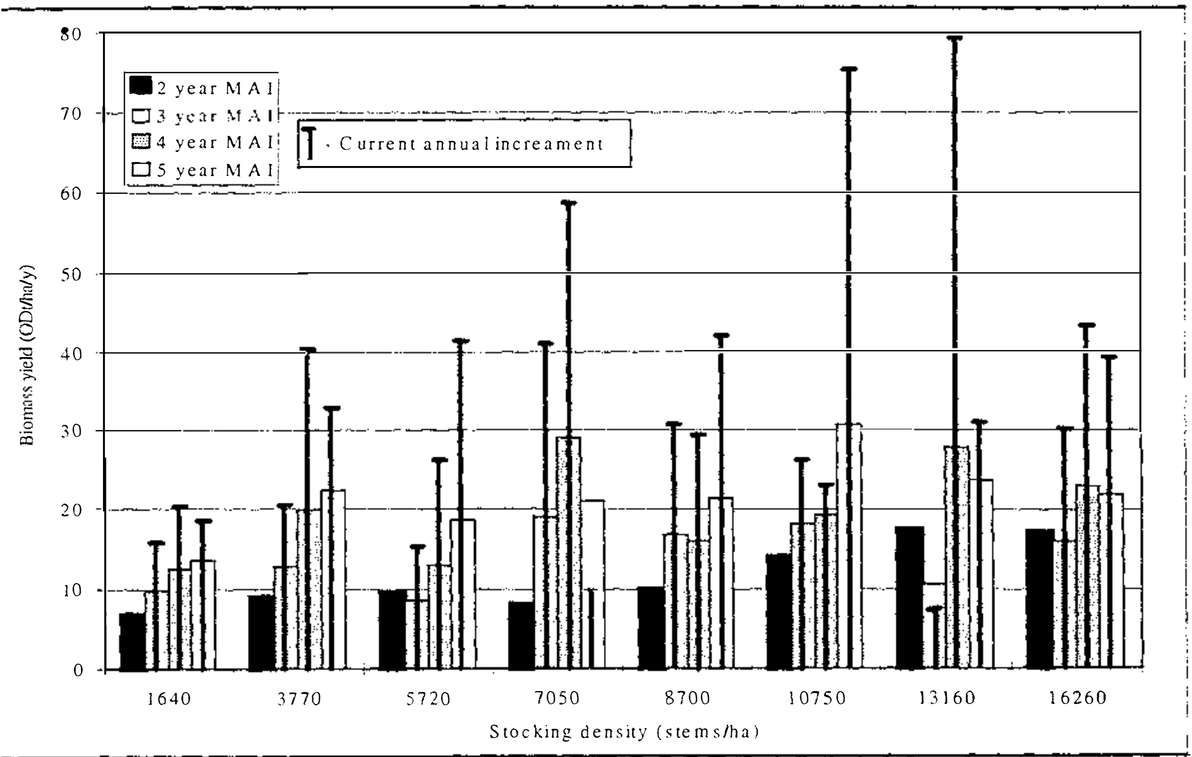

Figure 3.11 **Effect of stocking density and cutting age on yield (MAI and CAI)**

Like the tree dimensional and weight characteristics, yield (MAI and CAI) was influenced by stocking density and cutting age (Figure 3.11; see also Appendix 3.1). Although curvilinear relationship in which MAI increased with both stocking density and rotation length (figure 3.2) was evident, the trends differed with rotation length, and also with stocking density (figure 3.10). CAI was higher than MAI and also varied with both stocking density and rotation age, maintaining the curvilinear trends with stocking density. In 5 of the 8 stocking densities, the highest CAI was recorded in the 4th year, before it declined in the 5th year.

Appendix 3.1 shows that the yield between 4 and 5 year rotations were not statistically different. Similarly, the 3770 stems/ha stocking density was not statistically different from higher densities. This suggests that the optimum stocking densities and rotation length for this trial was about 3770 stems/ha and 4-5 years, respectively.

Coppice vs. establishment crop yields

Figure 3.12 presents a comparison of yields in both establishment and coppice crops among different stocking densities, cutting ages, and series of coppice (see also Appendix 3.2 which presents the statistical comparison of the results). Only the 2 year rotation had been seen through to the second and third coppice harvests while the 3 year rotation had been harvested over three times, the 4 year two times, and the 5 year only once.

Both figure 3.12 and appendix 3.2 show that yield was significantly influenced by both stocking density and type of harvest. The 1st coppice yield was significantly higher than the establishment yield and both the 2nd and the 3rd coppice yields, all of which were not significantly different. Yield in the 3, 4 and 5 year rotations did not differ among the different stocking densities. Similarly, the type of harvest (establishment, 1st or 2nd coppice) were not significantly different in the 3 year rotation, but the coppice yield in the 4 year rotation was less than the first rotation yield.

Stocking density, rotation length, coppicing, and yield relationships

The effect of stocking density on yield was dependent on cutting age. Yield increased with stocking density, reaching the peak between 7,050 and 13,160 stems/ha in the 3, 4, and 5 year rotations. In the establishment crops, the highest average yields over the 4 rotations were obtained in the higher stocking density plots but in the first coppice harvest, only cutting age had a significant effect (Appendix 3.1). The trends in the second coppice crop were different, with cutting age being highly significant while no apparent trends were observed with stocking density.

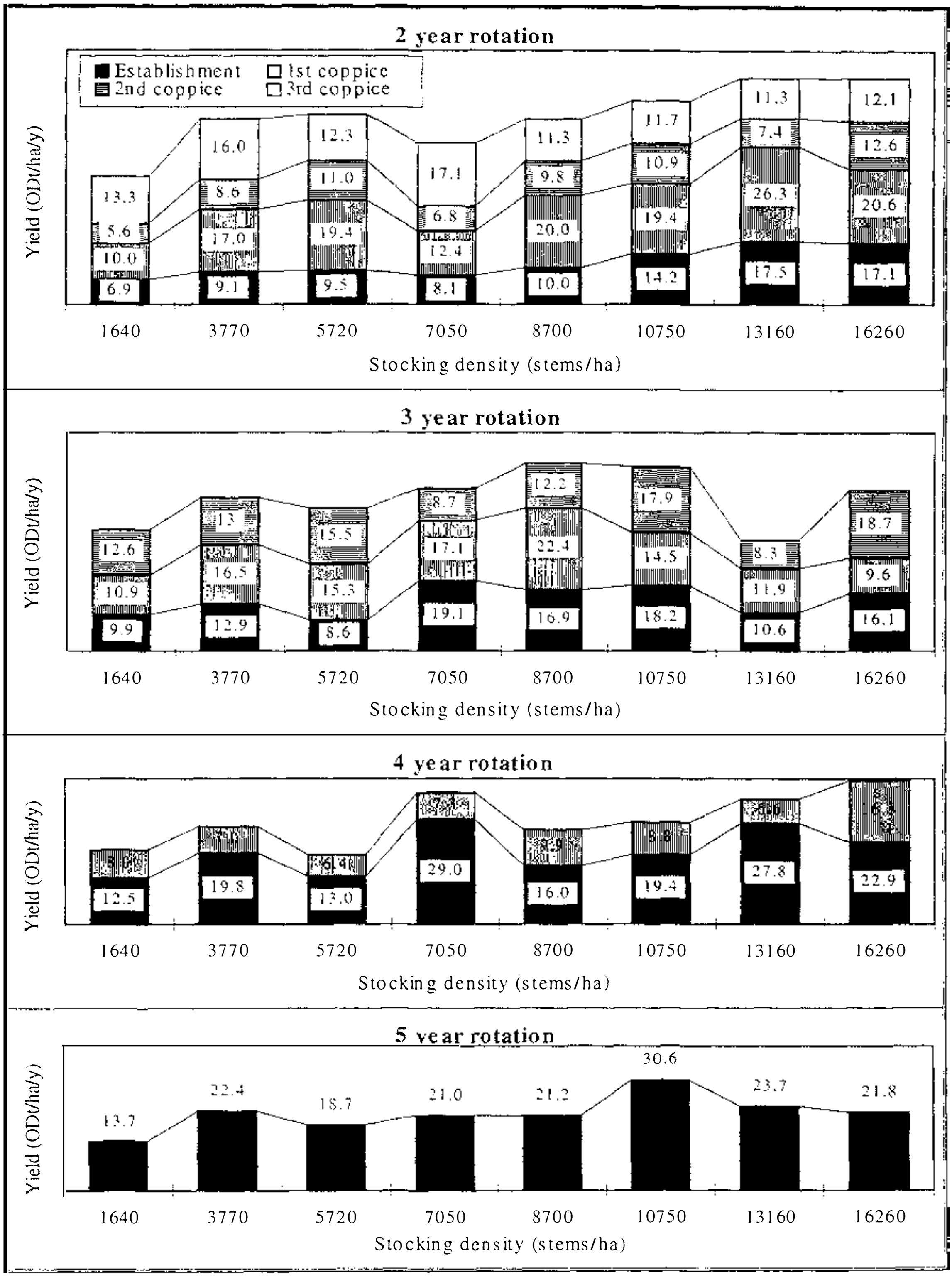

Figure 3.12 **Establishment and coppice yields (MAI) harvested at 2, 3, 4 and 5 year rotations in a "Nelder" design trial of *E.saligna***

Analysis of the effect of coppicing was only possible in the 2, 3 and 4 year rotations. The first coppice harvest in the 2 year rotations were higher than the establishment crops but subsequent coppice harvests declined, with the second coppice harvest being equal to the establishment harvest, while the third coppice harvest was less than the establishment crop. In the 3 year rotations, neither stocking density nor type of crop (establishment or coppice) produced significant differences in yield. The trend observed in the 4 year cycle, with the establishment crop having higher yields than the coppice crops was associated with possible sampling errors.

Yield optimisation

Figures 3.3 and 3.5 showed the MAI and CAI yields in 12 species, and in the "Nelder" trial, respectively. Like MAI, CAI exhibited significant variability in different species; between rotation lengths; and also between different stocking densities. Except in a few isolated cases, CAI in the 12 species was higher than MAI, although it showed declining trends from the highest values recorded in the 4 year rotations in most species. CAI in different stocking densities was also higher than MAI, being higher in the 4th year than in the 5th year in 5 of the 8 stocking densities.

Although the limited data at hand could be regarded as inadequate for the theoretical determination of the optimum rotation age (see figure 3.3) the fact that CAI was higher than MAI even at the longest rotation (5 years) used suggests that the plots had not reached the optimum cutting age where yield would be maximised. The declining CAI from the 4th year however indicated that such plots were approaching the optimum rotation lengths of maximum biomass production defined by the intersection of the CAI and MAI curves.

3.4.3 THE RELATIVE YIELD INDEX AND MULTI-OBJECTIVE EVALUATION OF SPECIES

The species index factors (Z), and species relative yield indices (RYI, as defined in section 3.3.6) for the 3 rotations (3, 4, and 5 years), and for each of the 12 SRF species are presented in table 3.4. The weighting (m_1, m_2 ..) of the objectives used in the index (diameter, height, tree weight etc.) are also shown.

Table 3.4 **SRF species and rotation lengths relative yield indices***

Species	Index factors (Z)**			RYI (Z x MAI x h_i)			RYI^{D} (RYI discounted, at 10%)		
	3 y	4 y	5 y	3 y	4 y	5 y	3 y	4 y	5 y
E.globulus	585	1006	1421 ^{a}	13739	38825	75310 ^{a}	10319	26515	46751 ^{a}
E.nitens	461	837	1261 ^{a,b}	6320	28057	55482 ^{a,b}	4752	19157	34448 ^{a,b}
A.dealbata	411	643	1035 ^{b,c}	4894	13568	31363 ^{b,c}	3679	9263	19478 ^{b,c}
E.ovata	280	606	918 ^{c}	1429	10612	25257 ^{b,c}	1073	7249	15675 ^{c}
S.mats x *alba* (1148)	365	555	853 ^{c}	2775	7544	19193 ^{c}	2088	5149	11913 ^{c}
S.kinuyanagi	397	608	761 ^{c}	3773	9907	14014 ^{c}	2834	6772	8706 ^{c}
P.eridano	300	388	752 ^{c,d}	1409	2484	13242 ^{c}	1059	1696	8226 ^{c}
P.radiata	273	467	734 ^{c,d}	1121	4246	11081 ^{c}	842	2903	6877 ^{c}
E.saligna	285	311	395 ^{d,c}	1481	1151	2763 ^{c}	1113	786	1715 ^{c}
S.mats x *alba* (1002)	132	154	397 ^{c}	171	185	2303 ^{c}	129	126	1428 ^{c}
P.tomentosa	193	268	338 ^{d,c}	367	724	1318 ^{c}	275	494	819 ^{c}
A.glutinosa	180	262	325 ^{d,c}	180	655	1041 ^{c}	135	447	645 ^{c}
Mean	322 ^{c}	509 ^{b}	766 ^{a}	3.138 ^{b}	9.830 ^{b}	21.031 ^{a}	2.358 ^{b}	6.713 ^{b}	13.057 ^{a}

* - Average values with the same letter are not significantly different

** $m_1, m_2, \ldots\ldots m_k$ factors (weights) were:

Intercept (yield, ODt/ha)	2.43648
Diameter (mm)	1.29904
Height (m)	1.01366
Tree wt (kg)	1
Harvest index (%)	1.10486
Rotation (years)	1.85035

Three observations were made from table 3.4:

1. The index factors (Z), the non-discounted relative yield indices (RYI), and the discounted relative yield indices (RYI^{D}) were significantly different among the species. Z however did not clearly distinguish the best species from the lot as did both RYI and RYI^{D}.

2. Z, RYI, and RYI^{D} were also significantly influenced by age. The older trees exhibited a higher discounted index indicating that selection of the longer rotations should not be restricted on the basis of the long waiting periods. Unlike Z which indicated that the three rotations tested were all different, both RYI and RYI^{D} showed that the 3 and 4 year rotations were not different.

3. The top three species were *E.globulus, E.nitens* and *A.dealbata*; while the 5 year rotation was better than the 3 and 4 year rotations.

A distinctive ranking of the species was clear. *Eucalyptus globulus* was the best species at all 3 rotation lengths evaluated, followed by *E.nitens*. *Salix matsudana* x *alba*, *Paulownia tomentosa*, and *Alnus glutinosa* performed badly at the three rotations, as did *E.saligna* which was observed to be heavily infested by *Ophelimus eucalypti* - a leaf gall wasp.

The relative yield indices for the establishment rotations of *E.saligna* planted in the "Nelder" radial trial are presented in table 3.5 which shows that (i) stocking density did not have a significant effect on the index factors (Z); (ii) although the influence of stocking density depended on the rotation length, RYI increased with the stocking density reaching a peak (which was different for different rotation lengths) before starting to decline.

Although stocking density influenced both RYI and RYI^D, the different densities did not separate out. Discounting the values at 10%, helped spread out the different densities, making it possible to pick out the better growth factors. Although the values of both yield and yield indices were comparable, incorporation of the seedling cost factor could reverse the index ordering in different stocking density plots. Like the species trials, the RYI in the "Nelder" radial trial increased with the rotation length, and the cutting age had a significant effect on both Z, RYI, and RYI^D. The introduction of economic factors and costs of money in the discounted relative yield index (RYI^D) makes both the stocking density and rotation age significant.

Table 3.5 **Relative yield indices* of the establishment harvest of *E.saligna* planted in a "Nelder" radial trial**

Stocking density	Index factors (Z)				RYI (Z x MAI x h_i)				RYI^D (RYI discounted at 10%)			
(trees/ha)	2 y	3 y	4 y	5 y	2 y	3 y	4 y	5 y	2 y	3 y	4 y	5 y
1640	194	316	430	537 ^{a}	347	1,064	2,419	4,485 ^{b}	287	799	1,652	2,785 ^{c}
3770	188	28[illegible]	477	617 ^{a}	615	1,372	4,819	9,681 ^{a,b}	508	1,030	3,292	6,011 ^{a,b,c}
5720	167	212	345	533 ^{a}	572	656	2,379	6,282 ^{a,b}	473	493	1,625	3,900 ^{b,c}
7050	160	322	553	514 ^{a}	518	2,337	9,631	6,589 ^{a,b}	428	1,756	6,578	4,091 ^{a,b}
8700	170	294	386	520 ^{a}	763	2,136	5,309	7,489 ^{a,b}	631	1,605	3,626	4,650 ^{a,b,c}
10750	198	281	399	628 ^{a}	1,234	1,945	5,414	12,307 ^{a}	1,[illegible]20	1,461	3,[illegible]98	7,642 ^{a}
1316[illegible]	233	207	478	504 ^{a}	2,775	966	8,908	8,240 ^{a}	2,293	726	6,084	5,116 ^{a}
1626[illegible]	195	250	419	461 ^{a}	1,166	1,689	6,336	6,025 ^{a,b}	[illegible]64	1,269	4,328	3,741 ^{a,b,c}
	d	c	b	a	c	c	b	a	b	b	a	a
Mean	188	270	436	539	999	1,521	5,652	7,637	826	1,142	3,860	4,742

* - Average values with the same letter are not significantly different

3.4.4 YIELD ESTIMATION IN SHORT ROTATION FORESTRY

Senelwa and Sims (1997a; Appendix R.1) developed regression equations relating tree dimensional variables obtained by non-destructive sampling, with tree dry weights obtained by destructive sampling of *Eucalyptus ovata*, *E.saligna*, *E.globulus*, *E.nitens*, and *E.regnans*, *Pinus radiata* and *Acacia dealbata*. The tree dry weights were plotted against three dimensional variables: stump diameter, D; tree height, H; stump basal area, A; and four selected combinations of these variables - D*H; D^2; D^2*H; and A*H. Plots of tree dry weights against either stump diameter, tree height or stump basal area indicated that the relationships were not linear. Plots against the power functions of the tree diameter, including those directly proportional to the stump cross sectional area (A, D^2, D^2*H and A*H), showed linear relationships. The data for each individual *Eucalyptus* species, for the pool of *Eucalyptus* species, and also for *P.radiata* and *A.dealbata* were fitted to linear models forcing the intercept to pass through the origin. For short rotation eucalypts, the model that best predicted tree dry weight (W, kg) was:

$$W = 1.22D^2 * H \times 10^{-4}$$

where D = tree stump diameter (mm) and H = tree height (m).

Since the model predicted above ground tree dry weights of eucalypts to within 18% accuracy, it was concluded that it was sufficiently accurate to estimate total biomass in SRF systems using non-destructive measurements. In addition the equation developed for eucalypts could be applied directly to other tree crops such as *P.radiata* and *A.dealbata* under SRF management regimes.

3.5 DISCUSSION

The series of experiments in this chapter addressed the following broad aspects of short rotation forestry: (i) yield of different species; (ii) the influence of silvicultural treatments - rotation length, stocking density, and coppicing; (iii) yield optimisation; (iv) species selection and the relative yield indices; and (v) non-destructive above ground biomass estimation. Although the importance of site selection, and the ability to undertake soil amelioration and fertilisation as outlined by Ledin and Alrikson, (1992) was recognised, it was not considered feasible for individual farmers particularly in developing countries. Also, since fuelwood is considered a relatively cheaper forest product compared to conventional forestry products (timber, pulpwood etc.), and since biomass has to compete with gas and coal which are relatively cheap, the objective of the work was to demonstrate its production at low cost. Thus, fertilisers were not applied, and no thinning or pruning was undertaken.

Although it would be useful to carry out an economic appraisal since SRF systems must be economically viable for the concept to survive, the economic and supply structures of SRF woody crop markets have not been fully established. Besides, some of the benefits associated with biomass energy systems are environmental (amelioration of degraded sites, CO_2 balancing, aesthetic etc.), in which case, its economic worth would be difficult to quantify as such benefits are not perceived in the market place. The quantity and value of energy produced under the different circumstances should be monitored and evaluated based on the current market either in terms of fuelwood ($/GJ, $/kWh), or fossil fuel savings ($). Thus, the selection of different species should be based on various agronomic and climatic factors but must underline the importance of demonstrated growth characteristics of the candidate crops.

The sampling method used in the 14 SRF tree species trial had the limitation of removing competition from the remaining trees which were then able to increase growth as a result. It was realised that the technique would favour incremental growth of the remaining trees in the plots after each harvest, and that ideally, it would have been better to determine and present yield based on effective plot populations due to variations resulting from differential competition in the plots. However, the results from the trial were considered to be indicative of the growth potential, and provided a general comparison of species, without showing actual yield data for large scale planting.

For these reasons, the results were considered to be acceptable estimates from small plots with an establishment stocking density of 3470 stems/ha, and provided a basis for the comparison of the species tested. The biomass material harvested also served as the source of samples for the laboratory assessments of the energy characteristics (chapter 4), and provided feedstock for the gasification trials (Chapter 5).

Although SRF systems emphasise total above ground biomass production, two types of yield were considered (i) total biomass yield, and (ii) stemwood biomass yield. Total biomass yield entails "whole tree harvesting", and is a good indicator of the site potential, and useful when integrated harvesting is to be employed. Stemwood biomass yield described the material with stem diameter above 40 mm. The ratio of stemwood yield to total biomass yield (the harvest index), is a measure of the recoverable potential of available biomass, and indicates the component which would normally be removed from the growing site for utilisation in conventional forestry practices. The harvest index was considered a useful parameter in this experiment since most harvesting and handling machinery in SRF to date is designed for the conventional forest products industry. Biomass yield was not expressed in terms of energy produced (MJ/ha/y) as was presented by Verma and Misra (1989). It was considered that the energy available in a biomass resource was dependent on the conversion technology used (direct combustion, gasification etc.).

3.5.1 GROWTH AND YIELD IN SRF SPECIES

Of the species evaluated, only *Pinus radiata* is a gymnosperm lacking the ability to coppice. All other species are angiosperms, which coppice to different degrees. Due to the short time period available for the study however, the series of experiments undertaken investigated coppicing and its effect on yield in *Eucalyptus saligna* only. The other 12 species were evaluated based on the yield of the establishment (first rotation) crop only, having been planted and managed under similar conditions. Further studies will be necessary to consider subsequent rotations.

Tables 3.1-3.3 and figures 3.3 and 3.6 showed the relative differences in growth and yield potentials of the different species. The fast growth and the subsequent high yields for

E.globulus (up to 72 ODt/ha/y in the 5 year rotation) and for many of the other *Eucalyptus* species, compared well with the highest quoted yields of 65 ODt/ha/y for *E.grandis* grown in Brazil (Evans, 1992), but was higher than yields previously obtained in New Zealand with eucalypts of 40 ODt/ha/y, (Kincheff and Carter, 1991). These high yields concur with the observation (Figure 3.1) that within the tropics and sub-tropics, and under similar growing conditions, eucalypts exhibit superior growth compared to most other species. Though these were experimental plots where yields obtained may not be achieved in large scale field planting, they indicated the relative yield potential of the twelve species, and showed that based on yield alone, and under New Zealand conditions, *E.globulus* and *E.nitens* should be preferred in an SRF scheme.

The relatively faster growth resulting in higher yields in some of the species over others was an inherent characteristic of those species. This characteristic is genetic and unique to respective species, and probably involve (i) better and more active site colonisation ability; (ii) better water (soil moisture) utilisation; (iii) better adaptability to soils and climatic conditions; and (iv) all year round growth (albeit slow in winter) compared with deciduous crops. The evaluation and selection of species for biomass production is based on identifying this better characteristics in candidate species, matching the species to the sites available, and developing ways to enhance the characteristics. In the range of species tested, *Eucalyptus globulus* was the most adaptable, and according to Schmidt (1973), the species had a "higher potential of using given space".

Since the results were based on small experimental plots (46 m^2) and subsequent harvests may have jeopardised the original stocking density objectives, it may be argued that:

1. The yields obtained at the 4 and 5 year rotations, in particular following the "thinning" resulting from the 3 year harvests will not be a true indication of large scale plantings. An important observation however is that only eucalypts exhibited the extra-ordinarily high yields. Other species had yields comparable to yields from other regions of the world (Figure 3.1), but still higher than could be obtained commercially.

2. The apparent high yields in some of the species could be attributed to the high stocking density of 3470 stems/ha used, and to the small plot and sample size. All the species in the

trial received similar treatments, but some of the species resulted in low yields similar to yields observed in other areas (see figure 3.1).

The yields of *E.saligna,* one of the most widely used eucalypts (FAO, 1979; Hillis and Brown, 1984; Bowersox *et al*, 1990) were observed to drop significantly between the 3, 4 and 5 year rotations. The drop was attributed to infestation by *Ophelimus eucalypti*, a leaf gall wasp which was not detected on the other *Eucalyptus* species. *O.eucalypti* is a Eulophid wasp which causes galls to form on the leaves of *Eucalyptus botryoides* and *E.saligna* by ovipositing in the leaf (Figure 3.13), (Walsh, 1995). The growth of the wasp larvae within the leaf leads to the formation and growth of galls. The complete defoliation which can lead to the death of well established trees may take 4-5 years in areas where the pest population is high.

Figure 3.13 ***Ophelimus eucalypti* (leaf gall wasp) infestation on *E.saligna***

The infestation is thought to reduce the photosynthetic surfaces of the leaves, effectively reducing the leaf photosynthetic capacity and therefore the plants metabolic activities and hence growth. Although the biology, ecology, and effect of this pest on the growth of trees is inconclusive, the infestation was believed to have resulted in the generally low yields of the species. Selection of *E.saligna* for SRF systems must take account of this pest problem, which was first observed in New Zealand in 1992 (Senelwa and Sims, 1995).

Another pest found on all the eucalypts at the trials was the giant emperor gum moth. This pest (Figure 3.15) was noticed in the summer but the active life over which it fed on the trees was thought to be short (probably a week for each caterpillar) before retreating into a cocoon. The insect is understood to remain dormant in the cocoon for the rest of the year before emerging. The eggs of the next generation are laid by the parent before they die. Though the caterpillars were highly active, and understood to consume the equivalent of their weight in a period of a few weeks, it was not possible to estimate the damage inflicted on the trees in terms of reduced growth and yield. This pest should be monitored further with a view to describing the biology, and quantifying the effects on tree growth and yield. The damage was considered insufficient to warrant chemical control.

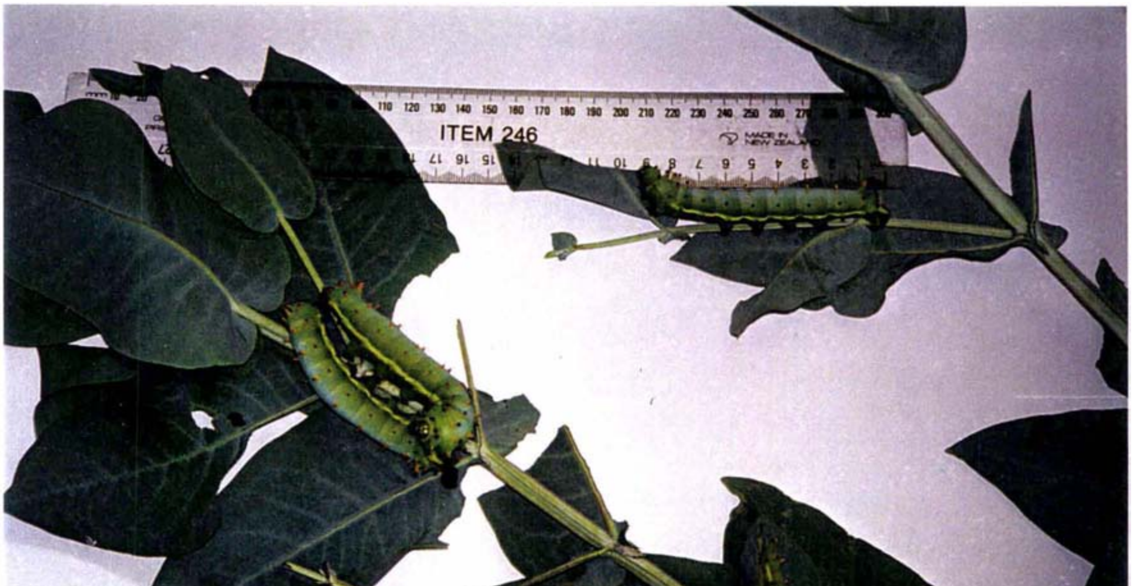

Figure 3.15 **Caterpillars of the emperor gum moths on *Eucalyptus* species**

Although the yields obtained for most of the species were within the range quoted for most species from other regions (Figure 3.1) (McElroy and Dawson, 1986; White *et al*, 1993; Ledin and Alrickson, 1992; Smith, 1977) - *Salix*, 17-35 ODt/ha/y; *Populus*, 10-27 ODt/ha/y; *Pinus*, 11-28 ODt/ha/y; *Eucalyptus*, 7-72 ODt/ha/y; and *Acacia*, 21-47 ODt/ha/y; they were considered high given that the trials did not involve intensive silvicultural tending. There was no irrigation (average annual rainfall in Palmerston North is about 970mm), and fertilisers were not applied. Also, the plots were not pruned or thinned, and no weed control other than mowing during establishment, was carried out for the entire trial period, relying on canopy closure to minimise the weed problems which were noted in the first year of planting. The high yields (except for *Salix matsudana* x *alba* (1002), *Paulownia tomentosa* and *Alnus glutinosa* which had total biomass yield of less than 10 ODt/ha/y) were partly due to the fact that the soils at the site were fertile, having been a livestock paddock previously. Since the site was located along a river valley, it is possible that the soil moisture content remained high for the period of growth. This was however not monitored.

Species periodic growth and the influence of stocking density

The slow growth in the first year of planting compared with the growth in the subsequent year (Figure 3.9) was believed to be a result of the planting (establishment) shock, a period within which growth may cease temporarily as the transplanted plants stabilise in their new environment (White *et al*, 1993; Sennerby-Forsse *et al*, 1993). During the establishment period, the plants require adequate time to develop a good root system which has been shown to require about 2 years regardless of the planting density (Wright, 1988). During this period, some species allocate carbohydrates to root growth rather than top growth. In a 1 or 2 year rotation, harvest occurs while the trees are just beginning to show vigorous top growth for eucalypts especially. After the establishment shock, the annual yield increment rises in subsequent years to reach a peak before starting to declining within the limits of silvicultural growth conditions. The intersection of the MAI and CAI curves (figure 3.3), constitutes the optimum rotation.

The trees were planted in November 1993, and the period of rapid growth following the first 12 months coincided with the summer period through to autumn (November 1993 - May 1994). During this period, the days were long with extended sunshine hours. These conditions favoured the rapid growth of the trees before entering the winter period. However, the growth curves (Figure 3.9) showed that the trees continued to grow even during the winter. The continuing growth in winter showed the advantages evergreen species possess over deciduous species when most metabolic activities are minimised.

Though there were no statistical differences in the height of trees among species and stocking densities, early tree growth showed a gradual variation with species (Figure 3.9). The lack of significance in the differences in height suggested that competition at the two stocking densities had not become a growth limiting factor, and that there was considerable variation among individual trees of the same species.

Stocking density showed a significant influence over stump diameter from 12 months onwards. There was no clear indication of the best stocking density in this trial, perhaps because the effects of competition had not set in by the age of 2 years. Similarly, both height and stump diameter were not influenced by species differences. Stocking density had no significant influence on tree height over a 24 months period even though trees in the higher stocking density plots were taller at 24 months.

The separation of the height growth curves over time (Figure 3.9), and the significant influence of stocking density on stump diameter after 12 months suggest that by then competition at the 16440 stems/ha stocking had become a growth limiting factor, leading to faster height increment in the higher stocking at the expense of stem diameter. The product of stump diameter and tree height (D*H), taken as the best indicator of early tree growth, also showed that stocking density significantly influenced tree growth after the age of 12 months. A ranking of the growth of each species at the juvenile stage using Duncan's multiple range test indicated that *E.globulus* and *E.nitens* (V) grew faster than both *E.nitens* (NSW) and *E.regnans* to the age of 18 months even though the relative growth rates did not show significant differences between 6 and 18 months.

The results of the rates of growth analysis (Figure 3.9 and Table 3.3) indicate that fast growth rates lead to bigger trees (relative to slower growth rates). However, the overall yield (MAI, ODt/ha/y) was mainly dependent on the stocking density (stems/ha). Thus, although the growth rates were high in the lower stocking density plots, the yield (ODt/ha/y) was highest in the higher density plots by virtue of the higher stem numbers.

3.5.2 THE INFLUENCE OF SILVICULTURAL TREATMENTS

The variation in tree growth characteristics (diameter, height, tree weight) and consequently yield with varying stocking densities and rotation lengths (Figures 3.5 and 3.7; and table 3.3) illustrates the importance of clearly defining the optimum stocking density and the rotation lengths for short rotation forestry systems. The curvilinear trends indicated that the optimum stocking density of SRF need not involve the highest stem numbers per unit area, and that the longest rotations do not necessarily result in the highest yields.

Stocking density

Figure 3.9 and table 3.3 (juvenile tree growth analysis) showed that up to the age of 1 year, stocking density did not have a significant effect on the growth of the trees (diameter and height). Beyond 12 months after planting however, the wider spaced trees showed a more marked increase in growth, particularly in stump diameter resulting in bigger trees being harvested after 2 years. However, the higher plant density (stems/ha) determined the overall yield (MAI) of the plots. Thus, the densely stocked plots, although with smaller trees, resulted in higher yields.

Figures 3.10 and 3.11 depict the curvilinear trends illustrated in figure 3.2 which shows that both diameter and tree dry weight decreased with increasing stocking density. Height remained steady while yield increased to a peak before starting to decline (Figure 3.11) over a range of plant densities. This trend suggested that the effects of competition, leading to reduced tree sizes in the closely spaced plots are annulled by the higher number of stems. Although the effects of competition were evident from the individual tree sizes, mortality and stunting did not result, at least till after the trees were more than 2 years old. Harvesting at this early age, before the crop realises its maximum growth potential is not advisable. The results indicate that the influence of stocking density is more pronounced in shorter rotations which concurs with earlier studies (Kincheff and Carter, 1991; Parrotta, 1989; Sennerby-Forsse, 1992; Harrington and Fownes, 1996; and Geyer *et al*, 1987; Heilman *et al*, 1972; Heilman and Peabody, 1981).

The optimal site stocking density led to a peak yield, beyond which the yields start declining. In the 2 year rotation however, yield consistently increased with stocking density. This shows that the net biomass production per individual tree is constant over a wide range of densities and it declines only if the resource supplying power is not fully utilised (Borman and Gordon, 1984; Harper, 1977). Variations in initial density are largely compensated for by variations in the amount of growth made by individual trees. This relationship describes the "law of constant final yield" (Kira *et al*, 1953; Harper, 1977), indicating that the total yield obtainable from a site becomes independent of increasing planting density, and that it may not be useful to have very high stocking densities if similar yields can be obtained when lower stocking densities are used. The lower stocking densities minimises the cost of plantation establishment as fewer seedlings are used. This concept may be used to determine the optimum stocking density in SRF systems where the crops are regularly harvested, and where maximum biomass production is the objective.

The trends in harvest index show that net stem production per given land area is greatest at high densities although individual trees are relatively smaller. The stand density influences the carbon allocation especially between branches and stems as most fast growing species grown at high densities reach a ceiling leaf area index very rapidly which ensures that (i) the shading at the forest floor reduces weed competition problems; and (ii) when the ceiling leaf area index is reached, the plantation's nutrient requirements are minimised due to a continuous recycling of nutrients in leaf litter. Less light penetration also promotes self pruning and forces individual trees to compete for light.

Rotation length

The influence of rotation length on tree growth and biomass yield (figures 3.8 and 3.10-3.12) resembled the pattern illustrated in figure 3.3, and indicated that:

1. Growth in above ground biomass in the early stages of tree growth is slow. The slow growth, lasting up to 1 year, is a result of the establishment shock suffered by trees following transplanting. During this period, most of the growth effort is directed towards development of the root system (Wright, 1988);

2. Technically, none of the species tested under the stocking densities used had reached the optimum rotation age defined by the intersection of MAI and CAI curves (Figure 3.3);

3. Although yield was still increasing by the time of all harvests, the rates of increase were not as high as they had been in the 4th year of growth; and that

4. The optimum physical rotation length was being approached by most species and at most stocking densities at the time of harvest in the 5th year of growth.

At shorter rotations, tree size distribution tended to be normal, being progressively positively skewed about the mean. This was attributed to the effect of competition among individual trees which in some cases leads to mortality. The growth of small individual trees is slowed in favour of the large ones and if the competition intensifies at extended rotations, the smaller stems/trees are eliminated. Similar trends were reported by Willebrand and Verjwist (1994); Willebrand *et al*, (1993); Koyoma and Kira, (1956); and Mohler *et al*, (1978).

Though MAI increased with rotation length, determination of the optimum rotation length would not simply involve the highest yielding rotation. Such decisions for an economic enterprise require financial evaluation, relating the benefits accrued (extra yield, CAI) by retaining the crops for a longer period, taking into consideration interest rates, the risks of investments, etc. Unfortunately, the trees used in estimating the yields were different (since trees were felled for yield measurement), and so the yield increments could not be traced to the same trees. Besides, the three rotations used, which provided only two points for CAI in the 12 species, and 3 points for the 8 stocking densities were not adequate to utilise the MAI/CAI theories in defining the optimum rotation particularly in the species trials.

Coppicing

The high yields in the 1st coppice harvest of the 2 year rotations (compared to the first rotation harvest), and the decline in subsequent coppice harvests was similar to previous trends (e.g. Sims, 1996; Jacobs, 1981; Dyson, 1974; Kaumi; 1983). Although coppicing does not always raise a site's growth potential, the higher yields may be attributed to a rapid occupation of the land area leading to a high leaf area at an early stage after harvest. In addition, such crops do not experience the establishment shock experienced by the first rotation crops. The established root system (developed by most plants in the first and second years of growth) ensures rapid leaf development especially at increased stocking density (stems/ha). In the subsequent harvests (i.e. in the second or third coppice crops), the yield starts declining due to (i) mortality of the stumps from increased competition; (ii) root mortality/senescence; (iii) introduction of disease through the cut surfaces; (iv) exhaustion of the site; and (v) possible infestation of pests (as may have been the case of *O. eucalypti* observed on *E.saligna*). Yields in subsequent coppice generations may also decline when the stump's (or root stock) active age approaches the end stock (i.e. the older the tree, the lower the coppicing vigour and therefore reduced yields), even though this aspect has not been documented. Further work is required to establish the reasons for the decline in yields observed.

The similarity and or the decline in coppice yields (when compared with the establishment yields) for the 3 and 4 year rotations (Appendix 3.2), and also the similarity for different stocking densities show that the growth and yield advantages resulting from high stocking densities, and from coppicing are maximised at low rotations. At longer rotations, the stand undergoes self thinning moderating the stem numbers.

3.5.3 YIELD OPTIMISATION

The process of evaluating SRF species, and of identifying and defining the optimum silvicultural treatments (e.g. stocking density and rotation length) for a selected species, and matching these silvicultural treatments to the growing site and species to produce defined products constitutes the process of yield and product optimisation. The results indicated that there were significant variations in growth and yield among (i) the 12 species over the 3 rotation lengths, and of the 4 species tried in the juvenile growth trial; (ii) the stocking densities and rotations evaluated in both the species and the "Nelder" radial trials; and (iii) establishment and coppice harvests of the "Nelder" radial trial.

In the 12 species, and in the 8 stocking densities evaluated, the longest rotations had the highest yields but the curvilinear relationships between yield and stocking density illustrated that high stocking densities did not translate into the highest yields (Figure 3.11). Further, an analysis of the juvenile tree growth patterns showed that harvesting early implies removing the crop before its maximum growth potential is realised. High stocking density is relevant at short rotations since the advantages of higher stem numbers at long rotations are annulled by self thinning and pruning, leading to insignificant differences in yield (Appendix 3.2).

The lack of significant differences in biomass yields (total MAI) between stocking densities of 3770 stems/ha and higher (Appendix 3.1), and also between the 4 and 5 year rotations indicates the optimum stocking densities (≈ 3770 stems/ha) and rotation lengths (4 years) for use in a short rotation forestry scheme. The use of stocking densities higher than this optimal is not advisable as it increases the costs of production (given that extra seedlings are involved), and produces small piece sizes (tree diameter, height and weight, and had low harvest index; figure 3.10). Similarly, use of longer rotations unjustifiably increases the costs of production through increased interest rates on longer investment periods.

Unlike MAI, CAI values indicate actual periodic growth phases of the different species. CAI showed that some species (*P.eridano*, *S.matsudana* x *alba* (1002), and *A.dealbata*) had a sluggish early growth (up to 4 years), accelerating the growth thereafter, with a near double CAI in the fifth year. By the fifth year, *S.kinuyanagi*, *E.ovata* and *A.glutinosa* had a similar CAI to that observed in the fourth year, showing that peak CAI had been attained.

For energy biomass from the whole tree, an economic and silvicultural generalisation is to harvest the crop once CAI falls bellow MAI. However, since the harvest index (proportion of the stemwood which would normally be removed from the site assuming machine harvesting), increased with cutting age, it would be advisable to time harvesting to optimise the recoverable biomass material from the site. Besides, the relationships between CAI and MAI in the present study were inconclusive, and could not be used to predict the optimum rotation lengths. The results were based on destructive sampling, with measurements on different trees and plots for each of the different rotations. Thus, subsequent yield did not strictly reflect an increment over the yield from the previous year.

3.5.4 SRF SPECIES SELECTION AND THE RELATIVE YIELD INDEX (RYI)

The emphasis of RYI results (tables 3.4 and 3.5) reflect the formulation of criteria for species selection for SRF schemes within a defined region. RYI provides a ranking of species and silvicultural treatments rather than providing a quantitative comparison. The study involved three major objectives of evaluation - species performance; rotation length; and stocking density. Another objective was the coppicing ability which unfortunately was applied to only the poorest performing *Eucalyptus* species (*E.saligna*). The methodology could be used in other regions, and may incorporate many more objectives.

RYI is a multi-objective evaluation of the species incorporating five objectives: (i) total yield; (ii) rotation length; (iii) stocking density; (iv) tree dry weight; (v) stump diameter; (vi) tree height; and (v) harvest index; and including time and its associated costs. It is argued that although total yield is useful in evaluating SRF species, information is also needed to indicate the handling characteristics, the recovery potential, piece size and the suitability of use. Optimisation of each of the objectives used in defining RYI for each species was linked to optimising the yield (section 3.5.3). However, none of the species studied had CAI lower than MAI by the 5th year, indicating that the species growth was still vigorous and that none of them had reached their optimum biological/silvicultural rotation cycle at the stocking density used. For some species, most of the CAI yield in the later years of growth was allocated to stemwood, accounting for the increased harvesting index. Further studies should be set up to establish as many plots as anticipated rotations, holding onto the crop till such a time that CAI curve falls below the MAI curve.

The preferred species for maximising biomass yields per hectare were *Eucalyptus globulus*, *E.nitens*, *Acacia dealbata*, *E.ovata*, *Salix matsudana* x *alba* (1148) and *S.kinuyanagi* in order of preference. All the other species evaluated (*Pinus radiata*, *Poplus eridiano*, *E.saligna*, *Paulownia tomentosa*, *Alnus glutinosa* and *S.matsudana* x *alba* (1002)) should not be considered. The poor performance of *E.saligna*, and the associated effect of the infestation by *Ophelimus eucalypti* was inconclusive, and requires further investigation.

3.5.5 SRF SYSTEMS FOR A VILLAGE BASED GASIFIER PLANT

Chapter 2 indicated that a village gasifier installation to supply 80 domestic consumers (with an average annual demand of 1820 kWh, electric) was 0.5 tonnes of feedstock daily, equivalent to 180 t/y. Table 3.2 and figure 3.8 showed that 6 of the species tested (*E.globulus*, *E.nitens*, *A.dealbata*, *E.ovata*, *S.matsudana* x *alba* and *S.kinuyanagi*) had high yields (section 3.5.4). The optimum stocking density was indicated to be about 3500 stems/ha, while the optimum rotation length was between 4-5 years.

These conditions of SRF systems production (i.e. 3500 stems/ha, and grown for 4 to 5 years), and the better species (excluding *Salix* species which do not grow in Kenya and in many tropical climates) would be recommended for trial plantings together with other known local / native species. Initially, single rotation (with replanting of the sites after harvest) management is recommended (as the results from the present study were more conclusive), but there are possibilities for coppice systems at shorter rotations, and slightly higher stocking densities.

Taking the average of the 4 species, yields of 27-39 and 41-55 ODt/ha/y stemwood and total biomass, respectively are possible. To supply the village gasifier annually therefore, the village would require a minimum of 10 hectares (i.e. 2.5 hectares annually) for the 4 or 5 years of the rotation length.

3.5.6 YIELD EQUATIONS IN SRF SYSTEMS

The models developed showed that the product of stump diameter squared and height (D^2*H), and basal area and height ($A*H$) were the best dimensional variables to use to estimate individual tree dry weight. The high correlation between stump basal area and tree dry biomass may be due to the fact that the bole weight represents the major proportion of the total above ground tree biomass. It could also be that a certain size range of stem is required to support a given total weight of biomass, and this might be a characteristic feature specific to genera.

A comparison of the statistics using the general linear models procedure of the SAS system, showed that the models for data from pooled *Eucalyptus* species were not significantly different from those of individual eucalyptus species data, with the exception of *E.regnans*. Thus, there is some similarity in tree form between stands of short rotation *Eucalyptus* forestry of different ages, stocking densities, and species. In addition woody biomass allometry does not appear to differ significantly within the same genus, nor between different SRF age groups, different SRF stocking densities, and even between SRF coppice and establishment crops. In general, woody biomass growth equations do not vary significantly provided that tree growth parameters fall within similar ranges among sample populations.

E.regnans appeared distinctly different from the other four eucalypts, perhaps because all *E.regnans* trees were only 2 years old and therefore not represented in the bigger size category. Senelwa and Sims (1995) previously indicated that the predictive power of the non-destructive measurements for yield improved with tree size, i.e. when competition among trees has become important. It is considered that a pooled model covering many eucalyptus species is feasible, providing the age, and planting densities are defined to be within those used in SRF schemes.

The higher correlation of stump diameter with tree dry weight showed that tree biomass in SRF schemes is a function of diameter as has been postulated by many earlier workers (Senelwa and Sims, 1997a; Tietema, 1993; Verwijst and Nordh, 1992; Mitchell and McBrayne, 1981). Height becomes important when considering a series of ages, and its inclusion into the model for SRF crops could be regarded as accounting for age effects.

The possibility of applying a pooled model to a range of eucalypts indicated that the generic and physiological differences among eucalyptus species may not be translating into physical differences, at least under SRF prescriptions. Since rotation length in SRF schemes is usually shorter than for industrial plantation forests, guidelines to estimate yield in SRF regimes using non-destructive measurements would be useful. Such guidelines would (i) provide a quick method to assess the quantity of biomass available at different stages of growth; (ii) enable direct comparison of yields and species; (iii) allow the determination of optimum rotation lengths and yields (Shiver and Brister, 1993, Senelwa and Sims, 1997a); and (iv) might assist in the future commercialisation of biomass energy farming by being able to predict crop yields prior to harvesting.

3.6 CONCLUSIONS AND RECOMMENDATIONS

This study showed that growth of SRF crops occurs in defined stages. The most prolific growth occurred in the 2nd, 3rd, and 4th years of growth, beyond which, growth rates declined due to competition within plots at the high planting densities used. In the first year, above ground growth was limited due to the establishment shock following transplanting.

The yields of the 12 SRF species studied were variable. Within a species, yield also varied with stocking density and rotation length. The high yield of some of the species showed that the stocking density of 3470 - 3770 stems/ha, and grown at rotations of 4 - 5 years gave highest yields and relative yield indices in both the species and stocking density trials. It was concluded that this stocking density (stems/ha) and rotation length (years) combinations provide the optimum silvicultural conditions for maximising biomass yields for short rotation forestry schemes within the Manawatu lowland region of New Zealand.

The high yields of *E.globulus*, *E.nitens*, *A.dealbata*, *S.matsudana* x *alba* (1148) and *S.kinuyanagi* showed the superiority of these species over the others when grown under the conditions in the Manawatu region. These silvicultural conditions and species, particularly the eucalypts are recommended as a starting point for trial plantings in rural areas of Kenya though other species showing high growth levels in the region should also be evaluated.

Appropriate choice of species to suit specific regions (defined by the soils, climate, etc.) was the most important factor to consider for maximising SRF yields. Other factors for enhancing growth and yields in SRF systems include stocking density and cutting age. Since yields in subsequent coppice harvests tended to be lower than the first rotation yields, coppicing regimes can not be recommended on the basis of higher relative yields alone. Further work is required to compare the two systems of coppicing and replanting, and the related costs of biomass production over a long term.

Development of models to estimate the total biomass in a SRF plantation without destructive sampling will help commercialise SRF schemes as the biomass products can be evaluated prior to harvest and a monetary value attached to the crop. The model $\mathbf{W = 1.22D^2{*}H \times 10^{-4}}$

was found to be the best predictor of tree dry weight (W, kg), based on stump diameter (D, mm) and height (H, m).

Relative yield indices incorporating total yield; rotation length; tree dry weight; stump diameter; tree height; harvest index; and the stocking density (stems/ha); and also including time and its associated costs were developed to evaluate SRF species. This methodology provided a useful measure to evaluate tree species for biomass production for a specific climate and soil type.

CHAPTER FOUR

ENERGY CHARACTERISTICS OF WOODY BIOMASS

4.1 INTRODUCTION

The importance of the development of energy crops for basic feedstock supply has been recognised (see chapter 3), and research programmes are focused on intensifying the biomass yield obtainable per hectare (ODt/ha/y) in the shortest time by selecting high yielding species; and by the manipulation of silvicultural systems including selection of stocking density, rotation lengths and coppicing regimes. These previous yield maximisation programmes often pay little attention to the desirable characteristics of the produce, and therefore to its quality as a fuel yet it is recognised that there is clear variation in the chemical and physical characteristics among species, among trees of the same species, and as a result of different management strategies. Few studies have been undertaken to quantify or define these variations, particularly with respect to biomass energy requirements from short rotation forestry systems.

Stevens *et al* (1985) stated that "the efficiency of biomass processes is extremely dependent upon recognising and exploiting the chemical and physical properties of the biomass". Butner *et al* (1988), and Davis *et al* (1984) showed that a detailed chemical and physical characterisation of the feedstock was helpful in identifying plant constituents that correlate with the products. They emphasised the need for such knowledge to tailor the nature of the wood to suit specific requirements. Ragland *et al*, (1991) indicated the importance of adequate knowledge of wood properties for the analysis and modelling of fuelwood combustion in stoves, furnaces and industrial processes.

The usefulness of woody biomass crops should also be rated on their reliability of supply and acceptability as a feedstock in the conversion process (Paisley and Litt, 1993). Thus, the woody biomass characteristics should be defined in relation to their anticipated applications, the source of the material and the prevailing growing conditions. It is the thesis of the present work that an understanding of the variation in properties among species, clones, and sources will facilitate the selection and silvicultural management requirements. It will also assist in establishing basic data needed to utilise the forest biomass as a source of chemicals

(Blankenhorn *et al*, 1985; Davis *et al* 1984), as well as to provide a reliable source of renewable energy. Better understanding may permit proper allocation of the different biomass materials to the most appropriate applications i.e., "design biomass". If gasification is used, the knowledge could enable accurate estimation of the expected plant performance in terms of gas yield and composition, flame temperature, and heat output on burning or in other conversions.

Chapter 3 demonstrated the differences in biomass yields (ODt/ha/y) (i) among different short rotation forestry species; and (ii) among different tree growing conditions (silvicultural treatments), and developed relative yield indices (RYI) ranking the different species based on yield and tree dimensional properties.

4.1.1 OBJECTIVES

The laboratory analyses described in this chapter were conducted on a range of short rotation forestry (SRF) species materials obtained from the harvests described in chapter 3. The objectives of the analyses were to:

1. document the variability in energy characteristics of a range of short rotation forestry (SRF) tree species grown under similar conditions;
2. investigate the influence of silvicultural management regimes on SRF biomass properties;
3. ascertain the variability in energy characteristics of tree components - wood, bark and leaves from the same tree;
4. identify the interactions of the energy characteristics in defining fuelwood quality; and
5. develop a fuelwood value index (FVI) for biomass fuels.

4.2. **FUELWOOD CHARACTERISTICS**

Biomass materials are made of cellulose, hemicelluloses and lignin. Other components including extractives, water and inorganic substances are usually not considered when determining the physical and structural properties of the wood. The proportion of these constituents varies greatly among species and among various parts of the tree. For the well understood uses of wood like structural timber, panel products, paper pulp, and direct firing for process heat, any minor variation in the constituents is not considered to be a significant factor. For speciality or developing uses like feedstock for chemical extraction, co-firing in fluidised beds, liquefaction and gasification, variations in the fuelwood characteristics may well influence selection of suitable feedstocks and may even restrict possible uses (Miller, 1982). This review section will consider (i) the energy properties of woody biomass materials including the quantity of bark on the tree stems, basic density, moisture content, ash content, volatile matter content, fixed carbon content, extractives content, and calorific value; (ii) the effect of silvicultural treatments on the woody biomass properties; (iii) the interaction of the properties and the effect of the interaction on fuelwood quality; and (iv) the fuelwood value index and species selection.

4.2.1 ENERGY PROPERTIES OF BIOMASS MATERIALS

The proportion of bark on the stem (bark : wood ratio)

Geyer (1981), Flower-Ellis and Olson (1981), Krigstin, (1985), and Sennerby-Forsse *et al* (1983) investigated the proportion of bark in different diameter stems from SRF coppice hardwoods and reported that the proportion of bark, as a percentage of total stem weight decreased with increasing stem diameters; varied with species, and also with the age of the tree. In *Salix* species, bark may account for up to 43% of the total stemwood dry weight in one year old stems (Krigstin, 1985; Sennerby-Forsse *et al*, 1983). In *Eucalyptus regnans* grown in New Zealand, the proportion of bark varied from 11% to 7% in 4 year and 17 year old stems (Frederick *et al*, 1985). This implies that the quantity of bark in the feedstock may be influenced by choice of species for planting, and through silvicultural manipulations.

Basic density

The basic density of wood (ρ_{μ}) is a measure of the mass of oven dry wood substance per unit volume (kg/m^3) when measured in the green (freshly cut) condition. It may be written as:

$$\rho_{\mu} = M_{o}/V_{\mu}$$

> where m_o is the oven dry weight of the material, V_μ is the volume of the wood at saturated moisture content.

The specific gravity of wood is the relative density of wood in comparison with a standard density, usually water at 10°C. This parameter provides an indication of the amount of cell wall substance contained in that species and indicates the quantity of available fuel (as carbon) in a given volume of the wood. Density plays an important role in the estimation of yield. In conventional forestry, high wood quality is often associated with high density levels, and has been found to be correlated with good strength properties and pulp yields (Koch, 1972; Olson *et al*, 1985).

Hardwood species tend to be denser (200-1300 kg/m^3) than softwoods most of which have densities below 700 kg/m^3. Although it is generally understood that the density of wood from different tree species falls within specific ranges which help distinguish the tree species (Desch, 1986), the density of wood is influenced by age of the tree prior to felling, growth conditions and position in the tree (Clarke, 1991; Bues, 1989;1990; Siren *et al*, 1987; Hytonen and Fern, 1984). For example, the density of *Salix viminalis*, has been reported to increase from 360 kg/m^3 in one year old shoots to 440 kg/m^3 in five year old shoots (Siren *et al*, 1987; Hytonen and Fern, 1984). In New Zealand, Miller and Young (1989) reported basic density ranging from 330 kg/m^3 in 2 year old shoots to 619 kg/m^3 in 28 year old trees while Cown *et al*, (1992) reported values of 311-438 kg/m^3 in 20 year old pines.

Moisture in biomass materials

Moisture in biomass materials exists in two basic forms - bound water within the cell wall, and free water in liquid form in the voids of the biomass. Biomass materials are hygroscopic (i.e. they absorb moisture from the atmosphere if at a lower moisture content, and vice versa when wet to attain an equilibrium moisture content which varies with species, the prevailing relative humidity and temperature of the air; length of exposure; and time of year). Moisture content (MC, % dry basis) describes the mass of moisture per unit mass of dry material.

Moisture content is the least controllable, and most heterogeneous quality factor that influences most physical properties of biomass. An increase in biomass moisture content leads to swelling of the material, a reduction in the mechanical strength, the thermal and electrical conductivities increase, etc. Moisture content is not an intrinsic property of biomass materials but is an important property with regard to most processing and conversion technologies. For thermo-chemical processing, an increase in MC reduces the conversion efficiency. It denotes the many variations in wood fuel because it influences (i) the net heating value of the material (since removal of moisture from a material is a temperature activated process); (ii) the ignition properties; (iii) the efficiency of fuel utilisation; and (iv) the dry matter content of the fuel.

Although the equilibrium moisture content varies with species, different moisture content levels in clones with similar productivities, and under similar conditions may indicate differences in water usage efficiency, and thus a varying adaptability to drier conditions (Anderson and Zsuffa, 1982). Young trees, particularly those in the fastest stages of growth, contain more moisture than those which are growing slowly or not at all (Tilman, 1978) and the foliage is more moisture laden than the bole. Within the bole, the sapwood contains more water than the heartwood.

Under the same conditions, the green moisture content of wood varies with species, and even with clone with MC values of up to 189%, dry basis (db) being reported. According to Kenny *et al*, (1992), there is a relatively low heritability of the wood and bark moisture content, variations being due more to the site, climatic conditions, age, tissue type, and position in the stem. For a given energy recovery process, all these moisture related variables must be considered when analysing the fuel feedstock.

Ash

Ash is the inert inorganic residue that remains in an oxidised form after the biomass fuel has combusted completely. Two sources of ash can be distinguished - foreign material picked up during harvesting and processing, and that of physiological origin. The latter for most biomass materials consists mainly of silicon oxides although some materials may have higher contents of base oxides of calcium, sodium, magnesium, and potassium.

Ash content varies considerably with species and site, being high in tropical hardwoods with values of up to 8% in *Pricasma excelsa* and *Strychnus ignanti.* In *Salix* species and *Populus* species, values of 1.1-2.8% have been reported (Mansilla *et al*, 1991; Aijala, 1982), while in *Pinus radiata*, *Eucalyptus globulus*, and *Acacia dealbata*, values as low as 0.4% have been reported (Mansilla *et al*, 1991; Pereira, 1988).

Young and Guinn (1966) studied within tree variability of seven species of pines. The highest ash content was found in leaves (3-8%), followed by bark (2-6%). The lowest ash concentration was found in wood (< 1%). Tischler and Karschon (1983) found a higher average ash content in bark (6.12%) than in the leaves (4.24%) or wood (1.2%) of *Eucalyptus camaldulensis.* Leaves tend to have the highest amounts of inorganic materials which form ash when the material is burnt. Dhamodaran *et al*, (1989) found significant differences in the ash content of samples taken at different heights within the same tree but reported no correlation. Stringer and Olson (1987) also found a positive relation in ash content with tree height, ranging from 0.56% at the ground level to 0.87% at 80% of the total height.

In the conventional forest products industry, high ash content (resulting from the high mineral content) is undesirable as it blunts cutting tools. In gasification and boiler technology, high ash content causes slagging leading to fouling (chapter 5).

Volatile matter

Volatile matter content (VM) is a measure of the carbohydrate content of the fuel which is convertible to hydrocarbons (Will, 1979). It indicates (i) the hydrogen / carbon ratio of the material which influences the ignition, extinction stability and char burnout characteristics of solid fuels (Eklund *et al*, 1987); and (ii) the percentage of fuel burnt in a gaseous state as opposed to the fixed carbon content which shows the fuel burnt out in the solid state.

The heating of wood under conditions devoid of air or oxygen has been defined as a destructive distillation process which occurs in definite temperature stages. Up to about 280°C, the gaseous products are non-combustible consisting mainly of water vapour. Between 280-950°C, there is active exothermic pyrolysis reaction producing combustible gases and leaving a graphitic network residue in which the carbon-carbon bonds are unbreakable by pyrolysis below 3000°C (Mingle and Bouble, 1968). The combustible gases constitute the volatile matter content of the material, the determination of which has been shown to be dependent on the furnace temperature. During devolatilisation, the volatile matter content increases with heating rate at the expense of the char yield. In biomass materials, the volatile matter content has been found to be consistent and repeatable at a temperature of 950°C, which has thus been recommended for its determination (Mingle and Bouble, 1968; ASTM E 872-82, 1992). Thus, between ambient temperature and 950°C, volatile matter yield (i) is dependent on furnace temperature; (ii) increases with decreasing particle size; and (iii) increases with heating rate (Mingle and Bouble, 1968).

Although the volatile matter content varies among different materials and even within species (Howlett and Gamache, 1977; Overand and Rivard, 1993), it seems to occur within a specific range for different materials. In sugar cane bagasse, it ranges from 69-71% of the total dry weight. Wood of hybrid poplars contains between 78-85%; western hemlock, Douglas fir and ponderosa pine contain up to 87%; cedar wood, 77%; jack pine, 74%; birch, 78%; maple, 76%; eastern hemlock, 72%, and pure cellulose, 90% (Najewicz and Furham, 1993; Paisley and Litt, 1993; Mingle and Boubel, 1968; Tilman, 1987). Bark contains about 10-15% less VM than wood. In general, the VM of cellulosic materials approximates to 90% of the dry weight of the initial feedstock (Antal, 1981).

Cellulose content determines the levels of devolatilisation of materials (Antal *et al,* 1978). Cellulose devolatilises to 90% of the original weight, manure, 55-60%; paper, 85%, hardwood, 80% and softwood 70%. However, theses materials can be completely volatilised when subjected to more rapid heating (Lewellen *et al,* 1976).

Fixed carbon

Fixed carbon is the carbon residue remaining after the extraction of volatile matter and ash in proximate analyses of biomass material. Like most other wood constituents, different species of wood have different amounts of fixed carbon. For instance, Douglas fir wood contains about 12.6% (cf. 25.9 % in bark); western hemlock wood 12.7% (24.3% in bark); red alder wood 12.5% (19.7% in bark); and black oak wood 13% (16.9% in bark) (Tilman, 1987). Therefore bark contains more fixed carbon (up to 34% of the total weight) than wood.

Extractives

Extractives are non-structural (i.e. are not essential structural components of the cell wall or the middle lamella) aromatic compounds in biomass materials which possess one or more phenolic hydroxyl groups. In wood, extractives include compounds like terpenes, tannins, resin, sugars, starches, fats, oils, proteins and organic acids, most of which are readily soluble in neutral organic solvents or cold water, forming 3-13% of the wood dry weight.

The diversity in the chemical characteristics and relative abundance of extractives accounts for some of the differences in certain wood characteristics such as natural durability and heat of combustion among forest products (Wang and Huffman, 1981). When the wood is used for pulp, a high extractives content causes foaming, reduces the pulp yield and increases the consumption of pulping chemicals (Pereira, 1988). However, in the timber industry, extractives are sometimes desirable as they impart colour to the wood. A high extractives content increases both the un-extracted density, and the durability of the wood.

The relative abundance, composition and nature of the different compounds among different species and clones of wood varies considerably being associated with the genetic variability of different materials(Anderson *et al,* 1984; Swan and Kellog, 1986). In general, softwoods tend to have higher extractives content than hardwoods even though the highest values reported (12.7%) was for *Paulownia tomentosa* (Olson and Carpenter, 1985). For most woods, the extractives content is below 10% (Koch, 1972; Krigstin, 1985; Blankenhorn *et al*, 1985; Fengel and Grosser, 1975). The extractives content in a given species increases with age, mostly as a result of the presence of more water soluble material for which phenolics account for a large part (Pereira, 1988). In *Eucalyptus globulus*, extractives content has been reported to increase by a factor of more than 60% between the second and third year of growth (Pereira and Miranda, 1991). Clark (1991) reported increasing extractives content with age in *E.regnans* and *E.obliqua*, but Blankenhorn *et al*, (1985) found the extractives contents to reduce with age in 1-4 year old *Populus* species trees.

The concentration of extractives also varies within the same tree. Extractives content in both bark and foliage is higher than that of wood from the same tree (Wang and Huffman, 1981; Fuwape, 1989), while heartwood tends to have higher extractive content than sapwood (Wang and Huffman, 1981). Also, the accumulation of extractives in the heartwood and resin ducts causes a maximum concentration in the base of older trees.

Heating value

Heating value is a thermochemical property used as a measure, or index of quality classification, for most fuels including fossil fuels used in combustion applications. Two categories of heating value are distinguished - the higher heating value (HHV), and the lower heating value (LHV). HHV is the heat produced at constant volume by the complete combustion of a unit quantity of fuel in an oxygen bomb calorimeter and measures the total energy embodied in a unit weight or volume of fuel. It includes the latent heat of vaporisation of the water in the combustion products (Prinzing *et al*, 1993). LHV is the HHV adjusted for both the amount of hydrogen and moisture in the feedstock. It is thus, closer to the heat which could be recovered in practice by using conventional burners.

The gross heat of combustion, derived from bomb calorimeter tests represents the heat generated by a fuel on complete combustion, and depends on the quantitative conversion of carbon and hydrogen to water and carbon dioxide. The combustion reactions in the bomb are forced to completion by the high oxygen pressure and the spark ignition, which results in explosive reactions due to the high oxygen concentrations. Heating value therefore is a function of the chemical composition, in particular with the carbon content (Susott *et al*, 1975; Doath, 1977; and Murphy and Masters, 1978). Variations in the heating values among different species, and also among different tree components therefore shows differences in the chemical composition which is used to demonstrate the quality of the fuel.

The heating values of different biomass materials (such as various tree species and crop residues) differ significantly. The variation in the heating values is associated with the different chemical composition (Tilman, 1978) and reflects the collective heating values of the wood components. For instance, the different components of Douglas fir have been found to have different heating values - hollocellulose (i.e. cellulose and hemicellulose), 17.5

MJ/kg, lignin, 26.7 MJ/kg, and extractives, 34.4-39.5 MJ/kg (Corder, 1975; Tilman, 1978; Kubler, 1982). Wang and Huffman (1982) showed the influence of different extractive content levels on the heating values of wood (in *Melaleuca quinquenervia*) material as ranging from negligible in the sapwood where the extractives content is very low, to 37% of the material's energy in the foliage with about 27% extractives content. Within the extractives, the carbon and hydrogen rich extractives have higher heating values than those that contain a lot of oxygen like the phenolics. Thus, there is a relationship between the lignin and extractives contents of a woodfuel, and its energy value (White, 1987). Measurements using differential scanning calorimetry have shown that water soluble extractive compounds have the greatest per unit energy content of the wood components (Krigstin *et al*, 1993). Removal of these materials leaves a low energy residue with about 16.8 MJ/kg and containing a proportionately higher content of oxygen.

Corder (1975) stated that the heating values for different tree species on a moisture free and resin-free basis is the same, being equivalent to 19.25 MJ/kg. Resin (one of the extractives) has a higher heating value than wood itself (with 39.5 MJ/kg). Thus, woods that contain a lot of resins such as pines, spruce, cedars, larch and Douglas fir (softwoods), have higher heating values ranging from 20.0 - 22.6 MJ/kg. The near resin-free woods such as true firs and most hardwoods like beech, elms, red maple, hickory, oak and sycamore have values ranging from 18.5-19.0 MJ/kg. However, the heating values quoted for most wood species by other workers (Rossi, 1984; Najewicz and Furham, 1993; Wang and Huffman, 1982), particularly for hardwoods, are much lower than the minimum value for Corder's resin-free wood. For instance, the highest quoted values are for Douglas fir bark and wood respectively at 21.93 and 20.37 MJ/kg oven dry weight. The lowest values quoted are for black oak (*Quercus* species) bark and wood having 17.09 and 18.65 MJ/kg, respectively (Rossi, 1984). The value quoted for hybrid poplars is 19 MJ/kg (Paisley and Litt, 1993), for willows, 19.2-19.6 MJ/kg (Krigstin, 1985). Sastry and Anderson (1980) found significant differences in the heating values ranging from 18.2 MJ/kg to 20.7 MJ/kg in 10 hybrid poplar clones. Wang and Huffman (1982) determined the calorific values of extracted and un-extracted heating values of tree components from two different species. Though extracted and un-extracted values were different, extracted materials did not have similar calorific values as suggested by Corder (1975).

Different tree components have different heating values. Howlett and Gamache, (1977) reported values of 17.7-21.0 MJ/kg for foliage materials, being higher in the foliage of softwoods. Although Haris (1985) found that red maple (*Acer rubrum*) and post oak (*Quercus stellata*) woods had higher heating values than bark of the same tree, most reports suggest that bark from the same tree and position has a higher heating value than the wood (Howlett and Gamache 1977). Molner and Nemath (1983) found that the heat of combustion for bark of *Robinia* species was 7.2% higher than that of stemwood. Tietema *et al*, (1991) found higher calorific values for bark than wood in arid species using the Wagner techniques (Wagner, 1979), while Krigstin (1985) found slightly higher heating values in bark than in wood of *Salix* species. The higher calorific value in bark could be associated with the higher extractives content. Molner and Nemath (1983) measured the heat of combustion in a bomb calorimeter to be 6-9% higher than the value computed from the composition of the chemical elements in *Robinia* species.

Haris (1985) found that branch wood had a lower heating value than stemwood, but there was no significant difference between wood or bark samples from different positions within the stem, different positions within the branch, or different branch positions for any of the three species tested: white oak, yellow poplar and sweet gum. In red maple (*Acer rubrum*), there was no difference in HHV between stemwood and branch wood, or between stem bark and branch bark. However, in post oak (*Quercus stellata*), the HHV of stem bark was significantly higher than that of branch bark, but there was no significant difference between stemwood and branch wood. For all the species tested, wood had a significantly higher HHV than bark (Haris, 1985). Dhamodaran *et al*, (1989) found no trend in calorific value with height in coconut stemwood.

The variations in the heating values in different species reflect inherent differences of the species, which may also be influenced by the growth conditions, and also the sampling and measurement methodologies.

4.2.2 INFLUENCE OF SILVICULTURAL TREATMENTS ON BIOMASS ENERGY PROPERTIES

Major changes in wood properties are associated with shorter rotations, which result in a higher proportion of juvenile wood. The young wood, compared with mature wood, contains a higher moisture content, lower density, and a higher proportion of reaction wood (Bendestein, 1978). Young trees have been shown to have a substantially higher content of foliage and bark biomass than older trees.

Knowles *et al*, (1993) found the average tree wood density of *P.radiata* decreased with higher stocking density in an agroforestry trial grown at Tikitere, New Zealand. The decline in density with increased stocking density is associated with the higher proportion of earlywood.

Harris and Young (1988) found the basic density of different *Eucalyptus* species grown in New Zealand to increase with age. The basic density of *E.nitens* increased from 420 kg/m^3 (1-10 y) to 455 (11-20 y) and 650 at above 50 years. *E.saligna* basic density increased from 440 kg/m^3 (1-10y); 490, (11-20 y); 575 (21-30 y); 635 (41-50 y); and 630 at above 50 years. Phelps *et al*, (1987) found that the density and fibre length from the basal portion of 3 year old first rotation *Populus* species trees to be higher than in 3 year old coppice crop. Cown *et al*, (1992) found the specific gravity of wood to differ with the age of the tree, gradually increasing throughout the juvenile growth period to maturity.

Blankenhorn *et al*, (1985; 1988) investigated the influence of age (1-8 years), and rotation on energy properties of trees. In the first rotation *Populus* hybrid grown at a spacing of 0.48 m^2/tree, wood density ranged from 349 to 480 kg/m^3 and reduced with age of the trees. Extractives content tended to be higher in younger material (except in bark), and was also higher in the second rotation than the first. Wood extractives content ranged from 9.81% to 4.78% in 1 and 4 year old trees. Bark extractives content were higher than those in wood, but did not vary with age.

Many previous reports have not shown the gross heat of combustion values to vary with age (Blankenhorn *et al*, 1985; Blankenhorn *et al*, 1988; Frederick *et al*, 1985; Hielman and Peabody, 1981), and according to Holt and Murphy, (1978) and Hielman and Peabody, (1981), the heating values do not change with stocking density. However, in one year coppice of *Vitex negundo* trials, Verma and Misra (1989) found that the heating values declined with increasing stocking density from 21.6 MJ/kg at 25,000 stems/ha to 20.4 and 19.6 MJ/kg at 50,000 and 75,000 stems/ha respectively. The stem ash content at 25,000 stems/ha was 3% compared to 2.5% and 2.4% at 50,000 and 75,000 stems/ha respectively. The reasons for the changes in heating values were not clear, but it was not stated whether the stemwood included bark or not.

4.2.3 INTERACTION OF PROPERTIES AND FUELWOOD QUALITY

In the analysis of the interrelationships of properties to define the relative quality of wood species for specific uses, different ratios relating different properties have been proposed (Hakilla, 1989; Butner *et al*, 1988; Ebeling and Jenkins, 1985). The ratios defined were shown to be related to the desired properties, some of which categorised different species into distinct groups, making it possible to rank the species from simple measurements.

The possible application of such ratios as indicators of quality, is born out of the fact that some factors impart a larger influence on wood properties than others. In this regard, fuelwood quality assessments have been based on the heating values per unit mass, other properties then being regarded as functions of heating value, and how they influence it. For instance, Hakilla, (1989), and Butner *et al*, (1988) presented heating value as a function of hydrogen and moisture contents:

$$LHV=HHV(0.2205H)-(2.42mc_{wb}/1-mc_{wb}),$$

where LHV is the lower heating value; HHV is the higher heating value; H is the hydrogen content of the wood (w/w); and mc_{wb} is the moisture content of wood on wet weight basis.

Ebeling and Jenkins (1985) related HHV with ash content and volatile matter content:

$$HHV=20.067-0.234Ash;$$

and

$$HHV=26.601 - 0.304Ash-0.082VM.$$

Other similar relationships have been developed by Demirbas *et al*, (1997); Sirisomboon (1991); Lyons *et al*,(1985), and by White (1987). These relationships demonstrated that there were relationships among the different properties of fuelwood. Although it is generally presumed that higher density woods have higher heating value, no correlation has been reported.

4.2.4 THE FUELWOOD VALUE INDEX AND SPECIES SELECTION

Purohit and Nautiyal (1987) proposed a fuel value index (FVI) applicable to the use of biomass in direct firing. The index included the calorific value and density of the wood as the most desirable properties, while high moisture and ash contents were considered undesirable characteristics. The best species maximised both the heating value and density, while it minimised the moisture and ash contents. The index was defined as:

$$FVI = \frac{HHV * \rho}{Ash * MC}$$

where FVI was the fuelwood value index, HHV was the higher heating value of the material, ρ was the basic density, while ash and MC were the percentage ash and moisture contents of the species wood samples respectively (Purohit and Nautiyal, 1987).

The species with the highest index was regarded as being the best for direct combustion.

Bhatt and Todaria (1992), argued that the moisture content of wood was not an intrinsic property of a biomass material (i.e. moisture content varied with season, dimension of the material, level of processing etc.) and suggested modifications to the Purohit and Nautiyal (1987) FVI model to eliminate the influence of moisture content. Thus, according to Bhatt and Todaria (1992), the new fuel value index was presented:

$$FVI_1 = \frac{HHV * \rho}{Ash}$$

Once again, the species with the highest FVI_1 was considered as the best.

For other applications, Chafe (1986, 1987a, 1987b) proposed the **R-ratio**, derived from volumetric shrinkage and basic density. The intersection point of the shrinkage and basic density functions was shown to be equivalent to the change in external wood volume during shrinkage or swelling per change in the weight of the associated volume of water, i.e.;

$$R = \frac{(Vg - Vo)}{Wv}$$

where R is the R-ratio; V_g is final wood volume after either swelling or shrinkage; V_0 is the initial volume of the wood; and W_v is weight of water.

The R-ratio was suggested as a timber index suitable for subjective ranking of species on the basis of dimensional stability (Chafe, 1987b).

Since all these indices incorporate a variety of variables, aiming to maximise the better attributes, while minimising the undesirable attributes, they provide a better assessment of the species with respect to desired applications. Thus, Senelwa and Sims (1997b) extended the fuelwood value index and the R-ratio concepts by incorporating multi-objective evaluation procedures previously used by Ramanathan and Ganesh (1995); Ramanathan and Ganesh (1993); Chetty and Subramanian (1988); Kambo *et al*, (1990/1991) and Cocklin *et al*, (1986) to demonstrate the potential for utilising multiple objectives in evaluating species for fuelwood production.

4.2.5 SUMMARY

The characteristics of woody biomass, and the relationships between the characteristics seem to be elaborate, but this study dealt with SRF material, most of which is harvested in the juvenile form. At this age, trends in properties are not well documented. Similarly, the effect of coppicing on these properties in SRF species and any resultant effects on fuelwood quality is not defined.

4.3 MATERIALS AND METHODS

Materials for these laboratory tests were obtained from harvesting the species and coppice trials at Massey University. The conditions of growth, and species yield factors were outlined in chapter 3. For each species, samples were collected from a minimum of 4 trees. Thus, the properties were not associated with particular trees but provide average values of trees from different plots.

4.3.1 EXPERIMENTAL VARIABLES

The variables evaluated in this series of experiments included ash content, volatile matter content (VM), fixed carbon content (FCC), organic solvent soluble extractives (OEC), total extractives content (TEC), higher heating value (HHV) and basic density. Three other properties - dry matter content, harvest index, and the proportion of bark on the stem were evaluated during harvesting.

Experiment A - Variation among SRF species

10 SRF species	Wood component	Ash, VM, FCC, OEC, TEC, HHV, density.
	Bark component	Ash, VM, FCC, OEC, TEC, HHV.

Breast height (≈ 1.3 m from the ground) stemwood samples were collected from ten species - *Eucalyptus globulus*, *E.nitens*, *E.saligna*, *Salix kinuyanagi*, *Salix matsudana* x *alba*, *Populus eridiano*, *Acacia dealbata*, *Paulownia tomentosa*, *Alnus glutinosa* and *Pinus radiata* grown in replicated blocks at a stocking density of 3470 stems/ha (see section 3.3.1). The samples were collected when the trees were harvested at 3 years old (see section 3.3.4). Basic density and the proportion of bark on the stem were also determined when the trees were harvested at the age of 4 and 5 years.

Experiment B - The influence of silvicultural treatments

E.saligna (wood)	4 Stocking densities	Ash, VM, FCC, OEC, TEC, HHV, density.
	4 Rotation lengths	Ash, VM, FCC, OEC, TEC, HHV, density.
	Coppice/Establishment	Ash, VM, FCC, OEC, TEC, HHV, density.

This experiment utilised breast height material obtained from *E.saligna* grown in a "Nelder" radial design trial (see section 3.3.3) to investigate (i) the influence of rotation length (1, 2, and 3 years); (ii) the influence of coppicing (cf. 6 year old establishment crop); and (iii) the influence of stocking density (1640, 3770, 7050 and 16270 stems/ha) on selected energy properties.

Experiment C - Variation of components within the tree

5 SRF species	Wood	Stump height	Ash, VM, FCC, OEC, TEC. HHV, density.
		Breast height	Ash, VM, FCC, OEC, TEC, HHV, density.
		40 mm td	Ash, VM, FCC, OEC, TEC, HHV, density.
	Bark	Stump height	Ash, VM, FCC. OEC, TEC, HHV.
		Breast height	Ash, VM, FCC. OEC, TEC, HHV.
		40 mm top diameter	Ash, VM, FCC, OEC, TEC, HHV.
	Leaf		Ash, VM, FCC, OEC, TEC, HHV.

Wood and bark from discs obtained from three positions in the tree (stump height, breast height, and 40 mm top diameter height) and leaf samples were collected from each of the 5 species - *Salix kinuyanagi, S.matsudana x alba, Eucalyptus saligna, E.globulus* and *E.nitens* grown in replicated blocks at a stocking density of 3470 stems/ha (see section 3.3.1). Like in experiment A, the samples were collected when the trees were harvested at 3 years old (see section 3.3.4).

Experiment D - Interaction of bioenergy properties

8 SRF species	Extractives (Extracted and non-extracted)	Ash, VM, HHV
2 SRF species	MC (oven dry, air dry, moist, soaked)	HHV
3 SRF species	Particle size (<0.25 to 4 mm mesh)	DM, Ash, VM, FCC

This experiment investigated the influence of selected properties (extractives content, moisture content, and particle size) on other biomass properties:

- **Extractives** - Residues from soxhlet and boiling water-bath extractions for the determination of total extractives content were analysed for ash content, volatile matter content, and heating values. The results were compared with the results of the original (un-extracted) samples.
- **Moisture content** - The moisture content of selected samples was varied between 0% (oven dried) to 37% (re-wetted after oven drying), and then tested for heating value.

- **Sample particle size** - Graded sample particle sizes were obtained using a series of mesh sizes from 0.25 to 4.00 mm. The different assortments of each of the three species were then analysed for dry matter, ash, volatile matter, and fixed carbon contents.

4.3.2 SAMPLING

Stump, breast and 40 mm top diameter lengths positions were marked on each tree after felling (see section 3.3.4). From each of these positions, wood discs, 30-40 mm wide and about 1 kg fresh weight were obtained using a power chain saw. A similar mass of leaves from each tree was randomly obtained. The samples from at least three trees in each plot were placed in separate paper bags and taken to the laboratory where the stem samples were debarked manually. All samples were spread out for air drying. Duplicate samples to determine dry matter content, proportion of bark on the stem, and basic density of both wood and bark were oven dried at 80°C to constant weight.

The disc samples were shredded, chipped, hammer-milled and sieved through a 250 μm mesh size. The material used for extractives content analysis was that retained when the samples were further sieved through a 180 μm mesh size and thus ranged from 180 - 250 μm particle size.

4.3.3 LABORATORY PROCEDURES

All tests were conducted using established standard laboratory procedures, distinguishing between wood, bark and leaf samples. Any deviations and or modifications from such procedures were specified accordingly. A total of eight properties were analysed.

- The proportion of bark on the stem at breast height

  Stem discs were cut perpendicularly from breast height positions (≈ 1.3 m from the ground) in the tree. The samples were debarked and then both the wood and bark weighed separately. The samples were oven dried at 80°C to constant weight. The proportion of bark on the stem was determined as the ratio of oven dry weight of bark to oven dry weight of wood.

- Basic density - the water displacement method

  Green freshly cut samples of wood and bark were soaked in water for about 6 hours before being immersed in a tared weigh balance. The weight of water displaced on total immersion was recorded, and the samples oven dried to constant weight (mass) at 80°C. The sample basic density (ρ_μ) was calculated as the final oven dry weight (M_o) divided by the weight of the water displaced, which represents the volume of the water, and therefore of the sample (V_μ, cm^3).

- Ash content: ASTM D 3174 - 89

  About 2 g of sample (<250 µm sieve) was weighed into a tared porcelain capsule (I g), and placed into a muffle furnace. The furnace temperature was increased gradually - 500°C in the first 1 hour, 700°C in the second, and 750°C in the last 2 hours. At the end of the fourth hour, the porcelin capsule was removed and cooled in a desiccant and weighed (f g). The ash content was calculated as:

  $$\text{Ash} (\%) = [(I-f) / I] \times 100$$

- Volatile matter content (VM): ASTM E 872 - 82 (Re-approved 1992)

  1 g of sample (pulverised to pass through a 250 µm sieve) was weighed into tared nickel-chromium crucibles with a closely fitting cover (I g), and placed into a muffle furnace maintained at 950°C ± 20°C. The crucibles were left for exactly 7 minutes, making sure that the covers were well seated on the crucible. After 7 minutes of heating, the crucible was removed, cooled in a desiccator and weighed (f g). Volatile matter content corrected for the sample moisture content, was calculated as:

  $$\text{VM} (\%) = [(I-f)/I] \times 100$$

- Fixed carbon content was determined by deducting the percentage of ash and volatile matter content on a dry weight basis, from the original sample dry matter weight (being 100%).

- Extractives content (OEC and TEC) method was adopted and modified from, Browning (1967), Koch (1970), and ASTM D 1105-84. Two kinds of extractives were distinguished (i) organic solvent soluble extractives (OEC) which are lipophilic i.e. those extracted by non-polar solvents (ethanol : benzene mixture, and ethanol); and (ii) total extractives (TEC) being the total quantity including lipophilic (organic solvent soluble) and hydrophilic extractives (water soluble).

  Approximately 2 g of oven dry ground wood (sieved to pass through a 250µm gauze but retained on a 180 µm) was weighed into pre-weighed 149 µm Estal Mono Polyester (BCEM HD 100 149) bags (W_o). The bags were placed in soxhlet extraction apparatus with ground glass joints, with 250 ml distillation flasks containing thimbles of alundum. The samples were extracted with 125 ml of a 33:67 volume mixture of 95% ethanol:benzene for 4 hours. The ethanol:benzene mixture was drained and rinsed with ethanol, followed by another 4 hours extraction with 125 ml of 95% ethanol. The alcohol was drained and evaporated to constant weight (W_m) to determine OEC. The samples were then boiled in distilled water at 100°C (boiling water bath) for 3 hours followed by oven drying at 80°C to constant weight (W_f). OEC and TEC were determined as a % loss in weights between W_o and W_m; and between W_o and W_f, respectively. The final extracted samples were tested for ash, VM and HHV.

- Higher heating value (HHV): ASTM D 2015 - 93.

  About 1 g of sample (pulverised to pass through a 250 μm sieve) was pressed into a pellet, and placed into the sample holder of the bomb calorimeter set-up, standardised by the combustion of a known weight of benzoic acid whose heat value is known (26.453 MJ/kg). The bomb was charged with oxygen to a consistent pressure of 30 atm. (3 MPa), admitting the oxygen slowly so as not to blow the sample from the holder. The temperature difference between the final temperature after ignition, and the initial steady temperatures of the bomb at start were used to determine the heating value of the sample, corrected for sample moisture content.

The standard procedures (ASTM D 2015 - 93) required that thermochemical corrections for heats of formation of nitric acid and sulphuric acid be applied. This was not done as it has been shown to account for only 0.1% of the resultant energy content (Leith, 1973) due to low nitrogen and sulphur contents of biomass materials. Besides, the energy remaining in the free acids is small compared with the differences in heat values that occur between replication (Gorbatora, 1964).

4.3.4 ANALYSIS OF RESULTS

The general linear models procedure of the SAS System was used to analyse the results for correlation analysis and trends with respect to tree species, tree parts, and silvicultural treatments, and to identify quality determining properties which were then used to develop a fuelwood value index (FVI). Duncan's multiple range test procedures were used to rank species with similar means. Unless otherwise stated, all effects were established at the 5% level of significance.

4.3.5 FUELWOOD VALUE INDEX AND SPECIES SELECTION

Correlation and regression analyses between heat values and other properties were carried out. The results of the regression were used to define a fuelwood value index (FVI) to enable different species to be compared for fuelwood suitability as follows:

- The heat value of each species was considered the ultimate fuelwood quality indicator, and all other properties were seen to either enhance or reduce it.

- Variables with positive parameter estimates were thought to enhance heat values and therefore formed the numerator in the FVI model.

- Variables with negative parameter estimates were thought to reduce the fuelwood quality by reducing the heat values. Such parameters formed the denominator of the FVI function.

- Handling characteristics of the biomass were incorporated by multiplying the base index with the basic density of the species. It was assumed that a good fuelwood species needed to be dense as this would minimise transport costs per unit weight therefore maximising payloads.

- Yield and piece size were incorporated through the relative yield index (see chapter 3).

The revised fuelwood value index was written as:

$$FVI = \frac{(aHHV * bX_1 * cX_2, \ldots\ldots)}{a_1 X_m * b_2 X_n, \ldots\ldots} * Density * RYI$$

where X_1, X_2, ..., are variables with positive parameter estimates (i.e., properties which enhance HHV), while X_m, X_n, ... are variables with negative parameter estimates (i.e., properties which reduce HHV); a, b, ... are factors describing correlations between heat values and other properties; density is the basic density of the species; and RYI is the relative yield index of the species determined in section 3.4.4.

The heat values used in the calculations incorporated species differences in the proportion of bark on the stem and the differences in heating values between bark and wood. It was assumed that the relative costs of production were incorporated through the relative yield index included, and the cost of time and money. All assumptions applying in the determination of the relative yield indices were assumed to apply in the fuelwood value index determinations.

4.4 RESULTS

The bioenergy properties of SRF species were examined under five categories (i) species variability; (ii) the influence of silvicultural treatments (rotation length, stocking density and coppicing); (iii) variation within the tree; (iv) interaction of fuelwood properties in defining fuelwood quality; and (v) fuelwood value index (FVI) and fuelwood species evaluation. Although the green moisture content of the trees was determined at harvest, the results were not reported here as moisture content is not an intrinsic property of biomass materials. However, its influence on the heating value of wood was examined, and will be presented in section 4.4.4.

4.4.1 EXPERIMENT A: SPECIES VARIABILITY

Table 4.1 presents the variability in fuelwood properties of wood and bark of 10 species.

Table 4.1 **Fuelwood properties of 3 year old SRF tree species***

	Ash (%)		Volatile matter, %		FCC (%)		OEC (%)		TEC (%)		HHV (MJ/kg)	
Species	Wood	Bark	Wood	Bark	Wood	Bark	Wood	Bark	Wood	Bark	Wood	Bark
E.globulus	1.0	3.9 ^{a}	92.8	87.5 ^{a}	6.2	8.6 ^{b,c}	2.8	4.7 ^{b}	4.7	10.0 ^{b}	19.7	17.9 ^{a,b}
E.nitens	1.2	3.6 ^{a}	91.9	86.2 ^{a}	6.9	10.2 ^{a,b,c}	2.9	8.1 ^{a,b}	4.7	18.3 ^{a,b}	20.2	18.5 ^{a,b}
E.saligna	0.9	4.4 ^{a}	92.8	85.4 ^{a}	6.3	10.1 ^{a,b,c}	2.0	5.5 ^{b}	3.3	17.0 ^{b}	19.8	17.8 ^{b}
S.kinuyanagi	0.8	4.7 ^{a}	94.3	85.6 ^{a}	4.9	9.7 ^{a,b,c}	4.3	7.6 ^{a,b}	7.8	14.1 ^{a,b}	19.9	19.6 ^{a,b}
S.mats alba	1.1	5.7 ^{a}	93.3	87.1 ^{a}	5.6	7.2 ^{c}	4.6	7.3 ^{a,b}	7.0	13.3 ^{a,b}	19.6	18.7 ^{a,b}
A.dealbata	1.4	3.9 ^{a}	91.5	80.1 ^{b}	7.2	16.0 ^{a}	4.3	15.3 ^{a,b}	6.8	25.1 ^{a,b}	19.7	20.5 ^{a,b}
P.radiata	1.1	2.5 ^{a}	91.7	83.7 ^{a,b}	7.3	13.8 ^{a,b}	3.4	12.6 ^{a,b}	6.3	25.9 ^{a,b}	20.5	20.6 ^{a}
A.glutinosa	0.7	2.7 ^{a}	95.1	85.2 ^{a}	4.2	10.6 ^{a,b,c}	4.1	6.1 ^{b}	6.5	20.3 ^{b}	19.8	19.1 ^{b}
P.eridiano	1.0	4.9 ^{a}	92.6	85.8 ^{a}	6.4	9.3 ^{a,b,c}	3.1	19.8 ^{a,b}	6.1	28.9 ^{a,b}	19.7	19.5 ^{a,b}
P.tomentosa	1.2	5.1 ^{a}	93.6	85.2 ^{a}	5.2	10.6 ^{a,b,c}	8.8	19.1 ^{a}	11.9	30.4 ^{a}	20.1	19.1 ^{a,b}
Mean	1.0 ^{b}	4.1 ^{a}	93.0 ^{a}	85.2 ^{b}	6.0 ^{b}	10.6 ^{a}	4.0 ^{b}	10.6 ^{a}	6.5 ^{b}	20.3 ^{a}	19.9 ^{a}	19.1 ^{b}
Std deviation	0.2	1.0	1.1	2.0	1.0	2.4	1.8	5.4	2.2	6.6	0.3	0.9

FCC = Fixed carbon content

OEC = Organic solvent soluble extractive content

TEC = Total extractives content

HHV = Higher heating value

* - Values with the same letter for any one property (average of wood and bark together) are not significantly different

The results table shows the following:

1. Most bioenergy properties do not differ significantly among species.

2. The wood properties were significantly different from those of bark, with wood having significantly lower contents of ash, fixed carbon, and extractives contents, but higher volatile matter content, and marginally higher heating values except for *A.dealbata* and *P.radiata*.

3. The variability in properties among the 10 species was highest in bark.

4. *Paulownia tomentosa* had very high extractives content. The species with the highest heating values (*P.radiata* and *A.dealbata*) had the lowest volatile matter contents. The bark and wood of *Eucalyptus* species had the lowest heat value and extractives contents, respectively.

5. The highest heating values were obtained in *P.radiata* which was the only softwood (gymnosperm) tested.

3.4.2 EXPERIMENT B: THE INFLUENCE OF SILVICULTURAL TREATMENTS

Table 4.2 shows the effect of cutting age on the (i) basic density of both wood and bark; (ii) the proportion of bark on the stem; and (iii) the harvest index for the 12 SRF species.

Table 4.2 **The influence of rotation length on selected physical properties of SRF species***

	Harvest index (%)				% bark to stem (wt)				Wood density (kg/m^3)				Bark density (kg/m^3)			
Species	3 y	4 y	5y		3 y	4 y	5y		3 y	4 y	5y		3 y	4 y	5y	
E.globulus	61	64	73	a	15	13	12	b	439	507	478	a	-	322	300	b
E.nitens	63	72	74	a	15	13	12	b	411	420	417	b	-	296	298	b,c
E.saligna	45	50	62	c,d	19	17	-	a	446	450	470	a	-	267	-	c
S.kinuyanagi	41	56	55	c,d,e	14	11	11	b,c	450	457	465	a	-	362	405	a
S.mats x alba 1148	44	56	65	b,c,d	10	10	9	e	357	373	360	c	-	291	273	b,c
A.dealbata	57	67	64	a,b	10	9	9	e	363	335	327	c	-	397	426	a
P.radiata	36	48	55	d,e	14	11	8	c,d,e	282	282	292	d	-	278	278	b,c
A.glutinosa	26	47	52	e	18	16	15	a	316	355	354	c	-	369	383	a
P.eridiano	44	58	64	b,c,d	14	11	10	b,c,d	279	284	283	d	-	271	311	b,c
S.mats x alba 1002	46	47	60	c,d,e	10	11	9	d,e	332	323	363	c	-	284	283	b,c
P.tomentosa	41	63	42	d,e	15	13	11	b	267	253	262	d	-	276	304	b,c
E.ovata	53	62	67	a,b,c	18	15	16	a	407	428	437	b	-	310	310	b
	b	a	a		a	b	c		a	a	a			a	a	
Mean	46	58	61		14	13	11		362	372	376		-	310	325	
Std	10	8	9		3	2	2		65	77	73		-	42	51	

* -Values with the same letter are not significantly different

From table 4.2, it is observed that:

1. Wood basic density differed significantly among the twelve species, and also among the 3, 4 and 5 year old samples in most of the species. *P.tomentosa*, *P.eridano* and *P.radiata* had densities less than 300 kg/m^3, while *Eucalyptus* species, and *Salix kinuyanagi* had densities exceeding 400 kg/m^3.

2. With the exception of *A.dealbata* and *A.glutinosa*, wood density was significantly higher than that of bark. Although the wood density in 2 of the species (*P.eridano* and *P.tomentosa*) remained similar among 3, 4 and 5 years, density appeared to increase with age even though the overall differences were not significant.

3. The harvest index (proportion of stemwood to total above ground tree biomass) varied with species, and also with cutting age. Older trees had a higher harvest index, but appeared to level off in the 4 and 5 year rotations. The proportion of bark on the stem was also significantly different among species, and it decreased with increasing cutting age.

“Nelder” radial trial stock

Figure 4.1 (and also appendix 4.1) show the effect of cutting age (1, 2, 3 and 6 years), stocking density (1640, 3770, 7040 and 16260 stems/ha), and coppicing on wood properties. All 1, 2, and 3 year old samples were coppiced material obtained from 6 year old root stocks, while the 6 year old material was the original single stem (establishment) crop of *E.saligna* planted in a “Nelder” radial design trial (section 3.3.3).

The results in the figure (and also in appendix 4.1) show the following:

1. About 20.4% of stem dry weight was bark. The proportion of bark did not show significant differences associated with either rotation age or coppicing; decreased with increasing stocking density; and was similar to those of *E.saligna* in the species trials tests (table 4.2). Although wood density increased with age, and varied with both stocking density and coppicing, the variations were not significant.

2. Ash content decreased with cutting age, but did not vary with stocking density.

3. Volatile matter increased with cutting age, but was not affected by stocking densities.

4. Both fixed carbon content and organic extractives content were not influenced by both stocking density, rotation lengths, and coppicing. Total extractives content decreased with cutting age but did not appear to be influenced by stocking density and coppicing.

5. Although heating value appeared to increase with stocking density, and decline with cutting age in the coppiced stock, the variation was not significant.

6. Coppiced stock did not appear different from the first rotation stock.

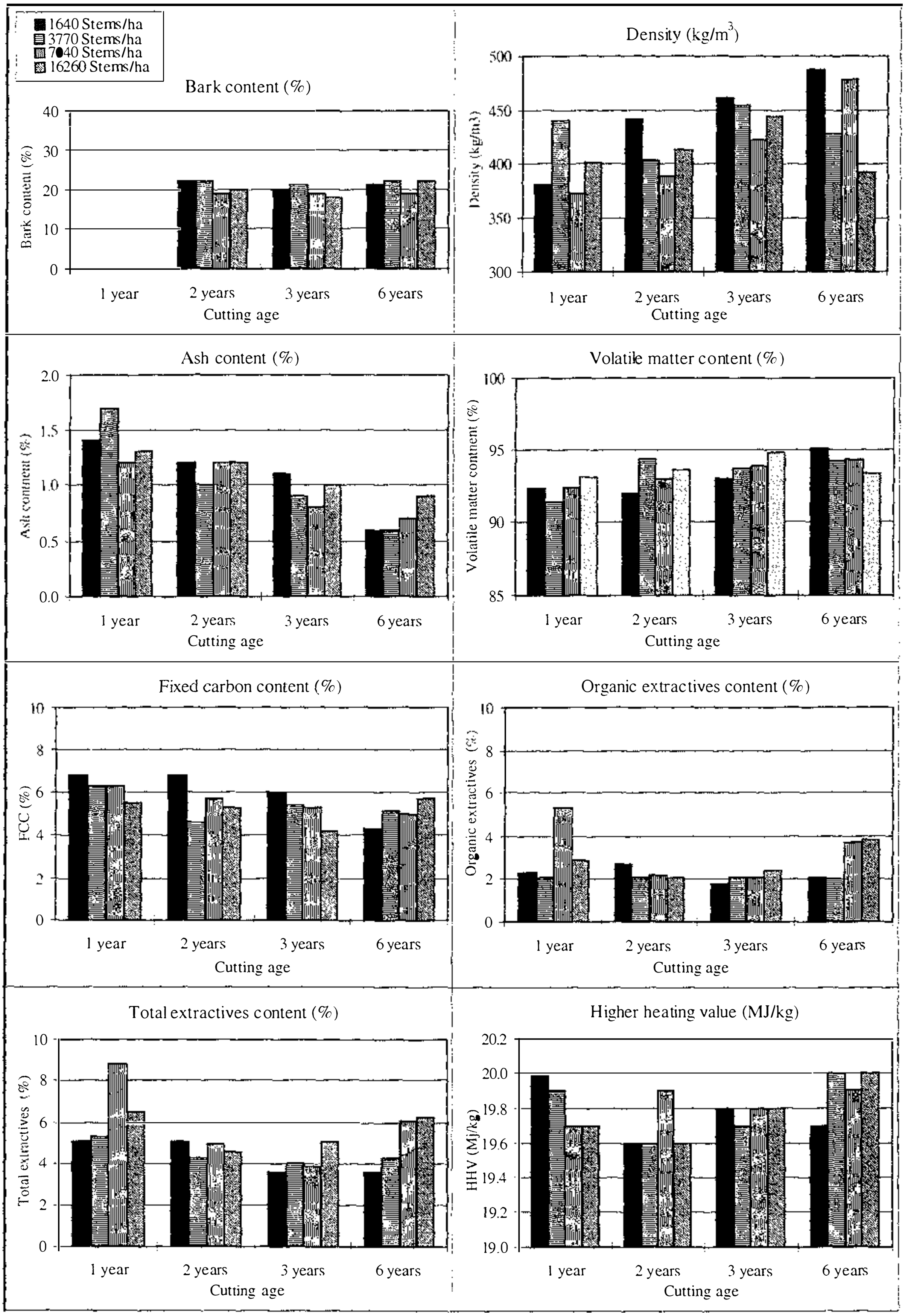

Figure 4.1 **The influence of rotation length, stocking density and coppicing on wood properties in a "Nelder" radial coppicing trial of *E.saligna***

4.4.3 EXPERIMENT C: TREE PARTS AND COMPONENTS

Table 4.3 shows the bioenergy properties of selected components for selected SRF species grown under similar conditions. The wood and bark samples were taken from disks taken at stump height (0.15 m), breast height and at the 40 mm top diameter.

Table 4.3 **Variability within tree parts and components* in 5 SRF species**

		Wood			Bark			Leaves
Property	Species/Height	Stump	Breast	40 mm td	Stump	Breast	40 mm td	
Basic density (kg/m^3)	*E.nitens*	430	411	402 ^{b}				
	E.globulus	453	439	485 ^{a}				
	E.saligna	485	446	436 ^{a}				
	S.kinuyanagi	461	450	435 ^{a}				
	S.mats x alba	388	357	349 ^{c}				
	Mean	443^{a}	421^{a}	421^{a}				
Ash Content (%)	*E.nitens*	1.1	1.2	0.9 ^{a,b}	4.3	3.6	3.1 ^{c}	3.6
	E.globulus	1.1	1.0	1.2 ^{a}	5.1	3.9	4.3 ^{b,c}	5.2
	E.saligna	0.8	0.9	1.0 ^{a,b}	5.4	4.4	5.0 ^{a,b}	5.5
	S.kinuyanagi	0.9	0.8	0.6 ^{b}	4.4	4.7	3.9 ^{b,c}	5.4
	S.mats x alba	0.8	1.1	1.1 ^{a,b}	-	5.7	- ^{a}	11.2
	Mean	0.9^{a}	1.0^{a}	1.0^{a}	4.8^{a}	4.5^{a,b}	4.1^{b}	6.2
Volatile matter content (%)	*E.nitens*	91.5	91.1	93.0 ^{a}	84.5	86.2	- ^{a}	84.6
	E.globulus	93.6	92.8	92.2 ^{a}	85.2	87.5	85.4 ^{a}	88.7
	E.saligna	91.7	92.8	91.4 ^{a}	84.8	84.5	- ^{a}	85.8
	S.kinuyanagi	92.3	94.3	94.9 ^{a}	80.8	85.6	87.4 ^{a}	85.6
	S.mats x alba	94.1	93.3	92.7 ^{a}	-	87.1	- ^{a}	87.4
	Mean	92.6^{a}	92.9^{a}	92.8^{a}	83.8^{a}	86.2^{a}	86.4^{a}	86.4
Fixed carbon content (%)	*E.nitens*	7.6	6.9	6.2 ^{a,b}	11.2	10.2	- ^{a}	11.8
	E.globulus	5.3	6.2	6.6 ^{a,b}	9.7	8.6	10.4 ^{a}	6.1
	E.saligna	7.6	6.3	7.6 ^{a}	9.7	10.1	- ^{a}	8.8
	S.kinuyanagi	6.8	4.9	4.4 ^{b}	14.8	9.7	8.8 ^{a}	9.0
	S.mats x alba	5.1	5.6	6.1 ^{ab}	-	7.2	- ^{a}	1.4
	Mean	6.5^{a}	6.0^{a}	6.2^{a}	11.4^{a}	9.2^{a}	9.6^{a}	7.4
Organic solvent soluble extractives (%)	*E.nitens*	4.4	2.9	3.9 ^{a}	6.3	8.1	9.8 ^{a}	22.7
	E.globulus	2.8	2.8	3.8 ^{a}	6.1	4.7	8.1 ^{a}	23.4
	E.saligna	3.1	2.0	5.7 ^{a}	3.8	5.5	10.5 ^{a}	18.0
	S.kinuyanagi	3.4	4.3	4.6 ^{a}	13.0	7.6	6.8 ^{a}	12.8
	S.mats x alba	3.0	4.6	5.6 ^{a}	-	7.3	- ^{a}	10.7
	Mean	3.3^{a}	3.3^{a}	4.7^{a}	7.3^{a}	6.6^{a}	8.8^{a}	17.5
Total extractives content (%)	*E.nitens*	7.1	4.7	5.9 ^{a}	17.9	18.3	30.5 ^{a}	42.3
	E.globulus	4.9	4.7	5.6 ^{a}	13.9	10.0	20.4 ^{a}	39.1
	E.saligna	4.9	3.3	8.8 ^{a}	16.2	17.0	26.1 ^{a}	31.4
	S.kinuyanagi	6.4	7.8	6.4 ^{a}	19.3	14.1	15.7 ^{a}	25.7
	S.mats x alba	5.2	7.0	7.7 ^{a}	-	13.3	- ^{a}	25.8
	Mean	5.7^{a}	5.5^{a}	6.9^{a}	16.8^{b}	14.5^{b}	23.2^{a}	32.9
Higher heating value (MJ/kg)	*E.nitens*	19.9	20.2	20.0 ^{a}	18.0	18.5	- ^{b,c}	22.6
	E.globulus	19.7	19.7	19.6 ^{a}	17.5	17.9	18.2 ^{c,d}	24.1
	E.saligna	19.9	19.8	19.7 ^{a}	17.4	17.8	18.1 ^{d}	21.6
	S.kinuyanagi	19.6	19.7	19.8 ^{a}	19.7	19.6	19.8 ^{a}	21.1
	S.mats x alba	19.5	19.6	19.8 ^{b}	-	18.7	- ^{b}	19.5
	Mean	19.7^{a}	19.8^{a}	19.8^{a}	18.2^{b}	18.5^{b}	18.7^{a}	21.8

* - Mean values with the same letter (property and material) are not significantly different

From the table, it is observed that:

1) Wood properties were distinctly different from those of bark and leaves. Wood and leaves had the lowest and highest ash content respectively. Leaves also had the highest heating values (e.g. 24.1 MJ/kg in *E.globulus*) and also the highest extractives content.

2) Sampling height did not significantly influence the properties of wood.

3) Although most bark properties along the stem were similar, there were significant differences associated with sampling height in ash content, total extractives content, and in the heating values. Whereas ash content declined, both TEC and HHV increased with sampling height.

4.4.4 EXPERIMENT D: INTERACTION OF PROPERTIES AND FUELWOOD QUALITY

The interaction of properties to determine fuelwood quality was examined at two levels (i) statistical correlation analyses between the general properties; and (ii) laboratory examination of the influence of selected properties (identified in the correlation analyses) on other key properties.

Statistical correlation analyses

The data in tables 4.1- 4.3, and in figure 4.1 were analysed to establish the correlations between the different bioenergy properties, and the influence of the interaction on the quality of fuelwoods. The results of the correlations are given in table 4.4.

Table 4.4 **Correlation analysis between properties**

	Density	Ash content	Volatile matter	Fixed carbon	Organic extractives	Total extractives	Heat value
Density	1						
Ash content	-0.254	1					
Volatile matter	0.075	-0.775	1				
Fixed carbon	-0.036	0.367	-0.868	1			
Organic extractives	-0.451	0.659	-0.714	0.539	1		
Total extractives	-0.497	0.753	-0.800	0.600	0.953	1	
Heating value	-0.308	-0.084	0.070	-0.057	0.472	0.238	1

Extractives contents (both organic and total) had the best correlation with all other properties except heating value. Increasing extractives content reduced basic density; increased ash content; reduced volatile matter content; and increased fixed carbon content. Heating value was poorly correlated with all other properties, the best being organic extractives, density and total extractives but with only 47%, 31% and 24% correlation coefficients, respectively. The correlation in properties highlighted the possibilities of using easily measurable characteristics to estimate other properties through regression relationships.

Influence of extractives - laboratory analysis

Samples for these tests were those left behind after both soxhlet and boiling water extractions had been conducted. The results of the tests on extracted samples were compared with those of un-extracted (whole) samples (table 4.5).

Table 4.5 **The influence of extractives on ash, VM and HHV on selected samples**

	% extractives		% ash		% volatile		Heat value, MJ/kg	
Sample	organic	total	extractd	whole	extractd	whole	extractd	whole
S.mats x alba Wood	4.6	7.0	0.2	1.1	-	-	19.8	19.6
E saligna, Wood	2.0	3.3	0.2	0.9	-	-	19.8	19.8
E nitens, Wood	2.9	4.7	0.2	1.2	-	-	19.9	20.2
S kinuyanagi, Wood	4.3	7.8	0.4	0.8	-	-	19.7	19.9
E globulus, Wood	2.8	4.7	0.3	1.0	98.8	92.8	20.2	19.7
A glutinosa, Wood	-	6.1	-	-	-	-	19.4	19.8
P radiata, Wood	3.4	6.3	-	-	-	-	20.7	20.5
A dealbata, Wood	4.3	6.8	-	-	-	-	19.4	19.7
P radiata, Bark	12.6	25.9	-	-	-	-	18.9	20.6
A dealbata, Bark	15.3	25.1	-	-	-	-	19.7	20.5
E globulus, Bark	4.7	10.0	0.9	3.9	-	-	17.8	17.9
S kinuyanagi, Bark	7.6	14.1	2.5	4.7	-	-	19.0	19.6
E nitens Leaves	22.7	42.3	2.2	3.6	-	-	21.9	22.6
E saligna Leaves	18.0	31.4	3.0	5.5	-	-	20.8	21.6
S kinuyanagi Leaves	12.8	25.7	3.0	5.4	-	-	20.8	21.1
E globulus Leaves	23.4	39.1	3.2	5.2	-	-	21.9	24.1

Extracted samples were different from the original samples with the most difference being observed in ash content which reduced by 38-84% of the original ash content. Volatile matter content (in the one sample tested) was increased by 6.5%. Heating values in extracted samples were lower than those of the un-extracted samples except in *S.matsudana* x *alba*, *E.globulus* and *P.radiata* where HHV increased following extractions. The changes in ash, volatiles and heating values were all correlated with extractives content.

Influence of moisture content - laboratory analysis

The influence of moisture on the heat value was tested in two species - *Pinus radiata*, and *Eucalyptus nitens*. Figure 4.2 was obtained by fitting linear functions to the data obtained. The figure illustrates that heating value decreases linearly with increasing moisture content. The slopes between the two species were not significantly different but the intercept factors were different, reflecting the heating values of the respective oven dry samples.

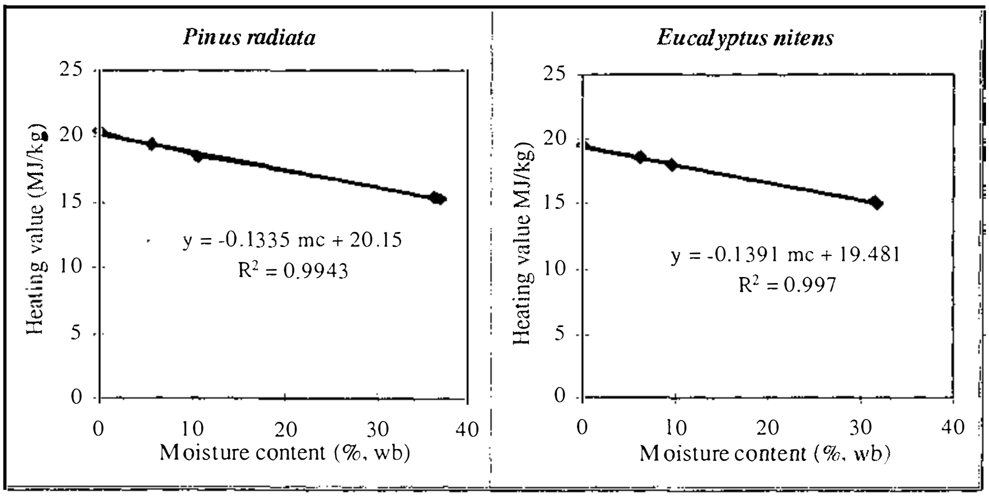

Figure 4.2 **Relationships between heat value and moisture content**

The coefficients of correlation (R^2) for the equations defining the effect of moisture (Figure 4.2) were significant, showing that moisture content was responsible for the variation in sample heat values. Although polynomial and exponential equations indicated better fits to the data ($R^2 > 99.9\%$), a linear function was considered adequate in emphasising the effects of moisture content.

Influence of particle size - laboratory analysis

Table 4.6 illustrates the influence of particle size (ranging from 0.25 mm to 4.00 mm) on the proximate analysis of three fuelwood species (*E.nitens*, *E.globulus* and *E.saligna*), and shows that particle size has a significant influence on the dry matter content (when the samples are exposed to the environment); the volatile matter (VM) content; and on the fixed carbon content (FCC). There was no statistical evidence to indicate that ash content varied with particle size. Both dry matter and fixed carbon contents increased with reducing particle size, while the VM increased with increasing particle size. Any interaction between particle size and species in influencing the properties examined was not significant.

Table 4.6 **The influence of particle size on proximate analyses of wood from 3 SRF species**

Species	Particle size (mesh, mm)	Dry matter content, %	Ash content, %	Vol. matter content, %	Fixed carbon content, (%)
E.nitens	< 0.25	91.3	1.4	91.8	6.8
	0.25 - 0.50	89.2	1.1	89.9	9.0
	0.50 - 1.00	88.8	1.4	96.4	2.2
	1.00 - 2.00	88.5	1.0	98.0	0.9
	2.00 - 4.00	88.4	0.7	97.5	1.8
E.globulus	< 0.25	91.2	1.0	93.8	5.1
	0.25 - 0.50	89.2	0.6	95.1	4.2
	0.50 - 1.00	88.9	1.1	96.6	2.3
	1.00 - 2.00	88.4	0.8	97.3	1.8
	2.00 - 4.00	88.2	0.8	97.9	1.2
E.saligna	< 0.25	91.0	0.8	93.3	5.9
	0.25 - 0.50	89.4	0.8	95.5	3.8
	0.50 - 1.00	89.0	0.7	95.9	3.4
	1.00 - 2.00	88.6	0.7	96.4	2.9
	2.00 - 4.00	88.5	0.7	97.2	2.2

4.4.5 REGRESSION ANALYSIS BETWEEN PROPERTIES

The results (tables 4.1 to 4.3, and figure 4.1) were used to develop models to characterise the relationships between the properties, and to explore the possibilities of estimating key properties from those that can be measured easily. Of specific interest was the heating value (regarded as the ultimate measure of fuelwood quality) and extractives content given the effect of extractives on other properties (see tables 4.4 and 4.5).

Stepwise and forward selection regression procedures were applied to define the relationships in properties. Table 4.7 lists multiple regression equations that identify interactions between the properties tested for all the 54 samples. Density was not measured on leaf samples nor on bark at the 3 year harvest when all the data used was gathered.

Table 4.7 **Multiple regression models relating bioenergy properties**[*]

	Parameter estimates										
Property	Intercept	Density	Ash	VM	FCC	OEC	TEC	HHV	R^2	F-test	Pr>F
Density	-570.59		6.61	10.47		-5.269		0.204	0.942	151	0.0001
Ash	94.15	0.003		-1.01		0.085		-0.003	0.999	16550	0.0001
VM	92.55	0.004	-0.98			0.073		-0.003	0.999	16522	0.0001
FCC	2.76					0.851			0.586	57	0.0001
●EC	-61.0●	-0.018	0.81	0.74	0.190			0.010	0.893	60	0.0001
TEC	1.02					2.220			0.079	3	0.0721
HHV	3740.50	0.969	-41.55	-43.71		14.377			0.359	5	0.0020

*-Only parameters meeting the 0.50 significance level were entered into the models

The test statistics (F-test, Pr>F, and R^2 values) show that models for prediction of TEC from other measured properties were not good. Also, the model for predicting HHV was weak. All other models were strong, and could be used to estimate the respective properties. Table 4.4 and 4.5 also indicate that extractives correlated highly with all other properties, and that extractives play a significant role in determining the heating value of materials.

Heating values

Multiple regression procedures of the SAS system were used to develop regression models relating heating values with other properties measured. Nine combinations of materials were used, and therefore nine different models were developed - wood, bark and wood, and bark from 10 SRF species, wood of Nelder trial *E.saligna*, leaf, and samples taken from different sections of the tree. The models are shown in table 4.8.

Although forward selection procedures would ensure that only parameters meeting a specified significance level were used, models which did not involve the selection of significance values were used (Table 4.8). All properties measured were included in the models, but the model with leaf samples alone was not full rank, i.e. the variables were a combination of other variables.

Table 4.8 **Regression models relating HHV and other biomass properties**

Model	Samples	Observ-ations	Factor coefficients							Test statistics			
			Intercpt	Density	Ash	VM	FCC	OEC	TEC	F-test	Pr>F	R2	R.bias
I	Leaf	5	227.2		-2.863	-1.985	-2.481	0.132	-	-	-	-	-55.0
II	Radial-wood	16	23.2	-0.0002	-0.510	-0.037	0.075	-0.252	0.176	0.4	0.8462	0.220	-0.1
III	All	54	-672.5	0.3557	5.651	5.752	-5.663	4.234	6.618	2.9	0.0200	0.314	115.1
IV	All-less leaf	49	-964.4	0.3819	7.783	8.331	-1.566	6.147	7.841	3.7	0.0060	0.380	126.6
V	Species-Wd	10	-87.6	0.0003	-1.260	1.057	1.603	0.302	-0.066	0.6	0.7445	0.533	9.2
VI	Species-Bk	10	71.6		-0.659	-0.545	-0.313	0.211	-0.108	2.1	0.2419	0.727	-2.3
VII	Sp Wd&Bk**	20	59.8		-0.797	-0.407	-0.224	0.274	-0.159	8.6	0.0007	0.755	-4.4
VIII	All others	12	-3745.7	0.5539	28.187	32.836	36.340	24.023	20.030	10.2	0.0111	0.924	372.7
IX	Sp Wd&Bk	20	61.5	-0.0006	-0.624	-0.436	-0.050	0.055	-0.009	339.8	0.0001	0.996	-7.5

** - Includes Nelder radial trial wood and bark samples, but wood density was not used in the model

Regression statistics of the models were compared, while the relative suitability of each model was based on the coefficient of correlation (R^2), the F-test, Prob>F, and the relative bias (Payandeh, 1981; Senelwa and Sims, 1997a), calculated as the average of:

$$R.bias(\%) = \frac{(Observed - predicted)}{Observed} * 100$$

All the models were significantly different among the different materials, and model IX, derived from the species trial samples (incorporating both wood and bark samples, and including the basic density values) was selected as best describing the heat value of biomass material. Although the absolute relative bias statistic of the model (|7.5|) was higher than the absolute relative bias values of 3 other models, its coefficient of correlation (R^2=0.9961) and F-test (339.8) were the highest recorded, and the Prob>F was the lowest (0.0001), showing that the model could explain most of the variation in the heat values of the materials. Besides, the model incorporated all the properties measured.

4.4.6 THE FUELWOOD VALUE INDEX (FVI)

The fuelwood value index (FVI) from section 4.3.5 was re-defined as:

$$FVI = \frac{aHHV * bOEC}{cDensity * dAsh * eVM * fFCC * gTEC}$$

> where a, b, c, d, e, f and g are respectively, the factor parameters in model `IX' (table 4.8), selected as best describing the heat value of biomass materials: heat value (1), organic extractives (0.055), basic density (0.0006), ash (0.624), volatile matter (0.436), fixed carbon (0.05), and total extractives (0.009).

When accounting for handling characteristics, the species basic density is incorporated to provide FVI^1 described as:

$$FVI^1 = (FVI)^{*\,Density}$$

The effect of yield on the suitability of SRF species was accounted for by incorporating the species relative yield index (RYI) from chapter 3, which incorporated the influence of yield (MAI, both total and stemwood, being defined by the harvest index), and rotation lengths to provide FVI^2 described by:

$$FVI^2 = (FVI)^{*\,Density\,*\,RYI}$$

The index (FVI^2), was defined for each harvest of the 10 SRF species. The heat values used in the calculations incorporated differences in the proportion of bark on the stem and the differences in heating values between bark and wood.

Assumptions

1. The relative costs of production were incorporated through the relative yield index, and the cost of time and money. In the species trial, the costs for any one year were constant having had the same stocking density. This was based on the assumption that the price of seedlings of different species was the same.

2. The costs of site preparation, and plantation management were the same for the different species, and that the costs of harvesting a unit yield were similar.

3. The only cost differentials therefore resulted from the rotation lengths, most of which were assumed to be adequately addressed by monetary discount rates.

4. Besides the costs of money (taken as 10% per year), other cost differentials in the "Nelder" design trial resulted from (i) differences in stocking densities; and (ii) differences with respect to seedling costs, or whether the crop was coppiced or single

stem at first harvest. In the case of coppice, one approach may be to spread the cost of seedlings by a factor throughout the entire life span of the rootstock.

Table 4.9 shows the results of the evaluation of the species, given the data obtained, and incorporating yield data from chapter 3. FVI was not defined for the Nelder radial trial stock since (i) most wood properties investigated did not vary significantly between the different rotation lengths and stocking densities; and (ii) properties of bark from the "Nelder" radial material were not investigated. The values obtained in the 10 species should however serve to indicate the trends.

Table 4.9 **Species fuelwood value index (FVI) and ranking***

Species	FVI	FVI^{1}	$FVI^{2,3y}$	$FVI^{2,4y}$	$FVI^{2,5y}$
Eucalyptus globulus	1.95^{d}	0.942^{a}	$9{,}719^{a}$	$24{,}974^{a}$	$44{,}034^{a}$
Eucalyptus nitens	1.88^{f}	0.761^{e}	$3{,}616^{b}$	$14{,}575^{b}$	$26{,}209^{b}$
Acacia dealbata	1.79^{I}	0.656^{g}	$2{,}415^{d}$	$6{,}081^{d}$	$12{,}786^{c}$
Salix kinuyanagi	2.10^{c}	0.936^{b}	$2{,}651^{c}$	$6{,}336^{c}$	$8{,}145^{d}$
Salix matsudana x *alba*	1.86^{h}	0.681^{f}	$1{,}422^{e}$	$3{,}507^{e}$	$8{,}114^{e}$
Populus eridano	1.90^{e}	0.536^{I}	568^{g}	909^{g}	$4{,}408^{f}$
Pinus radiata	2.15^{b}	0.604^{h}	509^{h}	$1{,}754^{f}$	$4{,}155^{g}$
Eucalyptus saligna	1.86^{g}	0.783^{d}	871^{f}	615^{h}	$1{,}343^{h}$
Alnus glutinosa	2.38^{a}	0.849^{c}	115^{j}	379^{I}	548^{I}
Poulownia tomentosa	1.78^{j}	0.455^{j}	125^{i}	225^{j}	373^{j}

$FVI^{2,3y}$ - 3 year $FVI^{2,4y}$ - 4 year $FVI^{2,5y}$ - 5 year

* - Values with the same letter are not significantly different

The ranking of the species depended on the factors included in the index. A basic FVI incorporating biomass properties ranked *A.glutinosa*, *P.radiata* and *S.kinuyanagi* as the best species, while *P.tomentosa*, *A.dealbata* and *E.saligna* were the worst species. Incorporation of the species basic density changed the ranking, making *E.globulus* and *S.kinuyanagi* as the best species, while maintaining *P.tomentosa* as the worst. A significant factor included in the index was the relative yield index (RYI) derived from chapter 3, and which incorporated the species yield factors, and the recoverable/harvestability factors. The inclusion consistently ranked *E.globulus* and *E.nitens* as the best species, and *P.tomentosa* and *A.glutinosa* as the worst species.

4.5 **DISCUSSION**

Since the trees used to test the species variability were grown and harvested under similar conditions (see section 3.3), the chances of variability in growth conditions contributing to the differences in properties (as shown by Koch, 1972) were assumed to be minimal. It was also assumed that the sample material obtained from the breast height position of the stem was representative of the entire stem. Further, since the trees were grown at the same time, the effects of age were eliminated, but the effects of silvicultural treatments were monitored separately using the "Nelder" radial design trial. Although the significance of obtaining ultimate analyses of the biomass feedstock was recognised, a working assumption that most wood species have similar elemental compositions was made (Corder, 1973; Koch, 1972; Lyons *et al*, 1985; Nordin, 1994).

Emphasis was placed on SRF species since SRF systems are expected to play a major role in future biomass energy schemes due to (i) the prevailing scarcity in fuelwood supplies in most developing countries (FAO, 1981); (ii) stringent conservation and environmental requirements in many regions prohibiting direct exploitation of natural vegetation etc. The properties which may be influenced by variations in silvicultural practices were included as variations would influence the suitability of the feedstock for gasification. Since bark is at times removed from sawlogs and used separately as a fuel source, its characteristics were examined independently of wood to distinguish the characteristics of bark which might influence the feedstock behaviour in reactors.

4.5.1 ENERGY PROPERTIES OF BIOMASS MATERIALS

The variations observed among different species (tables 4.1- 4.3) showed the genetic variability of the different species, and indeed defined the characteristic features of the different species, and may also determine the use to which the biomass may be put. Although similar variability had been reported by earlier workers (section 4.2), these work presented results from SRF materials.

Since major differences exist between (i) the properties of bark and the properties of wood from the same species; (ii) the properties of bark from different species; and (iii) the properties of leaves and both bark and wood (from the same tree, and from different trees), the use of a wide range of species, and also of a mixture of wood, bark, and foliage in specialist applications may require more careful consideration. The selection of species for SRF schemes must take account of these differences, and define the appropriate properties desirable for the specific application. However, the low variability in wood properties (tables 4.1-4.3, and figure 4.1) has major implications in that different woods of different species could be mixed without adversely compromising the fuelwood quality requirements.

The variability associated with silvicultural treatments (cutting age, stocking density and coppicing, Figure 4.1) showed that the properties may be manipulated if the requirements are identified, provided the factors which influence specific properties are known.

Proportion of bark on the stem (Bark : wood ratio)

The total quantities of bark on the stem in the age bracket considered were similar to those reported by Frederick *et al* (1985) for trees grown in New Zealand, but were much less than values reported by Geyer (1981), Flower-Ellis and Olson (1981), Krigstin, (1985), and Sennerby-Forsse *et al*, (1983). Although the ratio was expected to vary with species, the large differences between these earlier studies and the present study (table 4.2) were not expected. Since the present study, and that of Frederick *et al*, (1985) were conducted in New Zealand, unlike those that differ widely, some of the differences might be geographical.

The declining ratio of bark to wood with cutting age showed that the growth of tree components is not always a direct proportion. The wood fibres (i.e. xylem) in a stem accumulate faster than the phloem (bark forming tissue). Hence, more woody material is added between the 3 and 5 year rotations compared to the quantity of bark added. Although the ratios obtained were lower than those reported elsewhere, the quantities were significant, and demonstrate that proper utilisation of biomass should take account of the different properties of bark.

The variations in bark from different species, and also with cutting age show the importance of the choice of species for SRF schemes, and the need to clearly define the silvicultural requirements for the desired products. The variation with age also indicated that this property may be manipulated easily to obtain the optimum bark proportion on the stems. For instance, if bark characteristics have known adverse effects on the fuel feedstock quality, it might be useful to time harvesting operations not only to optimise yield, but also to minimise the bark content.

Basic density

The water displacement using water saturated samples methodology to determine basic density avoided the need to determine the volume/density relationships of the water bound within the samples since the density of the bound water becomes numerically equal to the normal density of water, 1 g/cm^3. The variations of different species observed in the density and even within the same tree at different heights, rotation age, and coppiced compared to establishment crops, indicated that the porosity, defined by the fraction of void volumes of the samples, was variable. This density value (ρ_μ, see section 4.2.1) can in turn be used to determine the porosity (V_a) of the samples, given the moisture content (MC) (Siau, 1984):

$$V_a = 1 - \rho_\mu (0.667 + 0.01MC)$$

This relationship indicates that the porosity, and therefore the density of the sample would vary with the moisture content of the material. This in turn would influence the heat values (see influence of moisture content, section 4.4.4), the heat transfer mechanisms, and the overall rates of reactions (see section 5.5.1). This relationship may also be used in evaluating the effect of moisture content on the gasification process (section 5.5.8).

The wood basic density results demonstrated that density is governed by an interaction of many factors - species of the tree, age of the tree from which the material is obtained, silvicultural practices under which the tree is grown and position of the sample within the tree. Although Ragland *et al*, (1991) suggested that the variation in dry density within a particular species does not exceed 10%, the present result indicates a wider variation associated with the cutting age, and also the stocking densities even though the latter were not significant (Figure 4.1). Results which also differ from the 10% variation limit, are those for *E.regnans* grown in New Zealand where density ranged from 376 to 428 kg/m^3 in 7 and 17 year old stocks, respectively (Frederick *et al,* 1982), and for hybrid cottonwood with a variation of 231 to 341 kg/m^3 in 2 year old to 320-410 kg/m^3 in 35 year old stock (Anderson and Zsuffa, 1975).

The lower density of bark compared to that of wood was due to the fact that bark is mostly composed of cork, a product of dead phloem and cortical tissues. However, the higher bark density than wood measured in some species in the 4 and 5 year old stock dispels the generalisation that wood has higher density. The reason for this difference in these two species - *Acacia* dealbata and *Alnus* glutinosa was not clear.

The basic density results obtained in the species trials for the 3, 4 and 5 year old stock agree closely with literature values for similar species in the same age bracket, in particular for *P.eridiano*, *P.tomentosa* and *Salix* species (Dickson *et al*, 1974; Frison *et al*, 1990; Aijala, 1982; Olson and Carpenter, 1985). The differences observed in other species were due to the differences in the age of the trees where the samples were obtained. The current experiments were based on 3-5 year old trees, a range which was probably much lower than that used previously. Similarly, the trends observed with age and between coppiced Vs establishment stock agreed with observations by Zobel *et al* (1965), Cown *et al* (1992), Seren *et al* (1987), Hytonen and Fern, (1984), and Frederick *et al*, (1982). The increasing density was due to the gradual decrease in the proportion of juvenile and reaction wood as the age of the tree increased, (Bendestein, 1978); younger trees having a higher proportion of corewood.

The results obtained with respect to sampling height provided no affirmative evidence to generalised trends. This observation helps to explain the contradictory conclusions made by many previous workers such as (i) Clarke (1991) who showed wood density to increase with sampling height; (ii) Frederick *et al*, (1982) who suggested that the basic density in *Eucalyptus regnans* decreased from the stump to breast height, from where it then started to increase with height; (iii) Desch (1986), and Wingate-Hill and Matheson (1983) who showed that the heaviest wood was found at the base of the tree, and that there was a gradual decrease in density in samples from successively higher levels in the trunk. Conversely, Manwaller (1979) indicated that density tended to remain relatively stable or decreased slightly with sampling height in the majority of species. When many species are examined, such minor differences average out and show no correlation with height as was found in the present study, and also by Taylor (1979), and by Stringer and Olson (1987).

Though plant spacing influences the distribution of juvenile and mature wood, and therefore the overall density (Bues, 1990), the effects resulting from the three silvicultural practices examined (age, stocking density and coppicing) were insignificant, as was also found by Pereira and Miranda (1991). This implies that density within the same species has no correlation with the tree growth rate.

Moisture in biomass materials

Since moisture content is not an intrinsic property of fuelwood materials, it was not investigated with a view to establishing its variability among species. It was however recognised that moisture content may vary with species due to differences in the hygroscopicity of the different fibre complexions, and that such differences may influence the suitability of biomass for various applications. Therefore, its effect on the heat values was analysed (sections 4.4.4 and 4.5.3), while its effect on the gasification of fuelwood is presented in chapter 5.

Ash

The low variability in wood ash content, coupled with the low quantities which averaged 1% of the wood dry weight (Table 4.1), indicated that (i) wood ash content may not be an appropriate criterion for distinguishing or evaluating species for quality; and (ii) low inorganic matter deposits in the cell wall structure which showed the high carbon content. Since the carbon content determines the reactivity of any fuel, it is reasonable to assume that the low ash content, and the possibly high carbon content implied high reactivity of the biomass fuel with a high heating value. The lack of variability with sampling height also showed that ash content of a species is genetic.

The higher content and variability in bark and leaves, 2.6-5.7% and 3.6-11.2% respectively (Table 4.3) indicated the differences in the three components of the tree, and showed the location of nutrient concentrations within the tree. This higher concentrations in bark and foliage were attributed to the concentration of K in the actively metabolising positions (crown/leaf area), where the nutrients from the soil are fixed before being relocated to other parts of the plant. Thus, the removal of foliage during harvesting entails removal of nutrients from the site, and the benefits of such an operation are dependent on the objective. In SRF systems, the requirements for artificial fertilisers would increase, increasing the costs of production. But in a land treatment system of effluent or sludge linked with a SRF system, the aim would be to remove the nutrients from the site. According to Guo (1997), whole tree harvesting systems should be used for effective nutrient removal. The fact that ash content in the wood reduces with age implies that short rotations signify a higher nutrient drain from the site, necessitating increased use of artificial fertiliser to maintain soil fertility where effluent / sludge is not applied. Besides, the proportion of bark in the material harvested at shorter rotations is higher (Table 4.2).

Volatile matter and fixed carbon contents

The volatile matter (VM) content values obtained in the experiments were higher than values reported previously for both wood and bark (see section 4.2.1). This could be attributed to the techniques used in the experimental apparatus and set-up which included a standard muffle (ashing) furnace, and utilising the recommended standard nickel-chromium volatile matter determination crucibles which could have resulted in differences in the heating rates. The air flows during the tests could have also resulted in the combustion of part of the char leading to higher values. Other differences could also be attributed to the juvenile nature of the test materials. The higher VM in wood (cf. bark and foliage), and the higher VM of the SRF biomass materials used (compared to reported literature values) indicated that (i) wood is a more reactive material than bark; and (ii) the SRF materials being mainly juvenile in nature is more reactive than older stock materials. However, the possibly higher reactivity resulting from higher volatile matter content did not imply higher heating values as suggested by Eklund *et al*, (1987).

Other than the possibilities of experimental errors resulting from the apparatus used, variation in the quantities of volatile matter content in wood is genetic, being attributed to variations in the volumetric percentage of the vessels in different species. The vessels in the wood determine the wood porosity, and together with occlusions (particle blockages of vessels) may determine the ease with which the volatiles escape from the wood structure during pyrolysis. If the passage ways are not clear, some of the volatiles transform into carbon which is then deposited within the char matrix as pyrolytic carbon (Kumar and Gupta, 1997). This pyrolytic carbon may then be detected as fixed carbon (FCC) posting low volatile matter contents with the species. This process is referred to as "cracking of hydrocarbons of the volatile matter".

Both volatile matter content and char yield are associated with vessel volume and structure. Vessels in the wood structure act as macropores and provide the path of least resistance as opposed to micropores. If the reactive volatiles cannot readily escape from the wood interior structures, some of them recombine to form char within the solid matrix. This provides an explanation for the higher degree of volatilisation in hardwoods than in softwoods and the relatively low VM (and higher measured FCC) in *P.radiata.*

In *Pinus radiata*, the flow of volatiles is restricted due to reduced macropore structures which suggest reduced wood structural porosity, and therefore restricted volatile matter movements as more volatiles become blocked. As a result they recombine to form char, increasing the fixed carbon content while reducing the volatile matter content measured. The low fixed carbon content values obtained in the other species reflect the high VM values, and show that not much of the material during combustion is consumed in the solid state. Increased VM with increasing vessels percentage suggests that hardwoods may be preferred to softwoods for feedstock for a downdraft gasifier as the volatiles produced can then be cracked to form the producer gas (see chapter 5).

During traditional combustion process, volatiles are driven off first and then burn in the gaseous state leaving behind the fixed carbon which later burns in the solid state, often seen as embers. Though higher VM increases the reactivity of the fuel, for instance easy ignition and char burnout, its effect on heating values, and possible effect on its suitability for gasification is not clear.

Extractives

The diverse nature and composition of extractives, and the quantities determined depend on the solvents and time used in the extraction method. The extractions employ a series of solvents, and in the case of wood, a mixture of 95% ethanol:benzene (33:67 volume), followed by 95% ethanol, and finally boiling distilled water has frequently been applied (ASTM D 1105 -84; Browning, 1967; Koch, 1972). The organic solvents dissolve the volatile oils, resins and fatty acids and pigments while the boiling water dissolves the carbohydrate components including starch, simple sugars, inorganic salts, and some organic acids. Prolonged heating / extraction in water should be avoided to minimise the degradation of wood through hydrolysis.

The values, variability and trends obtained (3-11.9% and 10-30% for wood and bark TEC respectively), and the fact that the highest contents in wood (11.9%) was recorded in *P.tomentosa*, agrees with previous observations (Koch, 1972; Krigstin, 1985; Blankenhorn *et al*, 1985; Anderson *et al*, 1984; Swan and Kellog, 1986; Wang and Huffman, 1982; Olson and Carpenter, 1985). *Eucalyptus* species had the lowest values of both categories of extractives, in both bark and wood, while *Pinus radiata* and *Acacia dealbata* bark had very high extractives contents, which have been exploited at commercial / industrial scales to obtain turpentine and tanning industry base chemicals.

The increase in extractives content with increasing stocking density, and the decrease with rotation age, in both coppice and establishment crops of all ages showed the quantities of water soluble materials in the samples at different periods of the tree growth. The trends were similar to trends reported by Blankenhorn *et al*, (1985) and Blankenhorn *et al*, (1988) who found reducing contents with age (1-4 years) in *Populus* species. However, it contradicted observations by Pereira (1988) that total extractives content for most trees increased with age as a result of more water soluble materials.

Heating value

Heat values in wood exhibited the least variability of all the properties tested with values ranging from 19.6-20.5 MJ/kg, a variation of only 5%, being well within the limits of 15% as indicated by Ragland *et al*, (1991). The heating values of the other components were however more variable - bark, 11.4%; and foliage, 15.9%. This variation could be significant when considered in terms of energy per hectare as the difference implies an extra 18 GJ/ha, or 1 ODt/ha of biomass assuming annual yields of 20 ODt/ha. The higher variation in bark and foliage in different species indicated that bark and foliage are more heterogeneous in nature than the wood, which mainly consists of cellulose, hemicellulose and lignin in almost equal proportions.

Although the relatively high HHV of *A.dealbata* and *P.radiata* bark (relative to those of wood) were in agreement with findings of Haris (1985), the overall results contradict most other reports (Howlett and Gamache, 1977; Molner and Nemath, 1983; Tietema *et al*, 1991; and Krigstin, 1985). Other than the methodology of calculating the calorific value from the Wagner (1979) techniques as employed by Tietema *et al*, (1991), the higher bark heating value could be a special feature unique to some species, part of which could be due to the higher extractives in bark as was found in the species exhibiting these characteristic in the present work (e.g. *P.radiata* and *A.dealbata*)

The lack of variability with respect to stocking density, cutting age and coppicing (Figure 4.1) contradicted observations made by Verma and Misra (1989) who reported increasing heating values with reducing stocking densities in *Vitex negundo*. The similarity showed that the heating values are genetic characteristics which may not be influenced by silvicultural manipulations.

In bark, the trend of increasing calorific value with height was apparent and significant, and could be associated with the significantly higher extractives content in the upper portions of the tree resulting from the metabolic activities in the actively growing regions (leaves and young buds). Other than for *S.matsudana x alba*, the foliage had the highest HHV of all the tree parts examined (Table 4.3). The deviation could be a result of the bugs infesting most leaves of these trees, which therefore could have reduced the organic matter content. The high heat values in the rest of the leaves (cf. wood and bark) were associated with the high extractives content in leaves.

The mean of the heating values of the 3 stem heights is a good indicator of the species calorific value as it evens out any variability shown with the breast height material. The difference between the highest and lowest wood heating value was only 0.3 MJ/kg (about 6 GJ/ha/y, compared with the 5.8 GJ/ha/y from the same species using breast height material only). The insignificant variation in wood indicates that in SRF system grown for energy, efforts need not be wasted on attempting to produce quality. The aim should be to produce as much biomass as possible since most tend to have similar heating values.

4.5.2 INFLUENCE OF SILVICULTURAL TREATMENTS ON PROPERTIES

The results in the figure 4.1, and in appendix 4.1 showed that except the proportion of bark on the stem, stocking density does not significantly influence biomass properties. Also, the lack of apparent differences between coppice stock and establishment stock despite the differences in age between coppice and establishment crops shows that coppicing does not significantly affect wood properties. Since the rootstock for both coppice and establishment crops were of the same age, it is possible that the two lots exhibited similar metabolic activities leading to similar properties.

Unlike both stocking density and coppicing, the significant differences in the properties of wood (ash content, volatile matter and total extractives content), and also the proportion of bark on the stem (see table 4.2) from different cutting age groups shows that rotation length has a significant effect on biomass properties. The differences also show the properties of biomass that are genetic, and those which are not, and therefore indicates possible intervention mechanisms for the variation of specific properties. Those that did not vary (density and heating values) are genetic and could only be modified through breeding and selection of appropriate species. Those properties which varied lend themselves to easy silvicultural manipulation.

From the plantation management point of view, and from the requirements of increasing biomass production, the results indicate that the most important aspect in SRF systems is in increasing the yield through silvicultural management, as the quality of biomass produced is not easily jeopardised through intensive production systems.

4.5.3 INTERACTION OF PROPERTIES AND FUELWOOD QUALITY

The quality of fuel for general utility applications is indicated by the amount of heat (energy) derived from a unit mass of the fuel (MJ/kg). Any property influencing the heat value, either positively or negatively, defines the fuelwood value, which can be built into an index for purposes of comparing different feedstocks. Such an index, being based on the higher heating values would be for general utility applications only. An index for other specialised applications such as gasification would require that the most desirable aspects of the feedstock are defined.

While density is a well known indicator of the properties of wood, it is not entirely satisfactory as a grading criterion for fuelwood requirements. The relationship between the different properties and heating values in defining fuelwood quality is of particular interest. The level of correlation observed between the different properties and HHV (Tables 4.4-4.5 and 4.7- 4.8) suggested that a re-examination of the contributory role of the different properties, as opposed to density alone, may be warranted.

Influence of moisture content on heating values.

The linear effect of increasing MC on heating values (Figure 4.2) confirmed the importance of drying the fuel before burning in order to obtain the most heat. Moisture which does not contribute to the heating values reduces the heat available from fuel by (i) lowering the initial gross calorific value of the wood; (ii) reducing the combustion efficiency as heat is absorbed in evaporation of water in the initial stages of combustion lowering both the flame temperature and the radiant heat transfer; and (iii) by the hydrolysis effect of hot water. Water, which is at or near boiling point promotes hydrolysis of the wood (Mithel *et al*, 1957). Thus, part of the wood chemicals (fuel substrate) are lost resulting in the production of water and carbon dioxide.

The similar slopes in figure 4.2 (illustrating the effects of moisture content on HHV) indicate that the influence of moisture and moisture content on biomass fuels does not depend on species, and suggests that the mechanisms of combustion in different biomass materials are similar. Murphey and Masters (1978) also found similar trends, but the best fit was an inverse logarithmic relationship between MC and calorific value for the different wood components. In their results, they found that MC accounted for different percentages of the variance of the heating values for the different wood components.

Influence of extractives content on ash content, HHV and VM

The correlation found between extractives content with ash, VM, FCC and HHV particularly, (tables 4.4-4.5 and 4.7-4.8) indicated that the properties are correlated, but the effect of one property over the other probably depend on the nature and quantity of the component. The effect of extractives content on HHV was not proportional to the quantities determined. It was more evident in bark (up to 8.2% reduction) and foliage (up to 9.1%) compared to only 1.5% in wood. The variation was due to the quantities of both OEC and TEC removed in the different materials.

The increase in HHV following extractives removal, or the fact that HHV did not change following the removal in some samples was not expected. This could be related to the type of extractives removed. Either the extractives did not produce more heat than the structural materials, or they were not combustible at all (e.g. inorganic salts), which may explain the reduced ash content in extracted samples. These mineral salts do not contribute to the heating value, but act as fillers. Lack of drastic variations in heating values following removal of extractives showed that material properties do not act in isolation by influencing other properties. Extractives removal did not deplete the heat content of the materials, nor did it produce residues with a uniform heating value as previously suggested by Corder (1975). Similarly, the extractives content did not account for 10-35% of the total heat content as suggested by Krigstin (1985) even though Howard (1973) correlated high extractives content with increased HHV of wood, and explained that the heating value of the extractives is about twice that of extractive free wood (section 4.2.1).

The contributions of different kinds of extractives to the heat content of test biomass materials was different as was also found by Wang and Huffman (1982). Some extractives contain terpenoid hydrocarbons and lipids while others contain phenolic compounds with higher oxidation levels than the former compounds. The hydrophilic compounds may also include mono- and oligo-saccharides, sugar alcohols, protein and mineral salts. Since combustion is an oxidation reaction and the heat of combustion of an organic compound is related to its level of oxidation or state of reduction (Sussot, *et al*, 1975), organic compounds containing only carbon and hydrogen produce more energy when burned than do those containing oxygen.

Effect of particle size on biomass proximate analysis

The trends observed (table 4.6) contradict previous observations which indicated that as the particle size increased, the reaction time and the residual weight increased (Maschio *et al* 1994a), and that VM increased with decreasing particle size (Mingle and Bouble, 1968). The observed trend of reducing VM with reducing particle size could be associated with the process of fine grinding of the material to obtain the finer particles. Such fine grinding results in heat generation that could have resulted in the expulsion of volatile matter. Further, Mingle and Bouble (1968) involved single particle experiment while the present study considered a group of particles.

Though the rate of solid fuel reaction depends on the surface area exposed per unit volume of fuel, the size of voids in the fire-bed reduces as the fuel particle size reduces. A point may be reached when the individual voids become so small that the resistance to passage of combustion or gasification products is unacceptable when the flow is impeded. If these products can not readily escape from the voids, they recombine to form char within the solid matrix resulting from the process of re-polymerisation of volatile material (Lewellen *et al*, 1977), being influenced by the residence times of the volatiles within the solid material during pyrolysis reactions.

The rate of combustion is proportional to the time it takes for the required heat to reach and ignite volatile constituents; this in turn is dependent on the exposed surface area per unit volume of fuel. In theory, the minimum particle size should be chosen since the total surface area of a given quantity of fuel is inversely proportional to the square of the average particle diameter. However, the size of voids in the fire-bed decreases as the particle size is reduced.

There is a possibility that the fine comminution damages the cell structures, or heats up the particle thereby reducing the VM. Increasing volatile matter had a direct effect on the fixed carbon content. The lack of significant influence showed that particle size reduction was a physical process which did not affect the chemical configuration of the materials. The trends observed in dry matter only showed the conditions of storage of the material prior to the tests.

Regression models

The correlation between the measured properties (Table 4.4) showed that heating value was poorly correlated with most other properties even though the regression model relating HHV and the other properties was significant (Table 4.7) but table 4.5 showed that the role of extractives content in isolation could be less than was portrayed in the correlation analysis. Also, although density had one of the best correlation with heat values, it was not a key determinant of heat value of a sample as the determination was based on unit weight i.e. the mass rather than the volume of the material was being used as the unit of measure. Inclusion of density (not measured for bark and leaf samples) in the model indicated a distortion of the R^2 values showing that density does not directly influence the heating value of a material determined on weight basis.

Table 4.8 demonstrated the differences in the models between different materials indicating that the heat value of biomass materials is a product (result) of complex interactions among different properties, and that no one property was directly responsible for the heating values of a material. Although the most significant property was extractives content (see the correlation analysis, table 4.4) which explained the better performance of the models which emphasised this property, high extractives contents do not necessarily indicate high calorific values of fuels, as these depended on the chemical characteristics of the extractives. Also, although ash represents only a small proportion of the total dry weight of wood, it was an instrumental factor in determining the combustion and heating characteristics, affecting the other properties examined.

4.5.4 THE FUELWOOD VALUE INDEX AND SPECIES SELECTION

Sections 3.3.6, 3.4.3 and 3.5.4 developed the species relative yield indices for evaluating SRF species based on yield characteristics. The fuelwood value index extended this concept by incorporating the measured properties of fuelwood species. The index optimised all attributes of species, by "minimising" undesirable attributes, while maximising the desirable properties (see sections 4.2.4, 4.3.5 and 4.4.6).

The use of the test statistics of the selected regression model (Model IX, Table 4.8) in describing the index ensured that the relative importance of the different characteristics were adequately addressed. Variables with negative estimators were assumed to reduce the heating values of samples under test and therefore formed the denominator of the index. OEC (positive estimator) and the HHV of the sample formed the numerator. This was based on the assumption that the best fuel would need high proportions of OEC, as it positively influences the heating value.

Only intrinsic properties (those properties which do not change with exposure environment) were used in determining FVI. Although moisture content was found to have a significant effect on HHV (Figure 4.2), it is not an intrinsic property of biomass fuels since the moisture content of biomass (a hygroscopic material) varies with the environment. All other properties were determined on oven dry basis, thus eliminating the influence of moisture, which was not included in the models in table 4.8

The techniques used to develop the fuelwood value index incorporated the features traditionally used in evaluating species in conventional forestry practices and goal programming techniques which have not been used previously in defining the quality of fuelwood or biomass materials. These techniques provide advantages in determining the weights of the different characteristics for appropriate definition of an ideal fuelwood.

Inclusion of wood density values in FVI calculations on the basis of ease of handling and transport costs assumed that the denser materials are easier and cheaper to handle. Further, it assumed that only the woody biomass (tree trunk) is utilised. The inclusion of species MAI (in the relative yield index, RYI calculations) indicated that the pre-requisite of a good tree species for SRF systems is high yield. This index also incorporated elements indicative of both quality of the material, handling costs, and the actual economic returns, assuming that the production system is a business venture with profit requirements. This methodology equates to the determination of biomass yield in terms of the energy produced (MJ/ha/y) as was indicated by Verma and Misra (1989), while indicating the other quality characteristics.

The quality of fuelwood (for general utility applications) was not significantly different with regard to tree species, stocking density, rotation age and position of the sample in the tree. Inclusion of yield factors segregated the species into different categories, and singled out the higher yielding species, *E.globulus, E.nitens*, and *A.dealbata* as being the choice species for

Manawatu, New Zealand. The quality of bark and foliage used as fuel was different and inferior to wood in most properties.

Normally, a species with high density wood, high calorific value, low ash content and low nitrogen is considered a more suitable fuelwood species (Bhatt and Todaria, 1992). The use of SRF biomass as a feedstock for energy or chemicals however does not only rely on the properties, but also on the biomass production and yield. Thus, the modified index relating the properties and yield was considered more applicable as it may indicate the actual returns obtainable from a planted site.

4.6 CONCLUSION

Laboratory measurements showed that the energy characteristics of woody biomass varies among species; and also among silvicultural treatments. The most variable properties were the density, and the proportion of bark on the stem. The properties also differed among components of the tree i.e. wood, bark and leaves, but not with sampling height within the tree. Although the properties are interrelated, no single property had an overwhelming effect on the heating value (MJ/kg) which is considered the ultimate measure of fuel quality. The correlation among properties suggests that each property must be considered in the design of conversion equipment.

For the species evaluated, wood density, the proportions of bark on the stem, and the significant differences between wood and bark energy properties have major implications on (i) the use to which the fuelwood is to be applied; (ii) handling, storage and transportation costs; and (iii) the design of conversion systems together with the related feed systems. Bark in the feedstock makes the material more heterogeneous, and predictions of its reactions and products more difficult. Results from the laboratory assessments provided an indication of the differences to be expected in terms of reactivity and energy recoveries in instances when bark is used as a fuel.

The effect of silvicultural treatments on such properties of the feedstock as the bark proportion indicated there are some opportunities for manipulation of tree growth conditions to harvest "tailor made biomass". However, the lack of effects of silvicultural treatments on higher heating values and quality in general, showed that the main concern in a short rotation forestry system should be to maximise yields. The quality of the fuelwood would not be jeopardised by intensive silvicultural interventions.

The fuelwood value index (FVI) methodology was developed to provide a process of ranking SRF species based on measured energy properties. The choice of preferred species depended on the factors desired for a particular energy application which were incorporated when formulating the index including density, heat values, and the relative yield index (incorporating yields, piece size etc., chapter 3). *E.globulus*, *E.nitens* and *A.dealbata* were identified as good SRF energy crops, while *P.tomentosa* and *A.glutinosa* would not be encouraged over the three rotations evaluated. The FVI methodology is superior to other techniques used previously as it incorporated many factors including yield, and assigned weights to desired objectives based on subjective correlations with HHV (MJ/kg) and yield (ODt/ha/y). Yield factors were more important than the differences in fuelwood quality characteristics when both attributes were used to evaluate species.

CHAPTER FIVE

THE AIR GASIFICATION OF SRF WOODY BIOMASS

5.1 INTRODUCTION

5.1.1 HISTORICAL OVERVIEW

The earliest recorded commercial gas producer (used in iron works in France) was built by Bischof in 1839, but according to Kaupp and Goss (1984), there had been earlier utilisation of producer gas including (i) Thomas Shirley who conducted experiments with carburetted hydrogen in 1669 and (ii) Dean Clayton who obtained coal gas from pyrolytic experiments around 1699. The first patents for gasification were issued to Robert Gardner (1788) and John Barber (1791). John Barber's patent considered the use of producer gas to drive an internal combustion engine.

Wood gasification experiments started in 1798. In 1801, the possibility of using waste gases escaping from charring wood was explored. By 1850, the technology had developed and was providing fuel for gas lights in large parts of London. In 1860, Linoir invented the first successful gas engine for stationery applications, but it was not until 1901-1903 that the first motor car was driven for over 1000 miles (Kaupp and Goss, 1984; Cash and Cash, 1940).

Early gasworks used iron retorts to heat the wood and coal fuels, pyrolysing them to gas, oils and charcoal. The use of fireclay and then silica retorts to achieve higher pyrolysis temperatures started in the late 19th and early 20th centuries. According to SERI (1979), the plants operated with thermal efficiencies which converted 70-80% of the energy in the fuel to saleable products. Although the development slowed down during the first world war (1914-18), the economic depression and the rise in price of imported petrol in many regions of the world following the war rekindled interest in the technology. The interest peaked during the 1939-45 war when many vehicles were fitted with gas producers, particularly in Europe, U.S.A, Australia and New Zealand. Gas generators were also used on tractors, boats, motorcycles and on railway shunting engines (SERI, 1979). Interest faded away due to the availability of cheap petroleum fuels and natural gas reserves, but recently, interest has been revived, particularly in large scale wood fired plants with the objective of seeking more environmentally acceptable and sustainable energy sources than coal. At the smaller domestic or village scale, interest has been stimulated by the demand to supply sustainable heat and power systems for communities, particularly in developing countries where large numbers of people have no access to electric power.

5.1.2 GASIFICATION PROCESSES

Gasification of organic matter based fuels can be biological or thermal. The biological processes take place through the synergistic action of a consortium of four types of bacteria (hydrolytic, fermentative, methanogenic and acetogenic) which operate in the absence of oxygen to produce a mixture of methane and carbon dioxide (Overand and Rivard, 1993). Thermal processes involving thermochemical degradation of biomass fuels include pyrolysis, liquefaction, gasification and combustion. The supply of air (as a gasifying agent) determines the products of the process. Under controlled air supply, char, pyrolysis liquids and a gas of low to medium heating value (3-21 MJ/Nm^3) are produced.

The process heat needed for thermal gasification may be generated either in situ in the gasifier (autothermal), or be applied externally (allothermal). The major fuel gases produced, carbon monoxide, hydrogen and methane, can be utilised as fuel gas in internal combustion engines which may be used to generate electricity or for transport by vehicles; for direct heating; for co-generation of heat and power; or as a synthesis gas in the process industry to produce methanol or ammonia (Hos and Groenveld, 1987; Strehler and Stutzle, 1987).

The most commonly used thermal gasifier types include the counter-current (updraft), co-current (downdraft), cross draft, and fluidized beds. The basic modes of operation of each of this types is presented in figure 5.1 which also illustrates the broad reaction zones - drying, pyrolysis, oxidation and reduction.

In the counter-current moving bed type (Figure 5.1a), feedstock flows in a direction opposite to the flow of air and the product gas flows in a direction opposite to the flow of ash. The gas which leaves the reactor together with the pyrolysis products and steam from the drying zone is often rich in heavy hydrocarbons (tar), and is good for direct heating.

Both feedstock and air in the co-current moving bed type (Figure 5.1b) flow in one direction (from top to bottom, hence referred to as a downdraft gasifier). All decomposition products from the pyrolysis zone are forced to pass through the oxidation zone under high temperature which converts most of the heavy hydrocarbons from the pyrolysis process into simple hydrocarbons, leading to a relatively low tar content in the gas compared with other gasifier designs.

In the cross-current gasifier (Figure 5.1c), the air and product gas move perpendicular to the flow of both the feedstock, and the ash, but in the fluidized bed design (Figure 5.1d), a hot bed of sand particles is kept under constant motion by the gasifying agent which is usually introduced through nozzles at the bottom of the gasifier, while the feedstock is introduced from the upper part of the reactor. Because of the design features of the fluidized bed, the temperature throughout the reactor tends to be more uniform (800-1000°C) than the other designs but the product gas often contains tar with large quantities of ash.

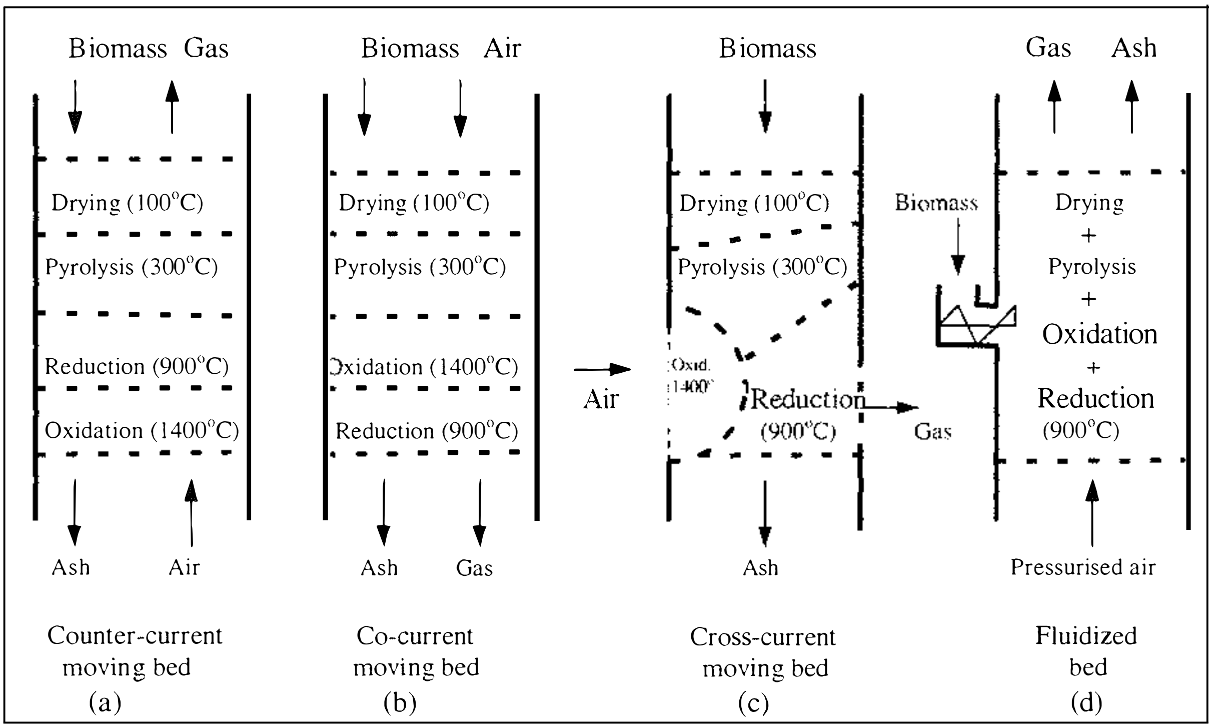

Figure 5.1 **Major types of Gasifier reactors**

5.1.3 THERMAL GASIFICATION OF WOODY BIOMASS

Thermal gasification of solid fuels including biomass, involves a combination of decomposition and devolatilisation reactions in an environment with controlled oxygen supply to produce volatile compounds and a char matrix. The volatile products are cracked at higher temperatures in secondary reactions, while the char is further gasified in the presence of air, O_2, or steam (gasifying agents) to produce additional combustible gases. The resultant combustible product gas mixture consists of H_2, CO, CO_2, H_2O, CH_4, higher hydrocarbons and some condensable tars. The gas mixture is referred to as "producer gas".

The processes and products of gasification are variable being influenced by reactor type, operating conditions and nature of feedstock (Maschio *et al*, 1994; Walawender *et al*, 1980; Raman *et al*, 1980; Beck and Wang, 1980; Antal *et al*, 1978; Howard *et al*, 1979; Kinoshita *et al*, 1991). The use to which the gas is put determines the product gas composition requirements. For fuelling internal combustion engines, the gas must be rich in combustible components and be free from tar and dust.

Although it is known that wood properties vary among species (Chapter 4), and that product gas composition is a function of fuel type and process conditions (Mendis *et al*, 1989a, 1989b), the influence of varying fuelwood characteristics on gasification behaviour, product gas component distribution and quality is not quantified, and therefore not well understood (Herguido *et al*, 1992; Walawender *et al*, 1988a). There is a lack of steady state data on the effects of gasifier operating variables on the nature of products. In addition, little work has been undertaken to investigate the influence of fuelwood species and their associated properties, yet commercialisation of gasification technology may require the use of a wide range of fuelwood species particularly from short rotation forestry (SRF) schemes. An understanding of the influence of tree species and the related biomass properties on thermochemical behaviour, system performance, and quality of gas produced, will be essential for confident modelling of conversion systems and possible scheduling of the product mix, all which are essential for commercialising the gasification technology.

Most studies on thermochemical gasification of biomass have utilised laboratory (bench) scale reactors where operating conditions follow strict laboratory controls, relying on scale-up of laboratory models to relate to field operating conditions (Garcia-Bacaicoa *et al*, 1994). Whereas this gives a good indication of the operating principles, the results are exaggerated when extrapolated to reflect commercial scale reactors (Corella *et al*, 1988), which are often riddled with field operating problems.

This present study:

a) used a small scale Fluidyne commercial downdraft reactor with the capability to supply sufficient gas to generate 35 kW electric (Williams, 1996); and

b) investigated the gasification characteristics of short rotation forestry (SRF) woody biomass.

The reactor demonstrated field operating conditions upon which laboratory controls were imposed. The feedstock evaluated was harvested from experimental renewable SRF systems which may become increasingly important in future commercial biomass energy schemes.

5.1.4 OBJECTIVES

The objectives of the gasification study were to:

1. outline the operating parameters for a 35 kW (electric) commercial downdraft gasifier;
2. evaluate the suitability of woody biomass from short rotation forestry systems as gasification feedstock; and
3. define features characterising a good fuelwood species for gasification purposes by matching the quantity and quality of gas produced with the fuelwood properties.

The Fluidyne gasifier was chosen for these experiments because it is manufactured in New Zealand and good back-up services could therefore be provided. Aspects of gasifier design to obtain improved operation performance were not covered in this study as the objective was to compare a range of woodfuels through a gasifier at standard settings rather than attempt to modify the gasifier design to suit the fuels.

5.2 WOODY BIOMASS GASIFICATION

5.2.1 PROCESS OF THERMAL GASIFICATION OF BIOMASS - A THEORETICAL BACKGROUND

Thermal gasification of biomass materials is a complex process due to the behaviour under high temperature of each of the components - cellulose, hemicellulose, lignin, and extractives. The process could be considered as an incomplete combustion process manipulated by (i) the design and physical configuration of the combustion equipment (the gasifier); (ii) controlling the quantity of air admitted; and (iii) the temperatures to yield a specific combination of products dominated by the product gas of defined composition. The process involves different physical and chemical transformations occurring in defined stages as shown in figure 5.2.

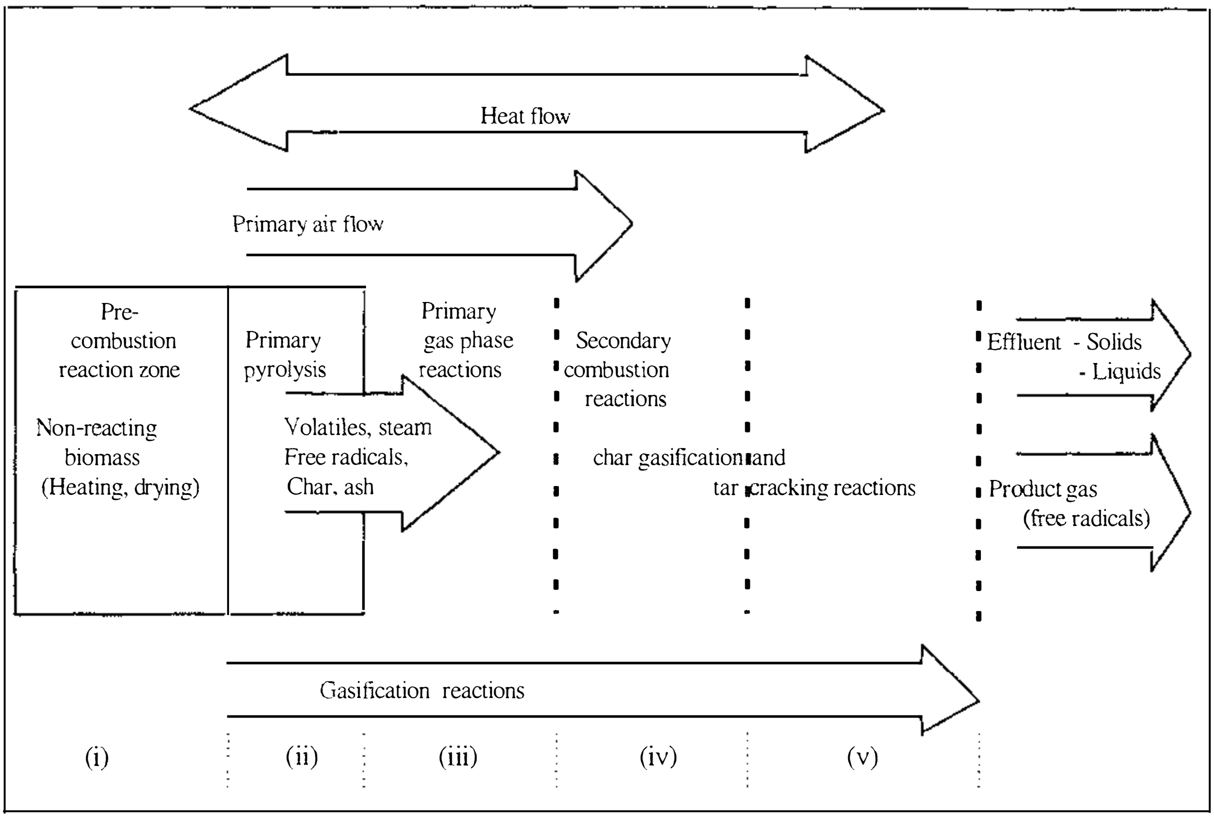

Figure 5.2 **Representation of the biomass gasification mechanisms**

The supply of air (oxidant) is limited by the configuration of the gasifier, deliberately designed to limit the primary gas-phase combustion, and eliminates the secondary combustion reactions which characterise biomass combustion reactions. The major stages include (i) heating and drying; (ii) pyrolysis; (iii) secondary gas phase reactions; and (iv) char gasification and tar cracking reactions.

The phases (i - iv) shown in figure 5.2 correspond to varying temperature levels reached within the gasifier (see figure 5.11). The overall process is dependent on the quantity of air available (oxidant) in relation to the quantity of feedstock, the nature of feedstock (Walawender *et al*, 1980; Raman *et al*, 1980; Beck and Wang, 1980; Antal *et al*, 1978; Howard *et al*, 1979), and the reactor temperature. The reactor temperature may be a function of gasifier design configuration (Figure 5.1), oxidant admitted, and the feedstock type. Although these relationships have not been well documented, variations of the processes result in the production of different products, and product distribution.

For a downdraft gasifier (Figure 5.1a), the reactor is distinguished by four major zones, each characterised by a defined combination of materials (inputs and or outputs) and temperature. The reactor zones (heating and drying; pyrolysis; oxidation; and reduction) are distinguished by the major reactions of gasification, and result in different combinations of products.

Heating and Drying

In an autothermal gasifier, heating and drying is preceded by pre-combustion reactions involving large quantities of heat generated from the in-situ combustion of part of the charge which provides the energy for subsequent endothermic reactions. The process is governed by thermal conductivity and the movement of moisture within and around individual feed particles. The heating of individual wood particles to temperature t (°C) may be related to its specific heat (C_P, J/g/°C) (Wenzl, 1970):

$$C_P = 0.266 + 0.00116\ t$$

Steady state flow of heat is described by Fourie's law, which is analogous to Darcy's law for the transport of fluids. Thus, the thermal conductivity of a material is equal to the flux divided by the gradient:

$$K = \frac{H/tA}{\sigma T/L} = \frac{HL}{tA\sigma T}$$

where K = thermal conductivity, W/mK; H = quantity of heat transferred, J; t = time interval, s; A = cross sectional area perpendicular to the direction of flow, cm^2; L = length of flow path in the transfer medium, cm; σT = temperature differential between the heat-transfer surfaces separated by L, °C.

Thermal conductivity (K) of woody materials varies with moisture content (MC), and is related to green specific gravity (S), and porosity defined by the fractional void volume (FVV) (Siau, 1984):

$$K_{MC<40\%} = [S(5.18 + 0.096MC) + 0.57FVV] \times 10^{-4}$$

When the moisture content exceeds 40%, a significant proportion of the moisture is free water in the lumens, which contributes to the over-all thermal conductivity more than the bound water. At that point, the constant 0.096 in the equation is replaced by 0.131 showing increased conductivity. Unfortunately, the removal of the moisture (drying) is a temperature-activated process which requires more energy.

These relationships show that the:

1. heating and drying of biomass materials are physical rather than chemical processes;
2. energy required for the heating and drying processes is increased by the presence of moisture in the feedstock which reduces the achievable efficiencies of conversion since a significant quantity of heat is required to dry the feedstock prior to the pyrolysis and gasification reactions;
3. drying process is associated with the density characteristics through the porosity of wood as defined by the void volume fraction. This relationship accounts for part of the different rates of heating and drying in different species, particularly between softwoods and hardwoods; and
4. particle size of the feedstock plays an important role in the heating and drying process.

Primary pyrolysis

Two mechanisms have been suggested for the pyrolysis of dry biomass materials (Figure 5.3). In mechanism (i) several sequential and competitive reactions predominate at low temperatures and slow heating rates. Under faster heating rates, mechanism (ii) becomes more important, with the production of levoglucosan through the rapid cleavage of the glycosidic bonds in the cellulose structure (Shafizadeh, 1977).

Some of the tars (levoglucosan) generated are combustible and undergo exothermic reactions beyond 500°C generating CO, CO_2 and H_2O. They may also reform into solid carbon (see section 4.5.1). Thus, Kumar and Gupta (1997) showed that the amount of deposited carbon in resulting chars increased with temperature peaking at about 800°C, beyond which it decreased until reaching about 1200°C. Increased carbon deposition was due to increased aromatisation in the char matrix.

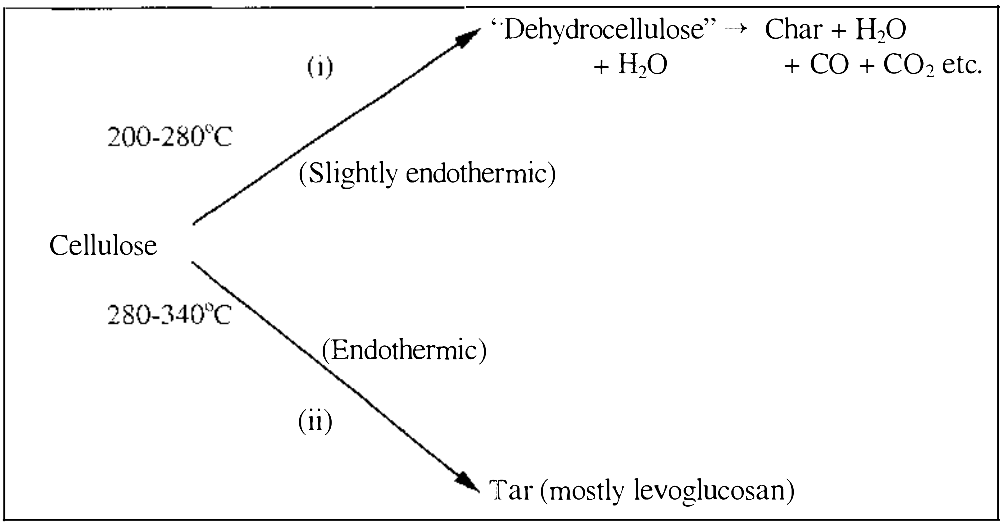

Figure 5.3 **Mechanisms of biomass pyrolysis**

The pyrolysis reactions and products are non-equilibrium and hard to predict, being dominated by pyrolytic oils and acids, water, solid char and a mixture of gases. Both the reactions and products are also dependent on temperature and period of heating; the ambient atmosphere, oxygen, water, and other reacting or inert gases; and the composition and physical nature of the feedstock, especially with respect to inorganic impurities which constitute the ash content of the feedstock. The yield of volatiles increases with the heating rates, but for the highest temperatures, the condensables (tar) are cracked and the gas content is increased. Char yield is minimised at low temperatures, slow heating rates and long residence times. The reactivity of char is influenced by the time/temperature history although the presence of ash affects the thermal behaviour of cellulosic materials. According to Ransfelt *et al*, (1978), char gasification does not significantly affect gasification of biomass below 800°C.

Secondary gasification reactions

Table 5.1 lists the dominant gasification reactions - pre-combustion and primary pyrolysis reactions (1); the carbon steam reaction (2); the reversible water gas reaction (3); the Boudouard reaction (4); water gas shift reaction (5); and the methane formation reaction (6).

The tar cracking reactions are not indicated in the table because they involve the volatile products from the pyrolysis reactions (these products are not known, and cannot easily be predicted). These reactions, together with the water-gas shift reactions generate carbon monoxide, hydrogen and water. According to Antal *et al,* (1981; 1978), Raman *et al*, (1981), and Schoeters *et al*, (1981), these reactions occur rapidly and dominate the gasification chemistry of biomass. Complete cracking depends on whether the pyrolysis products remain in the hot zone long enough. If the gas residence time in the hot zone is too short, or if the temperature is too low, medium sized molecules may escape and condense as tars and oils in the low temperature reduction zone of the system (FAO, 1986).

Table 5.1 **The main reactions in biomass gasification**

1. $\text{Biomass} + O_2 + \text{heat} \rightarrow C + CO_2 + CO + H_2O + \text{hydrocarbons} + \text{Heat}$
2. $C + H_2O \leftrightarrow H_2 + CO + 131.4\ \text{kJ (stp)}^*$
3. $C_xH_{2y} + xH_2O \Rightarrow CO + (1 + y)H_2 + \text{Heat}$
4. $C + CO_2 \leftrightarrow 2CO\ + 172\,600\ \text{kJ (stp)}$
5. $CO_2 + H_2 \leftrightarrow CO + H_2O\ - 41\,200\ \text{kJ (stp)}$
6. $C + 2H_2 \leftrightarrow 2CH_4\ - 75\,000\ \text{kJ (stp)}$

* - stp = standard temperature and pressure

The downdraft reactor design forces all the pyrolysis products to pass through the high temperature oxidation zone, and through the narrowest part (choke) of the reactor. The design ensures a high carbon conversion by subjecting the tars (hydrocarbons formed in the pyrolysis to high temperatures resulting in cracking and forming simpler molecules (H_2, CO, and CO_2 etc.), but places two significant restrictions on the woodfuel quality: (i) the fuel should carbonise to a strong structure with large particles which do not disintegrate to fines so that the gases will continue to flow easily through the reduction zone; and (ii) there is a limit to the moisture content of the feedstock due to the heat removal effects of water vapour both by chemical reactions and by physical evaporation in the drying zone.

The reactions take place under different conditions of temperature and oxidant levels, and therefore occur in different regions/zones of the gasifier (Figures 5.2). In practice, these regions are not distinct - there is considerable spread and overlap between the different zones, and the extent of each zone in an operation mode may depend on the load on the system. The combustion zone expands with the gas load, and affects both the size and position of the other zones. Similarly, the reactions are not confined to specific zones i.e. different zones may have more than one reaction taking place.

5.2.2 PRODUCTS OF BIOMASS GASIFICATION

The process of gasification has three broad product categories (i) the gases; (ii) the liquids (tars and the condensate); and (iii) the solids (ash, and unburnt char). The distribution of these products define the mass and energy balances which in turn determines the system efficiency. Baker *et al,* (1984) reported product distribution of 72-93% gaseous products, and 14-24% liquids. Although residual tar and ash have been utilised on a limited scale (Bristol *et al*, 1993; Coleman, 1993; Jefrey and Christine, 1993), the gas component is the most important product.

Producer gas

The quantities of gas produced per unit mass of feedstock varies with the type of gasifier, and depends on the operating conditions. Schoeters *et al*, (1981) reported values ranging from 2.8-2.9 kg of gas per kg of feedstock gasified, with the minor variations being attributed to the differences in temperature. ESMAP (1990) and Williams (1996) estimated a gas production of 2.185 m^3/kg and 2.4 m^3/kg of wood, respectively.

When pure oxygen is used as the oxidising agent, the product gas consists of H_2, CO, CO_2, H_2O, CH_4 and higher hydrocarbons. When air is used, nitrogen in the air is carried through the system and may form the bulk of the gas. The proportion of each of the constituent gases, and the characteristics of the gas including the heating values, the gas compressibility or real gas factor, and the densities of constituent gases determine the use to which the gas may be applied. They are also indicators of gasifier performance, and may be used to characterise the suitability of feedstocks for gasification. According to Moersch *et al* (1996), gas turbines and engines require a minimum lower heating value of 5 MJ/Nm^3 (MJ per normal, uncompressed m^3).

Table 5.2 compares the compositions of gas produced from different processes and feedstocks, and demonstrates the influence of both the processes and feedstock on the type of gas produced. Although Coovattanachai, (1989) argued that when air is used as the gasifying agent, the heating value of the product gas varies from 3-7.8 MJ/m^3, the table demonstrates that heat values higher than those stated are obtainable even when air is used. If oxygen is used, a medium heating value (12-20 MJ/m^3) gas is obtained. The actual heating value of the gas mixture depends on both the design of the gasifier, and the type of fuel, and the moisture content of the feedstock.

Table 5.2 **Product gas from the air gasification of different materials**

		Gas composition (%)							Heating value
Process	Feedstock	H2	CO	CH4	CxHy	O2	N2	CO2	(MJ/Nm3)
Battelle[1]	Solid wastes	21.6	21.0	1.8	0.5		43.3	11.8	8.215
Torax[1]	MSW	10.8	9.5	1.4	0.3	5.0	64.5	9.9	3.659
Monsanto Landgard[1]	MSW	6.6	6.6	2.8	1.7	1.6	69.3	11.4	4.105
Imbert[2]	Wood chips	19.1	18.6	0.9	2.2		49.8	9.4	7.983
Duvant[2]	Wood chips	17.5	15.5	2.0	0.0		50.5	14.5	5.772
Biomass[2]	Wood chips	17.5	19.7	3.5	1.8		42.7	12.7	8.774
Forintek[2]	Wood chips	16.7	16.0	3.2	1.9		45.5	15.8	7.788
Forintek[2]	Wood chips	15.1	11.9	2.1	1.5		50.9	17.7	5.956
Other designs[3]	Wood chips	13.3	21.5	3.7	1.9		46.2	13.4	7.798
"	Wood chips	12.7	15.5	5.7	2.4		47.9	15.9	8.061
"	Wood chips	16.6	17.6	5.4	1.8		45.7	13.1	8.774
Downdraft[4]	Wood chips	17.8	21.2	2.9	1.4		45.8	10.9	8.219
Downdraft[5]	Wood chips	19.2	22.3	1.6			42.4	13.8	6.040
"	"	18.3	21.5	0.9			45.2	13.5	5.550
Fluidised bed[6]	Corn stover	12.2	13.6	4.9	2.4		50.9	16.0	7.357

[1] Robinson (1980); [2] Overand (1980); [3] Hauserman (1995); [4] Graboski and Brogan (1988); [5] Chee (1987); [6] Park *et al*, (1981)

Liquid residues

Liquid residues constitute the condensate and according to Williams (1996), the residue should be water with fine solids in suspension which settle out on standing leaving water coloured slightly by dissolved ash. This liquid may also contain tarry material (condensed higher hydrocarbons). Corella *et al*, (1991) analysed the condensate and showed that it contained tars (polyaromatic hydrocarbons) which were responsible for the odour and toxicity. Although variability in condensate could be an indicator of reactor malfunction, gasification of different wood types produce different condensate types due to the nature of wood chemical composition, and the concentration of different mineral components.

Tests commonly used to assess liquid effluents for disposal requirements within environmental constraints include pH, electrical conductivity, turbidity, and chemical oxygen demand (COD) measured in parts per million (ppm). Although no such measurements / analyses have been reported on collected liquid condensate, the analysis may provide insights into the operation of the gasifier, and also provide information for determination of non polluting disposal requirements.

5.2.3 MASS AND ENERGY BALANCES

Mass and energy balances procedures entail the determination of the distribution of materials and energy (inputs and outputs) in the system, and facilitates the determination of both mass and energy conversion efficiencies. The calculations are based on the principles of conservation of mass and energy that serve to determine the flow, compositions, and temperatures of all streams in a flow-sheet (Reklaitis, 1983). The sum of inputs must equal the sum of outputs.

Material balance closure is the ratio of input weight to output weight, while the conversion efficiency is the percentage of the total input mass converted to clean dry gas. Consequently, the thermal efficiency is the percentage of energy in the feedstock (HHV) converted to the useful heat of combustion of the clean dry product gas. Given these ratios, gasification efficiency is defined as the gas energy output per wood energy input. Gasification efficiency is the ratio of the chemical energy converted into the product gas divided by the total chemical energy in the feedstock, based on the lower heating values (Wang and Kinoshita, 1994).

In a biomass gasifier, inputs include biomass feedstock, an oxidising agent (air), and steam (water). Outputs include product gas, liquids, and solid residues (ash and unreacted char). Thus, Walawender *et al,* (1988a), and Chee (1987) measured the chip feed rate, dry gas output rates, tar, and condensate for a 1600 MJ/h downdraft gasifier and found total mass balance closures of 95-103%, corresponding to 85-94% mass conversion efficiency; and a cold gas efficiencies of 58-73%. Graboski and Brogan (1988) measured input rates of the chips, air, and propane; and the output rates of char for a prototype commercial downdraft gasifier with a capacity of 15,800 MJ/h and obtained total mass closures of 96-97% corresponding to cold gas efficiencies of 79.7-79.3%.

Other measurements of mass and energy balances include those of Baker *et al* (1984); Graham and Huffman (1981); Corella *et al*, (1991); Walawender *et al* (1985a); Graboski and Brogan (1987); etc. Although these previous studies utilised different techniques in the measurements and determination of stream flows, the results illustrated the major material and energy components in the gasification of biomass. They illustrated that up to 80% of the carbon in the feedstock may be converted to gas products; up to 20% was in the liquid products; up to 5% was in tar; while the water soluble organic substances (pyroligneous acids) contained about 15%. The energy content of the cold clean gas was about 60% of the original wood energy while the sensible heat including the energy used to dry the wood accounted for 11% of total energy flowing into the system.

5.2.4 FEEDSTOCK FOR THERMAL GASIFICATION

A description of the feedstock for thermal gasification entails:

i) a broad identification of the feedstock, e.g. woody biomass, agricultural residues, municipal solid wastes and coal; and includes a description of the feedstock properties (heating values, density, volatile matter etc.). Cellulose, xylan and lignin have also been utilised in experiments.

ii) a definition of the level of processing including debarking, comminution (described by the feedstock particle sizes and particle size distribution), and drying (described by feedstock moisture content).

These different materials follow different charring and gasification patterns, and produce different results when gasified under similar conditions (Walawender *et al*, 1980; Raman *et al*, 1980; Beck and Wang 1980; Antal *et al*, 1978; Howard *et al*, 1979). The differences have been associated with the differences in the chemical and physical constitution of the biomass (Wilkins and Murray, 1980; Davies *et al,* 1984), and translate into the different pyrolysis / gasification products.

Beck and Wang (1980) gasified saw-dust and manure in a fluidized bed reactor under partial oxidation conditions, while Najewicz and Furham (1993) compared the characteristics of gas produced from bagasse, wood chips and coal. Kurkela *et al*, (1989) gasified peat and wood chips, forest waste chips, briquetted municipal solid wastes (MSW), a mixture of chopped MSW and wood chips, chopped straw, and a mixture of MSW and peat in an updraft gasifier. These tests showed that gas composition was different for each material. Sawdust produced gas in higher quantities and heating value than did cattle manure and coal under similar operating conditions. Wood chips resulted in a gas with the highest CO content (29%) but the lowest CH_4 (16%) and CO_2 (6.8%). The higher quantity and quality gas from woody material was attributed to its higher cellulose content.

Walawender *et al*, (1988a), and Chee (1987) compared the gasification characteristics of four species - cottonwood (*Populus deltoides*), silver maple (*Acer sacharinum*), black locust (*Robina pseudoacacia*) and oak (*Quercus* species). They reported low gas yields in silver maple attributed to the low chip bulk voidage but Graham and Huffman (1981) detected no differences among the four species in gas quantity, gas energy content, process efficiencies and general product distribution except lower char yield coupled with a higher liquid yield for poplar wood chips. Baker *et al*, (1984) had previously concluded that the gas obtained by gasifying *Eucalyptus*, *Acacia* and *Pinus* species was similar.

The production of charcoal of varying properties from different wood species (Abe, 1982; Davies *et al*, 1984), as well as different levels and mixture of gases when exposed to high temperatures indicates that wood properties influence (i) the charring and gasification characteristics; (ii) the level of gas yield when the material is gasified (Walawender *et al*, 1980); and (iii) composition of the product mix. Such differences are associated with differences in the chemical compositions of the feedstock particularly with respect to cellulose (Walawender *et al*, 1985).

5.2.5 EFFECT OF FEEDSTOCK PROPERTIES

The properties that have been considered as influencing the suitability of feedstock for gasification include (i) basic density; (ii) particle size distribution and bulk density; (iii) ash content; (iv) volatile matter content; and (v) moisture content.

Chapter 4 presented the variability, and basis of the variation in the properties of 10 SRF species. This section will consider the effects of the differences in feedstock properties on the processes and products of gasification in a bid to identify an ideal fuelwood species for production of gasifier feedstock.

Basic densities

Chee, (1987) and Walawender *et al*, (1988) related wood density (and the wood vessels volume percentage), with gas and char yields. They reported that yield and heating values of product gas increased with decreasing vessel volume percentage (increasing wood density) at the expense of char yield.

Particle size distribution and bulk density

Particle size and size distribution of a sample of chips define the bulk density which is in turn a measure of how densely the fuel will pack into the reactor, and defines the porosity of the wood chips in the fire-bed. It depicts particle settling and packing characteristics, and also defines the packing characteristics of the bed of hot charcoal through which gases and vapours must flow.

Although a few studies have investigated the influence of feed particle characteristics on the gasification behaviour and products (e.g. Payne *et al*, 1985; Chen and Gunkel, 1987; Graham and Huffman, 1981; Chee, 1987; Balci *et al*, 1993; and Raman *et al*, 1980), no standards exist for "acceptable" chips or chips size distribution for combustion purposes as acceptable requirements may vary with the type of process, and capacity of the reactor. Raman *et al*, (1980) and Graham and Huffman (1981) found that different particle sizes produced different gas yields and composition in a fluidized bed reactor and downdraft gasifier respectively. Graham and Huffman (1981) showed that the gas energy content and thermal efficiency of the gasifier dropped by using small size chips. Despite these previous studies on the relationships between particle size and size differences, the optimum particle size range for a downdraft gasifier design remains unclear.

Downdraft gasifiers require a porous bed (i.e. larger chip size) for maximum process efficiency since gaseous primary products must flow freely down through the bed for complete gasification and cracking to occur. According to Lyons *et al*, (1985), the minimum particle size for grate firing of solid fuels (referred to as the bed void fraction) is about 12 mm, and should be over one third to one sixth of the depth of the firebed (Perry *et al*, 1984). If the firebed is less than three particle diameters deep, the combustion air will not have the time to react fully with the fuel before it reaches the lower bed surface. If it is greater than six diameters, then the oxygen in the air is consumed well before reaching the lower surface, resulting in poor combustion on the upper layers of the fuel, and a non-radiant firebed top. Thus, the ratio of the largest dimension of the particle to the smallest cross section of a gasifier (usually at the throat or coke plate) should be at least 6.8 in order to avoid bridging (Kaupp and Goss, 1984). The bed void fraction depends on the ratio of particle to reactor diameter, confined within a range from 0.3 to 0.6 (Perry *et al*, 1984).

Ash content

High ash content materials imply that a big proportion of the material is inert, and does not contribute to the product gas yield. When present in large quantities, ash can also cause slagging and clinker in the reactor resulting from melting and agglomeration. At an ash content of between 6 and 12%, the extent of slagging will depend on the ash melting point which is influenced by the presence of trace elements giving rise to the formation of low melting point eutectic mixtures. Ash containing high alkali salts like sodium and potassium may convert the silica into low melting silicates at high temperature, and if the ash is present in large quantities, it could melt forming clinker. This molten material clings to internal surfaces of the gasifier, and may obstruct fuel flow, increasing the air/fuel ratio and therefore the temperature. The gas produced under such conditions has high CO_2 content from the combustion reactions. Slagging can lead to excess tar formation and/or complete blockage of the reactor. Slagging can also lead to air channelling which can lead to risks of explosion if the air-fuel ratio reaches the stoichiometric value for combustion.

Volatile matter content (VM)

Beck and Wang (1980) investigated the influence of volatile matter content on gas yield by gasifying oak wood saw dust with 95% VM, and manure with 75% VM, in a fluidized bed reactor. The higher gas yield from sawdust was attributed to its higher VM associated with high cellulose and hemicellulose content. Najewicz and Furham, (1993) found biomass to be more reactive than coal which he attributed to its higher volatile matter content, and Walawender *et al*, (1985) demonstrated that more gas with high carbon and energy recovery in a gasification system occurs during the cracking of the volatile matter. High VM materials are understood to produce higher quantities of hydrocarbons which are cracked to yield higher quantities of combustible gas.

Feedstock charring and reactivity properties

There is a positive correlation (with 99% probability) between char yield and lignin content, and a negative correlation (96% probability) between char yield and hemicellulose content (Mok *et al*, 1992), but no relationship was established between char yield and cellulose content. Thus, theoretically, higher yields of charcoal can be obtained from wood species with high lignin and low hemicelluloses content since hemicelluloses volatilises at low temperature. However, since lignin and hemicellulose contents in biomass are correlated, it is difficult to distinguish the effect of either component.

Feedstock moisture content

Sections 4.4.4, 4.5.3 and 5.2.1 indicated the possible effects, and the mechanisms by which moisture in biomass feedstocks might influence the suitability of feedstocks in thermochemical processes resulting in variations in the processes, products and products distribution. Thus, Walawender *et al*, (1988b) reported a linear decrease in dry feed rate, product gas heating value, gas-to-feed ratio, air-to-feed ratio, and cold gas efficiency, with increasing chip moisture content in a downdraft gasifier. Graham and Hufmann (1981) found gas heating values to decrease from 6.72 to 4.68 MJ/Nm^3, while the conversion efficiency reduced from 87 to 76% when the feedstock moisture content was increased from 13 to 34% (wet basis). Cousins (1980) found that the yields of CO declined by 14%, and of H_2 by 6% when feedstock moisture content increased from 0 to 20% in an oxygen blown gasifier. Yield of CO_2 increased, but that of CH_4 was not affected.

Mendis *et al,* (1984) found that the quantity of condensate produced increased with increasing feedstock moisture content, while Chen and Gunkel (1987) indicated that increasing the feedstock moisture content from 0% to 40% (dry basis) in a co-current gasifier (i) reduced both the equilibrium and oxidation temperatures; (ii) increased both the oxygen input and the oxygen to fuel ratio; (iii) increased the equivalence ratio; and (iv) increased the air to fuel ratio.

5.2.6 THE ROLE OF AIR

The quantity of air (oxidant) entering the gasifier can be expressed as a factor of stoichiometric air requirements (A_s) which is the mass of dry air required to burn a unit mass of dry fuel. Given A_S, the equivalence ratio (ER) is defined as the fraction of the stoichiometric air requirement used to gasify a unit of fuel (i.e. the ratio of air used to the stoichiometric air requirements of that fuel). ER indicates the solid char-air contact, and therefore the level of reaction and surface contact of the reactant.

Variation in the quantities of air used have a significant effect on the quantities and quality of gas produced (Schoeters *et al*, 1989; Cousins, 1980; Kinoshita *et al*, 1991). Beck and Wang (1980) demonstrated that the total gas yield was related to both the average reactor temperature and the ratio of air to dry ash-free feedstock while Bilbao and Garcia-Bacaicoa (1994) concluded that air flow rate was one of the most important variables influencing gasifier performance as it determined biomass consumption and product distribution.

Kurts, (1984) correlated the equivalence ratio with the total product gas yield, measured as the actual flow rate of air to the air flow rate necessary for complete combustion while Baker *et al*, (1984) measured the oxygen consumption rates in a gasifier using different moisture content feedstocks and found that 0.2 - 0.36 kg of oxygen was required for every kg of dry wood, and that wetter feedstocks required more oxygen. Schoeters *et a*l, (1989) reported decreased product gas heat values after the gas yield was increased by increasing the equivalence ratios. Cousins (1980) showed that the yield of the major constituents of the wood gas (CO, H_2 CH_4, CO_2 and H_2O) varied with the ratio of oxygen input. By increasing the oxygen input from 0.4 to 0.7 kg/kg of wood, the yield of CO passed through a maximum; those of H_2, CO_2, and H_2O increased; while that of CH_4 decreased. When the oxygen input was less than 0.45 kg/kg, tar was produced. Kinoshita *et al*, (1991) showed similar trends except that H_2 production reduced as the oxygen concentration increased. Char yield has also been found to reduce with increasing equivalence ratio.

In all these studies, the cold gas thermal efficiency remained stable up to an air factor of about 0.6 when it started to decline. The stability in thermal efficiency could be attributed to the increased quantity of gas produced, which compensates for the reduced heating values. These results demonstrate that for a given system, air flow variations modify the rate of biomass consumption and gas products generated but the variation (of air flow rate) has an insignificant effect on the fuel/air and gas/air ratio because biomass consumption varies in direct proportion to the air flow rate for any system.

5.2.7 THE ROLE OF HIGH TEMPERATURE

The major pre-cursors of thermochemical biomass gasification are the feedstock, air, and temperature. Of these, temperature has been shown to have the largest effect on both pyrolysis and gasification processes, char and gas yields, and the nature of products generated (Raman *et al*, 1980; Walawender *et al*, 1980). Feldman *et al*, (1981b); and Mok *et al*, (1992) showed the yield of char and its reactivity to be a function of the time/temperature history of the process. Shafizadeh and de Groot (1976) concluded that the thermal behaviour of biomass was influenced by temperature as well as its chemical composition.

Graboski and Brogan (1988) reported temperatures ranging between 1148°C and 1371°C in a downdraft modular skid mounted gasifier, while Baker *et al* (1984) recorded temperatures of up to 1200°C in an oxygen/steam fixed bed gasifier. Both Kinoshita *et al*, (1991) and Bhattacharya *et al,* (1986) recorded maximum gasifier temperatures of 1200°C while Cousins and Robinson (1985) reported temperatures of 1100°C in an oxygen blown downdraft gasifiers. In these studies, temperature varied within the reactor, and the highest temperatures were recorded at the centre of the reactor, and mostly near the air nozzles.

Corella *et al*, (1991), Herguido *et al*, (1992), Kinoshita *et al*, (1991), Gulyurtlu and Cabrita (1993), Singh *et al*, (1986) and Feldmann *et al*, (1981a) investigated the influence of temperature on biomass gasification in a fluidized bed reactor as did Geyer *et al*, (1987) who studied the gasification of 7 year old Siberian elm. Schoeters *et al*, (1981) examined the effect of temperature on the gasification of wood (gas composition, heating values, yield and energy recovery) in a fluidized bed reactor under partial oxidation conditions. Walawender *et al*, (1985b) demonstrated that the volumetric yield of the product gas varied linearly with temperature. Cousins (1980) and Bitwoft (1987) showed that biomass gasification at high temperatures resulted in a gas with a lower tar content. Williams and Belser (1991) found that the volume of gas yield, and the total gas heat value from the pyrolysis of rice husks both increased with reactor temperature.

The gas yield and net energy content increased when the temperature increased since the resulting proportion of H_2 and CO in the product gas increased while that of CO_2 declined. Although peak reaction temperatures did not significantly influence the heating values of the product gas, the overall cold gas efficiency increased due to increased gas yields (both mass and volumetric yields) (Bilbao *et al*, 1991b, Geyer *et al*, 1987; Walewander *et al*, 1985b), carbon conversion and hence energy recovery. The increased gas yields compensate for the slightly lower gas heating values, and therefore maintain the overall energy recovery from a unit mass of feedstock.

Temperature profiles

Many previous studies assumed either uniform temperature or variation in temperature along a single direction within the gasifier (Kinoshita *et al,* 1991; Wang and Kinoshita, 1991; Reed *et al*, 1988; Chen and Gunkel, 1987; and Chern, 1989) but Wang and Kinoshita (1994) examined the temperature profiles in a bench scale downdraft gasifier and analysed the influence of different gasifier configurations and operating parameters on the temperature profiles, and also on the gasifier performance. They concluded that gasifier configuration parameters could be adjusted to alter the temperature distribution within the gasifier in order to optimise gasifier performance. Bhattacharya *et al* (1986) examined temperature profiles in the centre of the reactor, and closer to the wall. The highest temperatures (1200°C) were recorded at the centre of the reactor. Plots of temperature against time exhibited minor fluctuations associated with fluctuations in steam flow rates. Cousins and Robinson (1985) reported variations in temperature at four positions (varying distance from the axis) of a cyclone air blown gasifier, while Reins (1984) used a Cast Refractory Microgasifier operating on carrot fibre to obtain temperatures data which was plotted against time of operation. He showed that there were rapid variations in the highest temperatures recorded over the 30 minute period of the reported run. The temperatures below the grate did not show similar movements, but increased gradually during the run.

In the literature, the relationships between high temperature and product gas quantity, gas quality, and general gasifier performance has been emphasised, but the role of a defined temperature profile has not been considered. Thus, it is not apparent what differences there may be when the temperature profiles are shifted within the reactor, and how such a shift may be brought about.

5.2.8 SAMPLE (MASS) LOADING

Sample loading defines the apparent mass density of the fuel within the reactor (i.e. the mass of feedstock per unit and controls the vapour phase concentration of volatile products, the total reactor pressure, the moisture content in the charcoal and the product gas yield. Mok *et al*, (1992) associated the rapid reactions at lower temperatures accompanied by higher heat release during char formation to high mass loading.

5.2.9 GAS RESIDENCE TIME

Residence time is the ratio of air velocity entering the gasifier at the nozzles (m/s) to the bed length (m). The residence time defines the distance the gas travels within the gasifier, i.e., from the nozzles to the grate (m, see section 5.3). From the residence time values, the hearth load is derived, being the superficial velocity (V_S) of the gas as it passes through the narrowest part of the gasification zone (choke). It defines the gas production rate expressed in volume of gas per unit of cross sectional area per second ($m^3/m^2/s$).

5.3 MATERIALS AND METHODS

5.3.1 INSTRUMENTATION AND SET-UP

The gasifier used in the experiments for this study was an autothermal Fluidyne design batch reactor, rated 35 kW electric. Figure 5.4 is a vertical section of the sketch of the Fluidyne gasifier showing the internal features, zoning and the locations of thermocouples used to measure the reaction temperature through the gasification zone.

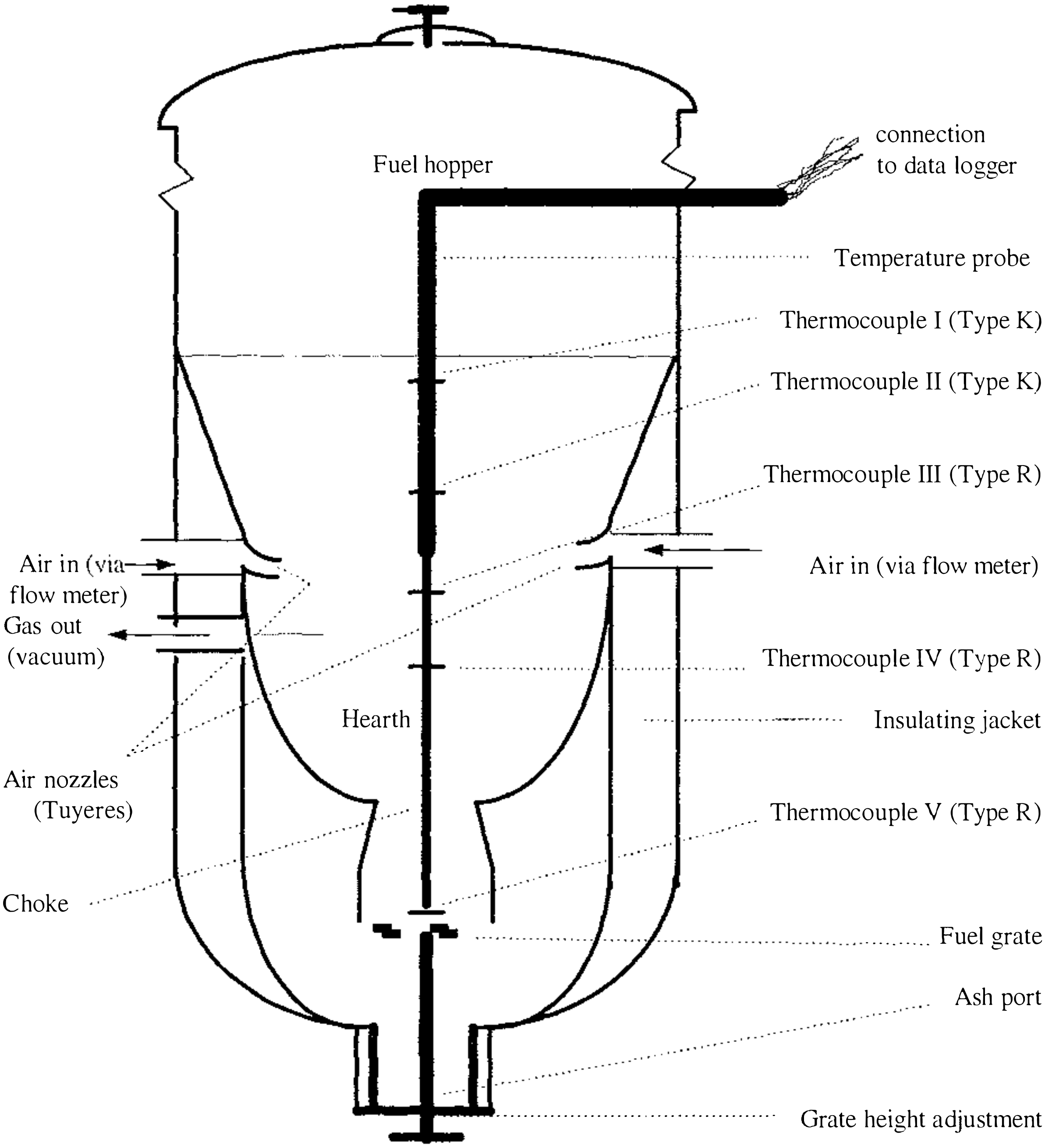

Figure 5.4 **Vertical cross section[a] of the Fluidyne downdraft gasifier**

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[a] **Not to scale**

The fire bed depth of the Fluidyne gasifier, defined by the distance between air nozzles and the fuel grate, was variable ranging from 180 to 275 mm. All tests were conducted at the deepest grate position. The gasifier had eight air nozzles (tuyeres, shown in figure 5.5) with a total inside nozzle area of 9.8 cm^2. The hearth area of the gasifier i.e. the total cross sectional area of the gasifier at the constriction was 122.8 cm^2 (diameter of 125 mm). This area defines the open space for passage of gas products. The nozzle/hearth area ratio was 0.08.

Five thermocouples - two of type K (chromel-alumel) and 3 of type R (platinum-rhodium), all rated at over 1600°C were built into a specially designed ceramic probe and installed to monitor temperature changes at strategic locations (T_I - T_V) within the gasifier (Figure 5.5).

Figure 5.5 **Position of the high temperature probe in the gasifier**

One thermocouple (T_{III}, type R) was placed in the line of the air nozzles (i.e. 275 mm above the grate) to monitor temperature changes in the exothermic combustion reaction zone. T_I and T_{II} (both type K) were placed 175 mm and 70 mm respectively above T_{III}. T_{IV} and T_V (both of type R) were placed 55 mm and 225 mm below it. Thus, the temperatures in the pyrolysis, combustion/oxidation zone, and gasification/reduction zone were all monitored.

Figure 5.6 illustrates the layout of the gasifier/gas clean-up/product collection ports while the photo in figure 5.7 illustrates the "Gas engine-generator set-up" showing the 35 kW (electric) gasifier rig, with the associated accessories as would be set up in a field operating mode. The power board, P; and a water trough, R demonstrated actual field operation and application. However, the engine was not hooked up during the tests evaluating the different species.

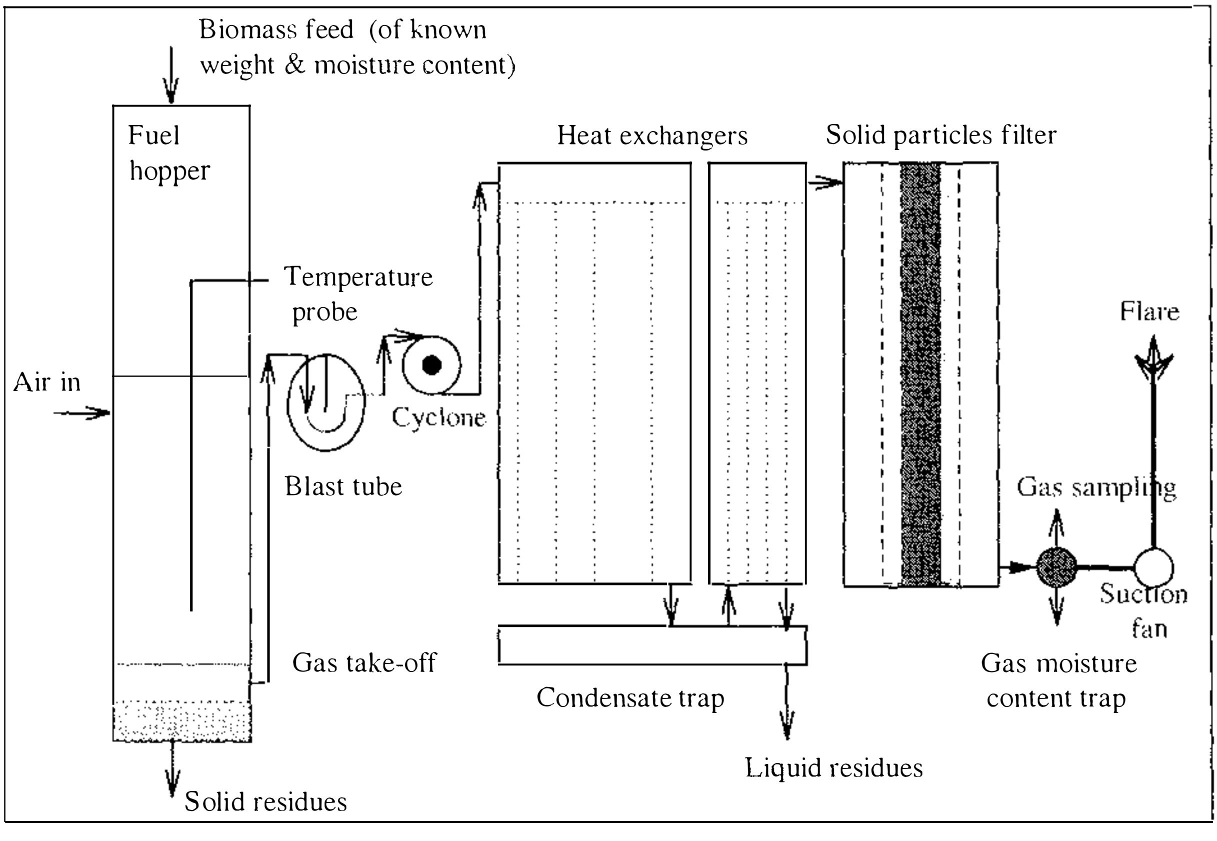

Figure 5.6 **Gasifier and product gas clean-up and sampling set-up**

On exit from the gasifier, the product gas was passed through a blast tube and cyclone where entrained particles of unburnt char were separated. The gas was then passed through two air-cooled heat exchangers in series which cooled the gas from the 150-200°C gas temperature in the blast tube to near ambient. The low temperatures obtained in the heat exchangers resulted in the condensation of reaction water from the product gas stream which was collected as liquid condensate. The resultant product gas, still carrying fine char, was passed through a filter bed of saw dust to remove the carbon fines and traces of tar.

Legend

A	Fuel hopper	G	Blast tube	M	Gas hose
B	Air inlet (via flow meter)	H	Cyclone	N	Internal combustion engine
C	Gasifier (hearth)	I	Heat exchangers	O	Alternator
D	Ash port	J	Saw dust filter	P	Power board
E	Grate height adjustment	K	Cooling fan	Q	Electricity cable
F	Gas outlet	L	Support frame	R	Water trough

Figure 5.7 **The Fluidyne Gas-engine generator rig**

Samples of gas were drawn off after the gas outlet, and passed through a moisture trap containing a weighed amount of oven dried silica gel. The quantity of gas passing through the trap was monitored and correlated with changes in weight of the silica gel in a sealed container to determine the gas moisture content.

Air flows into the gasifier were measured using an air flow meter. The entire apparatus was suspended and a load cell used to monitor weight change. This together with air flow measurements were used to monitor product gas production rates, and feedstock consumption rate excluding the solid and liquid residues which were retained in the system. Weight changes were recorded to the nearest 0.1 kg, temperatures to the nearest 0.1°C, and air velocities to the nearest 0.001 m/s. All instruments were connected to a data logging system.

Data-logging system

The data-logger used in the experiments was a Campbell Scientific 21XL Micrologger. During tests, the variables were scanned at 1 second intervals, and output every 1 minute as averages of the 60 readings over the minute during the period of each run which was normally about 2 hours depending on the fuel type. Output data was dumped on cassette tapes using an SG 93 interface and a data cassette recorder which was then downloaded into spreadsheet programmes.

5.3.2 TEST MATERIALS

The feedstock were obtained from 8 hardwood species - *Eucalyptus nitens*, *E.globulus*, *Populus eridiano*, *Salix matsudana* x *alba S.kinuyanagi*, *Acacia dealbata*, *Paulownia tomentosa*, and *Alnus glutinosa*, and 1 softwood species - *Pinus radiata.* All the trees were planted on the same site, received similar treatments (Chapter 3), and were all harvested at the age of four years. Laboratory samples for the analysis of the energy characteristics of the material (ash content, volatile matter content, extractives content; fixed carbon content and higher heating values) were obtained when the trees were 3 years old (Chapter 4), but the basic density and the proportion of bark were determined when the samples were harvested.

On harvesting, half the logs from each species were debarked. All samples were left to dry in the open prior to storing under cover. The logs were then chipped in a commercial chipper and the chips stored indoors for one year before gasification. Samples of the feedstock were screened through a series of sieves with different mesh sizes - 38 mm; 19 mm and 9.5 mm to give 4 size assortments. Screen trays were stacked (Figure 5.8) and shaken using an AC electric motor with a rotating swing axis for 4 minutes.

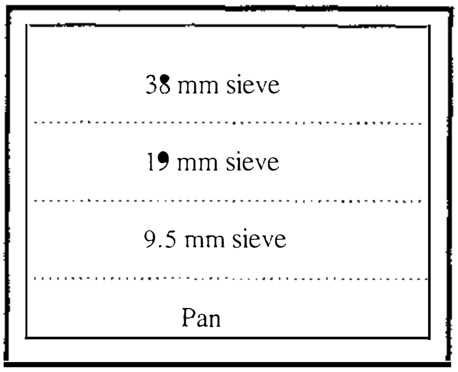

Figure 5.8 **Arrangement of the sieve trays**

The particle size distribution was determined by measuring the quantity of particles retained on each tray, and calculating it as a proportion of the total sample weight. The feedstock bulk density was determined by dropping chips samples into a 20 litre bucket from a height of 1.5 m, (simulating gasifier filling) and determining the weight of the chips when full.

Feedstock moisture content was varied from 0% (oven dry); 10-15% (air dry); and from 27-41% by wetting the samples and thoroughly mixing prior to gasifying.

5.3.3 EXPERIMENTAL VARIABLES AND SET-UP OF THE TESTS

The four variables under evaluation in this series of experiments were (i) tree species; (ii) influence of bark in the feedstock; (iii) feedstock moisture content; and (iv) feedstock particle size distribution and bulk density. The following experimental designs were adopted:

Experiment A - Species tests

Tree species	With bark	Oven dry (0% MC)	8 species
		Air dry (10-15% MC)	5 species
	Without bark	Oven dry (0% MC)	6 species
		Air dry (0-15% MC)	6 species

Nine species (*E.nitens*, *E.globulus*, *P.eridiano*, *A.dealbata*, *P.tomentosa*, *A.glutinosa*, *S.matsudana x alba*, *S.kinuyanagi* and *P.radiata*) were tested. The quantity of material available for some of the species was limited. Thus, not all species were duplicated in all tests. For instance, for oven dry samples, test included eight of the species with bark, and six species without bark, while tests on air dry samples involved five species with bark, and six species without bark. *E.saligna* was not included as the material collected from the 4 year harvest was insufficient for a full run. Tests of debarked *P.radiata*, *P.tomentosa*, *and A.glutinosa* were also not conducted due to lack of feedstock.

Experiment B - Moisture content tests

Species with and without bark	Moisture content	Oven dry (0%)	4 species
		Air dry (10-15%)	4 species
		Wet (>27%)	4 species

The effects of moisture content were evaluated using four species - *E.globulus* (with bark); *S.kinuyanagi* (without bark), *P.tomentosa* (with bark), and *E.nitens* (with bark).

Experiment C - Particle size and basic density

Species without bark	Particle size/ bulk density	Fine (< 19 mm sieve size)	3 species
		Mixed (not sieved)	3 species
		Coarse (> 19 mm sieve size)	3 species

Particle size/bulk density tests were carried out on three species which had been debarked - *E.nitens*, *E.globulus*, and *A.dealbata.* Fines were those that passed through a 19 mm sieve, while the coarse particles were those retained on it. Mixed particles were those not sieved, with particles ranging from powdered chips to the largest particles in the entire lot.

5.3.4 OPERATION OF THE GASIFIER AND GENERAL MEASUREMENTS

For each test, the hopper was filled with a weighed quantity of wood chips to be evaluated together with 0.5-1.5 kg of start-up charcoal. Samples of feedstock were concurrently oven dried to determine feedstock moisture content at loading. The velocity of air flow (m/s) into the gasifier was measured and converted to volume and weight (g, given the diameter of the orifice and density of air 1.23 kg/m^3). Temperatures were measured at five locations within the gasifier (Figure 5.4). Pressure differential was monitored using a manometer.

The rate of fuel consumption (and therefore gas production) was determined by the total weight loss of the apparatus adjusted upwards for the quantity of air used. Each run was assumed complete when the air flow rose sharply, and the temperatures at T_{III} and T_{IV} dropped sharply. In some cases, the apparent weight loss became negligible, and the flame went out). The gasifier was stopped by simultaneously cutting off the air supply, and stopping the suction fan.

Liquid and solid residues were collected separately at the end of each run. The amounts of residues were related to the duration of run, initial feedstock weight and the dry gas output. They were analysed for comments on disposal requirements.

5.3.5 PRODUCT GAS SAMPLING AND ANALYSIS

Gas samples were collected by vacuum suction from the main gas outlet line into gas tight bottles at 3, 5, 7, 9, 12, 15, 20, 30, 40, 60, 80, 100, 120, 140 and 160 minutes after starting the gasifier (or till the feedstock was exhausted). The samples were analysed using gas chromatography (Model: Shimadzu GC-8A), with a thermoconductivity detector (TCD). The GC column was packed with silica gel, 60/80 mesh, 18' x 1/8" stainless steel (SS) operating at 69°C. The carrier gas was helium (experimental grade, 014G). The GC machine, with cycle time of 22 minutes was programmed to detect H_2, CO_2, CO, N_2 and CH_4 and C_2H_6. Two replicate vials were analysed for each sample.

The results of gas analyses were used to evaluate product gas quality, and also to evaluate the processes of gasification as influenced by both feedstock and process variables.

5.3.6 LIQUID RESIDUES SAMPLING AND ANALYSIS

The quantity of liquid residues produced from each run was collected and measured. Samples of the condensate were collected in sample bottles and analysed for (i) pH; (ii) electrical conductivity (iii) turbidity; and (iv) chemical oxygen demand (COD).

5.3.7 SOLID RESIDUES SAMPLING

Solid residues were collected from the ash port, blast tube and cyclone (Figures 5.4 and 5.6) and weighed. Fine char from the cyclone was used in liquid residues cleaning tests (see section 5.4.9).

5.3.8 THEORY, DEFINITIONS AND DERIVATIONS

The feed, water, air and product gas flows, and the quantities of solid and liquid residues collected at the end of each run were multiplied by the period of run (minutes) to obtain the total quantity of each component in the system. These data were used to derive the material flows (as inputs and outputs) of the gasifier. Material flows were converted to weight over time to provide genuine comparisons between feedstocks, and between runs. The quantity of water in the feedstock and after release, flowing through the system, (g/h) was calculated from moisture content measurements, weight of batch feed loaded into the gasifier, and the time taken to exhaust the charge. Run averages of the input and output flows data were used to calculate the mass balance, residence time, gasification and specific gasification rates, hearth load, equivalence ratio (ER), and the net water formation. Gas composition was used to calculate the gas relative density, heating value and other quality and conversion efficiency measures.

- **Mass balances**

  There were 2 inputs into the system - feedstock and air with masses M_F and M_A. The third input - water depended on the moisture content of the feedstock, and could be presented as M_w. The output streams from the reactor were product gas (M_{PG}), solid residues (M_{SR}), and liquid residues (M_{LR}).

  From the law of conservation of mass, the mass balance was derived as:

  $$M_F + M_A + M_W = M_{PG} + M_{SR} + M_{LR}$$

  The main interest was product gas, while solid and liquid residues were only monitored for determining overall conversion efficiencies, and for their disposal requirements.

- **Residence time (s)**

  Residence time was calculated as the ratio of air velocity (V_a, m/s) into the gasifier, to the fire-bed length (l; 0.275 m), ignoring the presence of the fuel. It is the time the gas produced remains within the gasifier fire-bed region:

  $$R = V_a / l$$

- **Specific dry gasification rates (SGR)**

The average rate of dry fuel gasification (g/s) per unit gasifier grate area (0.0123 m^2) was determined from mass flows, and the moisture contents of the fuel determined on batch loading. The specific gasification rate was given as:

$$SGR = (\text{dry rate of fuel use, g/s})/0.0123\ m^2$$

- **Hearth load (Superficial gas velocity) (H_L)**

The hearth load is given by the volumetric flow rate of the product gas (V, m^3/s) divided by the cross sectional area of the gasifier at the constriction (choke), (a, m^2). The hearth load defines the gas production rates expressed in gas volume per cross section area - time (volume/area - time) = length/time = velocity:

$$H_L = \frac{V(m^3/s)}{a(m^2)}$$

$$H_L = m/s$$

- **Equivalence ratio (ER)**

The equivalence ratio (ER) defines the ratio of the mass of the oxidant (M_A) to the mass of fuel (M_F) divided by the oxidant stoichiometrically required per unit mass of dry feedstock (6.21 kg/kg of dry wood). It expresses the quantity of air (M_A) used as a proportion of the stoichiometric air requirements (A_S) used to gasify a given unit of fuel:

$$ER = (M_A / M_F) / 6.21$$

- **Net water formation (NWF)**

NWF was calculated as the ratio of the difference between all water contained in the products (including collected liquid residues and the gas moisture, M_{LR}), to all the water in the feed (M_W) for a given weight of the dry feedstock (M_F):

$$NWF = M_{LR} - M_W / M_F$$

- **Product gas heating value**

Gas heating value was estimated as the sum of the calorific values of the components, each multiplied by the corresponding mole fraction, the sum so obtained being corrected for the compressibility of the mixture (DIN 51 858, 1982; Rose and Cooper, 1977). The compressibility or real gas factor was derived from an analogous sum of component contributions plus a sum of terms for the interaction between components.

The uncorrected sum of heating values of the combustible components (CV_m) may be derived as:

$$CV_m = x_1 CV_1 + x_2 CV_2 + \dots\dots\dots,$$

where CV_m was the summation of heating values of the product gas constituents (kJ/mol); x_1, x_2, ... are mole fractions, and CV_1, CV_2, ... are heating values[a] (kJ/mol) of the product gas components.

The compressibility factor Z_m for the mixture was given by:

$$Z_m = 1 - (x_1\sqrt{b_1} + x_2\sqrt{b_2} + ...)^2 + 5 \times 10^{-4}(2x_H - x_H^2)$$

where x_H was the molecular fraction of hydrogen present in the mixture, and b_1, b_2 ... are gas law deviations of the components (except hydrogen), as defined by the ideal gas function:

$$b^{b} = 1 - (PV/RT)$$

where P = pressure, V = volume, R = the molar ideal (universal) gas constant, and T = the thermodynamic ('absolute') temperature (°K) (DIN 51858). The corrected calorific value (CV) of the gas was therefore given by:

$$CV = CV_m/Z_m$$

- **Heat value of the stoichiometric gas air mixture**

The heating value of the mixture was calculated from the respective heating values, the stoichiometric oxygen requirements, and the volume of each component in the mixture:

$$H_{ig} = \frac{12.68*^{V}CO + 10.8*^{V}H_2 + 35.9*^{V}CH_4}{1 + 2.38*^{V}CO + 2.38*^{V}H_2 + 9.52*^{V}CH_4}$$

where H_{ig} is the heating value of the stoichiometric mixture of producer gas and air in MJ/m^3; and ^{V}I is the volume fraction of the respective gases before mixing with air (FAO, 1986).

- **Cold gas efficiencies (CGE)**

CGE was defined as the ratio of output product gas energy to the input feed energy.

- **Product gas relative standard density**

The relative density was estimated from the densities of individual product gas components:

$$d_j(real) = \frac{\rho_{n,j}(real)}{\rho_{n,L}(real)}$$

where d_jn is the real relative standard density of component j; ρ_{nj} (real) and $\rho_{n,L}$(real) are the real standard density of the pure component j, and air (1.2930 kg/m^3) respectively (DIN 51858).

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[a] The molar heat values of the gas components were taken as H_2 - 286 kJ/mol, CO - 283 kJ/mol, CH_4 - 891 kJ/mole and C_2H_6 - 1560 kJ/mol.

[b] The compressibility factors of the different gases are: CH_4, 0.9981; C_2H_6, 0.9916; CO, 0.9995; CO_2, 0.9943; H_2, 1.0006; N_2, 0.9997; and O_2, 0.9992 (Rose and Cooper, 1977).

$$d_j(ideal) = \frac{M_j}{M_L}$$

where M_j and M_L are the molar masses of component j and of air (28.963 kg/kmol) respectively. The ideal relative standard density (d_G, *ideal*) of the gas mixture of n components was shown as:

$$d_G(ideal) = \sum_{j=1}^{n}\left[x_j * d_j(ideal)\right]$$

where x_j was the percentage of the quantity of substance of component j; and d_j was the ideal gas relative standard density of that gas component.

The real relative standard density (d_G, *real*) was derived as

$$d_G(real) = d_G(ideal) * \frac{Z_{n.L}}{Z_{n.G}}$$

where $Z_{n.L}$ was the real gas (compressibility) factor for air (0.99940), and $Z_{n.G}$ was the real gas (compressibility) factor for the mixture (see the product gas heating value equation above) was:

$$Z_{n.G} = 1 - (X_1\sqrt{b_1} + X_2\sqrt{b_2} + ..)^2 + 5 \times 10^{-4}(2X_H - X_H^2)$$

5.3.9 ANALYSIS OF RESULTS

The SAS System was used to statistically analyse the results, and to define the influence of different aspects of the feedstock. Regression and correlation analyses were carried out to relate the gasifier performance indicators with the operation and feedstock variables.

5.4. RESULTS

Data from one of the gasifier test runs are used to illustrate the processes and products of downdraft air gasification in section 5.4.1. This is followed by a comparison of feedstocks from different SRF species (section 5.4.2) and the associated properties (section 5.4.3). The evaluation of feedstock properties emphasised feedstock moisture content and particle size distribution presented under sections 5.4.4 and 5.4.5, respectively. The role of air flows in air gasification is presented in section 5.4.6, while that of temperature is presented in section 5.4.7. The final sections (5.4.8 and 5.4.9) present the characterisation of solid and liquid residues.

Detailed tree growth conditions, and bioenergy properties were presented in chapter 3 and chapter 4, respectively, but table 5.3 presents a summary of the feedstock characteristics including feed particle size distribution (% weight) and bulk densities. Properties of samples with bark were adjusted proportionately to account for the differences in properties between wood and bark.

Table 5.3 **Gasifier feedstock and wood chips properties**

Feedstock type	Bark content (%)	Basic density (kg/m^3)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Extractives		Heat value (MJ/kg)	Particle size (mm) (% weight distribution)				Bulk density (kg/m^3)
						Organic (%)	Total (%)		> 38	19-38	9.5-19	<9.5	
A.dealbata (B)	9	340	1.6	90.5	8.0	5.3	8.4	19.8	33	46	17	4	183
A.dealbata (NB)	0	335	1.4	91.5	7.2	4.3	6.8	19.7	31	46	18	5	181
A.dealbata (NB; S_F)	0	335	1.4	91.5	7.2	4.3	6.8	19.7	0	1	83	16	166
A.dealbata (NB;S_C)	0	335	1.4	91.5	7.2	4.3	6.8	19.7	33	48	19	0	173
A.glutinosa (B)	16	357	1.0	94.0	5.2	4.4	8.7	19.7	35	45	14	6	186
E.globulus (B)	13	472	1.4	92.1	6.5	3.0	5.4	19.5	28	47	19	6	232
E.globulus (NB)	0	507	1.0	92.8	6.2	2.8	4.7	19.7	24	54	18	4	243
E.globulus (NB; S_F)	0	507	1.0	92.8	6.2	2.8	4.7	19.7	0	46	48	6	227
E.globulus (NB;S_C)	0	507	1.0	92.8	6.2	2.8	4.7	19.7	14	69	17	0	232
E.nitens (B)	13	398	1.5	91.2	7.3	3.6	6.5	20.0	19	52	25	4	198
E.nitens (NB)	0	420	1.2	91.9	6.9	2.9	4.7	20.8	27	52	19	2	208
E.nitens (NB;S_C)	0	420	1.2	91.9	6.9	2.9	4.7	20.8	26	59	15	0	192
E.nitens (NB;S_F)	0	420	1.2	91.9	6.9	2.9	4.7	20.8	0	32	63	5	182
P.eridano (B)	11	283	1.4	91.9	6.7	5.1	8.6	19.5	35	42	15	8	151
P.eridano (NB)	0	285	1.0	92.6	6.4	3.1	6.1	19.7	32	48	17	3	
P.radiata (B)	11	282	1.2	90.8	8.0	4.5	8.5	20.5	38	44	15	3	142
P.tomentosa (B)	13	256	1.7	92.5	5.9	10.1	14.3	20.0	37	42	15	6	145
S.kinuyanagi (B)	11	444	1.2	93.3	5.4	4.7	8.5	19.9	30	45	17	8	198
S.kinuyanagi (NB)	0	457	0.8	94.3	4.9	4.3	7.8	19.9	32	46	15	7	
S.matsx alba (NB)	0	373	1.1	93.3	5.6	4.6	7.0	19.6	33	45	15	7	174

B- With bark; NB- No bark; S_F- Sieved fines; S_C - Sieved coarse

There were differences in the properties of materials from different species, and also between samples with bark and those without bark. Although all samples were chipped under similar conditions, there were noticeable differences in particle size distributions among different species; and also between samples with and without bark. The bulk of the particles (42-54%) ranged between 19 and 38 mm mesh. The largest particles (>38 mm) accounted for 19-38%, while particles less than 9.5 mm ('fines') provided less than 10% of the total weight. Samples with bark had a marginally higher proportions of 'fines'.

Bulk density was significantly different in different species. It was highly correlated with species basic density, and depended on whether the wood was debarked or not. Debarked samples had marginally higher bulk densities compared to those with bark, but were not statistically different. The larger particles (retained on a 19 mm screen on sieving) did not provide the highest bulk densities.

Preliminary trials were conducted to identify the optimum operating conditions with respect to air flows, and other adjustable gasifier parameters including the bed depth (fire bed). An attempt to estimate the quantity of tars produced was made (Senelwa *et al*, 1996), but was not undertaken further having been found to constitute about 1% of the total weight of products. Exhaustion of the feedstock in the gasifier was indicated by a rapid increase in air intake, a rise in temperature at thermocouple T_{II} and T_{I}, but a rapid drop at T_{III} and T_{IV}. When left undisturbed the flare was extinguished as the gas flowing through was dominated by air. The last gas sample taken was determined by the time the batch of feedstock in the hopper was used up. Extra gas samples were drawn towards the end when feed exhaustion was noticed to provide data for comparing start-up, steady state conditions, and conditions in the gasifier when the feed depleted.

5.4.1 PROCESSES AND PRODUCTS OF GASIFICATION

This section presents the processes and products of gasification of oven dry *Paulownia tomentosa* with bark. The run provides an illustration of the basic gasifier operation principals, sampling techniques, and base trends drawing on data from all other tests.

Material flows and products of downdraft air gasification

Figure 5.9 shows the rate of feedstock flow described by the mass loading of the gasifier; air flow; and gas production for a typical test run of the Fluidyne gasifier and indicates the trends in the instantaneous feedstock use describing the difference between air flow and gas production curves.

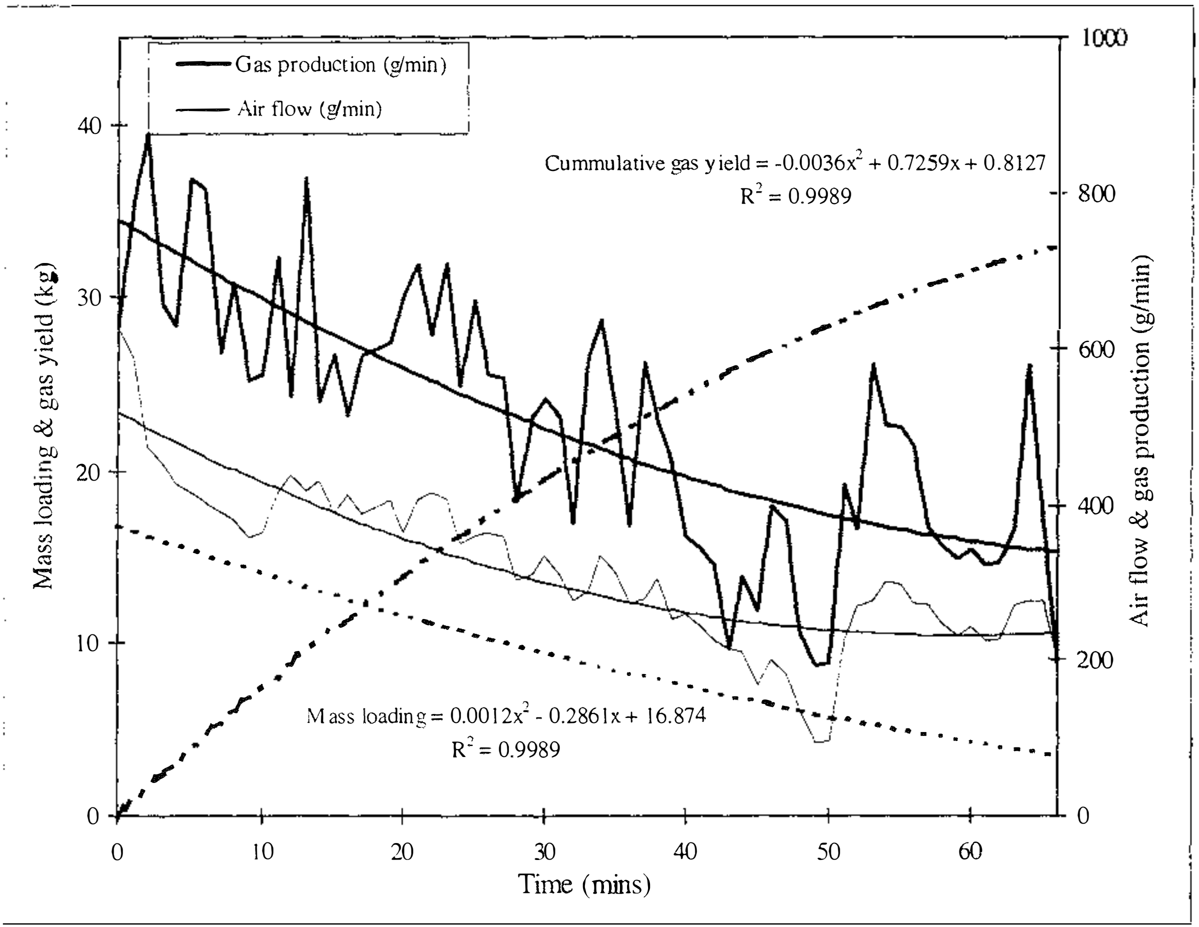

Figure 5.9 **Example of material movements in a down draft gasifier**

From figure 5.9, it is observed that:

1. the flow of both air and product gas were cyclic, fluctuating between random highs and lows;
2. the pattern of product gas flows was similar to that of the air flow but it exhibited larger swings. The similarity shows that gas production was a function of the quantity of air used;

3. the instantaneous rate of feedstock use (difference between the gas production and air flow) declined over the time of run, and showed the effects of mass loading on gasification; and
4. the highest air flows leading to high gas production rates were observed early in the run.

The mass loading curve describes the quantity of residual feedstock in the gasifier, and can therefore be used to describe the rate of gasification. Plotting gas accumulation over time provided the rate of gas accumulation. These flows were used to derive the gas production per unit of dry feed, G_P (g/g), which was compared with the measured dry gas production rates.

At the end of the 66 minutes when the test run was stopped:

i) 55% of the total input weight was air (M_A). Dry feed provided the other 45% since the feedstock was oven dried;

ii) dry product gas accounted for 83.6% of total outputs; liquid residues (collected condensate and gas moisture), 6.7%; and solid residues (char and ash), 9.7%. This was 31.870 kg (30.7 m^3) of product gas, 2.321 kg of liquid residues and 3.707 kg of solid residues.

iii) the mass balance (ratio of output weight to input weight) was 100.3%, showing that a small portion of the inputs were not accounted for, perhaps due to leakage of air into the system.

Product gas

Gas samples were scheduled to be drawn at regular intervals at up to 140 minutes in every test run. However, the 16.954 kg batch load (full hopper) of oven dried *P.tomentosa* (with bark) illustrated here was used up within 66 minutes. Therefore, only 12 samples were drawn for chromatography analysis at 3, 5, 7, 9, 12, 15, 20, 30, 40, 57, 60 and 65 minutes.

Product gas moisture content at the point of sampling was 4% (weight basis). The gas was assumed to be free of solids and other tarry liquids having been passed through the filtration and cooling systems. Results of the GC analysis and the heating values of both product gas and the stoichiometric product gas-air mixture of the samples are presented in figure 5.10 which shows that the gas consisted of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), and carbon dioxide (CO_2). Gas heating values are indicated, showing that gas composition and quality varied over the period of the test.

In this example (figure 5.10), the proportion of "inert" N_2 present declined from about 80% in the air at the beginning and stabilised at about 50% after 5 minutes running time. All other gases measured started from zero, with the first gas sample drawn indicating the lowest values, increasing by small proportions till becoming reasonably stable after 5 minutes. Increases in the levels of H_2 and CO resulted in reductions in the proportion of N_2 present.

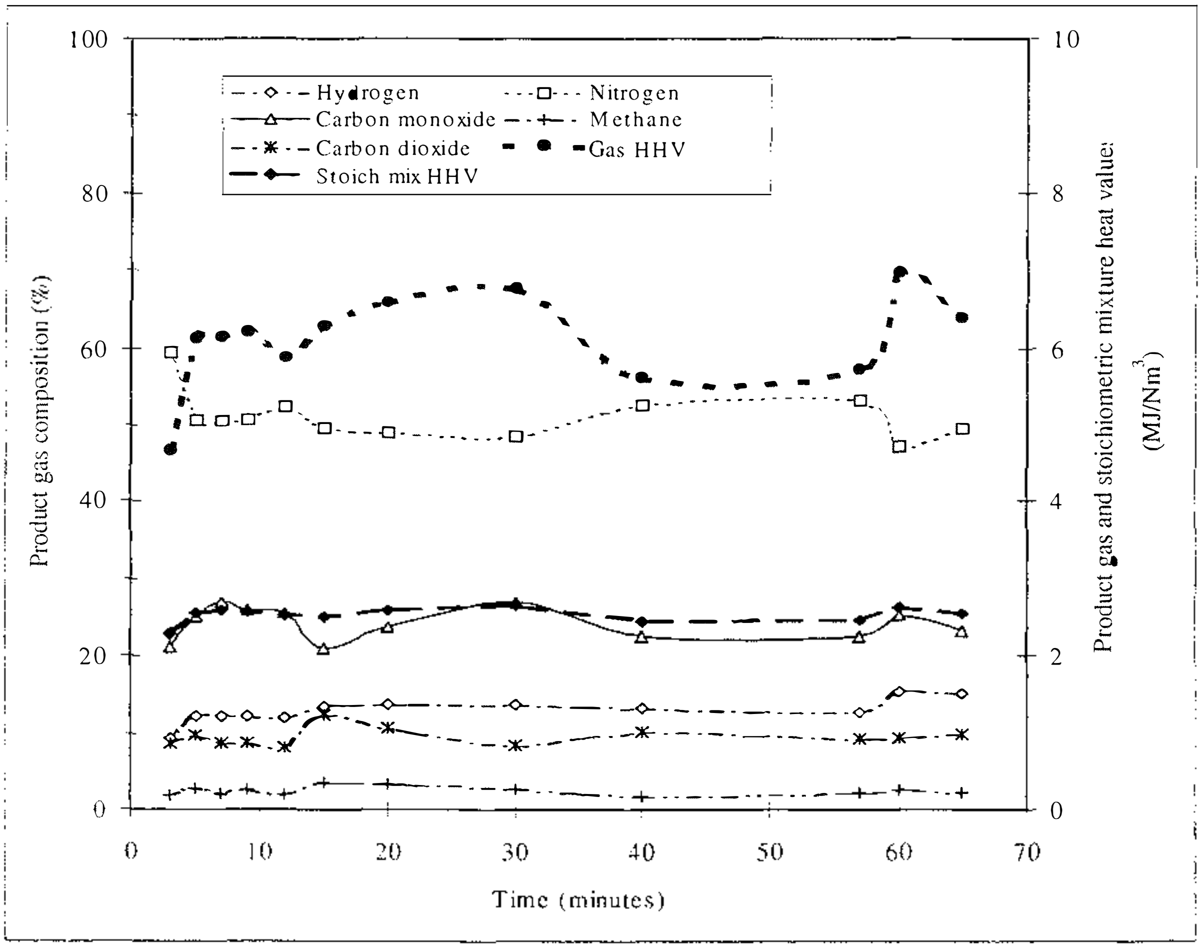

Figure 5.10 **Example of variation in gas composition and heating value during a run of one hopper batch of feedstock**

N_2 constituted the bulk of the gas with 47-60% of the total dry gas; CO was the second most abundant taking up 21-27% while H_2 accounted for 9-15%. CO_2 provided 8-13% and CH_4, 1-3%. Ethane (C_2H_6) was not detected in any of the 12 samples taken, and suggested that the total quantity of higher hydrocarbons including ethane was not significant. There was an upward surge in H_2, CO and CO_2 contents in the last 2 samples towards the end of the batch while that of N_2 dipped.

Product gas heating values ranged from 4.669-6.967 MJ/Nm^3, being highest when H_2, CO and CH_4 levels were high. The heating value of the stoichiometric product gas-air mixture was 2.273-2.635 MJ/Nm^3. Another important property of the product gas was the gas standard relative density which ranged between 0.9521 and 0.9745. This properties determine the quality of gas produced, defined by the requirements for internal combustion engines which also included the contents of residual moisture and dust particulates in the product gas stream, and the gas CO/H_2 ratio.

Temperature

Figure 5.11 shows plots of temperature at the five different points within the gasifier over the period of the test and indicates that there were random variations in temperature throughout the period of the run. The highest temperatures were recorded at position T_{III} directly in front of the air nozzles (Figure 5.4), and the highest temperature in this example (1194°C) was recorded in the 4th minute. Other high temperatures were recorded at T_{IV} while the lowest temperatures were at T_I. The variations in temperature were most evident in the hottest regions of combustion / oxidation (T_{III}) and reduction reaction (T_{IV}). Temperature rose from ambient at start to reach one of the peaks. Beyond the peak temperature (often attained in the first 5 minutes of the run), the temperature declined and often fluctuated to within certain boundaries for different zones. Other noticeable movements in temperatures in a final phase, signalled exhaustion of the feedstock in the reactor, and where the reaction almost ceased, as the mass loss stagnated. Temperatures closest to the grate (T_V) showed least variations.

The five temperature curves define the run temperature profile, and illustrates that temperature within the gasifier varies with position. This profile defines the reactor zones - the heating and drying; pyrolysis; oxidation; and reduction (sections 5.2; see figure 5.21). Although all variations in temperature appeared to be random, they were significantly affected by both time of measurement and the location of measurement (T_I-T_V). The temperature at each position was unique to that positions, indicating a defined temperature profile. The lowest average temperature (398°C) was recorded at T_I, while the highest (up to 1194°C, with an average of 955°C) was at T_{III}. The highest temperature on T_{II} was 909°C; 1099°C on T_{IV}; and 847°C on T_V. There was good positive correlation between T_{II}, T_{III}, T_{IV} and T_V (Appendix 5.1), and all had a similar pattern of movement over the period of test. Exit temperatures (T_V) were considered high enough to obtain complete cracking of the tars to yield a clean gas free of tars.

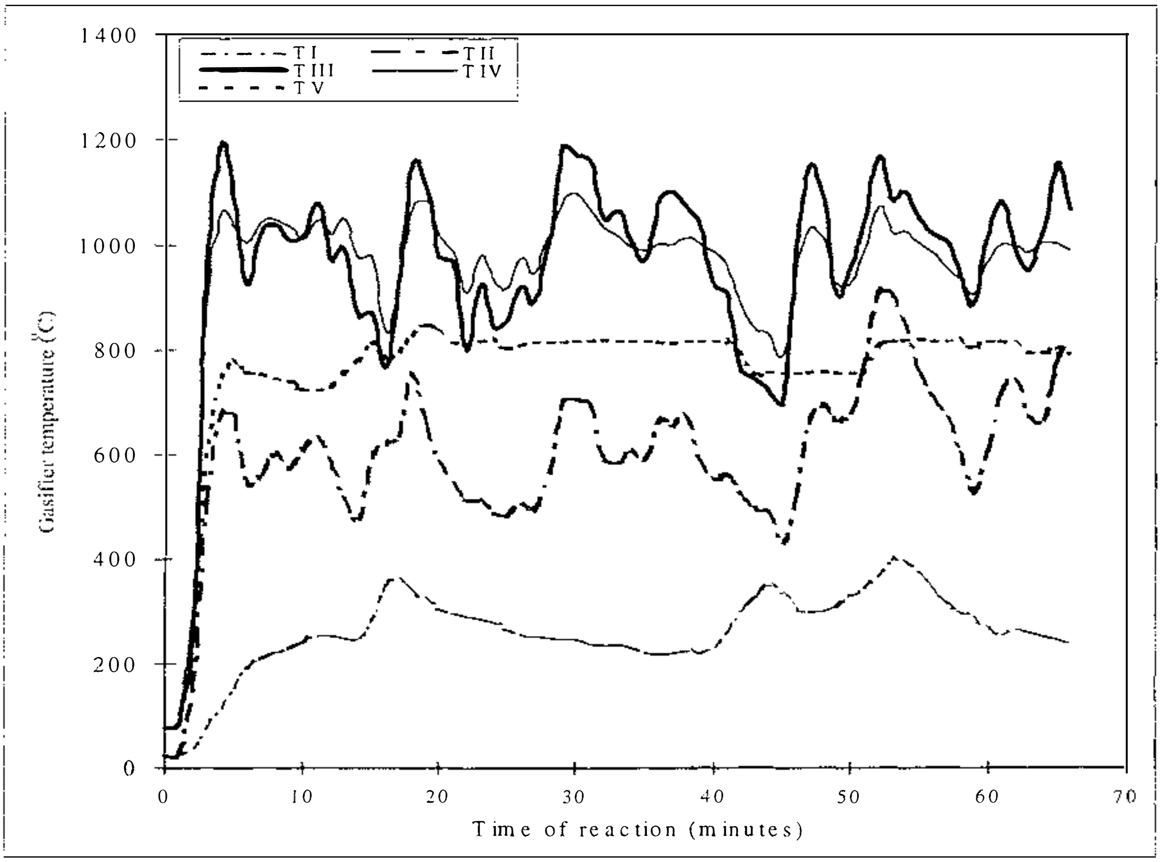

Figure 5.11 **Example of a profile of temperature in a down draft gasifier**

Table 5.4 presents the summary data of the gasification of oven dry *Paulownia tomentosa* with bark used to illustrate the processes and products of down draft gasification of woody biomass from short rotation forestry. The water input recorded of 0 g/h showed that the feedstock was oven dried. The ratio between reaction liquids and dry feedstock weight was equal to the net water formation, and showed the extent to which feed hydrogen was converted to product gas.

Table 5.4 **Summary of the process and products of downdraft air gasification (An example using oven dried *P.tomentosa* feedstock)**

Feedstock			Oven dry *P.tomentosa* with bark
Run time (min)			66
Total feed weight (g)			16954
Material flows (g/h)	Inputs	Feed (M_F)	15413
		Water (M_W)	0
		Air (M_A)	19140
	Outputs	Product gas (M_{PG})	28973
		Solid residues (M_{SR})	3370
		Liquid residues (M_{LR})	2321
Mass balance (%)			100.3
Residence time (s)			2.6
Gasification rate (g/s)			3.07
Specific gasification rate (g/s/m^2)			245
Hearth load (m/s)			0.699
Equivalence ratio (ER)			0.195
Net water formation (NWF, %)			15
Average run temperature (°C)	T_I		260
	T_{II}		599
	T_{III}		955
	T_{IV}		948
	T_V		761
	Maximum		980
Average run gas composition (%)	H_2		12.9
	N_2		51.1
	CO		24.1
	CH_4		2.5
	CO_2		9.5
Product gas quality	Gas relative density		0.962
	CO/H_2 ratio		1.87
	% combustible component		40
	HHV - Product gas (MJ/Nm^3)		6.112
	HHV - Stoichiometric mixture (MJ/Nm^3)		2.524
Gasification ratios	Air:feedstockstock (g/g)		1.59
	Gas:feedstock (m^3/kg)		2.31
	Gas:feedstock (Gp, g/g)		1.88
	Gas energy:feedstock (MJ/kg)		11.05
	Reaction liquids:dry feed (g/g)		0.15
	Total liquid residue:dry product gas (g/g)		0.08
Input feed energy (MJ/h)			308
Product gas energy (MJ/h)			170
Cold gas efficiency (CGE, %)			55.2

Mass loading and rate of gasification

The weight of feedstock remaining in the gasifier (and hopper) over the period of the run (Figure 5.9) showed an example of the mass (sample) loading curve, and also the rate at which the feedstock was gasified. The curve also indicates the influence of time of reaction on the processes. The mass loading curve equation shows the actual rates of reaction, and indicate that mass loading did not influence the composition of gas obtained within steady state operations[‡] showing that variations in the gas quality were not associated with the changes in the vapour phase pressures within the reactor.

Interaction of the process

Statistical correlation analyses (Appendix 5.1) show that:

1. Temperatures within the gasifier exhibited similar patterns of variation, mostly relying on the variation of T_{III}. High temperature led to the production of a gas with higher H_2, CO and CH_4, but reduced N_2 and CO_2. Heating values of the product gas were higher at higher gasification temperatures. The most significant of the temperatures were on T_{IV}, T_V and T_I.

2. The effect of temperature in different zones of the gasifier defined the gasifier temperature profile and showed that variations in the temperature in the gasifier results in the production of a different combination of products. Higher temperature led to higher gasification rates and high yield.

3. High air flow rates resulted in the production of a gas with high N_2 and CO, but a reduced H_2, CH_4 and CO_2. The gas produced had lower heating values.

4. High N_2 implied lower contents of all other gas components, and reduced heating value.

Summary tables similar to table 5.4 were compiled for each test run, and used to compare feedstocks from different SRF species; feed moisture content levels; the influence of bark in the feedstock; and the influence of particle size distribution and bulk density on the performance of the gasifier, and also the effects on product gas quality.

[‡] i.e. when the temperature was judged to be stable

5.4.2 THE INFLUENCE OF FEEDSTOCK TYPE - TREE SPECIES

This section provides comparative data and analysis among different species, between materials with bark and those without bark, and compares the gasification characteristics of air and oven dry feedstock. A total of 25 test runs lasting between 61 and 137 minutes were analysed. Each of the runs involved the variation of one or more aspects of the feedstock (see section 5.3.3).

The results are presented in table 5.5 for the gasification processes and in table 5.6 for gas analysis and process efficiency data. Both tables distinguish between oven dry and air dry, and between samples with and without bark, and indicate the significant differences between feedstock types for selected measurements. T_{III} measurements were not available for all runs as the probe had been damaged internally on two occasions. The data was therefore analysed as an unbalanced incomplete block design.

Tables 5.5 and 5.6 show that the effect of species, bark, and moisture content was variable in the different measurements. Out of the three experimental factors identified in the two tables, the contrast between oven dry and air dry feedstock was the most apparent even though it was difficult to isolate the independent effects of either factor. The influence of species, bark and moisture content on temperature was dependent on the reaction zone within the gasifier, with the most effect being noticed on T_{III} and T_{IV} which showed significant differences among different species, between samples with and without bark, and between oven and air dry samples.

Table 5.5 **Process variables in the gasification of SRF species* (air dry or oven dry, and with or without bark)****

	Run time	Inputs flow rate (g/h)			Outputs flow rate (g/h)			Mass balance	Residenc time	Gasificat-ion rate	Specific gasific rate	Hearth load	Equiva ratio	Net water formation	Average run temperatures (oC)				
Feedstock	(min)	Feed (M_F)	Water (M_W)	Air (M_A)	Gas (M_{PG})	Solids (M_{SR})	Liquids (M_{LR})	(%)	(s)	(g/s)	(g/s/m^2)	(m/s)	(ER)		T_I	T_{II}	T_{III}	T_{IV}	T_V
Oven dry, with bark																			
A.dealbata	98	13446 ^{a}	0 ^{b}	23280 ^{a}	33120 ^{a}	1227	2415 ^{a}	100.1 ^{a,b}	3.2 ^{a}	3.12 ^{a}	249 ^{a}	0.843 ^{a,b}	0.272	18 ^{a,b}	393 ^{a}	634 ^{a}	-	950 ^{c}	753 ^{a}
A.glutinosa	86	14073 ^{a}	0 ^{b}	23640 ^{a}	34042 ^{a}	1811	2674 ^{a}	102.2 ^{a,b}	3.2 ^{a}	3.28 ^{a}	262 ^{a}	0.693 ^{a,b}	0.264	19 ^{a,b}	408 ^{a}	657 ^{a}	1020 ^{a}	1001 ^{a}	793 ^{a}
E.globulus	93	15286 ^{a}	0 ^{b}	25260 ^{a}	36576 ^{a}	1419	2711 ^{a}	100.4 ^{a}	3.5 ^{a}	3.57 ^{a}	285 ^{a}	0.860 ^{a}	0.260	18 ^{a,b}	213 ^{a}	461 ^{a}	-	891 ^{b,c}	744 ^{a}
E.nitens	96	15041 ^{a}	0 ^{b}	21960 ^{a}	33408 ^{a}	1457	2392 ^{a}	100.7 ^{a}	3.0 ^{a}	3.57 ^{a}	286 ^{a}	0.809 ^{a}	0.229	16 ^{a,b}	286 ^{a}	538 ^{a}	862 ^{a,b}	899 ^{b,c}	751 ^{a}
P.eridano	74	14735 ^{a}	0 ^{b}	24300 ^{a}	35482 ^{a}	1345	2816 ^{a}	101.6 ^{a}	3.3 ^{a}	3.52 ^{a}	281 ^{a}	0.890 ^{a}	0.259	19 ^{a,b}	501 ^{a}	707 ^{a}	955 ^{a,b}	947 ^{b,c}	767 ^{a}
P.radiata	90	12849 ^{a}	0 ^{b}	19260 ^{a}	28512 ^{a}	2142	2141 ^{a}	102.1 ^{a}	2.6 ^{a}	2.90 ^{a}	232 ^{a}	0.823 ^{a}	0 236	17 ^{a,b}	225 ^{a}	565 ^{a}	959 ^{a}	971 ^{a}	777 ^{a}
P.tomentosa	66	15413 ^{a}	0 ^{b}	19140 ^{a}	28973 ^{a}	3370	2321 ^{a}	100.3 ^{a}	2.6 ^{a}	3.07 ^{a}	245 ^{a}	0.699 ^{a}	0.195	15 ^{b}	260 ^{a}	599 ^{a}	955 ^{a}	948 ^{a,b,c}	761 ^{a}
S.kinuyanagi	78	15257 ^{a}	0 ^{b}	22800 ^{a}	34790 ^{a}	1885	2988 ^{a}	104.2 ^{a}	3.1 ^{a}	3.73 ^{a}	299 ^{a}	0.807 ^{b}	0.235	20 ^{a}	399 ^{a}	599 ^{a}	898 ^{a,b}	937 ^{a,b}	723 ^{b}
Mean		14512 ^{a}	0 ^{b}	22455 ^{a}	33113 ^{a}	1832	2557 ^{b}	101.4 ^{a}	3.1 ^{a}	3.34 ^{a}	267 ^{a}	0.803 ^{a}	0.244	18 ^{a}	336 ^{a}	595 ^{a}	942 ^{a}	943 ^{a}	759 ^{a}
Oven dry, no bark																			
A.dealbata	67	15336	0	19140	30298	1864	2821	101.5	2.8	3.45	276	0.763	0.196	18	346	615	-	928	746
E.globulus	90	17109	0	24180	36691	2571	2915	102.2	3 3	3.90	312	0.896	0.222	17	303	548	-	945	770
E.nitens	114	12787	0	19500	29146	1258	2135	100.8	2.7	3.02	241	0.709	0.240	17	242	552	-	959	782
P.eridano	82	13151	0	19140	27475	1815	1877	96.5	2.6	2.63	210	0.672	0.229	14	310	611	946	957	746
S.kinuyanagi	82	13311	0	18240	27648	1107	2908	100.4	2.5	2.93	235	0.643	0.215	22	302	576	986	1000	690
S.mats x alba	76	16198	0	25980	37728	1901	2930	100.9	3.5	3.70	296	0.914	0.252	18	357	576	-	931	782
Mean		14649 ^{a}	[illegible] ^{b}	21030 ^{a}	31498 ^{a}	1753	2598 ^{a,b}	100 ^{b}	2.9 ^{a}	3.27 ^{a}	262 ^{a}	0.766 ^{a}	0.226	18 ^{a}	310 ^{a}	580 ^{a,b}	966 ^{a}	953 ^{a}	753 ^{a}
Air dry, with bark																			
A.dealbata	88	14156	1776	24420	35424	1889	3399	100.9	3.3	3.47	277	0.848	0.271	11	249	444	-	820	746
A.glutinosa	90	13560	1678	23520	33466	2498	3208	101.1	3.2	3.15	252	0.804	0.273	11	303	538	880	915	742
E.globulus	137	11025	1546	22980	31910	801	2906	100.2	3.1	2.85	228	0.768	0.328	12	295	469	735	830	749
E.nitens	75	16066	2154	24600	35539	5218	3881	104.2	2.7	3.45	276	0.734	0.241	11	325	517	822	869	716
P.tomentosa	74	13011	1808	22500	30413	996	2585	91.1	3.1	2.55	204	0.731	0.272	6	281	533	842	894	739
Mean		13563 ^{a}	1792 ^{a}	23604 ^{a}	33350 ^{a}	2280	3196 ^{a,b}	99.5 ^{a}	3.1 ^{a}	3.09 ^{a}	247 ^{a}	0.777 ^{a}	0.277	10 ^{b}	291 ^{b}	500 ^{b,c}	820 ^{b}	866 ^{b}	738 ^{a}
Air dry, no bark																			
A.dealbata	61	13814	1388	26160	35309	1703	2258	94.9	3.6	2.95	237	0.846	0.298	6	172	389	694	792	657
E.globulus	136	11522	1436	20100	29779	881	2578	100.5	2.7	3.03	243	0.713	0.274	10	291	501	804	874	718
E.nitens	100	13253	2015	23040	34099	1292	3551	101.7	3.1	3.47	277	0.818	0.273	12	246	444	-	860	752
P.eridano	81	12957	1851	21480	31507	1734	3609	101.5	2.9	3.15	252	0.754	0.260	14	267	484	768	845	714
S.kinuyanagi	121	10555	1819	16800	24883	1643	3144	101.7	2.3	2.53	202	0.575	0.250	13	455	641	878	876	518
S.mats x alba	81	14756	1828	19800	29491	3341	3081	98.7	2.7	3.03	242	0.701	0.211	8	327	525	792	851	733
Mean		12809 ^{a}	1723 ^{a}	21230 ^{a}	30845 ^{a}	1766	3037 ^{a}	99.9 ^{a}	2.9 ^{a}	3.03 ^{a}	242 ^{a}	0.735 ^{a}	0.261	10 ^{b}	293 ^{b}	497 ^{c}	787 ^{b}	850 ^{b}	682 ^{b}

* - Average values (of a parameter e.g. feed flow, M_F) for each species with the same letter are not significantly different

** - Average values (for each of the treatments - with or without bark, and air dry or oven dry) with the same letter are not significantly different.

Material flows and products distribution

The patterns in the flow of inputs and outputs, and of temperature variations over the period of run for different materials resembled those obtained in section 5.4.1. The flows were generalised to represent the overall distribution of materials in an operating Fluidyne gasifier (Figure 5.12), distinguishing between inputs, outputs and material balances from oven dry (OD) and air dry (AD) feedstock.

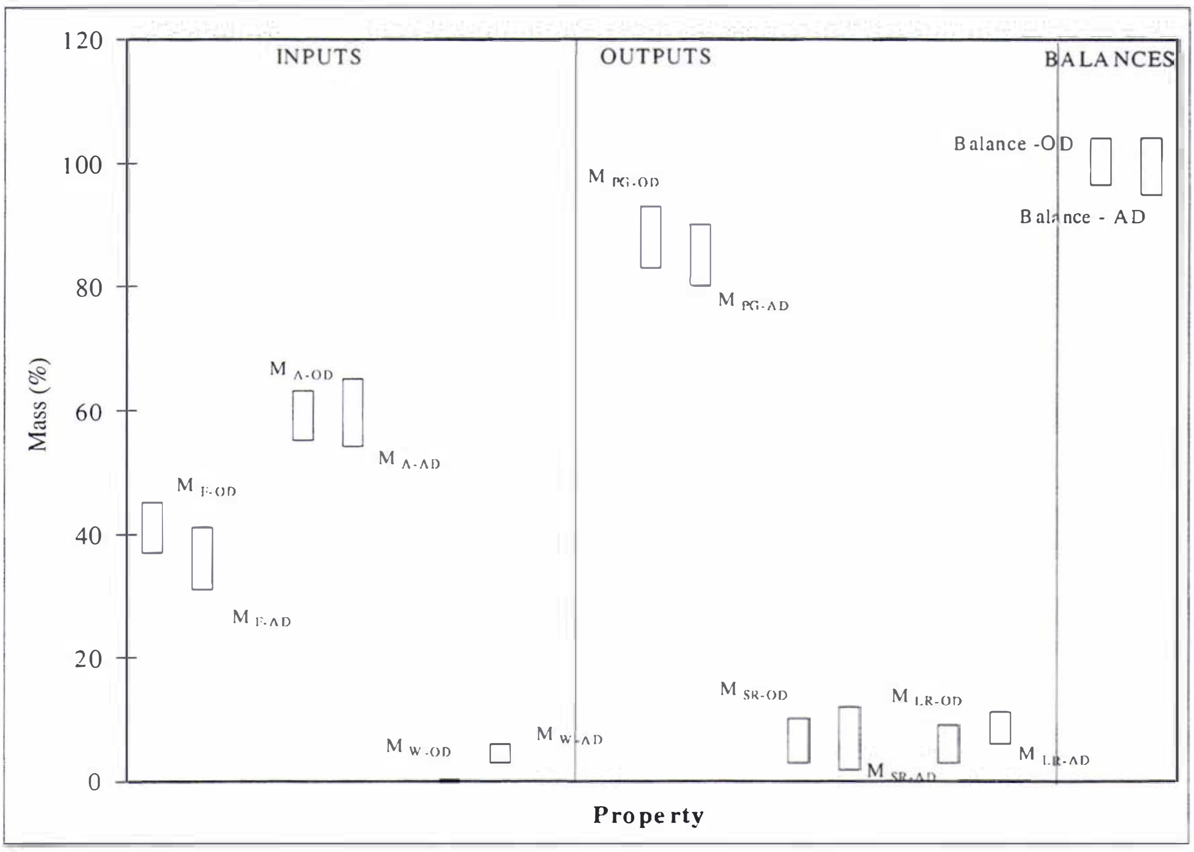

Figure 5.12 **Materials and products distribution in oven dry and air dry feedstocks**

Both table 5.5 and figure 5.12 show that:

i) the proportion of feedstock weight decreased with increasing feed moisture content, and that the flow of air varied with moisture content;

ii) the bulk of the outputs was product gas, accounting for 83-93%;

iii) the overall mass balance closures varied between 91% and 104%;

iv) the mass conversion efficiency ranged between 81-91%; and

v) the scatter in inputs and outputs (i.e. the difference between the lowest and highest values) was higher in air dry samples than oven dry ones.

When the results of the species tests are considered on the basis of volume rather than mass of feedstock, significant differences are revealed in terms of material inputs and outputs with respect to feed flow and air requirements. The feed flow rates ranged from 51351 cm^3/h in *S.kinuyanagi* to 74765 cm^3/h in *P.tomentosa* while the quantity of air used ranged from 2 g/cm^3 in *E.globulus* to 3.9 g/cm^3 in *P.tomentosa.* The quantity of gas produced per unit volume of feedstock was also different, ranging from 0.4 g/cm^3 in *P.tomentosa* to 0.8 g/cm^3 in *E.globulus*. These dry feed input variations of 10 to 17 kg/h for air dry and oven dry feedstock show the operating capacity of the gasifier, resulting in the production of 24 to 42 kg/h (23.9-41.1Nm^3/h) of dry product gas. The variations in flow rates also illustrate the influence of feedstock density on gasifier sizing. For every 1 kg of dry feed used, 1.9-3.1 kg of gas was produced, being equivalent to 2.1-3.3 Nm^3 of dry gas. The average hearth load values obtained for air dry and oven dry feedstock of 0.773 $m^3/m^2/s$ provide the capacity of the gasifier in values that may be used for comparative purposes as the hearth load is based on hearth size.

Gas composition and quality

The number of gas samples drawn was not equal for all test runs as it relied on the time taken for the batch feed to be exhausted. A minimum of 10 samples were drawn, six of which were drawn under steady state operation. Data from all the samples were averaged to provide means (table 5.6) for the different species, and for different moisture and bark contents.

The gas was dominated by nitrogen constituting 51-62% and 54-60% in oven dry and air dry samples respectively, even though the differences among the feedstocks was not significant. CO, which was statistically different in different species, and also between air and oven dry samples constituted 20-26% and 19-23% in oven dry and air dry feedstock respectively. H_2 which was different in different species accounted for 8-13% and 10-12% in oven dry and air dry feedstock respectively. CO_2 ranged from 7.5-9.5% and 7.9-10.6% in oven and air dry feedstock, while CH_4 provided only 1.8%-2.5%, being marginally higher in the oven dry samples. The proportion of ethane, the highest hydrocarbon detectable was negligible, being 0% in most samples.

Table 5.6 **Gas analysis and process efficiencies from the gasification of SRF species* (air dry or oven dry, and with or without bark)****

Feedstock	Gas composition (%)					Gas quality			Air to dry feed (g/g)	Gas to dry feed ratio (m^3/kg)	Gas to dry feed (g/g)	Gas to dry feed (kJ/g)	Rxn liquid to dry feed (g/g)	Total liquid to dry gas (g/g)	Cold gas efficiency
						Relative density	Heat value MJ/Nm^3								
	H_2	N_2	CO	CH_4	CO_2		Pure gas	Stoi mixt.							
Oven dry, with bark															
A.dealbata	10.8 ^{a,b}	54.6 ^{a}	24.9 ^{b}	2.1 ^{a,b}	7.6 ^{a,b}	0.949 ^{a}	5.634 ^{b}	2.478 ^{a,b}	1.91	2.57 ^{a,b}	2.46	13.17	0.18	0.073	67 ^{a}
A.glutinosa	11.0 ^{a,b}	53.8 ^{a}	23.8 ^{b}	2.3 ^{a,b}	9.1 ^{a}	0.957 ^{a}	5.592 ^{b}	2.458 ^{b}	1.93	2.66 ^{a}	2.42	12.94	0.19	0.079	66 ^{a}
E.globulus	10.0 ^{a,b}	56.4 ^{a}	23.5 ^{a,b}	2.1 ^{a,b}	8.0 ^{a,b}	0.952 ^{a}	5.304 ^{a,b}	2.409 ^{a,b}	1.82	2.51 ^{a,b}	2.39	12.08	0.18	0.074	62 ^{a}
E.nitens	11.9 ^{a,b}	52.6 ^{a}	24.5 ^{a,b}	2.4 ^{a,b}	8.7 ^{a,b}	0.956 ^{a}	5.912 ^{a,b}	2.508 ^{a,b}	1.62	2.35 ^{a,b}	2.22	12.55	0.16	0.072	63 ^{a}
P.eridano	10.2 ^{a,b}	57.8 ^{a}	21.6 ^{b}	2.1 ^{a,b}	8.5 ^{a,b}	0.954 ^{a}	5.052 ^{b}	2.342 ^{b}	1.81	2.53 ^{a,b}	2.41	11.61	0.19	0.079	60 ^{a}
P.radiata	12.4 ^{a}	52.6 ^{a}	25.5 ^{a}	1.8 ^{b}	7.5 ^{b}	0.953 ^{a}	5.994 ^{a}	2.515 ^{a}	1.80	2.54 ^{a,b}	2.22	12.68	0.17	0.075	62 ^{a}
P.tomentosa	12.9 ^{a,b}	51.1 ^{a}	24.1 ^{a,b}	2.5 ^{a}	9.5 ^{a}	0.962 ^{a}	6.112 ^{a,b}	2.524 ^{a,b}	1.59	2.31 ^{b}	1.88	11.05	0.15	0.080	55 ^{a}
S.kinuyanagi	10.3 ^{b}	54.6 ^{a}	23.9 ^{b}	2.5 ^{a,b}	8.8 ^{a,b}	0.956 ^{a}	5.603 ^{b}	2.457 ^{b}	1.71	2.49 ^{b}	2.28	12.21	0.20	0.086	61 ^{a}
Mean	11.2 ^{a}	54.2 ^{a}	24.0 ^{a}	2.2 ^{a}	8.5 ^{b}	0.955 ^{b}	5.650 ^{a}	2.461 ^{a}	1.77	2.49 ^{b,c}	2.29	12	0.18	0.077	62 ^{a,b}
Oven dry, no bark															
A.dealbata	10.3	54.2	23.6	2.4	9.4	0.958	5.516	2.439	1.42	2.16	1.98	10.44	0.18	0.093	53
E.globulus	10.1	53.8	26.0	2.5	7.7	0.948	5.815	2.521	1.66	2.39	2.14	11.82	0.17	0.079	60
E.nitens	12.5	53.1	24.7	2.2	7.5	0.951	6.007	2.517	1.69	2.41	2.28	13.03	0.17	0.073	63
P.eridano	9.0	58.3	23.4	1.8	7.5	0.950	4.991	2.361	1.69	2.30	2.09	9.91	0.14	0.068	50
S.kinuyanagi	8.3	61.5	20.3	2.3	7.6	0.950	4.675	2.262	1.49	2.15	2.08	9.22	0.22	0.105	46
S.mats x alba	9.7	55.3	23.4	2.5	9.0	0.956	5.429	2.428	1.82	2.52	2.33	12.09	0.18	0.078	62
Mean	10.0 ^{a}	56.0 ^{a}	23.6 ^{a}	2.3 ^{a}	8.1 ^{b}	0.952 ^{b}	5.406 ^{a,b}	2.421 ^{a}	1.63	2.32 ^{c}	2.15	11.08	0.18	0.083	56 ^{b}
Air dry, with bark															
A.dealbata	11.4	55.3	21.2	1.9	10.3	0.967	5.167	2.348	1.99	2.79	2.50	11.11	0.11	0.096	63
A.glutinosa	9.7	59.5	19.5	1.9	9.8	0.963	4.602	2.241	2.13	2.91	2.47	9.73	0.11	0.096	56
E.globulus	11.2	56.3	21.5	1.8	9.2	0.962	5.155	2.351	2.25	3.00	2.89	12.59	0.12	0.091	74
E.nitens	12.0	53.8	22.1	2.2	10.0	0.964	5.537	2.419	2.27	3.16	2.21	10.41	0.11	0.109	59
P.tomentosa	10.6	54.3	22.8	2.3	10.0	0.963	5.412	2.414	1.87	2.44	2.34	10.70	0.06	0.085	61
Mean	11.0 ^{a}	55.8 ^{a}	21.4 ^{b}	2.0 ^{a}	9.9 ^{a}	0.964 ^{a}	5.175 ^{b}	2.355 ^{b}	2.10	2.86 ^{a}	2.48	10.91	0.10	0.095	62 ^{a}
Air dry, no bark															
A.dealbata	9.5	60.2	20.4	1.9	7.9	0.954	4.750	2.269	2.16	2.78	2.56	10.53	0.06	0.064	59
E.globulus	11.5	55.1	21.1	2.1	10.1	0.967	5.294	2.364	1.89	2.71	2.58	11.77	0.10	0.087	67
E.nitens	10.5	56.2	20.8	2.2	10.4	0.965	5.060	2.331	1.93	2.75	2.57	10.90	0.12	0.104	60
P.eridano	11.2	55.2	20.8	2.2	10.6	0.967	5.205	2.352	1.91	2.71	2.43	10.71	0.14	0.115	62
S.kinuyanagi	10.4	56.3	22.2	1.9	9.2	0.961	5.114	2.361	1.89	2.68	2.36	9.88	0.13	0.126	58
S.mats x alba	10.2	58.9	19.2	1.9	9.8	0.964	4.693	2.242	1.73	2.49	2.00	8.05	0.08	0.104	46
Mean	10.5 ^{a}	57.0 ^{a}	20.8 ^{b}	2.0 ^{a}	9.7 ^{a}	0.963 ^{a}	5.019 ^{b}	2.320 ^{b}	1.92	2.69 ^{b}	2.42	10.31	0.10	0.100	59 ^{a,b}

* - Average values (of a parameter e.g. gas H_2 content, %) for each species with the same letter are not significantly different

** - Average values (for each of the treatments - with or without bark, and air dry or oven dry) with the same letter are not significantly different.

Both product gas and stoichiometric gas-air mixture heating values ranged from 4.602 MJ/Nm^3 to 6.112 MJ/Nm^3 and from 2.241 MJ/Nm^3 to 2.524 MJ/Nm^3, respectively. The heating values were significantly higher in oven dry samples, and also varied with species. Although the gas relative density varied between different runs and even within the same run, being affected by changes in air flows, temperature, and depending on whether the feedstock was oven dried or air dried, it did not have a significant effect on the gas heating values.

Process efficiency

Energy inputs were calculated from feedstock heating values (table 5.2) while outputs were derived from product gas compositions and yield. Calculations for solid and liquid residue energy content were not included as the heating values of these minor components were not determined. The energy lost as sensible heat to the atmosphere was ignored.

Although the cold gas efficiencies appeared different in different species, there were no patterns to suggest that it was influenced by species. It tended to be slightly higher in runs which utilised debarked feedstock, ranging between 46-67% in oven dried and 46-76% in air dried feedstock.

Interaction in gasification parameters

Statistical correlation analyses of the results in tables 5.5 and 5.6 (Appendix 5.2) showed that the most significant parameters in downdraft gasification of woody biomass includes feedstock moisture content, air flows, and operating temperature. High feedstock moisture content led to (i) higher air to feed ratios; (ii) higher gas yields per unit of feedstock used; (iii) higher liquid residues production; (iv) suppressed reaction temperatures particularly at T_{III} and T_{IV}; and (v) influenced the overall gas composition by promoting the formation of CO_2 at the expense of CO. Although gasification of high moisture content feedstock appeared to result in production of slightly higher quantities of gas, it compromised on the gas CO content, and consequently the gas heating values.

Higher air flows enhanced gas outputs, gasifier residence time, gasification rates, hearth load, equivalence ratio, overall total gas energy and therefore the cold gas efficiency. High temperatures particularly at T_{IV} led to the production of gas with low CO_2 content but higher CO content. High temperature at both T_{III} and T_{IV} were associated with reduced ER.

5.4.3 INFLUENCE OF FEEDSTOCK PROPERTIES

Correlation analyses between feedstock properties (table 5.2), and the processes and products of gasification are presented in table 5.7. A negative correlation indicates suppression effects.

Table 5.7 **Correlation between feedstock properties and processes and products of gasification**

		Basic density (kg/m^3)	Ash (%)	VM (%)	FCC (%)	OEC (%)	TEC (%)	HHV (MJ/kg)	Bulk density (kg/m^3)
Feedstock properties	Basic density	1.00							
	Ash (%)	-0.42	1.00						
	Volatile matter (%)	0.30	-0.73	1.00					
	Fixed carbon (%)	-0.26	0.60	-0.98	1.00				
	Organic extractives (%)	-0.60	0.55	0.00	-0.13	1.00			
	Total extractives (%)	-0.64	0.45	0.08	-0.19	0.97	1.00		
	Higher heat value (MJ/kg	0.02	0.02	-0.22	0.25	-0.01	-0.04	1.00	
	Bulk density (kg/m^3)	0.97	-0.22	0.08	-0.05	-0.60	-0.66	-0.01	1.00
Run time (min)		0.64	-0.29	0.08	-0.03	-0.45	-0.47	0.17	0.67
Inputs and outputs (g/h)	Feed (M_F)	-0.06	0.26	-0.13	0.08	0.10	0.06	-0.17	0.01
	Water (M_W)	0.00	0.02	0.01	-0.02	0.00	-0.02	-0.01	0.01
	Air (M_A)	0.03	0.35	-0.27	0.23	-0.08	-0.10	-0.29	0.27
	Gas (M_{PG})	-0.02	0.32	-0.27	0.23	-0.10	-0.11	-0.33	0.16
	Solids (M_{SR})	-0.13	0.11	-0.03	0.01	0.12	0.13	0.00	-0.13
	Liquids (M_{LR})	0.09	-0.15	0.19	-0.18	-0.08	-0.07	-0.16	0.04
Mass balance		-0.05	-0.04	-0.03	0.04	-0.13	-0.07	-0.14	-0.08
Residence time		-0.01	0.30	-0.21	0.18	-0.04	-0.07	-0.34	0.23
Gasification rate (g/min)		0.22	0.14	-0.18	0.17	-0.25	-0.27	-0.15	0.34
Specific gasification rate ($g/s/m^3$)		0.22	0.14	-0.19	0.17	-0.25	-0.27	-0.15	0.35
Equivalence ratio (ER)		0.12	0.12	-0.14	0.15	-0.18	-0.17	-0.15	0.27
Net water formation, %		0.10	-0.27	0.19	-0.16	-0.13	-0.06	-0.06	-0.01
Temperature (°C)	T_I	-0.04	-0.18	0.32	-0.33	0.07	0.16	-0.36	-0.19
	T_{II}	-0.25	-0.15	0.27	-0.28	0.24	0.34	-0.13	-0.39
	T_{III}	-0.20	-0.22	0.31	-0.29	0.24	0.39	0.33	-0.40
	T_{IV}	-0.07	-0.25	0.28	-0.25	0.12	0.21	0.18	-0.18
	T_V	-0.21	0.30	-0.31	0.30	0.03	0.01	0.11	0.01
Gas composition (%)	H_2	-0.18	0.46	-0.48	0.44	0.20	0.17	0.40	-0.05
	N_2	0.08	-0.40	0.37	-0.32	-0.23	-0.19	-0.37	-0.04
	CO	0.06	0.17	-0.24	0.24	0.05	0.04	0.30	0.12
	CH_4	0.14	0.07	0.19	-0.26	0.23	0.17	0.09	0.13
	CO_2	-0.16	0.15	0.06	-0.11	0.21	0.18	-0.12	-0.11
Gas quality	Std gas relative density	-0.16	0.15	0.02	-0.06	0.19	0.17	-0.07	-0.12
	CO/H_2 ratio	0.20	-0.30	0.25	-0.22	-0.13	-0.12	-0.13	0.12
	Combustible component	-0.02	0.32	-0.37	0.34	0.14	0.12	0.40	0.08
	Product gas HHV	-0.02	0.34	-0.35	0.32	0.18	0.15	0.42	0.07
Conversion ratios	Air to feed (g/g)	0.05	0.14	-0.15	0.15	-0.15	-0.11	-0.12	0.18
	Gas to feed (m^3/kg)	-0.01	0.12	-0.16	0.16	-0.16	-0.11	-0.16	0.08
	Gas to feed (g/g)	0.08	0.09	-0.15	0.16	-0.21	-0.19	-0.19	0.18
	Gas to feed (kJ/g)	0.05	0.30	-0.40	0.38	-0.09	-0.08	0.11	0.21
	Liquid to gas (g/g)	0.20	-0.35	0.36	-0.34	-0.08	-0.05	0.03	0.01
Energy In		-0.06	0.27	-0.17	0.12	0.11	0.06	-0.02	0.01
Gas energy		0.00	0.46	-0.41	0.36	0.01	-0.02	-0.06	0.22
Cold gas efficiency (%)		0.07	0.30	-0.35	0.32	-0.10	-0.10	-0.07	0.26

Table 5.7 shows that:

1) Except for heating values, the feedstock properties were highly correlated (also see chapter 4).

2) Although the correlation between feed properties and the gasification processes and parameters were poor, they show specific trends between the properties, the gasification processes and products.

3) Although basic density had poor correlation with all parameters measured except the time of run, the gasification of high bulk density feedstock involved extended gas residence times, high gasification rates, and high equivalence ratios. Such materials gasified at suppressed temperatures particularly on T_{II} and T_{III}. The correlation between bulk density and gas quality was poor.

4) The gasification of high ash content materials resulted in relatively higher air flows and higher gas yields. Gasification temperatures associated with high ash content feedstock were generally suppressed, but the reactions involved extended residence times. The gas produced had relatively higher heat values due to higher H_2 and suppressed gas N_2 content. Consequently, cold gas efficiency was high. Lower quantities of liquid condensate was also collected.

5) Feedstocks with a high volatile matter content were associated with higher gasification temperatures (T_I - T_{IV}), but not at T_V. The quantity of liquid residue from such feedstock was high. The gas produced had high N_2 but was low in H_2. Gas heating values and cold gas efficiency were reduced.

6) The effects of fixed carbon content were a mirror image of the effects of volatile matter content because the quantity of fixed carbon is dependent on the determined volatile matter content. High FCC feedstocks were associated with suppressed T_I - T_{IV} temperatures (but elevated T_V); resulted in the production of a gas rich in H_2 and CO, but low in N_2, CH_4 and CO_2. The heating values of the gas was high and the CGE increased. The quantities of liquid residues generated were lower.

7) Feedstock with high extractives contents were associated with higher gasification temperatures, and produced gas with lower contents of N_2, but higher H_2, CH_4, and CO_2, and also higher gas HHV.

8) Feedstocks with high heat values gasified at suppressed pyrolysis temperatures (T_I - T_{II}), but at higher char gasification and tar cracking temperatures (T_{III} - T_V), and involved shorter residence times. The quantity of air used, and also the quantity of gas produced were suppressed. The gas had lower contents of N_2, but higher H_2 and CO contents. The gas heat values were higher but due to the effects on the quantity of gas produced, the effect on cold gas efficiency was not significant.

5.4.4 INFLUENCE OF FEEDSTOCK MOISTURE CONTENT

This section presents results of 19 runs (using 4 species - *Salix kinuyanagi*, *Eucalyptus globulus*, *E.nitens* and *Paulownia tomentosa*) where the moisture content of the feedstock was deliberately varied. The section draws on trends in section 5.4.3 (comparing oven dry and air dry samples). Figures 5.13 and 5.14 illustrate the effects of feedstock moisture content on gasification processes of debarked *S. kinuyanagi*.

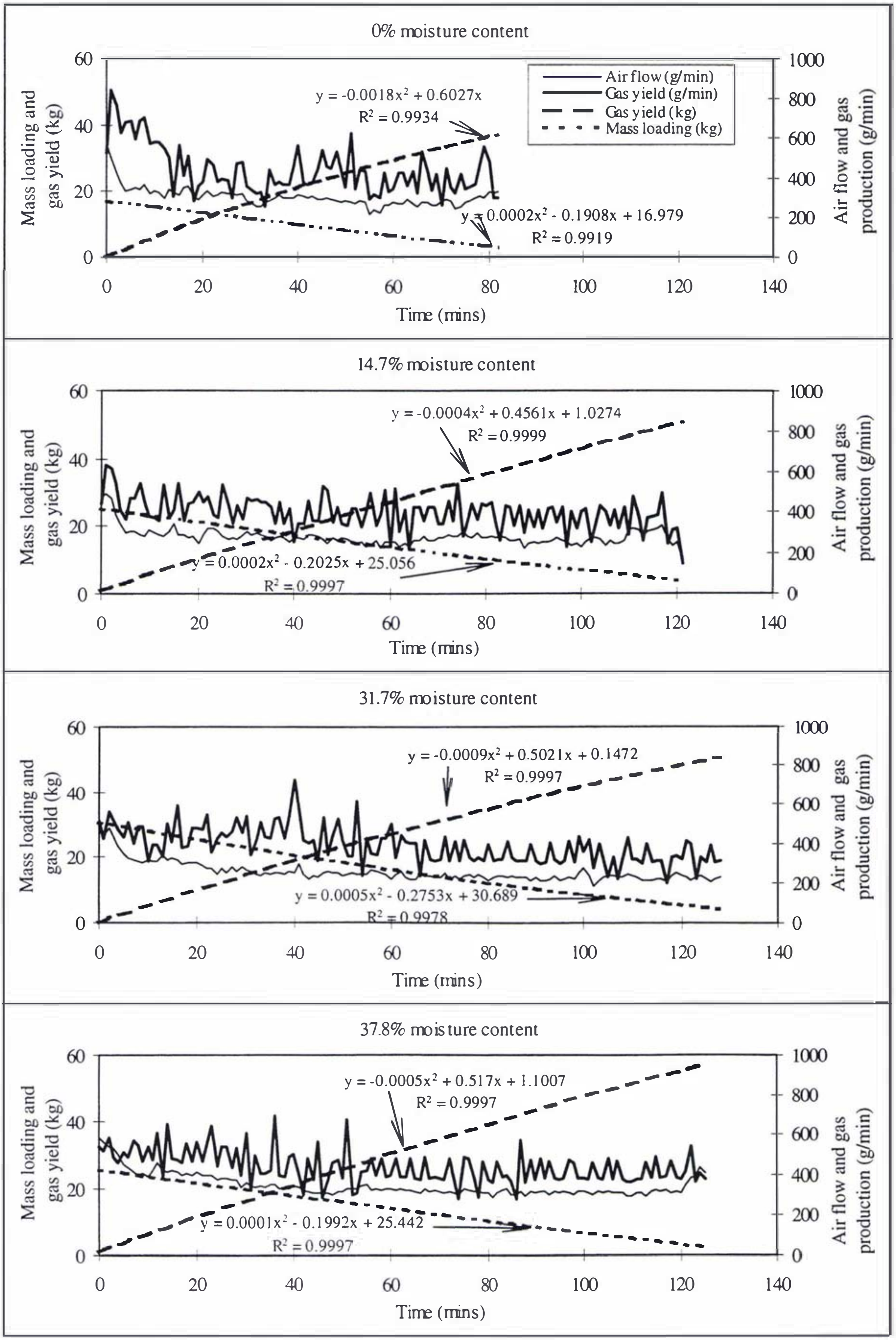

Figure 5.13 **The effect of feed moisture content on gasification of *S.kinuyanagi* with bark**

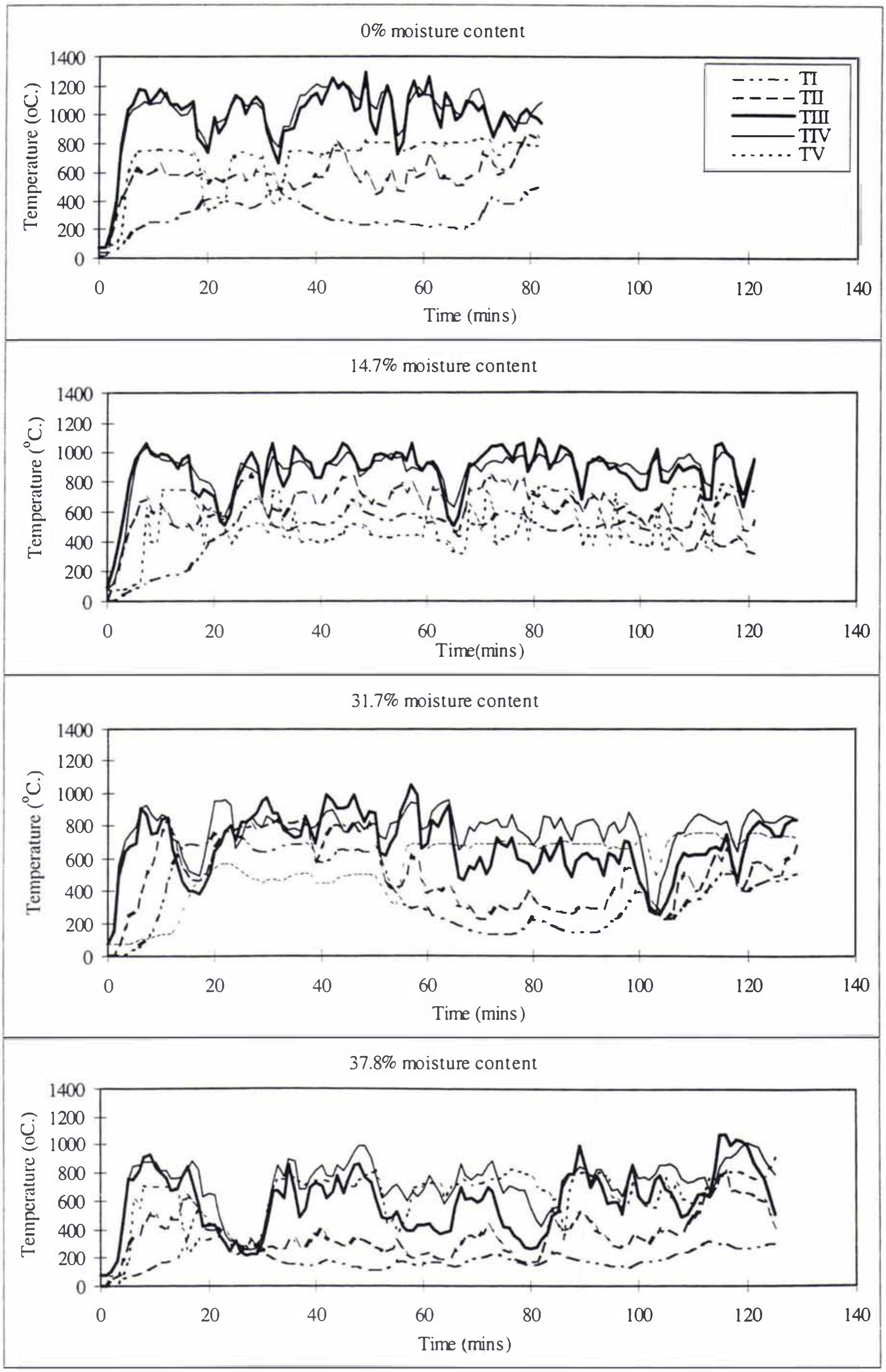

Figure 5.14 **The effect of feed moisture content on gasification temperature** of ***S.kinuyanagi***

Both figures 5.13 and 5.14 show that:

1. The pattern of variation in the flow of air (M_A) and product gas yield (M_{PG}) for all moisture content levels were similar, and resembled those observed for oven dry P.tomentosa (Figure 5.9). The range in air flows between the highest and lowest values were more pronounced in the oven dry feedstock, but the high moisture content reduced both feedstock (M_F) and air flows (M_A). The quantity of air required per unit of dry feedstock in high moisture content feedstocks was higher, marginally raising the equivalence ratio.

2. Both mass loading and gas yield graphs are linear functions indicating the rates of gasification.
3. The ratio of dry feedstock to total inputs increased with reducing moisture content.
4. The proportion of dry product gas decreased with increasing feedstock moisture content, while the proportion of liquids increased.

5. The net water formation associated with very high moisture content of feedstocks was negative indicating that some of feedstock moisture was converted to gas, forming H_2.

6. The overall gasifier temperature was a function of feedstock moisture content. Despite increased air flows (hence higher ER, implying more combustion reactions) in the gasification of high moisture content fuels, the average reaction temperatures on T_I - T_{IV} were lower than those obtained in the gasification of dry feedstock. Increasing feedstock moisture content also resulted in an overall shift in the temperature profiles with the highest temperature zone being shifted towards the grate. Gas exit temperatures (T_V) were not affected.

Data from the four species were averaged and summarised in tables 5.8 and 5.9. Of particular interest were gasification rates; temperature; product gas composition and heating values. Although air flow rates (g/h) were not statistically affected by the higher feedstock moisture content, high moisture content feedstocks resulted in significantly higher equivalence ratios. The quantity of reaction water generated per unit of dry feedstock, which also defines the net water formation, decreased (reaching negative values) with increasing moisture content, but the product gas yield, solid residues production, mass balance, residence time and the hearth load were among the factors not affected by feedstock moisture content. Although the effect of moisture content on temperature depended on the gasifier zone, drier feedstock resulted in higher temperatures.

Table 5.8 **The effect of feedstock moisture content on downdraft gasification processes***

	Run	Feed	Inputs flow rate (g/h)			Outputs flow rate (g/h)			Mass	Resid.	Gasific.	Specific	Hearth	ER	NWF	Average run temperatures (°C)				
Feedstock	time (min)	MC (%)	Feed (M_F)	Water (M_W)	Air (M_A)	Gas (M_{PG})	Solids (M_{SR})	Liquids (M_{LR})	balance (%)	time (s)	rate (g/s)	gas. rate (g/s/m^2)	load (m/s)			T_I	T_{II}	T_{III}	T_{IV}	T_V
E.globulus (B)	93	0.0	15286 ^{a}	0 ^{c}	25260 ^{a}	36576 ^{a}	1419 ^{a}	2711 ^{b}	100.4 ^{a}	3.5 ^{a}	3.57 ^{a}	285 ^{a}	0.860 ^{a}	0.260 ^{b}	18 ^{a}	213 ^{a,b}	461 ^{a}	-	891 ^{a}	744 ^{a}
E.globulus (B)	137	12.3	11025 ^{a,b}	1546 ^{b}	22980 ^{a}	31910 ^{a}	801 ^{a}	2906 ^{b}	100.2 ^{a}	3.1 ^{a}	2.85 ^{a,b}	228 ^{a,b}	0.768 ^{a}	0.328 ^{b}	12 ^{a,b,c}	295 ^{a}	469 ^{a}	735 ^{b}	830 ^{a,b}	749 ^{a}
E.globulus (B)	123	13.5	11921 ^{a,b}	1862 ^{b}	22080 ^{a}	31622 ^{a}	1375 ^{a}	3249 ^{b}	101.1 ^{a}	3.0 ^{a}	3.02 ^{a,b}	241 ^{a,b}	0.758 ^{a}	0.291 ^{b}	12 ^{a,b}	309 ^{a}	448 ^{b}	-	807 ^{b}	747 ^{a}
E.globulus (B)	121	27.4	10580 ^{b,c}	3999 ^{a}	22260 ^{a}	31277 ^{a}	1158 ^{a}	4407 ^{a}	100.0 ^{a}	3.0 ^{a}	2.87 ^{a,b}	230 ^{a,b}	0.737 ^{a}	0.331 ^{b}	4 ^{c}	204 ^{a,b}	361 ^{b}	-	734 ^{b}	739 ^{a}
E.globulus (B)	122	41.2	8783 ^{c}	6161 ^{a}	21600 ^{a}	30298 ^{a}	1197 ^{a}	5925 ^{a}	102.4 ^{a}	3.0 ^{a}	2.77 ^{b}	221 ^{b}	0.707 ^{a}	0.386 ^{a}	-3 ^{c}	120 ^{b}	217 ^{c}	-	468 ^{c}	694 ^{a}
E.nitens (B)	96	0.0	15041 ^{a}	0 ^{c}	21960 ^{a}	33408 ^{a}	1457 ^{a}	2392 ^{b}	100.7 ^{a}	3.0 ^{a}	3.57 ^{a}	286 ^{a}	0.809 ^{a}	0.229 ^{b}	16 ^{a}	286 ^{a,b}	538 ^{a}	862 ^{a}	899 ^{a}	751 ^{a}
E.nitens (B)	75	11.8	16066 ^{a,b}	2154 ^{b}	24600 ^{a}	35539 ^{a}	5218 ^{a}	3881 ^{b}	104.2 ^{a}	2.7 ^{a}	3.45 ^{a,b}	276 ^{a,b}	0.734 ^{a}	0.241 ^{b}	11 ^{a,b,c}	325 ^{a}	517 ^{a}	822 ^{b}	869 ^{a,b}	716 ^{a}
E.nitens (B)	121	35.4	10957 ^{b,c}	6003 ^{a}	24840 ^{a}	33638 ^{a}	2881 ^{a}	5195 ^{a}	99.8 ^{a}	3.4 ^{a}	2.83 ^{a,b}	226 ^{a,b}	0.788 ^{a}	0.356 ^{b}	-7 ^{a,b}	163 ^{a,b}	331 ^{c}	610 ^{c}	723 ^{b}	728 ^{a}
E.nitens (B)	132	39.9	9122 ^{c}	6048 ^{a}	24600 ^{a}	30586 ^{a}	522 ^{a}	5502 ^{a}	92.1 ^{a}	3.4 ^{a}	2.02 ^{b}	161 ^{b}	0.714 ^{a}	0.424 ^{a}	-6 ^{c}	172 ^{b}	294 ^{c}	469 ^{d}	554 ^{c}	702 ^{a}
P.tomentosa (B)	66	0.0	15413 ^{a}	0 ^{c}	19140 ^{a}	28973 ^{a}	3370 ^{a}	2321 ^{b}	100.3 ^{a}	2.6 ^{a}	3.07 ^{a}	245 ^{a}	0.699 ^{a}	0.195 ^{b}	15 ^{a}	260 ^{a,b}	599 ^{a}	955 ^{a}	948 ^{a}	761 ^{a}
P.tomentosa (B)	74	12.2	13011 ^{a,b}	1808 ^{b}	22500 ^{a}	30413 ^{a}	996 ^{a}	2585 ^{b}	91.1 ^{a}	3.1 ^{a}	2.55 ^{a,b}	204 ^{a,b}	0.731 ^{a}	0.272 ^{b}	6 ^{a,b,c}	281 ^{a}	533 ^{a}	842 ^{b}	894 ^{a,b}	739 ^{a}
P.tomentosa (B)	87	37.7	10150 ^{c}	6142 ^{a}	25500 ^{a}	33523 ^{a}	1750 ^{a}	5680 ^{a}	98.0 ^{a}	3.5 ^{a}	2.62 ^{b}	209 ^{b}	0.783 ^{a}	0.395 ^{a}	-5 ^{c}	181 ^{b}	326 ^{c}	602 ^{d}	755 ^{c}	750 ^{a}
S.kinuyanagi (NB)	82	0.0	13311 ^{a}	0 ^{c}	18240 ^{a}	27648 ^{a}	1107 ^{a}	2908 ^{b}	100.4 ^{a}	2.5 ^{a}	2.93 ^{a}	235 ^{a}	0.643 ^{a}	0.215 ^{b}	22 ^{a}	302 ^{a,b}	576 ^{a}	986 ^{a}	1000 ^{a}	690 ^{a}
S.kinuyanagi (NB)	121	14.7	10555 ^{a,b}	1819 ^{b}	16800 ^{a}	24883 ^{a}	1643 ^{a}	3144 ^{b}	101.7 ^{a}	2.3 ^{a}	2.53 ^{a,b}	202 ^{a,b}	0.575 ^{a}	0.250 ^{b}	13 ^{a,b,c}	455 ^{a}	641 ^{a}	878 ^{a,b}	876 ^{a,b}	518 ^{a}
S.kinuyanagi (NB)	129	31.7	9338 ^{bc}	4334 ^{a}	15360 ^{a}	23386 ^{a}	2141 ^{a}	4672 ^{a}	104.0 ^{a}	2.1 ^{a}	2.50 ^{a,b}	200 ^{a,b}	0.530 ^{a}	0.258 ^{b}	4 ^{c}	392 ^{a,b}	502 ^{b}	680 ^{b}	776 ^{b}	563 ^{a}
S.kinuyanagi (NB)	125	37.8	8305 ^{c}	5047 ^{a}	20820 ^{a}	27533 ^{a}	602 ^{a}	5189 ^{a}	97.5 ^{a}	2.8 ^{a}	2.18 ^{b}	175 ^{b}	0.628 ^{a}	0.394 ^{a}	2 ^{c}	201 ^{b}	359 ^{c}	593 ^{c}	711 ^{c}	624 ^{a}

* - Values with the same letter are not significantly different

Table 5.9 **The effect of feedstock moisture content on product gas composition, quality and gasification efficiencies**[*]

	Feed MC	Gas composition (%)					Gas quality			Air to dry feed	Gas to dry fed	Gas to dry feed	Gas to dry feed	Rxn liquid to dry feed	Total liquid to dry gas	Cold gas efficiency
							Std relati	Heat value (MJ/Nm^3)								
Feedstock	%	H_2	N_2	CO	CH_4	CO_2	density	Pure gas	Stoi mixture	(g/g)	(m^3/kg)	(g/g)	(kJ/g)	(g/g)	(g/g)	
E.globulus (B)	0.0	10.0 ^{a}	56.4 ^{b}	23.5 ^{a}	2.1 ^{a}	8.0 ^{c}	0.952 ^{c}	5.3[illegible]4 ^{a}	2.409 ^{a}	1.82 ^{c}	2.51 ^{c}	2.39 ^{c}	12.08 ^{a}	0.18	0.074 ^{b}	62 ^{a}
E.globulus (B)	12.3	11.2 ^{a}	56.3 ^{b}	21.5 ^{a}	1.8 ^{b}	9.2 ^{b}	0.962 ^{b,c}	5.155 ^{a}	2.351 ^{a}	2.25 ^{b,c}	3.00 ^{b,c}	2.89 ^{b,c}	12.59 ^{a}	0.12	0.091 ^{b}	74 ^{a}
E.globulus (B)	13.5	10.7 ^{a}	56.0 ^{b}	21.0 ^{a}	1.9 ^{b}	10.4 ^{b}	0.966 ^{b}	5.035 ^{a,b}	2.326 ^{a}	2.09 ^{b,c}	2.90 ^{b}	2.65 ^{b,c}	11.16 ^{a}	0.12	0.103 ^{b}	66 ^{a}
E.globulus (B)	27.4	12.1 ^{a}	56.5 ^{a}	17.4 ^{b}	1.6 ^{c}	12.4 ^{a}	0.982 ^{a}	4.746 ^{b,c}	2.208 ^{b}	2.36 ^{b}	3.26 ^{a}	2.96 ^{b}	10.00 ^{b}	0.04	0.141 ^{a}	71 ^{a}
E.globulus (B)	41.2	8.7 ^{a}	63.1 ^{a}	13.4 ^{b}	1.2 ^{d}	13.7 ^{a}	0.992 ^{a}	3.371 ^{c}	1.868 ^{c}	2.85 ^{a}	3.96 ^{a}	3.45 ^{a}	6.78 ^{b}	-0.03	0.196 ^{a}	59 ^{a}
E.nitens (B)	0.0	11.9 ^{a}	52.6 ^{b}	24.5 ^{a}	2.4 ^{a}	8.7 ^{c}	0.956 ^{c}	5.912 ^{a}	2.508 ^{a}	1.62 ^{c}	2.35 ^{c}	2.22 ^{c}	12.55 ^{a}	0.16	0.072 ^{b}	63 ^{a}
E.nitens (B)	11.8	12.0 ^{a}	53.8 ^{b}	22.1 ^{a}	2.2 ^{b}	10.0 ^{b}	0.964 ^{b,c}	5.537 ^{a}	2.419 ^{a}	2.27 ^{b,c}	3.16 ^{b,c}	2.21 ^{b,c}	10.41 ^{a}	0.11	0.109 ^{b}	59 ^{a}
E.nitens (B)	35.4	11.4 ^{a}	59.4 ^{a}	14.0 ^{b}	1.5 ^{c}	13.7 ^{a}	0.988 ^{a}	4.029 ^{b,c}	2.029 ^{b}	3.08 ^{b}	4.12 ^{a}	3.07 ^{b}	7.90 ^{b}	-0.07	0.154 ^{a}	61 ^{a}
E.nitens (B)	39.9	7.4 ^{a}	67.8 ^{a}	10.3 ^{b}	1.2 ^{d}	13.3 ^{a}	0.993 ^{a}	2.799 ^{c}	1.652 ^{c}	2.86 ^{a}	3.53 ^{a}	3.35 ^{a}	5.60 ^{b}	-0.06	0.180 ^{a}	47 ^{a}
P.tomentosa (B)	0.0	12.9 ^{a}	51.1 ^{b}	24.1 ^{a}	2.5 ^{a}	9.5 ^{c}	0.962 ^{c}	6.112 ^{a}	2.524 ^{a}	1.59 ^{c}	2.31 ^{c}	1.88 ^{c}	11.05 ^{a}	0.15	0.080 ^{b}	55 ^{a}
P.tomentosa (B)	12.2	10.6 ^{a}	54.3 ^{b}	22.8 ^{a}	2.3 ^{b}	10.0 ^{b}	0.963 ^{b,c}	5.412 ^{a}	2.414 ^{a}	1.87 ^{b,c}	2.44 ^{b,c}	2.34 ^{b,c}	10.70 ^{a}	0.06	0.085 ^{b}	61 ^{a}
P.tomentosa (B)	37.7	9.9 ^{a}	62.3 ^{a}	12.2 ^{b}	1.5 ^{d}	14.1 ^{a}	0.990 ^{a}	3.560 ^{c}	1.890 ^{c}	3.04 ^{a}	3.95 ^{a}	3.30 ^{a}	7.25 ^{b}	-0.05	0.169 ^{a}	58 ^{a}
S.kinuyanagi (NB)	0.0	8.3 ^{a}	61.5 ^{b}	20.3 ^{a}	2.3 ^{a}	7.6 ^{c}	0.950 ^{c}	4.675 ^{a}	2.262 ^{a}	1.49 ^{c}	2.15 ^{c}	2.08 ^{c}	9.22 ^{a}	0.22	0.105 ^{b}	46 ^{a}
S.kinuyanagi (NB)	14.7	10.4 ^{a}	56.3 ^{b}	22.2 ^{a}	1.9 ^{b}	9.2 ^{b}	0.961 ^{b,c}	5.114 ^{a}	2.361 ^{a}	1.89 ^{b,c}	2.68 ^{b,c}	2.36 ^{b,c}	9.88 ^{a}	0.13	0.126 ^{b}	58 ^{a}
S.kinuyanagi (NB)	31.7	9.9 ^{a}	61.6 ^{a}	13.7 ^{b}	1.7 ^{c}	13.1 ^{a}	0.984 ^{a}	3.850 ^{b,c}	1.982 ^{b}	2.13 ^{b}	3.20 ^{a}	2.50 ^{b}	6.48 ^{b}	0.04	0.200 ^{a}	48 ^{a}
S.kinuyanagi (NB)	37.8	9.4 ^{a}	64.6 ^{a}	13.7 ^{b}	1.2 ^{d}	11.2 ^{a}	0.975 ^{a}	3.528 ^{c}	1.913 ^{c}	2.70 ^{a}	3.48 ^{a}	3.32 ^{a}	7.09 ^{b}	0.02	0.188 ^{a}	57 ^{a}

* - Values with the same letter are not significantly different

Gas composition and quality

The results demonstrate that increasing feedstock moisture content did not have a significant effect on the H_2 content of the gas, but led to an increase in gas N_2 and CO_2, and a decline in CO and CH_4 contents. This decrease in CO and CH_4 over unchanged H_2, and increasing N_2 and CO_2 contents resulted in lower gas heating values indicating polynomial tendencies (figure 5.15). The stoichiometric gas-air mixture heat values were also significantly influenced by feedstock moisture content (table 5.9).

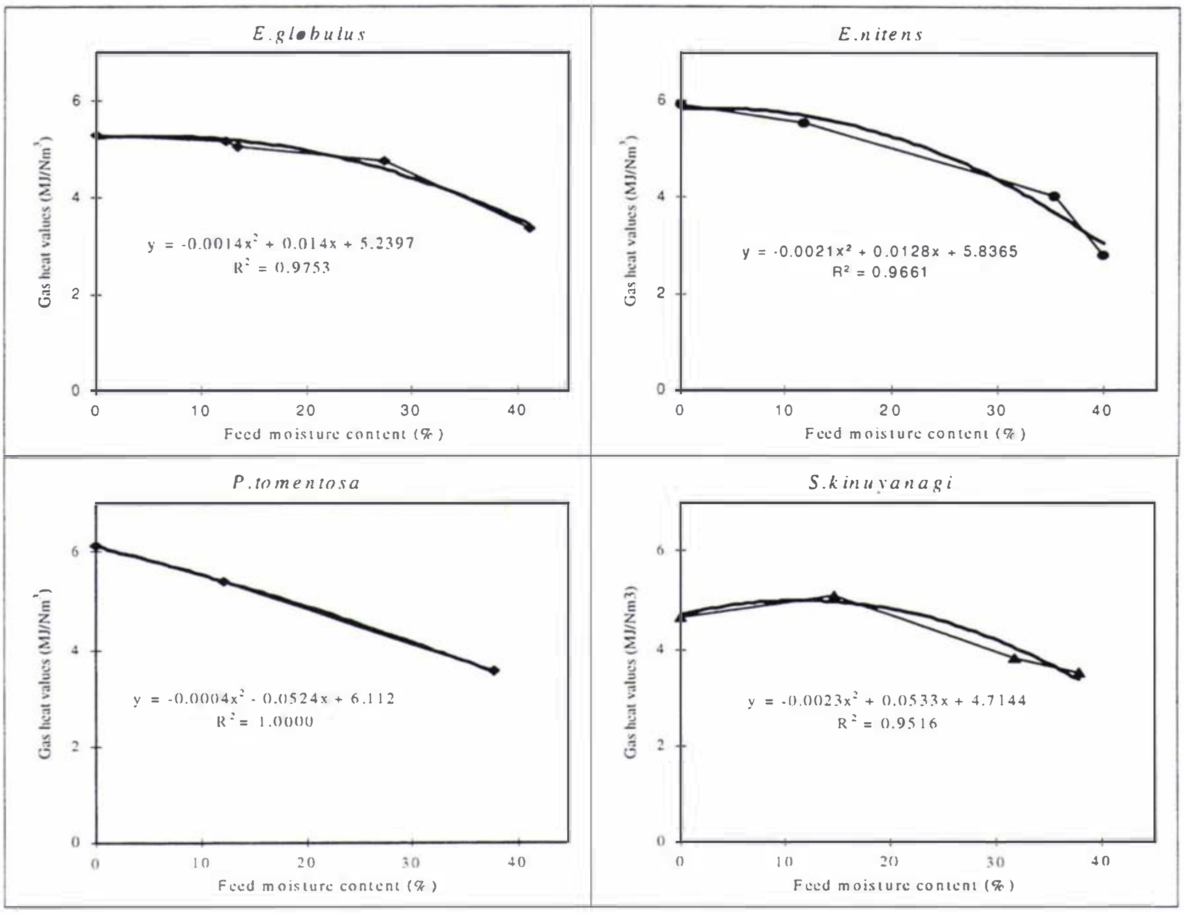

Figure 5.15 **The influence of feedstock moisture content on gas heat values**

The data in tables 5.5-5.9 may be plotted as linear functions of feedstock moisture content (figures 5.16 and 5.17) to illustrate the overall effect of feedstock moisture content on gasification processes and products to illustrate that (i) feed rate (M_F) and gas production rate (M_{PG}) declined with increasing feedstock moisture content; (ii) the mass of liquid residues (collected condensate, M_{LR}, and gas moisture) increased; and (iii) air flows (M_A) changed little.

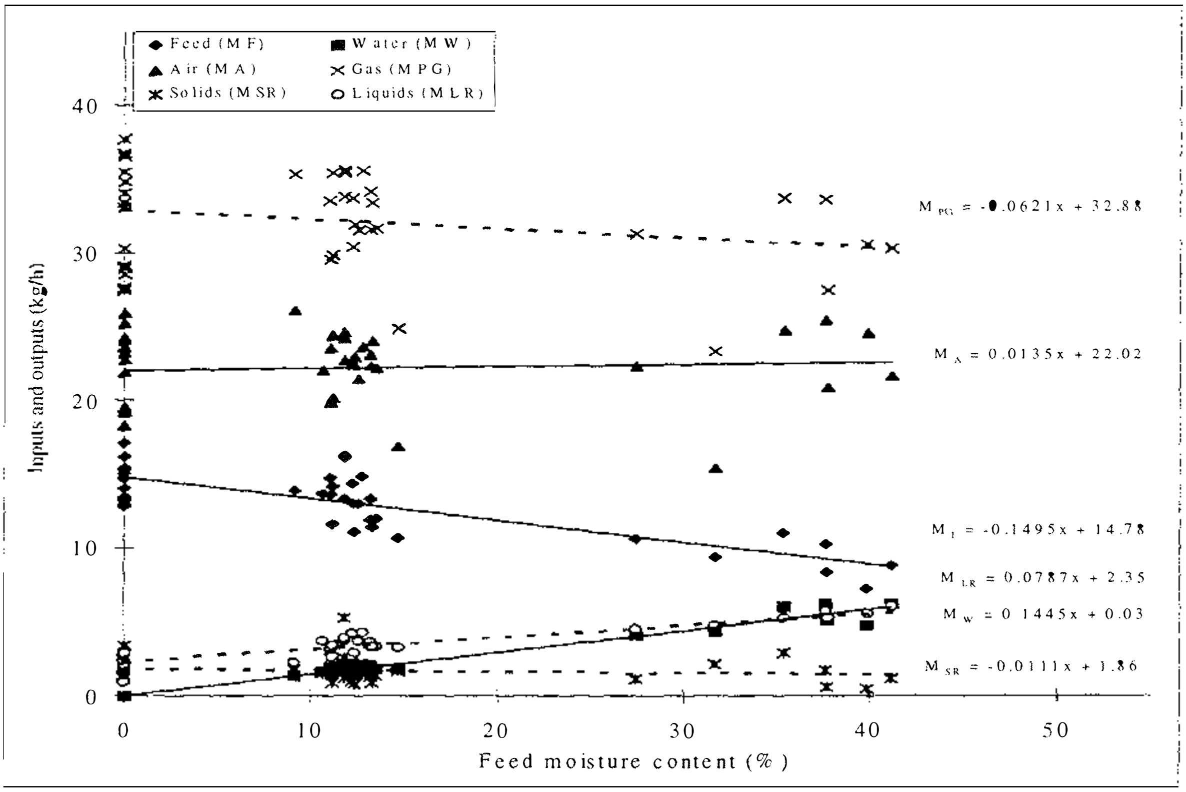

Figure 5.16 **The influence of feedstock moisture content on operating conditions**

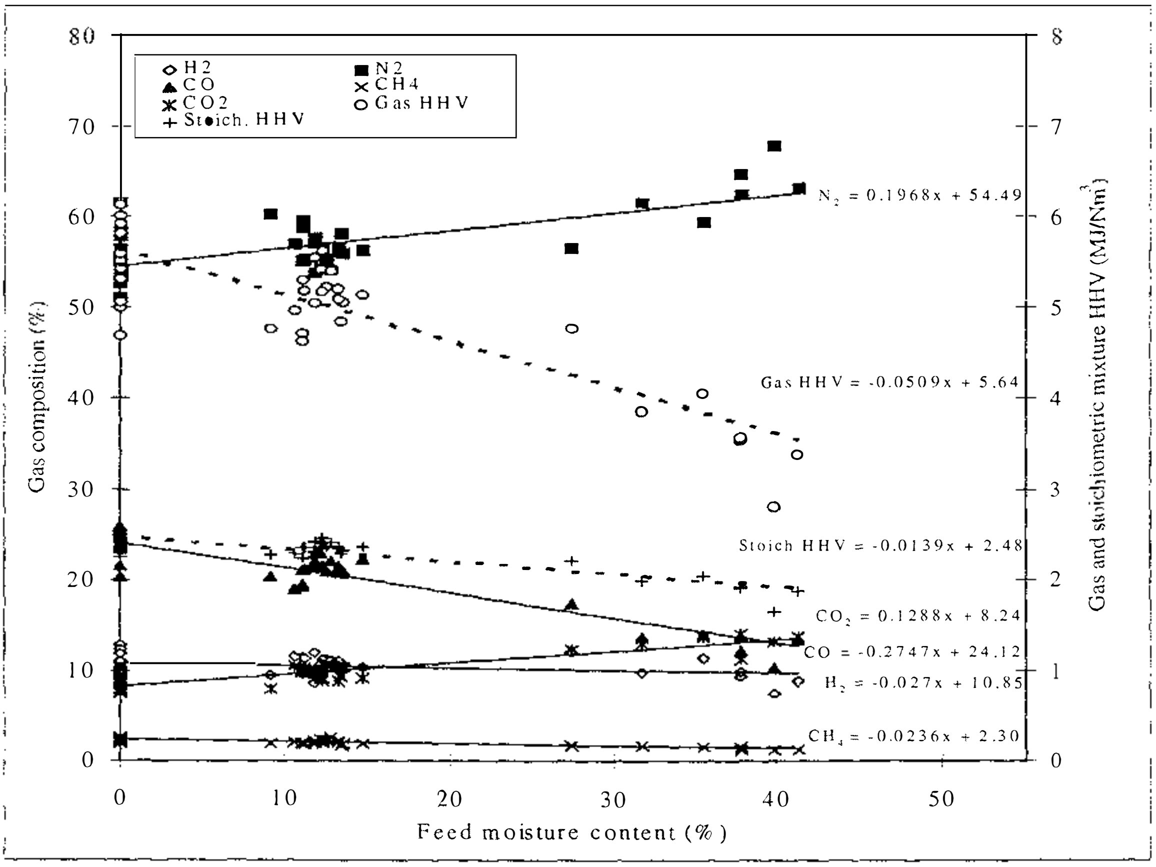

Figure 5.17 **The effect of feedstock moisture content on product gas quality**

Product gas composition and heating values were functions of feedstock moisture content. Both gas N_2 and CO_2 contents increased with increasing moisture content. CO and CH_4 decreased, while H_2 was not significantly affected. Consequently the heating values of both product gas and the stoichiometric gas air mixture obtained from high moisture content feedstocks was reduced.

5.4.5 PARTICLE SIZE DISTRIBUTION AND BULK DENSITY

Appendix 5.3 and 5.4 show the results of the gasification of the various particle size distribution and bulk densities of selected species. Although all samples were air dried, there were some variations in moisture contents - *A.dealbata* (9.1-11.7%), *E.globulus* (11.1-12.8%), and *E.nitens* (13.2-13.3). The variations were statistically insignificant, and were therefore ignored. The highest temperatures among the particle sizes tested were achieved when large particles were used though this did not influence the products of gasification, nor the quality of the gas produced.

5.4.6 AIR FLOWS AND THE EQUIVALENCE RATIO (ER)

Figure 5.18 shows the relationships between air flow (kg/h) and total gas yield (kg/h), product gas heating value (MJ/Nm^3), and the stoichiometric gas-air mixture heating values (MJ/Nm^3), while figure 5.19 shows the influence of equivalence ratio on gas composition and heating value.

Both figures 5.18 and 5.19 demonstrate that (i) high air flows resulted in higher gas yields; and (ii) air intake (as a proportion of the total material flows, and defining the equivalence ratio, ER) has a significant effect on both gas yield and quality. The product gas resulting from the use of large quantities of air had higher quantities of non combustible components (N_2 and CO_2), but lower contents of combustible components (CO, H_2 and CH_4) leading to a significant drop in heat values. The good coefficients of correlation (R^2) between ER and most of the parameters shown in figure 5.19 show that it may be possible to predict gas composition and heating values (with reasonable accuracy) if the quantity of air used is known.

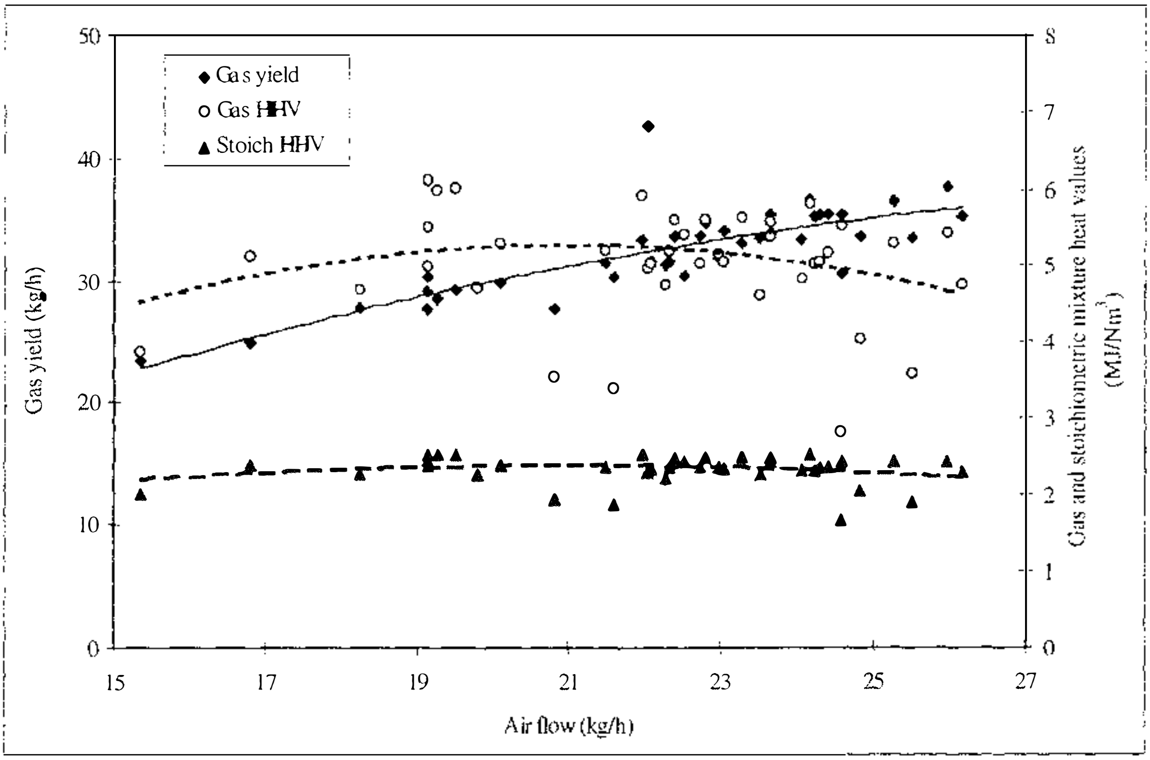

Figure 5.18 **The effect of air flow on gas yield and heat values**

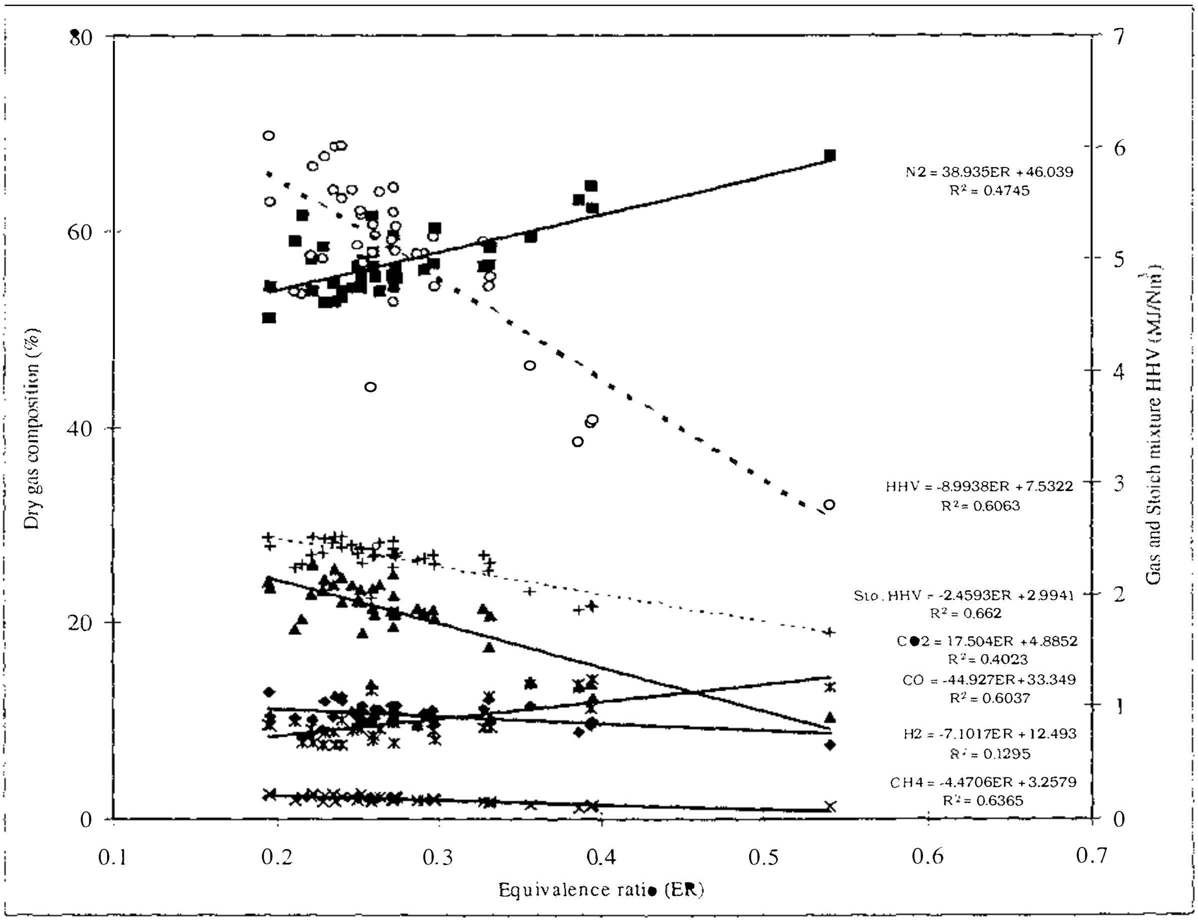

Figure 5.19 **The effect of equivalence ratio (ER) on gas quality**

5.4.7 TEMPERATURE

The correlation analyses (Table 5.7, and Appendices 5.1 and 5.2), showed that (i) high temperatures resulted in the production of a gas with higher heating values as it contained higher quantities of CO and CH_4; (ii) high temperatures were beneficial for high gas yields; and (iii) feedstock type had a significant effect on reaction temperatures which in turn directly influenced the distribution and type of products.

Peak temperature

Tables 5.5 and 5.8 showed that the highest average temperatures were recorded at the T_{III} and T_{IV} locations, and that the gasification of high moisture content feedstocks, and also of small particle sizes feedstocks reduced the maximum temperatures recorded. Although the role of other process conditions like moisture content and particle size were recognised, the variations were not deliberate.

Table 5.10 shows the highest temperatures for each test run (before averaging out). Although some samples with bark had higher temperature than those without bark, the differences were not significant.

Table 5.10 **Maximum recorded temperatures from each run**

Feedstock with bark		**Temperature (°C)**	**Location**
A.dealbata	Oven dry	1253	T_{IV}
	Air dry	1040	T_{IV}
A.glutinosa	Oven dry	1293	T_{III}
	Air dry	1152	T_{III}
E.globulus	Oven dry	1091	T_{IV}
	Air dry	1100	T_{IV}
E.nitens	Oven dry	1306	T_{III}
	Air dry	897	T_{IV}
P.eridano	Oven dry	1267	T_{III}
	Air dry	-	-
P.radiata	Oven dry	1242	T_{III}
	Air dry	-	-
P.tomentosa	Oven dry	1194	T_{III}
	Air dry	1169	T_{III}
S.kinuyanagi	Oven dry	1321	T_{III}
	Air dry	-	-
Feedstock without bark			
A.dealbata	Oven dry	1194	T_{IV}
	Air dry	999	T_{III}
E.globulus	Oven dry	1168	T_{IV}
	Air dry	1126	T_{III}
E.nitens	Oven dry	1105	T_{IV}
	Air dry	1050	T_{IV}
P.eridano	Oven dry	1155	T_{III}
	Air dry	1000	T_{III}
S.kinuyanagi	Oven dry	1290	T_{III}
	Air dry	1095	T_{III}
S.mats x *alba*	Oven dry	1134	T_{IV}
	Air dry	1022	T_{III}

Figure 5.20 illustrates the effects of changing temperature on input and output flows and shows that (i) dry feed rate (M_F) was not significantly influenced by temperature; (ii) the pattern of variation in air flow (M_A) was similar to that of product gas yield (M_{PG}), except that the air flows appeared to dip with increasing temperature; (iii) within the range of the tests, high temperatures were also associated with a reduction in the quantities of liquid residues (M_{LR}); (iv) at lower temperatures, the water input (M_W) was marginally less than the quantity of liquid residues generated. This trend was reversed at higher temperatures where M_W was slightly more than the liquid residues.

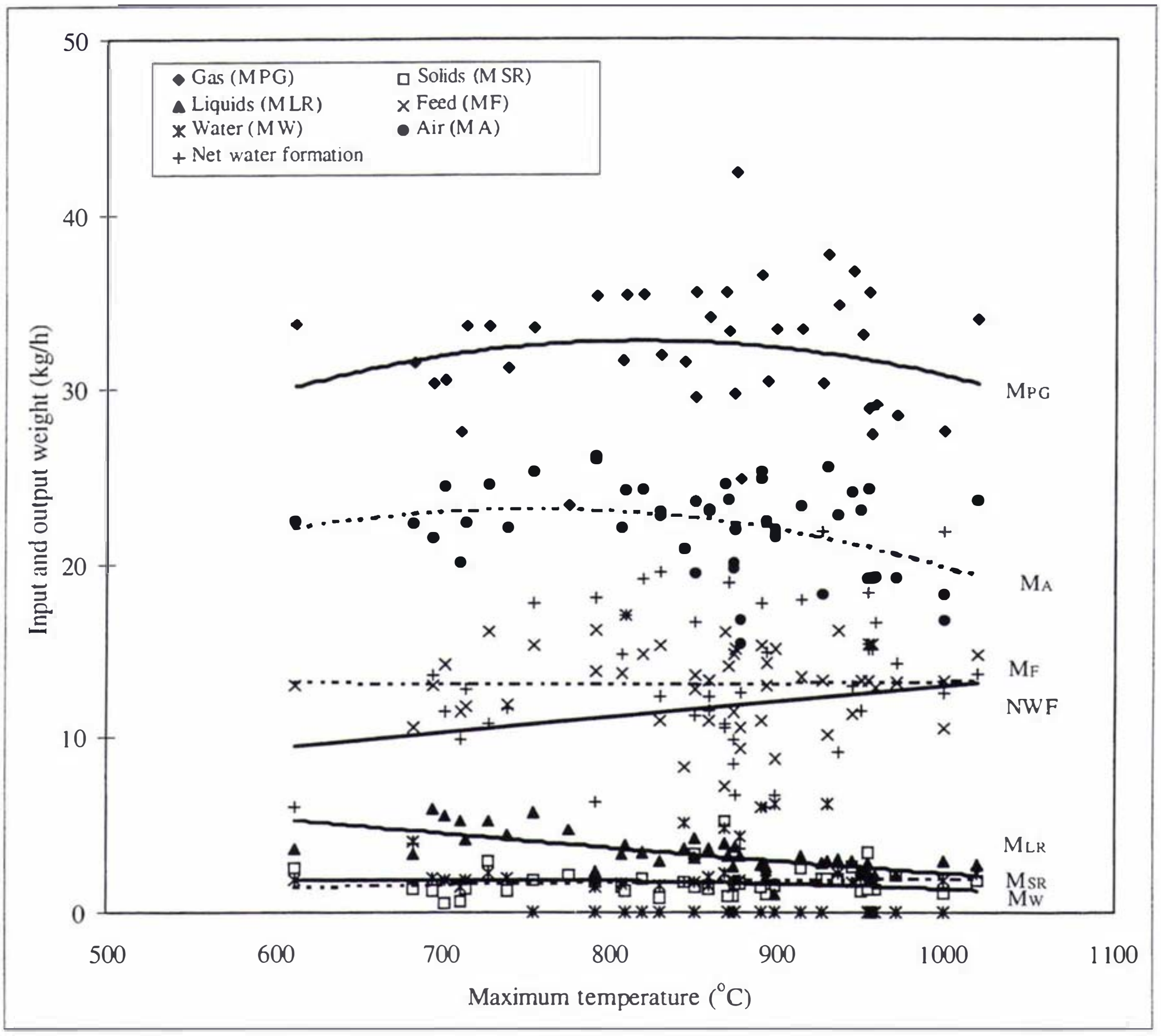

Figure 5.20 **The influence of temperature on input and output flows**

Temperature fields

Temperature profiles (Figures 5.11 and 5.14) showed the variation in temperature at 5 locations of the gasifier for individual test runs. Although minor variations in the temperature profiles were observed with differences in the species, feedstock moisture content, and particle size distributions, the pattern of variation was similar in all tests, and could not be traced to species differences, or to the quantity of bark present. Therefore, data from all reported runs were combined and summarised in a temperature field diagram (figure 5.21) showing plots of the minimum, median, mean and maximum temperatures against the distance between the thermocouples and the grate. More than 3000 data values for each thermocouple were used, each being an average of 60 readings taken every second.

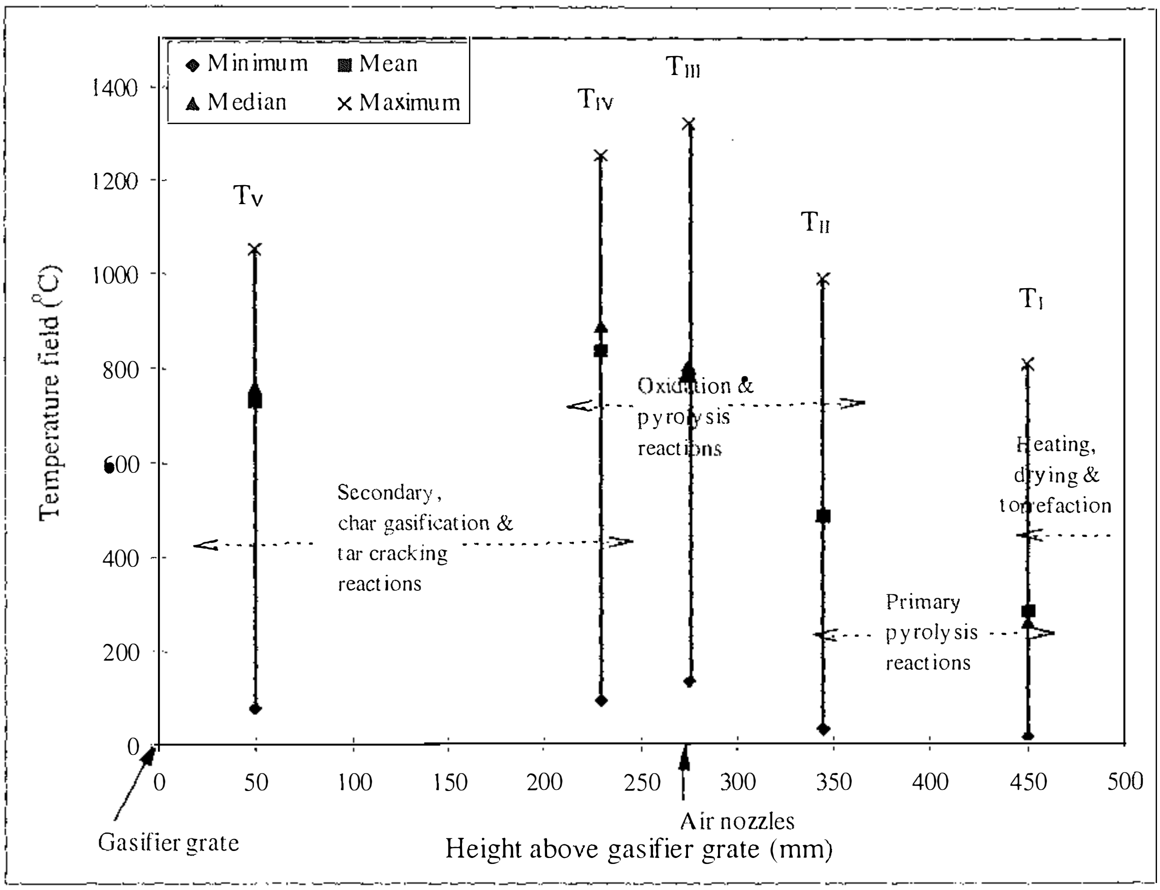

Figure 5.21 **Temperature fields in the Fluidyne downdraft gasifier**

Despite considerable overlap between the regions and reactions, the diagram (Figure 5.21) distinguishes the gasifier into major reaction zones, namely:

a) Heating, drying and torrefaction zone (450 mm above the grate). In a properly working gasifier, the temperature does not exceed 200°C. The figure indicates a temperature of up to 800°C, illustrating the effects overlapping with pyrolysis zone. The wood was brownish, and often had a thin coating of tar. Depending on the quantity of charge in the gasifier at the time of stopping, the wood was either dry, or wet from the reaction moisture from the gasification reactions. Temperature in this zone was not monitored.

b) Primary pyrolysis zone (between 340 and 450 mm from the grate). The maximum temperature recorded was 1000°C. The bed consisted of a mixture of torrefied wood and charcoal.

c) Oxidation/combustion zone monitored by T_{III} was located around 270 mm above the grate and in line with the air nozzles. The highest temperatures were recorded in this region. The bed consisted of light textured charcoal, torrefied wood, and ash.

d) Char gasification and tar cracking zone was monitored by T_{IV}, about 230 mm above the grate.

e) T_V located 50 mm from the grate showed the gas temperature on exiting from the gasifier bed, and indicated the temperature of gasification products was in equilibrium.

The lowest temperatures were registered on T_I, and corresponded to the heating and drying zone. The highest temperatures were recorded from the gasification of oven dry feedstock in the T_{III}-T_{IV} region (table 5.10). This corresponded to the pre-combustion/oxidation zone adjacent to the air nozzles (figure 5.4), and was characterised by rapid non-random movements in temperature (T_{III} and T_{IV} curves, figure 5.11). A top elevation view of the undisturbed bed showed grey shades (lobes) of ash (in a char matrix) protruding from the air nozzles (Figure 5.22).

Figure 5.22 **Top view of an un-disturbed oxidation/combustion zone within the gasifier**

The ash indicated very high ashing temperatures due to the rich oxygen environments around the nozzles resulting from the combustion reactions. However, slagging of the ash resulting in clinker formation was not observed. The gasifier design did not permit direct alterations of temperature for direct investigation of the influence of temperature on other processes. Maximum temperature data from all runs were plotted against gas yield and quality (Figure 5.23).

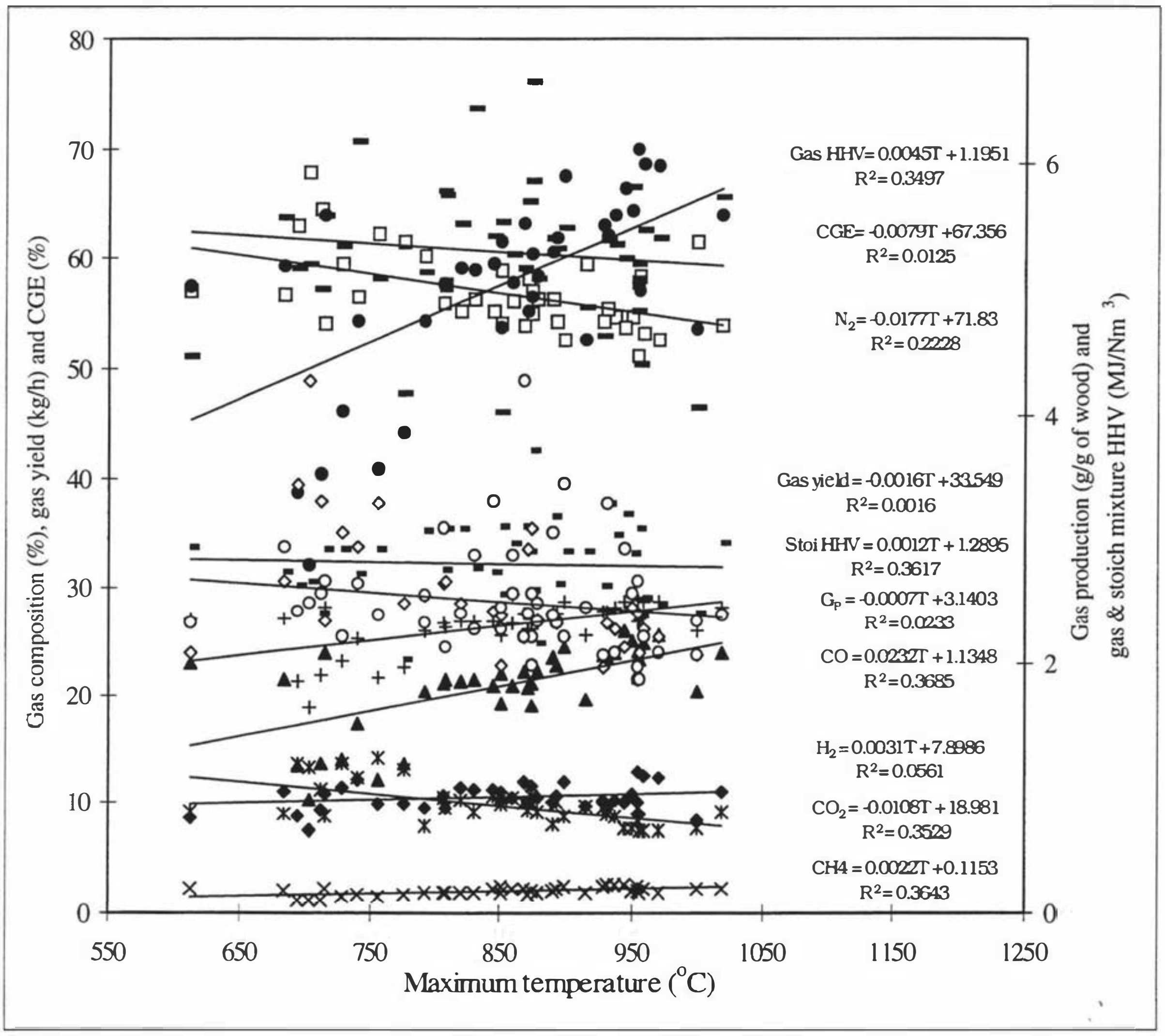

Figure 5.23 **The influence of maximum gasifier temperature on gas yield and quality**

The most dramatic effect was observed in the product gas heating values, and CO content (%) which continued to increase with temperature over the range recorded. High temperature resulted in higher gas contents of CO, H_2, and CH_4, while the content of N_2 and CO_2 was reduced. Consequently, the product gas heat values, and also the heat values of the stoichiometric gas-air mixture were increased.

Although all the correlations between temperature and the parameters shown in figure 5.23 were low, the correlation with (i) gas production per unit weight of feedstock (G_P, g/g), (ii) gas yield (kg/h), and (iii) gas hydrogen content was very poor. Due to this relationship, the cold gas efficiency incorporating gas heating values and yield, and the feedstock weight and heating values also declined .

5.4.8 SOLID RESIDUES

The yield of the solid residues (consisting of un-reacted char and ash) was not significantly influenced by any of the experimental variables investigated (See tables 5.5, 5.9 and 5.11). There was no correlation between the dry feedstock used, and the quantity of solid residues collected. Similarly, there was no relationship between the quantity of solid residues and temperature. The yield of solid residues did not indicate the suitability of a feedstock. Although not monitored specifically, char yield was independent of the starting material, mostly relying on when the run was stopped, and the quantities that dropped out through the fuel grate on loading. Also, no correlation was observed between feedstock ash content and solid residues collected.

5.4.9 LIQUID RESIDUES (CONDENSATE)

Two categories of liquid residues were identified - collected condensate, and the gas moisture content determined by the gas moisture content trap containing oven dried silica gel (desiccant). The gas had a moisture content of 4-6% (40-50 g per m^3 of gas). It was assumed that the gas moisture content was free of solids having been passed through a series of filters and heat exchangers (Figures 5.6 and 5.7).

The yield of liquid residues increased with increasing feedstock moisture content (table 5.8; and figure 5.20), but was neither influenced by the air flows nor the tree species (table 5.5). Increasing quantity of liquids generated at elevated feedstock moisture content - 180, 230, 240, 300, 400g at 0 (OD), 12.3, 13.5, 27.4 and 41.2% moisture content in *E.globulus*, was equivalent to 70-130 g/kg of gas from oven dry and air dry samples, increasing to 200g per kg of gas in samples with a moisture content of 41.2%. On a weight basis, 170 and 210 g of liquid residues were generated from the gasification of oven dry and air dry samples respectively. About 1 - 3.9 kg of liquid condensate was generated per hour. From the condensate yield, the net water formation (NWF) was calculated and shown to be equivalent to the ratio between reaction water and dry feed. NWF was found to be higher in oven dry samples.

Table 5.11 presents results of the analysis of collected liquid residues. The properties of the condensate indicate that it would be unacceptable to dispose of the effluent from a gasification plant directly into water ways, or onto land without pre-treating it. The table also shows that different tree species produced different types of liquid residues, and that the feedstock moisture content had a significant effect on the properties of the condensate generated.

Correlation analyses between liquid residues properties (table 5.11) and feedstock properties, and also of gasification parameters (Appendix 5.5) showed that both pH and electrical conductivity (EC) were significantly influenced by both feedstock characteristics (table 5.3) and the gasification processes but turbidity and COD did not have good correlations. Feedstocks with high ash, high fixed carbon and high moisture content, and those containing bark produced liquids with high pH which was also associated with high residence times, high hearth load and high ER. The gas produced had high CO_2. The factors associated with low pH were high feedstock volatile matter and high reaction temperatures, which also produced gas with high CO and CH_4 contents and therefore had high heating values.

Condensate with low EC was produced from the gasification of feedstock with high basic density which also had high volatile matter and high moisture content, and was associated with high ER resulting in a gas with high N_2 and CO_2. High EC condensate was generated from high ash, fixed carbon content feedstocks containing bark. High EC condensate was also associated with extended residence times, high NWF, high reaction temperatures, and the gas having high H_2, CO and CH_4 contents and therefore high heating values.

A sample of the condensate was compared with condensate cleaned by filtration through a filter paper (150 watman paper); filter paper and fine charcoal from the cyclone; and filter paper with charcoal from the gasifier ash port. 300 ml of condensate were passed through 25.2 g of either activated charcoal or charcoal granules, and turned over three times. The results (bottom of table 5.11) indicated significant changes in the filtrate after treatment with both charcoal and activated charcoal residues, and indicates the potential in utilising the solid residues in the treatment of the liquid residues prior to disposal.

1. The filter paper- activated charcoal resulted in a significant increase in pH (from 4.68 to 6.70) showing reduced acidity. Electrical conductivity increased but the turbidity decreased. COD increased.

2. Filter paper- granule charcoal resulted in a slight increase in pH, electrical conductivity; and COD, but the turbidity dropped significantly.

3. Filter paper resulted in a significant reduction in turbidity but an increase COD. Both pH and electrical conductivity were not changed.

Table 5.11 **Analysis of collected liquid residues (condensate)**

Feedstock		pH	Electrical conductivity	Turbidity	COD (ppm)
Oven dry, with bark					
A.dealbata		5.12 ^{a,b}	17640 ^{a}	3500 ^{a,b}	25000 ^{a,b}
A.glutinosa		4.94 ^{a}	13900 ^{a,b}	6030 ^{a,b}	5000 ^{b}
E.globulus		4.64 ^{a,b,c}	13100 ^{b}	4270 ^{a,b}	75000 ^{a,b}
E.nitens		4.49 ^{a,b}	10360 ^{b}	3290 ^{a,b}	125000 ^{a,b}
P.eridano		5.20 ^{a,b}	14600 ^{b}	975 ^{b}	62500 ^{a,b}
P.radiata		5.18 ^{a,b}	12200 ^{b}	6130 ^{a}	112500 ^{a,b}
P.tomentosa		4.88 ^{b,c}	13800 ^{b}	5510 ^{a,b}	72500 ^{a,b}
S.kinuyanagi		4.38 ^{c}	11500 ^{c}	3620 ^{a,b}	115000 ^{a,b}
Mean		4.85 ^{a,b}	13388 ^{a}	4166 ^{a,b}	74063 ^{a}
Oven dry, without bark					
E.globulus		4.36	8200	6970	47500
E.nitens		4.92	10900	2460	110000
P.eridano		4.46	10100	2880	52500
S.kinuyanagi		3.32	3420	4290	92500
S.mats x alba		5.22	11370	2270	67500
Mean		4.46 ^{a,b}	8798 ^{c}	3774 ^{a}	74000 ^{a}
Air dry, with bark					
A.glutinosa		6.25	15100	2970	35000
E.globulus		4.95	11230	3150	32500
E.nitens		4.71	10800	4260	127500
P.eridano		5.29	13500	1490	110000
P.tomentosa		4.24	9400	497	62500
Mean		5.09 ^{a}	12006 ^{a,b}	2473 ^{a}	73500 ^{a}
Air dry, without bark					
A.dealbata		4.87	15080	3400	87500
E.globulus		4.69	10200	4180	95000
E.nitens		5.18	9300	3450	130000
P.eridano		4.81	9800	3870	50000
S.kinuyanagi		3.67	4600	2310	55000
S.mats x alba		5.51	11600	1370	122500
Mean		4.79 ^{a,b}	10097 ^{b,c}	3097 ^{a}	90000 ^{a}
Feedstock moisture content effects					
E.globulus (B)	0	4.64 ^{b}	13100 ^{a}	4270 ^{a}	75000 ^{a}
E.globulus (B)	12	4.95 ^{b}	11230 ^{a,b}	3150 ^{a}	112500 ^{a}
E.globulus (B)	14	6.60 ^{a}	11300 ^{a}	5030 ^{a}	52500 ^{b,c}
E.globulus (B)	27	7.41 ^{a}	8600 ^{b}	3150 ^{a}	95000 ^{a,b}
E.globulus (B)	41	7.03 ^{a}	5900 ^{b}	922 ^{a}	47500 ^{c}
E.nitens (B)	0	4.49 ^{b}	10360 ^{a}	3290 ^{a}	125000 ^{a}
E.nitens (B)	12	4.71 ^{b}	10800 ^{a,b}	4260 ^{a}	127500 ^{a}
E.nitens (B)	35	6.28 ^{a}	6100 ^{b}	2770 ^{a}	100000 ^{a,b}
E.nitens (B)	40	5.30 ^{a}	6500 ^{b}	3090 ^{a}	75000 ^{c}
P.tomentosa (B)	0	4.88 ^{b}	13800 ^{a}	5510 ^{a}	87500 ^{a}
P.tomentosa (B)	12	4.24 ^{b}	9400 ^{a,b}	4960 ^{a}	62500 ^{a}
P.tomentosa (B)	38	6.73 ^{a}	8780 ^{b}	7580 ^{a}	12500 ^{c}
S.kinuyanagi (NB)	0	3.32 ^{b}	11370 ^{a}	4290 ^{a}	115000 ^{a}
S.kinuyanagi (NB)	15	3.67 ^{b}	4600 ^{a,b}	2310 ^{a}	92500 ^{b}
S.kinuyanagi (NB)	32	4.02 ^{a}	4870 ^{b}	2880 ^{a}	60000 ^{a,b}
S.kinuyanagi (NB)	38	4.91 ^{a}	5720 ^{b}	4850 ^{a}	22500 ^{c}
Treatments (Filtrate properties		***			
Original		4.68	10200	2850	32500
Filter paper-Activated charcoal		6.70	16850	595	95000
F.paper-charcoal		4.83	11400	129	92500
Filter paper		4.68	10300	177	70000

* - Species values for a parameter (e.g pH) with the same letter are not significantly different

** - Means (with or without bark) values with the same letter are not significantly different

*** - Pre-disposal treatment oppotunities

5.5 DISCUSSION

Chapter 4 identified differences in properties among species (table 5.3), being associated with genetic variability among the species, and also with the tree growth conditions. Similarly, the minor variations in particle sizes and particle size distribution of the wood chips of different species, despite all samples being prepared and chipped by the same machine suggests that the variation was an inherent property of the species. This differences in chips dimensions were associated with the species tissue structure and chemical composition including the fibre lengths, availability of vessels and wood rays, and the chemical compositions including the distributions of lignin, cellulose and hemicelluloses, together with other non-structural materials. The higher proportion of fines in samples with bark indicated that the chipping characteristics of bark differed significantly from those of wood, again associated with differences in fibre layering, structure, and chemical composition.

5.5.1 DOWNDRAFT AIR GASIFICATION OF SRF WOODY BIOMASS

The Fluidyne gasifier is an autothermal, batch type reactor (Figure 5.4), combusting part of the feedstock to provide the energy required for the gasification process. Under normal operations for the generation of producer gas, it would be a batch process requiring re-filling with feedstock periodically. For these experiments, refilling was not necessary as the aim was to compare the performance of the different fuels, and to monitor the effects of mass loading on the product gas. Feedstock flow and movement into the pyrolysis and gasification zones within the gasifier was by gravity following the utilisation of the feedstock in the gasification zone.

The gas components monitored - CO, CO_2, N_2, H_2, and CH_4, were equilibrium products from the gasification of biomass. Under stable equilibrium conditions, the process may be presented as:

$$\begin{aligned} CH_{\alpha}O_{\beta} + yO_2 + zN_2 + wH_2O = {} & x_1 C + x_2H_2 + x_3H_2O + x_4CO \\ & + x_5CO_2 + x_6CH_4 + x_7C_{\mu}H_{\pi} + x_8O_2 + x_9N_2 \end{aligned}$$

where $CH_{\alpha}O_{\beta}$ represents biomass, $C_{\mu}H_{\pi}$ represents the higher hydrocarbons starting from ethane; and y, z, w and x_i are the molar numbers of the various components. Theoretically, zN_2 is equivalent to x_9N_2, i.e. the inert nitrogen contained in air used in the process.

Each of the products components in this general reaction is formed through different reactions, and under different conditions (see section 5.2.1, and table 5.1). Carbon monoxide was formed via a combination of the endothermic Boudouard, water gas shift, reversible water gas shift, tar cracking, and char gasification reactions. Hydrogen formation, like carbon monoxide, was also endothermic and involved the reversible water gas, tar cracking and water gas reactions. Methane and carbon dioxide formation reactions are both exothermic with the latter providing the energy required for the formation of carbon monoxide and hydrogen.

Ethane (C_2H_6), the heaviest hydrocarbon considered was not detected in almost all samples collected. It represents one of the non-equilibrium gases from the process. Other non-equilibrium components (such as those that may have been continuously vaporising from the tarry substances often collected on the cooler surfaces of sampling bottles e.g. phenols, cyclohexanes, benzene, as well as oils and tars) were disregarded, being in low volumes or not being readily combustible. They were thought to have an insignificant effect on gas heating values. No effort was made to detect these heavier hydrocarbons which were concluded to be present in very minute quantities, if at all.

Since nitrogen forms about 0.1% of the total wood dry weight (Desrosiers, 1979), and is easily volatilised on wood drying, its contribution to the overall nitrogen content in the gas was assumed to be insignificant. The nitrogen component of the gas was that carried over from the air used as the gasifying agent while the carbon dioxide component was generated from the exothermic pre-combustion and pyrolysis reactions which also generated large quantities of water. The CO_2 participates in the Boudouard, and in the water gas shift reactions, and also in the tar cracking reactions to generate CO and H_2. Water (H_2O) on the other hand is utilised in the carbon steam, the reversible water gas, water gas shift, and in the tar cracking reactions to generate CO and H_2 (see section 5.2.1, and also table 5.1). Residual water forms the condensate residues.

Gasifier operating conditions

From the general reaction of biomass gasification above, and from the observations made (see section 5.4), the process of downdraft air gasification is an interaction of many factors. The interaction may be presented as:

$$f(\alpha, \beta, p, T, w, ER, X) = 0$$

> where α and β denote inputs of hydrogen and oxygen in biomass feedstock ($CH_{\alpha}O_{\beta}$); p and T denote pressure and temperature, respectively; w was the feedstock moisture content (dry weight); ER the equivalence ratio representing the quantity of air used per unit feed; and X represents the composition of the gasification products, i.e., $X \equiv x_1, x_2, x_3, ..., x_9$.

This relationship indicates that the nature of the gas product was a function of the type of biomass (through α and β); gasification conditions (p and T); moisture in biomass, w; and the quantity of air admitted through the equivalence ratio (ER). The fact that air flow into the gasifier was by suction, indicates that the reactions took place under partial vacuum. The minor pressure differences (monitored across the gasifier bed), were not expected to influence the products of gasification under proper operating conditions. Measurement of pressure only indicated the flow of materials across the bed.

The aim of the gasification study was to understand the factors which lead to the maximisation of CO, H_2, and CH_4 outputs in the general reaction equation above, incorporating α, β,T, w and ER, and by evaluating the interactions of these factors. Variations in temperature and air flows in the different runs (tables 5.5 and 5.8) indicated the differences among the gasification of the various feedstocks tested.

Section 5.4 showed the relationships between feedstock moisture content, equivalence ratio, and peak temperature on the gasification processes and products (input and output flows, gas composition, and heating values). The graphs in figures 5.15-5.20 and 5.23 show actual laboratory data fitted to linear models including those for the product gas yield, gas composition, and gas heating values. The results of gas yield, gas composition, and products distribution may be related to the theoretical product gas distribution from a 'model wood/cellulose' ($CH_{1.4}O_{0.59}$ containing 51% carbon, 40% oxygen, and 6% hydrogen), derived from stoichiometric relationships in the reactions of wood with air. The weight distribution of inputs and outputs from these reactions is shown in table 5.12.

1. Pyrolysis (ER=0):
$$CH_{1.4}O_{0.59} = 0.64\ C_s + 0.44H_2 + 0.15H_2O + 0.17CO + 0.13CO_2 + 0.005CH_4$$

2. Ideal gasification (ER = 0.275)
$$CH_{1.4}O_{0.59} + 0.29O_2 + 1.1N_2 = 0.63H_2 + 0.9CO + 0.1CO_2 + 1.1N_2 + 0.07H_2O$$

3. Combustion in excess air (ER ≥ 1)

$$CH_{1.4}O_{0.59} + 1.05O_2 + 3.99N_2 = 0.15H_2 + 0.67H_2O + 0.11CO + 0.89CO_2 + 3.99N_2$$

Table 5.12 **Theoretical products distribution in thermochemical processing of biomass**

	Inputs (g)			Outputs (g)						
Process	Wood	O2	N2	H2	H20	CO	CO2	N2	CH4	C
Pyrolysis	1.000	-	-	0.039	0.118	0.208	0.250	-	0.004	0.336
Gasification	1.000	0.406	1.349	0.055	0.055	1.103	0.193	1.349	-	-
Combustion	1.000	1.471	4.891	0.013	0.528	0.135	1.715	4.891	-	-

The table 5.12 shows that under ideal gasification of 1 g of wood, up to 1.158 g of combustible gas (H_2 and CO), or 42.11% of total outputs, may be generated. The combustible components provided up to 40% (molar volumes) from oven dry feedstock, declining to 31% from air dry, and to 19% from wet biomass samples with a moisture content of 40% (wet basis). These variations indicated that the conditions of gasification in the present study were not ideal, and that the efficiencies of conversion were low. For instance, the equivalence ratios obtained (tables 5.5 and 5.8) were low, even for oven dry samples. One explanation for the discrepancy may be that the wood used in theoretical derivations assumed a fixed composition ($CH_{1.4}O_{0.59}$). In reality, wood is more complex, having three main building blocks (cellulose, hemicellulose and lignin), with other components like extractives and ash.

Other products identified in the present work included methane (and ethane in negligible quantities), indicating the significant contribution of pyrolysis to the overall gasification process and products. The presence of ethane shows the availability of non-equilibrium products in the gas as outlined above.

The combustion reaction defines the fuel stoichiometric air requirements, and shows that complete combustion requires 1.476 g O_2/g wood, equivalent to 6.364 g air/g wood. Gasification on the other hand requires 0.406 g O_2/g wood, being equivalent to 1.755 g air/g wood.

Sample (mass) loading

Figure 5.9 showed that the instantaneous rate of feedstock use declined with time of run. Further, the peak temperatures in all tests decreased soon after full load (e.g. see figure 5.11 and 5.14). This indicated that the reaction occurred more rapidly when the mass in the reactor was higher, resulting in a higher heat release leading to the higher temperatures.

The quantity of fuel in the gasifier controls the total system pressure and the vapour phase concentrations of the volatile pyrolysis products. This changing phase concentrations define the effects of mass loading, and show that as the quantity of feedstock in the reactor reduces, the reactions proceed at a slower rate. Although these variations did not appear to affect gas composition, they reduced the gas production rates which could therefore be directly associated with the changes resulting from the single loading of the gasifier. If the volume of the fuel contained in the hopper could be maintained automatically using a continuous feed system, some of the variations could probably be reduced.

5.5.2 PRODUCTS OF BIOMASS GASIFICATION

Three product categories were identified - gas, solids and liquids. A fourth product, sensible heat, was not quantified but may be harnessed in a co-generation set-up to provide on site industrial heating.

Product gas

The quantity of gas produced per unit weight of dry feedstock gasified, 1.88-2.89 g/g for dry feedstock rising to 4.27 g/g in wet feedstock showed the quantities of gas achievable from a unit mass of feedstock. This rates compared well with those reported previously (ESMAP, 1990; Schoeters *et al*, 1981; Williams, 1996; see section 5.2.2). The gas, dominated by nitrogen (51-62%), carbon monoxide (19-26%), hydrogen (8-13%), carbon dioxide (7.5-10.6%) and methane (1.8-2.6%) showed that the processes were dominated by gasification reactions (table 5.1) resulting in stable equilibrium products.

Both product gas and stoichiometric gas-air mixture heating values were a function of the gas composition. Using the constituent gas heating values and the total gas molar volumes, it was possible to determine the significance of each component in terms of its contribution to the overall heat values of the product gas: CO, 45-59%; H_2, 25-34%; and CH_4, 13-25%. The high contribution of methane relative to its proportion in the gas (1-3% of the total gas molar volume) was due to its higher heat value (891 kJ/mol), compared to either hydrogen (286 kJ/mol) or carbon monoxide (283 kJ/mol). Higher gaseous hydrocarbons were insignificant, with ethane failing to register in any of the samples. Since neither N_2 nor CO_2 contributed to the heating value of the gas, they could be regarded as inert fillers.

The gas compositions obtained in the present study differed from those reported from other downdraft gasification studies particularly with respect to the proportion of nitrogen and hydrogen, (table 5.2)[§]. The gas components identified however, were stable equilibrium products, and indicated that the residence times, and the temperatures obtained permitted adequate time for completion of the reaction prior to gas exit. Although the gas heating values from air dry and oven dry feedstock (4.602 - 6.112 MJ/Nm^3, table 5.6) were comparable to those reported in other studies (table 5.2), they contained less H_2, and higher CO and CH_4 contents. This was considered desirable for use of the gas in internal combustion engines as the net energy content of the engine gas mixture remains relatively high since less energy is taken up in the process of water formation in the engine. The heating value of the gas obtained, and the associated stoichiometric gas air mixture heating value (2.241-2.524 MJ/Nm^3) showed that the gas was of acceptable quality for operating internal combustion engines, previously shown to require product gas with a minimum heating value of 5 MJ/Nm^3 (Moersch *et al*, 1996).

Although the tar cracking and reforming processes is complex and difficult to predict (as it relies on the nature of hydrocarbon resulting from the pyrolysis processes), the accumulation of tar in the sampling bottles, and in the cooler surfaces of the flare fan could not be explained since the gas exit temperature (T_V) exceeded the tar cracking temperature (>700°C) in most runs. This presence of tar, despite the high temperatures in the hearth, and at the gas exit suggests that some tars formed by the thermal treatment of biomass are resistant to further chemical disintegration, resulting in traces of tar in the gas regardless of the temperature. This phenomenon, together with the associated influence of species and other gasification conditions requires further investigation.

[§] Although the design of the gasifier was not considered in this study, some of the differences were associated with the design and configuration of the gasifier, influencing the modes of fuel and air delivery. Other differences could be associated with differences in feedstock used. Again, this was not considered as it was not possible to test the feedstocks used previously

Solid residues

Since solid residue generation was not sensitive to the nature of the feedstock material, the quantities produced were not emphasised as they depended on the period of reaction, time of stoppage, and the initial batch feeding system, including the quantities dropping out through the fuel grate. Similarly, the type of residue generated did not indicate the degree of reaction as they varied from raw wood chips, torrefied wood, to charcoal and ash. Slagging of the ash resulting from the fusion of base metal oxides was not experienced in the experiments, perhaps since the ash content of the biomass materials used was low, ranging from 0.8-1.7% on dry weight basis (Table 5.3, and chapter 4).

Liquid residues

The quantity of liquid residues generated, 1-3.9 kg/h, equivalent to 20-80 g/kg of dry gas produced, indicated that appropriate disposal systems for these significant residues have to be planned along with intended gasifier installations. The reduction in the quantities of liquid residues produced from the gasification of feedstock with lower moisture content showed the efficiencies in conversion which was also associated with higher reaction temperatures. Indeed the quantity of liquid residues generated at higher temperatures was less than the total water input evaluated as the net water formation (NWF).

NWF had a significant bearing on the energy balances of the gasification processes as it indicated the quantity of hydrogen withdrawn from the reaction to form water in combustion reactions, and also in water gas shift reactions (Table 5.1). The water formed, together with unreacted feedstock moisture was then mixed with condensable tars and oils while dissolving some of the solids in the ash. The low yield of liquid residues at high reaction temperatures was a result of increased cracking of reactive tars and enhanced reaction of char which consumed additional water in the water gas shift reactions.

The properties of the liquid residues (table 5.11) indicated that it would be unacceptable to dispose of the liquid wastes from gasification into water-ways, or onto land without pre-treatment. Thus, characterisation of the liquid residues was also aimed at determining the disposal requirements. The results also indicate the efficiencies of gasification, and also show the nature of the original feedstock.

The pH of the condensate indicated the quantities of dissolved salts, which was a reflection of the level of combustion reactions. High pH showed a high concentration of dissolved metallic oxides and salts, which could show the extent of combustion reactions resulting from excessive air supply leading to combustion. A low pH implied insufficient oxygen supply during gasification leading to pyrolysis reactions producing pyroligneous acids which dissolve in the water of reaction. Trapping of the carbon dioxide in the water (both reaction and feedstock moisture) may result in the formation of carbonic acid which may reduce the pH, but which could also reduce the ash content from the combustion reactions, by reacting with the metallic salts/oxides leading to further reduction in the pH.

Condensate COD indicated the amount of oxidising agent used to break down organic matter under strongly acid conditions at 150°C, and measured the organic material present. The high COD values indicated that large quantities of organic carbon were present, and indicated a reduction in the overall efficiencies obtained as each carbon atom withdrawn from the product gas indicate losses in energy.

Of the four tests on the liquid condensate (Table 5.11), pH provided the more comprehensive indication of the gasification process, and could therefore be correlated with other factors like the quantities of air used (ER) and temperature to indicate the efficiencies of gasification, and or to predict the nature of products. The lack of significant difference between condensates produced from the gasification of the various species, with and without bark showed that the variation in properties associated with the different feedstocks did not impact on the nature of the liquid residues. However, the differences resulting from the feedstock moisture content levels suggest that the nature of the liquid residues was associated with the actual process of gasification.

In the absolute absence of air, woody biomass undergoes pyrolysis generating pyroligneous acids, charcoal, water, and a mixture of gases. Although the liquid condensate was not analysed to identify its composition, it was believed to be rich in pyroligneous acids and condensable tars (rich in phenols) from the pyrolysis reactions. These materials were dissolved in reaction water resulting in acidic pH. However, in conditions of excess air supply, i.e. combustion, the most prominent products tend to be CO_2, H_2O and ash. Although the CO_2 may dissolve in the water to form carbonic acid, the ash dissolved in water predominates to provide an alkaline pH. Optimum gasifier operation at controlled air supply conditions limits combustion reactions, and therefore limits the formation of CO_2.

The increase in pH, increase in conductivity and decrease in the turbidity following filtration through activated charcoal (section 5.4.9; table 5.11) was associated with the adsorption capabilities of the fine char, associated with the high surface area volume relationships. The higher COD of the filtrate from activated charcoal was associated with the minute nature of the particles which slipped through the watman filter paper, and therefore contributed to the COD. These results provide good opportunities for tackling a serious problem of liquid residues disposal in a biomass gasifier system.

5.5.3 MASS AND ENERGY BALANCES

Elemental balances were not undertaken as the wood species elemental composition was assumed to be uniform within limits over the range of species, and both the solid and liquid residues were not separated into their constituent parts - i.e. the solid residues were not separated into ash, charcoal etc. while the liquid residue was not distinguished into tars, water etc. Senelwa *et al*, (1996) previously determined the tar content by drying the condensate trapped at 80°C to constant weight. The difference between initial and final oven dry weights of the trap were regarded as the tar content, estimated to be less than 1% of the total output weight. Similarly, ash output was not measured, but could be calculated from the reaction rates, and the ash contents of the feedstock.

Although the material balance closures should conform to the law of conservation of mass, the masses between the inputs and outputs did not balance indicating that the conversion efficiency was not 100%. In some runs, mass balances exceeded 100% indicating that there were materials flowing into the system, (possibly air) which was not measured. Test runs with closures of less than 100% indicated losses which could be attributed to masses of fuel converted to sensible heat (generated by the combustion reactions) since the reactor used was autothermal. According to Chern *et al,* (1989), complete closure is rarely achieved for real processes, partly due to the inherent variability in woody materials, measurement errors and system fluctuations. Part of the heat drives the pyrolysis reactions, while the sensible heat is lost to the atmosphere.

Measurements of weight loss of the entire system to assess the gas yields was accurate. Since the gasifier was batch fed, and was sealed after filling and prior to firing, leakage problems, as encountered by Graboski and Brogan (1988), with air leaking through the screw feeder were not encountered. Problems associated with using nitrogen tracer techniques to calculate air and product gas flow rates were not experienced since air flow rates, and the apparent change in weight were measured directly.

Energy balances

The energy contents of both waste streams (liquid and solid residues) could not be ascertained since their respective compositions were not determined. Further, the energy lost as sensible heat was not estimated. Consequently, it was not possible to determine accurate energy balances of the system. The main interest was product gas, and the yields of this were used to determine overall system efficiencies measured as cold gas efficiency. The energy lost as sensible heat to the surrounding could be harvested using a co-generation system - an option which could be considered in industrial gasification applications.

5.5.4 ENERGY CONVERSION EFFICIENCIES

The performance of the gasifier in the present study was evaluated by (i) gas yield defined by weight (converted to volume) per unit weight of feedstock on a dry basis; and (ii) gas quality, defined by the heating values of both pure gas and the stoichiometric product gas-air mixture. Other performance indicators included the proportion of combustible component, and the CO/H2 ratio. These measurements were used to derive the cold gas efficiency (CGE).

Maximum CGE was obtained when both gas yield per unit weight of feedstock (g/g of dry feedstock) and product gas heating values were optimised. This coincided with high equivalent ratios resulting from higher air flow rates. Overall, the CGE values of 46-74%, with a mean of 60% was low, even though the values were comparable to those reported previously (e.g. Corella *et al*, 1991, and Baker *et al*, 1984). This low energy conversion efficiency was attributed to the fact that (i) some of the feedstock energy was retained in the solid residues, and also in the tarry liquid condensate which also had suspended solids of carbon particles; (ii) other energy was lost as sensible heat to the surroundings; and (iii) a significant proportion of the energy was used to drive the endothermic conversion reactions (table 5.1), as the reactor was autothermal. Reasons for the extreme cold gas efficiencies values i.e. the highest and lowest values were not clear but (i) the low values of 46-55% were obtained when the equivalence ratios were low (0.195-0.229); and (ii) the high values of 66-74% were obtained at near optimum ER values of about 0.275.

5.5.5 FEEDSTOCK CHARACTERISTICS

Section 5.4.3 and table 5.7 showed that the feedstock properties (table 5.3) were correlated with both process and products of gasification (including the properties of the liquid condensate, Appendix 5.3). The different properties influenced different aspects of gasification, including products distribution to varying degrees.

Basic density

The heat capacity and heat transfer of biomass materials are both dependent on the density defined by the void volumes (Section 5.2.1). Thus, the percentage of vessels in the structure of the biomass influences the ease with which primary volatiles can escape from a pyrolysing chip. Any blockages to such movement may result in the "cracking of the hydrocarbons of the volatile matter" (see section 4.5.1; and also sub-section on volatile matter below), resulting in pyrolytic carbon which is often difficult to gasify. These differences could be responsible for some of the differences in gas yields among species, but the poor correlation between basic density and gasification parameters (Table 5.7) contradicts this understanding, indicating that variations in vessel volume did not influence the gasification processes.

Ash

Since the feedstock used did not have high ash contents (Table 5.3), the effect of ash content on the reduction of the actual organic matter which forms the actual available substrate for the formation of gas was not significant. Also, slagging was not observed in the present experiments probably because all feedstock used had ash contents below 6% of the total dry weight, and also probably because the temperatures used did not exceed the melting point of the ash present.

The marginal increase in ash content within the range used however exhibited higher reactivity resulting from the catalytic effects of ash in thermal reactions of biomass. These catalytic effects of ash resulted in relatively higher air flows and higher gas yields. The reactions involved extended residence times, reduced liquid residues production, and the gas produced had relatively high heat values due to the high gas H_2 and low N_2 content. Consequently, the cold gas efficiency was high.

Ash from biomass may catalyse the water gas shift and the char steam reactions resulting in higher gasification rates and product yields (Fung and Graham, 1979; Herguido *et al*, 1992). The differences in the type and quantity of ash in the biomass also determines the extent of catalytic activity as shown by Herguido *et al*, (1992) when they compared gas yield from straw with wood chips and thistle in steam gasification.

Volatile matter content and fixed carbon content

Gasification of high volatile matter (VM) feedstocks is characterised by the generation of pyrolytic volatiles at low temperatures. These volatiles react with air in combustion reactions, resulting in high temperatures, and leading to the formation of H_2O and CO_2 from the oxidation of H_2 and CO. This combustion, rather than secondary gasification of the pyrolysis products results in the suppressed heating values of the gas generated, and the cold gas efficiencies, but insufficient tar cracking leading to high tar contents in the product gas. For such materials, the gas phase gasification reactions do not play a significant role in the determination of CO content in the gas as most of the volatiles undergo combustion reactions before reaching the secondary reaction stage.

The degree of volatilisation of different materials determines the suitability of feedstocks for gasification associated with the cellulose contents, and also of the structure of wood determining the flow of volatiles on heating. This suitability is dependent on whether the volatiles generated undergo secondary reduction/gasification, or undergo combustion reactions. It was expected that the gasification of wood, and of wood and bark would be different. The minimal variations, particularly among species was due to the low variation in the VM of wood especially.

Sections 4.2.1 and 4.5.1 showed the variations in volatile matter and FCC in different species, and associated the differences to the structure of wood, illustrating that the porosity of materials determine the flow of volatile materials from a pyrolysing wood chip. During carbonisation, the volatile matter evolved collides with the pore walls and reaction surfaces. The collisions enhances the cracking of the hydrocarbons leading to production of hydrogen and pyrolysis carbon (Kumar and Gupta, 1997). However, the results obtained from the different species did not show these effects, suggesting that the structure of the species used was not very different.

The effects of fixed carbon content (FCC) were a mirror image of the effects of volatile matter content because the quantity of fixed carbon is dependent on the determined volatile matter content. Therefore, high FCC feedstocks were associated with suppressed temperatures (except at T_V). This resulted in the production of a gas rich in H_2 and CO, but low in N_2, CH_4 and CO_2, showing that the dominant reactions were the reversible water gas, tar cracking, Boudouard, and water gas shift reactions. This effect of both VM and FCC shows the importance of the two major reaction stages of gasification, and the role of feedstock. Optimum gasification requires that the reactions proceed in defined stages to optimise each product, since the secondary gas phase reactions rely on earlier reaction products. The feedstock should pyrolyse generating proportional quantities of both volatiles and char to participate in the gas phase reactions to enhance generation of CO.

Extractives

The role of feedstock extractives in enhancing gasification temperatures, and in the production of a gas with lower contents of N_2, but higher H_2, CH_4, and CO_2 and therefore high gas heating value, was not clear. Although it is possible that most extractives are easily volatilised and then consumed in combustion reactions immediately after pyrolysis, the most likely explanation is that some of the extractives are catalytic and selectively enhance the production of hydrogen in the water gas shift reaction, and methane in the methane formation reaction without involving air and the reduction of CO_2.

Feedstock heating value

The influence of feedstock heating values on the gasification process was not apparent partly because the variation in the heating values of the species tested was not significant. The suppressed heating and pyrolysis temperatures (T_I - T_{II}), higher char gasification and tar cracking temperatures (T_{III} - T_V), coupled with shorter residence times, suggested that the pyrolysis of high

HHV feedstock occurs at low temperatures, and the volatiles produced react generating large quantities of heat without requiring large quantities of air. Since air requirements are suppressed, the quantity of gas produced was also reduced, and had lower N_2 but higher H_2 and CO contents. For the dominant products, i.e. H_2 and CO, the dominant reactions included the reversible water gas and tar cracking reactions.

Interactive effects

Although the differences observed in gasifier performance for different species were assumed to indicate inherent differences among the species, and therefore provided a means of identifying the suitability of a species for gasification, the process of gasification involved the interaction of many variables and none of the measured feedstock properties had an overwhelming influence on the process and products of gasification, with correlation coefficients being less than 50% (see table 5.7). This suggested that feedstock properties do not act in isolation. Thus, isolation of the effects of specific properties over certain aspects of the process was difficult, and the differences observed in tables 5.5 and 5.6 may not be attributed solely to the species differences. Also, the presence of bark in the feedstock did not significantly influence the gasification processes and products.

5.5.6 TREE SPECIES

Of the tree properties listed in table 5.3, basic density and bulk densities had the most variability among the species. Chapter 4 (table 4.2) showed that there were distinct categories with no apparent overlaps in the basic density of the species tested. All other properties were characterised with overlaps, and the range between the lowest and highest values (standard deviation) were not as dramatic as for density. Unfortunately, though density could be used to characterise the different tree species, both basic density and bulk density of the feedstock had very poor correlation with process and products of gasification (see sections 5.4.3 and 5.5.5). One reason for the lack of correlation was the fact that all measurements were based on the mass of feedstock and not volume, and that the dry matter involved in all the species, regardless of their densities, was similar.

The variations observed in the gasification of the range of SRF fuelwood materials (Tables 5.5 and 5.6) reflected the differences in the properties of the feedstock (table 5.3; also see chapter 4).

The main differences observed in the gasification processes were the temperatures, particularly in the gasification, char reduction, and tar cracking regions (T_{III} and T_{IV}). The differences observed in the gasification and tar cracking zone temperatures (T_{III} and T_{IV}), appeared to be associated with the volatile matter content of the feedstock (see section 5.5.5). These variation, which does not appear to have been reported previously suggests that species differences affect the process of char reduction, and indicate that the different species produce chars with different structures.

The insignificant differences in the heating/drying and pyrolysis zones (T_I and T_{II}) suggested that both heating/drying and pyrolysis processes were not sensitive to species differences. These observations contradict the heating/drying theories (see section 5.2.1) which showed the processes to be a function of the density (and void volume). The heating/drying theories are probably applicable within the range of water boiling temperatures, and not beyond 170°C registered at T_I. Variations expected in the pyrolysis zone (T_{II}) were not observed. Ash contents of the different species were not significantly different, and therefore did not influence the drying, heating or pyrolysis temperatures.

The proportion of bark in the feedstock did not result in major differences in both the processes and products yet the properties of bark were shown to be significantly different from those of wood alone (see chapter 4). The variation in the temperatures between feedstock moisture content and whether with or without bark conforms to theoretical expectations (see section 5.2.1) as does the influence of moisture content (section 5.2.6 and 5.5.8). The inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock when compared to debarked samples.

The fact that different species of wood exhibited different temperature profiles with the reactions having different temperature peaks; and since the gasification rates, and the flow of materials (inputs and outputs), and that there were differences in the gas mixtures indicate that wood properties influence (i) the charring and gasification characteristics, (ii) the level of gas yield when the material is gasified; and (iii) composition of the product mix as outlined in section 5.5.5. The significant differences in the species, with regard to feedstock flows when considered on a volume basis have major implications on the design of feeding systems for future automation.

The overall variation in the quality of gas from each of the species, and determined by the heating values (MJ/Nm^3) of both the product gas and of the stoichiometric mixture of the product gas and air, (table 5.6) showed the differences in the gasification characteristics of the species. The close similarity in gas type was due to the fact that the properties which significantly influence the gasification processes did not vary significantly. Differences in the feedstock (by species, with or without bark, and moisture content levels) also showed significant differences in the nature of liquid residues due to the differences in the chemical composition of the feedstock (e.g. ash content and type), and the effect of the feedstock type on the gasification process. Higher pH of the liquid residues associated with high residence times, hearth load and high equivalence ratios, and a gas with high CO_2 showed high combustion reactions which led to high temperatures.

5.5.7 INFLUENCE OF FEED PARTICLE SIZE DISTRIBUTION AND BULK DENSITY

It was expected that differences in particle sizes and size distribution, which also influenced the bulk density, would influence the process and products of gasification. The insignificant differences in the gasification of the three particle size ranges in this study (despite the influence of particle size on volatile matter content, section 4.4.4, table 4.6) showed that the behaviour of the materials was identical. This similarity could be (i) due to the fact that the range in particle sizes used was too narrow; and (ii) due to the similarity in the mass transfer mechanisms which tend to be identical in powders and chips from the same source. Further, it is possible that the heat transfer was not a limiting factor for the particle size range used, which showed that the macro-pore structure of the chips did not affect their reactivity at the temperature range used. It also indicated that the same micro-pore structure exists in both powdered and larger size particles when pyrolysed.

Wood burns in the gaseous state, and the rate of combustion is proportional to the time it takes the required heat to reach and ignite the volatile constituents which in turn is dependent on the surface area per unit volume of fuel. Since particle size influences heat transfer particularly during the pyrolysis stages of gasification process (see section 5.2.1), coarse particles have lower heating rates. Thus, pyrolysis occurs at lower temperatures compared to the smaller particle which have a high effectiveness factor which defines the particle-oxidant contact. This effect is more marked in the second step of char gasification involving steam and gases produced during pyrolysis. For small particles therefore, the char produced is highly porous, with an effectiveness factor tending towards unity whereas char from bigger particles has smaller surface area/volume ratio. However, the size of voids in the bed decreases as the particle size is reduced. A point is reached when individual voids become so small that the resistance to passage of combustion air and gasification products is severely limited. Consequently, the volume and velocity of excess air through the furnace must be increased. This results in the loss of a considerable amount of heat energy to raise ambient air to exhaust temperature and the high velocity may cause entrainment of light fuel particles in the flue gas. Then, higher reactivity advantages of smaller particles is probably overshadowed in practice by the resistance to gas passage, and to the fact that fines in wood chips are associated with non wood components including bark and inorganic particles.

Smaller particles increase the pressure drop through the fuel bed, and may influence the oxygen penetration depth leading to a lower air/wood ratio which indicates that less air is used (Appendix 5.3) and that the gasification rate is reduced. This may lead to incomplete gasification of the material, resulting in an increase in the quantity of charcoal collected from the ash chamber, and production of a gas with a high tar content. Larger particles on the other hand may cause bridging within the hopper and incomplete carbonisation because of the fuel residence time in the carbonisation zone being too short, together with excessive void space.

For optimal operation of a downdraft gasifier, the fuel size range distribution should be as narrow as possible to give a uniform fuel bed. If the size range is too wide, the air and gases are drawn through an uneven fuel bed caused by separation of the fine and coarse particles. This leads to hot and cold spots which may in turn lead to channelling (where the fuel is selectively burned through the bed in regions of least air resistance). If the particles are too small, the temperature in the fuel bed varies more widely with height, and might lead to channelling where flames are drawn downwards in forced convection by suction. This results in poor oxidant distribution across the reaction zone allowing pyrolysis products to pass directly through the bed, thus reducing the gasification efficiency, and may lead to a gas with high tar content.

Although chips bulk density was previously regarded as a critical property for wood chips used as a fuel in combustion systems (section 5.2.8), it did not have a significant effect on the gasification result in the present study, probably because the range in chip sizes was too limited.

5.5.8 THE ROLE OF HIGH TEMPERATURE

The temperature profile and fields (figures 5.11, 5.14 and 5.21; and table 5.5) showed that the highest temperatures were recorded next to the air nozzles, and in a narrow band (T_{III} and T_{IV}). Further, figure 5.21 showed that the different temperature bands define the gasifier reactor zones, while figure 5.23 demonstrated that average gas compositions and quality had linear relationships with gasification temperatures. The moderate temperatures above the air nozzles (at T_I and T_{II}) confirms that the dominant reaction in this zone was pyrolysis generating char, pyrolytic gases and water. The high temperatures directly in front of the air nozzles resulted from the exothermic combustion and flaming pyrolysis reactions following air injection. Under this condition, biomass is converted into char, water vapour and carbon dioxide. These high temperatures also crack the tar formed in the pyrolysis zone thereby reducing the tar content of the product gas by breaking it into simpler combustible molecules (H_2 and CO) which increases the heating values. Since the tar cracking reactions are endothermic, they provide a "heat sink" which reduces the temperature to below 900°C. The reduction in temperature slows down the rate of reaction until it becomes insignificant below 600°C in the exiting gas stream. At this temperature, the reaction almost ceases, "freezing" the reduction reaction. The decline in temperature towards the grate also signifies char reduction with H_2O and CO_2 to form CO and H_2 in the reversible water gas reaction.

The peak temperature zone and the immediate drop defines the region of oxygen exhaustion in the gaseous stream and therefore defines the end of the combustion/oxidation reactions, and indicates the point where the system changes from being net exothermic to net endothermic. The effect of high temperature on the different reactions, e.g. the formation of H_2 and CH_4 at moderate gasification temperature similar to pyrolysis reaction temperatures, compared to the high temperature requirements for the secondary gas phase and tar cracking reactions producing CO demonstrates the importance of correct temperature profiles within the reactor.

The gasifier should be designed to match specific temperatures with the major gasification reactions. Temperatures in the drying/pyrolysis zones (at T_I and T_{II}) should not exceed 400°C / 700°C as this indicates combustion reactions of the pyrolytic volatiles resulting in low CO and high N_2 gas content (as observed for oven dry *P.eridano* with bark, tables 5.5-5.6). Such temperatures indicate that the volatiles are burnt, and therefore not available for subsequent gas phase reactions. However, these drying and pyrolysis temperatures should not be as low as those obtained for air dry *A.dealbata* with bark.

The highest temperatures should be obtained beyond the pyrolysis stage (at T_{III}, resulting from air injection) to provide the energy required for endothermic gas phase and tar cracking reactions. Due to these reactions, the temperatures should decline towards T_{IV}, reaching about 700°C at the grate i.e. exit gas temperature. Variations to this profile indicate variations to the bed dynamics, and that the products of gasification would be unpredictable. This explains some of the differences observed in the gas quality of samples drawn at different times within any one run. For instance, oven dry *P.eridano* with bark had very high temperatures at T_{II} to T_V at 30, 60 and 65 minutes. The gas obtained during such variations had low contents of both CO and H_2, but had high N_2 content showing that the volatiles generated did not take part in the gas phase reactions.

The proportion of CO present in CO/CO_2 mixtures in equilibrium with solid carbon (charcoal) increases with temperature between T_{II} and T_{IV}. This indicates that CO formation is not limited to the primary decomposition reactions which occur at lower temperatures, but it is also a major product of the secondary cracking reactions of tars at elevated temperatures, and the endothermic Boudouard reaction. It also explains the lower production of both CO_2 and liquid condensate at higher temperatures.

The marginal variations in the quantities of H_2 and CH_4 with increasing temperature suggests that these gases were generated in the primary reactions which occur at low temperatures. These observations reflect the influence of temperature profile in the gasification of biomass, indicating that very high temperature are mostly crucial in the secondary gas phase reaction zones. However, the secondary reactions which contribute to CO are finite, being determined by the available CO_2, and temperature.

Although gasifier operating temperature determines equilibrium composition of the gas, it was not an independent variable. It depended on the particle size; the moisture content; the fuel type (ash content, extractives, volatiles and heating value); and the equivalence ratio (ER). Due to the effects of temperature on gas composition, it is concluded that high temperature was essential for the production of a high heating value gas. Temperature controls the chemical equilibrium and kinetics of gasification, influencing the product gas composition, quantity, tar yield, and overall gasifier performance.

Variations in temperature

The cyclic variations in temperature (e.g. see figures 5.11 and 5.14), especially near the nozzles (at T_{III} and T_{IV}) were related to the changes in air flows (e.g. see figures 5.9 and 5.13), and indicated rapid reactions involving all reactions in table 5.1. These cyclic variations were due to:

i) the heterogeneous nature of the wood material leading to localised (in-situ) variations in reactions and reaction rates resulting in localised adjustments in the temperature profiles;

ii) the non-uniformity in the processes of fuel delivery, settling and breakdown related to the heterogeneous, and also the anisotropic nature of biomass resulting in differences in its thermal, chemical and physical properties (Chapter 4, and table 5.3); and

iii) the fluctuations in air flow/delivery and outlet gas flow.

The similarity in the cyclic movements of the temperatures for the species evaluated shows the similarity in the nature of woody biomass. Figure 5.14 demonstrated the effect of feedstock moisture content on temperature profiles and suggested that the gasifier establishes different operating conditions such as bed depth, based on the nature of the fuelwood material. Changing feedstock properties e.g. moisture content, alters the bed dynamics which influences peak temperature, temperature profiles, and temperature fields achievable with any feedstock. The higher feedstock moisture content shifts the range and position of temperature profiles (table 5.8, and figure 5.14), shifting the highest temperatures towards the grate. The curves resulting from the different moisture contents indicated that the temperatures in the oxidation zone following the introduction of air affected all the other reactions, and so affected the chemical equilibrium as well as the reaction rates, such that the overall peak temperature was reduced.

The lower fluctuations at T_V indicated that the reactions had ceased, and that the gasification products at the grate were in equilibrium. This temperatures (T_V) next to the grate in most tests were higher than 700°C, which is higher than the minimum required for tar cracking. It was therefore expected that the tars should be fully cracked, but this was not the case as the gas contained some tar. Although the temperature at the grate was possibly not uniform. The lower temperature spots could therefore have allowed non-equilibrium pyrolysis products like tar to escape before being cracked. It is also possible that some tars formed by the thermal treatment of biomass are resistant to further chemical disintegration, resulting in traces of tar in the gas regardless of the temperatures.

5.5.9 AIR FLOW AND EQUIVALENCE RATIOS

Figures 5.9 and 5.13 showed cyclic movements in air flows, and indicated that air flow influenced (i) the temperatures of the processes; (ii) gas production rates; and (iii) gas quality. Figure 5.12 demonstrated that air provided the bulk of inputs into the gasifier. Further, the good correlation coefficient (R^2) between product gas composition and heating values provide a quick way of estimating the gas composition and quality if the air flows into the gasifier can be established.

Table 5.5 indicated that the quantity of air used per unit weight of feedstock did not vary significantly among species on weight basis. On a volume basis however, the quantity of air required per unit volume of material was significantly different for each species, ranging from 2 g/cm^3 in high density species to 3.9 g/cm^3 in low density species. This relationship suggests that the fuel - air contact was different in the different species. Although this aspect was not investigated in detail, design of gasification systems may need to take into account the differences in densities of different species.

The ranges of air to feedstock weight ratios observed, 1.42-2.25 for air and oven dry samples, compared well with those reported previously by Chen and Gunkel (1987) of 1.772 for oven dry wood; Walawender *et al*, (1985a), 0.99 to 2.08 using wood chips with moisture content 5.5 - 16.5%; and Garcia-Bacaicoa *et al*, (1994), 2.082. The similarity shows that there was a direct relationship between the amount of air used in the process, and the amount of wood consumed which in turn influenced the product distribution, and gas quality

The equivalence ratio obtained (0.195 - 0.272 in oven dry and 0.211 - 0.328 in air dry samples, with an average of 0.250) was less than the optimum ER (0.275) (see section 5.5.1), and indicated that air flow was not adequate for the rates of gasification. The low ER in oven dry feedstocks suggests insufficient air fuel contact which could result in insufficient gasification reactions, often leading to lower gas yields. The higher ER in air dry samples showed the air requirements for combustion to provide the heat for drying the fuels, and suggested lower energy efficiencies. The effect of air flow (ER) on the gasification of biomass materials was associated with the effect of ER on gasifier temperature. The apparent decline in temperature associated with increasing ER was due to the fact that (i) the feedstocks associated with high ER were often wet; (ii) the increased air flows created a cooling effect on the gasifier; and (iii) excessive air flows reduced the residence times. The temperature of the gas at equilibrium, and just prior to exiting the reactor (T_V) was least affected by the variation in air flows.

Product gas heat value (energy content) passed through a maximum point and then started declining with increasing air flow (figure 5.18). At low air inputs, the calorific value of the gas was significantly lower due to incomplete gasification and the predominance of pyrolysis products in the gas. At higher air inputs, the gas heat value was reduced due to the higher concentrations of non-combustion products in the gas (CO_2 and N_2). Gas yield also increased at higher air factors with a large proportion of the gas being CO_2 and N_2. Although the energy recovery remained unchanged with increasing air flow, the optimum point for gasification is when the product of the gas heating values and gas volume is optimised. When the air to fuel ratio is high, the quantity (%) of CO_2 and N_2 increases which results in low gas heating values. The increased CO_2 results from the partial oxidation of hydrocarbons.

It was apparent that higher air intake was associated with higher temperatures in the oxidation and reduction zones of the gasifier. This may be associated with increased tar cracking, higher CO and H_2, and reduced H_2O and tar content of the gas. Conversely, higher airflow rates imply excessive combustion reactions consuming both the raw materials, and part of the product gas components. This leads to production of a gas with high CO_2 and H_2O, together with the carry forward N_2.

Excessive addition of air (high ER) resulted in consumption of H_2 and CO until combustion conditions are approached at an ER of 1.0. Beyond ER of 0.275, the heating value of the gas approaches zero as the CO and H_2 are consumed i.e. the product gas undergoes combustion. The chemical energy stored in the gas is maximised at an ER of about 0.275 (Figure 5.18), which usually corresponds to complete carbon uptake (table 5.12). By pre-determining the optimum ER of a reactor taking into account the differences in biomass feedstocks, it may be possible to tune the reactor to produce specific product gas distribution for any given application.

5.5.10 INFLUENCE OF FEEDSTOCK MOISTURE CONTENT

Tables 5.5 and 5.6 showed that the processes and products of the gasification of air dry feedstock were significantly different from those of oven dry feedstock while section 5.4.4 emphasised that dry feedstock gasified better than wet feedstock. Increased feedstock moisture content reduced the rates of gasification (dry weight); temperature; and gas quality. Although air flow rates were not statistically affected, the quantity of air per unit dry weight of feed was generally higher, resulting in higher ER. Further, the quantity of reaction water generated per unit of dry feedstock, which also defines the net water formation, decreased (reaching negative values) with increasing moisture content.

Section 4.5.3 demonstrated the importance of drying the fuel before burning it in order to obtain the most heat. Moisture reduces the heat available by (i) reducing the combustion efficiency as heat is absorbed in evaporation of water during the first stage of combustion, by lowering the flame temperature, and consequently reducing radiant heat transfer; (ii) altering optimum temperature profiles leading to thermal imbalance in the reactor by shifting the high temperature gasification zone towards the grate while having lower pyrolysis temperatures; and (iii) by hydrolysis where heating of wood in water which is at or near boiling point promotes hydrolysis of the wood (Mithel *et al*, 1957).

Section 5.2.1 showed that the thermal conductivity of woody materials was a function of wood density-porosity-moisture content relationships and that feedstocks with high moisture content required that extra energy be expended to drive out the moisture. Although the results obtained did not provide clear trends regarding overall thermal efficiencies, water in thermochemical processes is a known thermodynamic dilutant which absorbs large quantities of latent heat during its expulsion in the drying process. Further heating of the particles may therefore be hindered by the heat requirements of moisture evaporation so that pyrolysis takes place at lower temperature and rate leading to higher char yield. Besides, in downdraft gasifiers, the moisture from wet fuels passes through the oxidation zone, leading to lower temperatures. Thus, in the gasification of feedstocks with high moisture content, it gets difficult to reach a high enough temperature to have sufficient CO_2 reduction to CO and tar cracking. As a result, the yield of the gas, as a proportion of the raw material reduces (Kaupp and Goss, 1984).

Since the Fluidyne gasifier was autothermal, the high feedstock moisture content required the combustion of large proportion of the feedstock to provide the heat for the drying processes, thus reducing the achievable conversion efficiencies. Also the gas CO content is decreased while that CO_2 is increased (figure 5.17), partly due to the increased combustion reactions to generate the heat to evaporate the excess moisture prior to the actual gasification reactions (shown by increased ER, table 5.8), and also due to the reduced levels of the Boudourd and water gas shift reactions which utilise CO_2 to generate CO (table 5.1).

Although part of the moisture in the feedstock may be reduced to hydrogen, the largest quantity ends up as moisture in the gas, cooled and collected as condensate. In the present experiments, high feedstock moisture content reduced the % volume of CO but did not increase the quantities of H_2 in the gas, even though the air dry sample appeared to have higher hydrogen contents resulting in marginally higher heating values which resulted in the polynomial trends observed in figure 5.15. This low heat value from oven dried *S.kinuyanagi* compared to air dry samples, was a deviation from the trends observed in other parameters. Use of wet feedstock drives the homogenous water gas shift equilibrium to the right resulting in excessive water in the gas.

The net water formation (NWF) indicates the volumes of water produced in pre-combustion and primary pyrolysis and in the water gas shift reaction (table 5.1). It also shows the liquid condensate formation from the actual gasification processes rather than from the water in the feed. It is a measure of the extent at which hydrogen was withdrawn from the products.

5.5.11 SRF SPECIES FOR DOWNDRAFT GASIFICATION

Although gas composition differed among species, no one species was identified as providing the utmost gas quality desired. This was attributed to the interactive effect of the three main factors identified - temperature, equivalence ratio, and moisture content; and also due to the fact that the species characteristics did not vary over a wide range. None of the species could therefore be ruled out. Similarly, the presence of bark in the feedstock was not found to reduce the quality of feedstock used for gasification.

5.6 CONCLUSIONS

The processes and products of gasification were found to be a function of (i) gasification temperature (ii) feedstock moisture content; and (iii) equivalence ratio (ER) defined by the quantity of air used. High temperature (above 1000°C) produced larger quantities of gas with high heating values. Although high temperature is recommended in the operation of a downdraft gasifier for high quantity (g/g of dry feedstock), and for the production of higher quality gas (high gas heating values), the temperature profiles and fields need to be optimised through appropriate gasifier design to ensure progressive temperature changes to optimise the different reactions constituting the gasification process.

The ER values of 0.195-0.328 (with an average of 0.250) were less than the optimum value of 0.275 and indicated that air flow was not optimum for most runs, resulting in insufficient gasification reactions (tending towards pyrolysis), and lower gas yields. High feedstock moisture content reduced the reaction temperatures; altered the optimum temperature profiles; reduced the available feedstock substrate through hydrolysis, thereby reducing the quantity of gas achievable; and produced a gas with high moisture content, high CO_2 and N_2 content, but lower CO and CH_4 contents, hence reduced heating value.

Variations in properties among the short rotation forestry (SRF) species used was not an important factor in determining the processes of gasification, and did not significantly affect the quantity and quality of gas generated. Also, the gasification processes and products did not vary significantly on the basis of the presence of bark in the feedstock. Similarly, the nature and quantity of solid and liquid residues produced was not sensitive to the species or feedstock properties. This indicated that in a short rotation forestry scheme producing feedstock for gasifier applications, the main objective should be to maximise yield.

The gasification of 1 kg of air dry and oven dry feedstock resulted in the production of 1.88-2.89 kg of dry dust free gas, being equivalent to 2.1-3.0 Nm^3 of dry gas per kg of dry wood. This product gas was dominated by nitrogen, 51-62%; carbon monoxide, 19-26%; hydrogen, 8-13%; carbon dioxide, 7.5-10.6%; and methane, 1.8%-2.5%. The proportion of ethane, the highest hydrocarbon detectable, was negligible in most samples.

The heating values of the product gas and stoichiometric gas-air mixtures defined the quality of the gas. These were significantly higher from the oven dry samples, and also varied with species, ranging from 4.602 to 6.112 MJ/Nm^3 and from 2.241 to 2.524 MJ/Nm^3, respectively. The gas was considered to be of sufficient quality for operating internal combustion engines.

The quantity of liquid residues generated, 70-126 g/kg of wood (or 67-131 g/Nm^3 of gas) was considered high. The characteristics of the residues showed that the wastes were toxic and could not be disposed of directly into waterways or landfills without treatment. A first pre-disposal treatment would be to filter the condensate through the solid residues (charcoal) collected from both the ash port, and the cyclone. This simple treatment has the ability to reduce the pH and the electrical conductivity, thereby reducing the potential harmful effects on the environment.

CHAPTER SIX

OVERVIEW DISCUSSION AND CONCLUSIONS

The study acknowledged that adequate availability of appropriate and sustainable energy resources was a pre-requisite for economic development, particularly for countries with intermediate technologies that tend to be energy intensive. It was held that in Kenya and other developing countries, considerable environmental, technical and economic gains could be made from the adoption of a biomass energy option focusing on thermal gasification for electricity generation. Successful implementation of this option was considered to be dependent on careful evaluation of a range of aspects, each of which could have alternative routes (Figure 6.1).

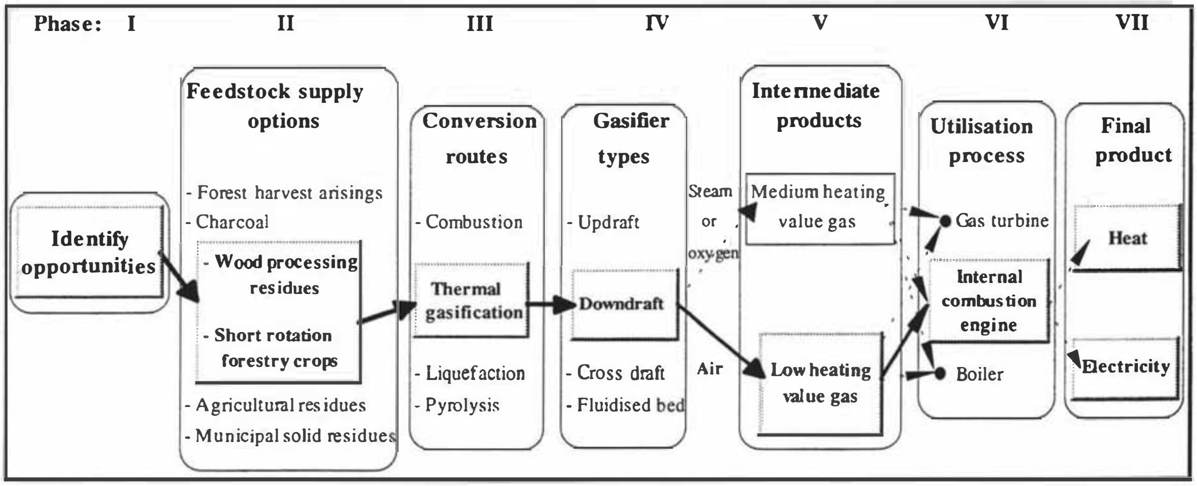

Figure 6.1 **Summary of the main phases necessary for implementation of the biomass gasification option for electricity generation**

The first five phases (figure 6.1) were evaluated in this study:

i) the identification of the opportunities for renewable energy technologies, and the definition of appropriate biomass energy applications;

ii) the identification of available biomass feedstock supplies in sufficient quantities including biomass production in a sustainable manner;

iii) the determination and definition of the quality (and suitability) of feedstocks from different sources to suit gasification conversion technologies;

iv) the downdraft gasification of different biomass feedstocks under optimum conditions to generate a low or medium heating value gas (LHV, 3-7.8 or MHV, 12-20 MJ/Nm^3); and

v) the characterisation and evaluation of the product gas.

Thus, the study sought to identify areas where environmental, technical and economic advantages could be achieved from a biomass fuel option in terms of sustainable utilisation, convenience, and system reliability.

6.1 IDENTIFICATION OF BIOENERGY APPLICATION OPTIONS

Analyses of energy procurement and utilisation profiles in Kenya, (including petroleum, coal, electricity and biomass) defined the methodology for the identification of bioenergy applications, while demonstrating the feasibility of small-scale biomass-to-electricity systems on a decentralised basis. The reliance on imported commercial energy (oil, coal and a proportion of hydro-electricity) without commensurate expansion in exports, was considered economically unsustainable for Kenya. This highlighted (i) the constraints in the national energy sector and identified the opportunities for new technologies, and (ii) the importance of developing local bioenergy resources. Although Kenya has significant hydro and geothermal resources, the lack of financial resources has hampered the development and subsequent extension of the electricity grid to the majority of rural areas where nearly 75% of the population live.

An alternative electricity supply based on biomass gasification whereby the gas could be used to run an internal combustion engine driving an alternator to generate electricity on small decentralised basis was found to be technically feasible. The location and citing of such installations to take advantage of the ready market for the power generated in the rural communities was constrained by the availability of biomass feedstock in sufficient quantities and quality. The most suitable sites were identified as sawmills where sufficient quantities of wood process residues were potentially available to run a gasifier to produce 300 MWh of electricity, and which could be retrofitted to generate another 580 MWh of heat.

The study recommended (i) the setting up of a demonstration plant at any one of the sawmills to raise the awareness and encourage potential investors to set-up similar projects; and (ii) interventions to intensify the biomass resource base through the establishment of short rotation forestry (SRF) field trials at one or more locations to evaluate a range of high yielding species under combinations of silvicultural treatments to assess the potential energy yield in terms of GJ/ha/year.

6.2 FEEDSTOCK SUPPLY OPTIONS - SRF SPECIES EVALUATION

Short rotation forestry (SRF) trials conducted at Massey University in Palmerston North, New Zealand demonstrated the relationships between yield optimisation and key silvicultural aspects of intensive biomass production. In particular, the study showed that:

1. the choice of species for a given location was the most important factor in programmes aiming to maximise yields as variations of between 10 to 70 ODt/ha/y were measured from the small plots between the lowest and highest yielding SRF species, all other factors being constant;

2. high stocking densities up to 16,260 stems/ha, and shorter rotations did not translate into the highest mean annual incremental yields as harvesting too early (e.g. 2 year rotations) removed the crop before its maximum growth potential was realised under local conditions;

3. the optimum stocking density and rotation length for *Eucalyptus* species were about 3,500 stems/ha and 4-5 years in this temperate climate and on fertile soils; and

4. optimum rotation lengths and stocking densities under coppice regime was inconclusive particularly at rotations longer than 2 years. For the 2 year rotation, the first 2 year old coppice growth (harvested in year 4) had higher yields than the first rotation single stem harvest at year 2, while subsequent harvests produced yields similar to the first rotation yield.

The large differences in species yield potential indicated the large gains to be made by selecting appropriate species for specified regions. For any specific region, field trials need to be conducted to establish the choice species and to determine the optimum conditions for each of the species prior to commercial plantings. To supply a 40-50 kW (electric) village gasifier, the study identified a land area requirement of approximately 10 ha/y, given the yields that could be expected by planting some of the best species identified.

In addition to biomass yield evaluation, the study showed that there were variations in fuelwood properties among species but these differences did not significantly influence the quality of the fuelwood, based on the heating values (MJ/kg). The most notable differences among the species evaluated was in the density of the wood, and in the proportion of bark on the stem, which varied with silvicultural treatments. Such variations have implications for feedstock handling, drying, storage and transportation costs, and on the design of both feeding and conversion systems.

Two indices were developed for ranking tree species - the relative yield index (RYI) and the fuelwood value index (FVI). These demonstrated methodologies for evaluating fuelwood species. The process of defining RYI entailed evaluating the yield potential of a range of SRF species in a given region, and incorporating the factors which influence the yield while accounting for handling, storage and transportation requirement. For the FVI, analysing the fuelwood properties of the biomass produced together with the factors that influence these properties defined the suitability of the species. The relative importance of each attribute used to develop the indices showed that the most gains were attainable by maximising yields, achieved by appropriate choice of species. Selecting the optimum growing conditions was also a key factor. The methodology may be applied to other applications provided the feedstock requirements are described. The relative influences of both yield and feedstock characteristics in the two indices indicated that most research and production management effort in a biomass system should be concentrated on achieving high yields.

6.3 THE GASIFICATION OF SRF BIOMASS

Although SRF woody biomass properties differed among species, and these properties affected parameters in the process of gasification, the behaviour of the different feedstocks in the gasifier, and therefore the products of gasification, were not significantly variable among the SRF species evaluated. Similarly, the inclusion of bark in the feedstock did not adversely affect the suitability of the feedstock in terms of gas produced.

The study showed that the three most important factors in downdraft air gasification of woody biomass were (i) the feedstock moisture content; (ii) the equivalence ratio defined by the air flow; and (iii) temperature. These three factors were highly correlated, in that a variation of any one factor resulted in changes in all the others. Feedstocks with high moisture content gasified at lower temperatures; required larger quantities of air to allow for the combustion of part of the feedstock to generate heat for drying the charge; and resulted in a poorer quality gas richer in carbon dioxide and nitrogen, but lower in carbon monoxide, hydrogen and methane content. The overall heating value of the gas was therefore reduced.

The quality and quantity of gas generated did not significantly differ with species, and did not vary on the basis of the presence of bark in the feedstock. Similarly, the nature and quantity of the solid and liquid residues produced was not sensitive to the species or feedstock properties. This confirms that in a short rotation forestry scheme producing feedstock for gasification applications, the main objective should be to maximise yield, rather than to develop specific fuelwood characteristics of the biomass.

The pH, chemical oxygen demand (COD), electrical conductivity and turbidity of the condensate showed that it would be environmentally unacceptable to dispose of the residue into water-ways or onto land without pre-treatment. An initial step would be to filter the residue through the solid residues collected from both the ash port and cyclone. This must be considered when developing a wood gasification project.

6.4 SHORT ROTATION FORESTRY, GASIFICATION AND BIOMASS-ELECTRICITY SYSTEMS

The study has demonstrated there is feasibility for a full economic and social evaluation of small-scale biomass-electricity systems for rural remote areas. It identified potential sites as being sawmills with large quantities of residues currently requiring disposal. A village installation to supply approximately 160 MWh of electricity annually would require about 0.5 tonnes of dry feedstock daily. In Kenya, this is not currently available from local farms in rural areas where land use competes with food crops.

Short rotation forestry (SRF) plantings have the ability to supply the energy feedstock requirements, but would require at least 10 hectares of land, such that 2.5 hectares can be harvested per year for a recommended 4 year rotation of the plantations assuming that yields of 27-39 and 41-55 ODt/ha/y stemwood and total biomass, respectively are possible. Of the 12 species evaluated in the Manawatu conditions, only 5 species had high yields at the recommended rotation and stocking density (3,500 stems/ha) but were grown in small plots. The selection of the species would need to be based on local trial plantings and corrected for lower yields associated with commercial scale plantings.

The energy characteristics of the feedstock from the different species would not limit the choice of species as the variability among high yielding hardwoods as evaluated in this study was not significant. Further, the presence of bark in the feedstock is of negligible consequence to the quality of biomass for thermal gasification.

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APPENDICES

Appendix 2.1

Rural households survey questionnaire

RURAL HOUSEHOLD ENERGY PROCUREMENT AND UTILISATION ACTIVITIES SURVEY IN VIHIGA / KAKAMEGA DISTRICTS REGION, KENYA

Kingiri Senelwa
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Number [ ] **Date [ ]**

A. General information

i) Location [ ] Sub-location [ ] Village [ ]

ii) Assessment of infrastructure

Roads	:	Tar	[ ]	Gravel	[ ]	Others	[ ]
Educational	:	Primary	[ ]	Secondary	[ ]	Tertiary	[ ]
Health	:	Dispensaries	[ ]	Clinics	[ ]	Hospitals	[ ]
Commercial	:	Markets	[ ]	Shopping	[ ]	Others	[ ]
Industry	:	Food	[ ]	Wood	[ ]	Pottery	[ ]
Others	:						

Comments :

B. Household

i) Household head : [ ] Occupation [ ]

ii) Family size : [ ] - Age (y) - <10 [ ] 10-25[ ] 25-50[ ] >50 [ ]

iii) Farm size : [ ]

iv) Income activities: [ ]

v) Combined monthly/daily income [ ]

C. Land use activity (Land allocation, ha; % of total)

Homestead [ ]

Agriculture - arable [ ]

grazing [ ]

Forestry [ ]

Others [ ]

D. Agricultural activities

Commercial / subsistence [ ]

Crops : Main [ ]

Others [ ]

Livestock & poultry Main [ ]

Others [ ]

Others

Comments:

E. Forestry formations

i) **Types** Woodlots [ ]

Shelterbelts [ ]

Fences [ ]

Homestead [ ]

Others

ii) **Species**

Woodlots	:Dominant	[ ]	Others [ ]
Fences	:Dominant	[ ]	Others [ ]
Fruits	:Dominant	[ ]	Others [ ]
Ornamental	:Dominant	[ ]	Others [ ]
Ritual	:Dominant	[ ]	Others [ ]
Others	:		

Management :

Comments :

Cultural aspects in tree production:

External support (and type) in tree cultivation:

F. Forest products utilisation

			Sources
Products (& ranking):	Timber	[ ]	[ ]
	Fuelwood	[ ]	[ ]
	Charcoal	[ ]	[ ]
	Poles + posts	[ ]	[ ]
	Curving	[ ]	[ ]
	Other	[ ]	[ ]

G. Energy resources and requirements

Requirements	**Daily/monthly quantities**	**Expenditure (Kshs/week)**	**Comments**
i) Woodfuel			
Firewood (kg)	[ ]	[ ]	
Charcoal (kg)	[ ]	[ ]	
ii) Oil			
Petrol (l)	[ ]	[ ]	
Diesel (l)	[ ]	[ ]	
kerosene (l)	[ ]	[ ]	
LPG (kg)	[ ]	[ ]	
iii) Crop residues			
Woody (kg)	[ ]	[ ]	
Others (kg)	[ ]	[ ]	
iv) Dung	[ ]	[ ]	
v) Others	[ ]	[ ]	

Procurement	**Distance from home (km)**	**Expenditure (time / day)**	**Description/comments**
i) Woodfuel			
Firewood (kg)	[ ]	[ ]	
Charcoal (kg)	[ ]	[ ]	
ii) Oil			
Petrol (l)	[ ]	[ ]	
Diesel (l)	[ ]	[ ]	
kerosene (l)	[ ]	[ ]	
LPG (kg)	[ ]	[ ]	
iii) Crop residues			
Woody (kg)	[ ]	[ ]	
Others (kg)	[ ]	[ ]	
iv) Dung	[ ]	[ ]	
v) Others	[ ]	[ ]	

H. Comments

Appendix 2.2

Medium-large scale sawmills annual residues, gas and electricity production potential

Industry	Log intake	Timber	Processing residues		Potential gas	Gas heat	Electricity	Co-gen heat
	(t)	output (t)	Sawdust (t)	Solid (t)	10^6 m^3	1000 GJ	1000 kWh	1000 kWh Th
Amalgamated	10511	3889	1051	5676	12.40	56.62	4280	7947
Anan	2605	964	261	1407	3.07	14.03	1061	1969
Augustin	1204	446	120	650	1.42	6.49	490	910
Baraget	1545	572	155	834	1.82	8.32	629	1168
Benjamin	1021	378	102	551	1.20	5.50	416	772
Biashara	3192	1181	319	1724	3.77	17.19	1300	2413
Buuri	1094	405	109	591	1.29	5.89	446	827
Cartu	1366	506	137	738	1.61	7.36	556	1033
Cedar	2616	968	262	1412	3.09	14.09	1065	1977
Cyrus	804	298	80	434	0.95	4.33	327	608
D.Kirimi	999	370	100	540	1.18	5.38	407	755
Delta	2564	949	256	1384	3.02	13.81	1044	1938
E.Rift	6145	2274	615	3318	7.25	33.10	2502	4646
Elgeiyo	10024	3709	1002	5413	11.83	53.99	4081	7578
E.Nkonge	1275	472	128	689	1.50	6.87	519	964
F.I.T.C.	4183	1548	418	2259	4.94	22.53	1703	3162
Gachagua	3726	1379	373	2012	4.40	20.07	1517	2817
Gaitara	971	359	97	525	1.15	5.23	396	734
Gatei	1087	402	109	587	1.28	5.86	443	822
G.Wachira	3185	1178	319	1720	3.76	17.16	1297	2408
Githinji	1041	385	104	562	1.23	5.61	424	787
Githui	1180	437	118	637	1.39	6.36	480	892
Ibonia	722	267	72	390	0.85	3.89	294	546
Inono	1384	512	138	747	1.63	7.45	563	1046
Italian F.	734	271	73	396	0.87	3.95	299	555
J.Mwangi	1149	425	115	620	1.36	6.19	468	868
J.Wanjau	1001	370	100	540	1.18	5.39	407	757
Kamunya	923	341	92	498	1.09	4.97	376	698
Kaptagat	1251	463	125	675	1.48	6.74	509	946
K.Nyange	1228	454	123	663	1.45	6.61	500	928
Kazi Mingi	1477	547	148	798	1.74	7.96	601	1117
Kiambogo	1314	486	131	709	1.55	7.08	535	993
Kifuku & K	848	314	85	458	1.00	4.57	345	641
Kihara	1414	523	141	764	1.67	7.62	576	1069
Kinale	9531	3526	953	5147	11.25	51.33	3881	7205
Kiongera	1351	500	135	729	1.59	7.28	550	1021
K. Rono	722	267	72	390	0.85	3.89	294	546
Kiragati	1256	465	126	678	1.48	6.76	511	949
Kitiro	2585	956	259	1396	3.05	13.92	1053	1954
Kumali	738	273	74	398	0.87	3.97	300	558
Kunyiha	1254	464	125	677	1.48	6.76	511	948
L.Wambui	1493	552	149	806	1.76	8.04	608	1129
M.Gatembo	950	352	95	513	1.12	5.12	387	718
Molo	1016	376	102	548	1.20	5.47	414	768
M.Mbogori	2482	918	248	1340	2.93	13.37	1011	1877
Muinami	904	334	90	488	1.07	4.87	368	683
Nanyuki	773	286	77	417	0.91	4.16	315	584
Nat. Pencil	989	366	99	534	1.17	5.32	403	747
Ngumi	2020	747	202	1091	2.38	10.88	822	1527
Njoro Match	971	359	97	525	1.15	5.23	396	734
Njoro Umoja	854	316	85	461	1.01	4.60	348	646
North Tetu	769	284	77	415	0.91	4.14	313	581
Nyaru	6588	2438	659	3557	7.77	35.48	2682	4980
Oasis	831	308	83	449	0.98	4.48	339	629
Omega	1361	503	136	735	1.61	7.33	554	1029
P.Nduiga	916	339	92	494	1.08	4.93	373	692
Rafiki	949	351	95	513	1.12	5.11	387	718
RAI Ply	18771	6945	1877	10137	22.15	101.11	7643	14191
Rindikiri	1658	613	166	895	1.96	8.93	675	1253
Rongai	1426	528	143	770	1.68	7.68	581	1078
Ruringu	1027	380	103	555	1.21	5.53	418	777
Salama	1014	375	101	547	1.20	5.46	413	766
Samkoi	2681	992	268	1448	3.16	14.44	1091	2027
S.Kibe	861	318	86	465	1.02	4.64	350	651
Sokoro	31604	11693	3160	17066	37.29	170.22	12868	23892
T.Wakaba	2603	963	260	1406	3.07	14.02	1060	1968
Turi	856	317	86	462	1.01	4.61	348	647
Waithaka	811	300	81	438	0.96	4.37	330	613
Wambari	1039	384	104	561	1.23	5.59	423	785
Wananchi	1591	589	159	859	1.88	8.57	648	1203
Wanjema	1006	372	101	543	1.19	5.42	410	761
Wason	2248	832	225	1214	2.65	12.11	915	1699
Yacoob Deen	786	291	79	425	0.93	4.24	320	595
TOTAL	**187066**	**69215**	**18707**	**101016**	**221**	**1,007.59**	**76166**	**141422**

Appendix 3.1

The influence of stocking density (stems/ha) and rotation length (years) on tree size and yield in a "Nelder" radial trial of *E.saligna*[*]

Socking density (Stems/ha)	Stump diameter (mm)					Height (m)					Tree size (OD kg)					MAI (ODt/ha/y)					Harvest index (%)				
	2 y	3 y	4 y	5 y		2 y	3 y	4 y	5 y		2 y	3 y	4 y	5 y		2 y	3 y	4 y	5 y		2 y	3 y	4 y	5 y	
1640	89	137	166	189	a	3.5	4.4	5.0	5.6	a	8.4	18.1	30.4	41.9	a	6.9	9.9	12.5	13.7	b	26	34	45	61	d
3770	71	95	149	170	b	2.8	4.2	5.9	7.3	a	4.8	10.3	21.0	29.7	b	9.1	12.9	19.8	22.4	a,b	36	38	51	70	b,c,d
5720	55	73	106	157	b,c	2.7	4.4	5.8	6.1	a	3.3	4.5	9.1	16.4	c	9.5	8.6	13.0	18.7	b	36	36	53	63	c,d
7050	52	94	134	124	c	2.7	4.6	6.5	5.8	a	2.3	8.1	16.5	14.9	b,c	8.1	19.1	29.0	21.0	a	40	38	60	61	b,c,d
8700	48	82	88	122	c,d	2.8	5.0	5.7	6.1	a	2.3	5.8	7.4	12.2	c	10.0	16.9	16.0	21.2	a,b	45	43	86	68	a,b
10750	54	70	86	119	c,d	3.1	4.6	5.9	6.8	a	2.7	5.1	7.2	14.2	c	14.2	18.2	19.4	30.6	a	44	38	70	64	a,b,c
13160	49	53	86	89	d	2.7	4.2	5.7	5.0	a	2.7	2.4	8.4	9.0	c	17.5	10.6	27.8	23.7	a	68	44	67	69	a
16260	49	56	80	82	d	3.4	4.4	6.1	6.4	a	2.1	3.0	5.6	6.5	c	17.1	16.1	22.9	21.8	a	35	42	66	60	a,b,c,d
	d	c	b	a		c	b	a	a		c	c	b	a		b	b	a	a		b	b	a	a	
Mean	58	83	112	132		3	4	6	6		4	7	13	18		12	14	20	22		41	39	62	65	

[*] - Average values with the same letter are not significantly different.

Appendix 3.2

Comparison of first rotation and coppice yields (ODt/ha/y) and the influence of stocking density (stems/ha) and rotation length (years) in a "Nelder" radial trial of *E.saligna*[*]

Stocking density (Stems/ha)	Harvest yields (MAI, ODt/ha/y)									
	2 year rotation				3 year rotation			4 year rotation		5 year rotation
	Estblishment	1st coppice	2nd coppice	3rd coppice	Estblishment	1st coppice	2nd coppice	Estblishment	1st coppice	Estblishment
1640	6.9	10.0	5.6	13.3 ^{b}	9.9	10.9	12.6 ^{a}	12.5	8.0 ^{a}	13.7 ^{a}
3770	9.1	17.0	8.6	16.0 ^{a,b}	12.9	16.5	13 ^{a}	19.8	7.0 ^{a}	22.4 ^{a}
5720	9.5	19.4	11.0	12.3 ^{a,b}	8.6	15.3	15.5 ^{a}	13.0	6.4 ^{a}	18.7 ^{a}
7050	8.1	12.4	6.8	17.1 ^{a,b}	19.1	17.1	8.7 ^{a}	29.0	7.3 ^{a}	21.0 ^{a}
8700	10.0	20.0	9.8	11.3 ^{a,b}	16.9	22.4	12.2 ^{a}	16.0	9.9 ^{a}	21.2 ^{a}
10750	14.2	19.4	10.9	11.7 ^{a,b}	18.2	14.5	17.9 ^{a}	19.4	8.8 ^{a}	30.6 ^{a}
13160	17.5	26.3	7.4	11.3 ^{a}	10.6	11.9	8.3 ^{a}	27.8	6.6 ^{a}	23.7 ^{a}
16260	17.1	20.6	12.6	12.1 ^{a}	16.1	9.6	18.7 ^{a}	22.9	13.5 ^{a}	21.8 ^{a}
Mean	^{b,c} 11.6	^{a} 18.1	^{c} 9.1	^{b} 13.1	^{a} 14.0	^{a} 14.8	^{a} 13.4	^{a} 20.1	^{b} 8.4	21.6

[*] - Average values with the same letter are not significantly different.

Appendix 4.1

Effect of stocking density, cutting age and coppicing on wood properties of 6 year old rootstock trees of *E.saligna* planted in a "Nelder" radial trial

Property	Stocking density (Stems/ha)	Coppice			Establishment	
		1 year	2 years	3 years	6 years	Average
Proportion of bark on the stem (%)	1640		22	20	21	21 ^{a}
	3770		22	21	22	22 ^{a}
	7040		19	19	19	19 ^{b}
	16260		20	18	22	20 $^{a.b}$
	Mean		20.8 ^{a}	19.5 ^{a}	21.0 ^{a}	
Wood basic density (kg/m^3)	1640	380	441	461	487	442 ^{a}
	3770	440	404	454	428	432 ^{a}
	7040	372	388	422	478	415 ^{a}
	16260	401	413	444	392	413 ^{a}
	Mean	398.3 ^{a}	411.5 ^{a}	445.3 ^{a}	446.3 ^{a}	
Ash content (%)	1640	1.4	1.2	1.1	0.6	1.1 ^{a}
	3770	1.7	1.0	0.9	0.6	1.1 ^{a}
	7040	1.2	1.2	0.8	0.7	1.0 ^{a}
	16260	1.3	1.2	1.0	0.9	1.1 ^{a}
	Mean	1.4 ^{a}	1.2 $^{a.b}$	1.0 $^{b.c}$	0.7 ^{c}	
Volatile matter content (%)	1640	92.3	92.0	93.0	95.1	93.1 ^{a}
	3770	91.4	94.4	93.7	94.2	93.4 ^{a}
	7040	92.4	93.0	93.9	94.3	93.4 ^{a}
	16260	93.1	93.6	94.8	93.4	93.7 ^{a}
	Mean	92.3 ^{b}	93.3 $^{a.b}$	93.9 ^{a}	94.3 ^{a}	
Fixed carbon content (%)	1640	6.8	6.8	6.0	4.3	6.0 ^{a}
	3770	6.3	4.6	5.4	5.1	5.4 ^{a}
	7040	6.3	5.7	5.3	5.0	5.6 ^{a}
	16260	5.5	5.3	4.2	5.7	5.2 ^{a}
	Mean	6.2 ^{a}	5.6 ^{a}	5.2 ^{a}	5.0 ^{a}	
Organic extractives content (%)	1640	2.3	2.7	1.8	2.1	2.2 ^{a}
	3770	2.1	2.1	2.1	2.0	2.1 ^{a}
	7040	5.3	2.2	2.1	3.7	3.3 ^{a}
	16260	2.9	2.1	2.4	3.8	2.8 ^{a}
	Mean	3.2 ^{a}	2.3 ^{a}	2.1 ^{a}	2.9 ^{a}	
Total extractives content (%)	1640	5.1	5.1	3.6	3.6	4.4 ^{a}
	3770	5.3	4.3	4.1	4.3	4.5 ^{a}
	7040	8.8	5.0	3.9	6.1	6.0 ^{a}
	16260	6.5	4.6	5.1	6.3	5.6 ^{a}
	Mean	6.4 ^{a}	4.8 ^{b}	4.2 ^{b}	5.1 $^{a.b}$	
Higher heating value (MJ/kg)	1640	20.0	19.6	19.8	19.7	19.8 ^{a}
	3770	19.9	19.6	19.7	20.0	19.8 ^{a}
	7040	19.7	19.9	19.8	19.9	19.8 ^{a}
	16260	19.7	19.6	19.8	20.0	19.8 ^{a}
	Mean	19.8 ^{a}	19.7 ^{a}	19.8 ^{a}	19.9 ^{a}	

* - Average values with the same letter are not significantly different

Appendix 5.1

Correlations between measured gasification process variables over the time of a batch fuelwood conversion process (OD *P.tomentosa)*

		Average gasifier temperature (°C)					Feed	Air flow	Mass	Gas	Residenc	Gasifica	SGR	Gas composition (%)					CO/H_2	Std ga	HHV (MJ/Nm^3)	
	Time	T_I	T_{II}	T_{III}	T_{IV}	T_V	weight	flow	loss	yield	time	rate, g/s		H_2	N_2	CO	CH_4	CO_2	ratio	r.dens	Pro.gas	S.mixture
Time	1.00																					
T_I	0.55	1.00																				
T_{II}	0.54	0.63	1.00																			
T_{III}	0.33	0.46	0.88	1.00																		
T_{IV}	0.28	0.55	0.82	0.95	1.00																	
T_V	0.43	0.70	0.76	0.83	0.93	1.00																
Feed weight (g)	-0.99	-0.58	-0.54	-0.36	-0.32	-0.48	1.00															
Air flow (g/min)	-0.82	-0.57	-0.53	-0.42	-0.42	-0.54	0.84	1.00														
Wt change (g/min	-0.34	-0.09	0.13	0.29	0.35	0.24	0.32	0.29														
Mass loss	0.99	0.58	0.54	0.36	0.32	0.48	-1.00	-0.84	1.00													
Gas yield	0.99	0.59	0.54	0.36	0.32	0.49	-1.00	-0.84	1.00	1.00												
Residence time	-0.82	-0.57	-0.53	-0.42	-0.42	-0.54	0.84	1.00	-0.84	-0.84	1.00											
Gas production	-0.76	-0.46	-0.35	-0.20	-0.19	-0.33	0.78	0.84	-0.78	-0.77	0.84											
Gasification rate	-0.34	-0.09	0.13	0.29	0.35	0.24	0.32	0.29	-0.32	-0.32	0.29	1.00										
Specific gas. rate	-0.34	-0.09	0.13	0.29	0.35	0.24	0.32	0.29	-0.32	-0.32	0.29	1.00	1.00									
% H_2	0.52	0.69	0.29	0.26	0.36	0.80	-0.55	-0.48	0.55	0.56	-0.48	-0.48	-0.48	1.00								
% N_2	-0.32	-0.64	-0.40	-0.35	-0.67	-0.81	0.34	0.39	-0.34	-0.35	0.39	0.55	0.55	-0.81	1.00							
% CO	-0.27	0.04	-0.06	0.48	0.78	0.11	0.25	0.20	-0.25	-0.25	0.20	0.28	0.28	0.24	-0.46	1.00						
% CH_4	0.17	0.44	0.41	-0.01	0.20	0.48	-0.16	-0.25	0.16	0.17	-0.25	-0.71	-0.71	0.25	-0.58	-0.20	1.00					
% CO_2	0.38	0.31	0.41	-0.23	-0.19	0.42	-0.37	-0.46	0.37	0.38	-0.46	-0.69	-0.69	0.13	-0.26	-0.66	0.77	1.00				
% combustible	0.13	0.50	0.20	0.47	0.78	0.61	-0.16	-0.17	0.16	0.16	-0.17	-0.21	-0.21	0.76	-0.88	0.78	0.21	-0.22				
CO/H_2 ratio	-0.66	-0.69	-0.34	0.05	0.07	-0.77	0.69	0.61	-0.69	-0.69	0.61	0.68	0.68	-0.80	0.53	0.37	-0.40	-0.56	1.00			
Std gas r.density	0.64	0.38	0.40	-0.11	-0.28	0.53	-0.64	-0.63	0.64	0.64	-0.63	-0.67	-0.67	0.51	-0.37	-0.60	0.54	0.84	-0.85	1.00		
Prod.gas HHV	0.27	0.62	0.33	0.39	0.66	0.74	-0.29	-0.30	0.29	0.30	-0.30	-0.48	-0.48	0.83	-0.98	0.53	0.52	0.11	-0.49	0.27	1.00	
Sto.mixture HHV	0.10	0.52	0.27	0.45	0.81	0.64	-0.12	-0.17	0.12	0.13	-0.17	-0.30	-0.30	0.70	-0.92	0.75	0.38	-0.09	-0.24	0.00	0.95	1.00

Appendix 5.2

Correlations and interaction between processes in downdraft gasification of SRF species woody biomass (All tests)

		Inputs and outputs flows (g/h)					Mass	Resid.	Gasifi.		NWF	Temperatures (°C)					Gas composition (%)					HHV (MJ/Nm³)		Ratios				Cold
		Feed	Water	Air	Gas	Liquid	balanc	time	rate	ER	(%)											Product	Air:gas	Air:feed	Gas:feed	Gas:feed	Gas:feed	gas
		M_F	M_W	M_A	M_{PG}	M_{LR}	(%)	(s)	(g/s)			T_I	T_{II}	T_{III}	T_{IV}	T_V	H_2	N_2	CO	CH_4	CO_2	gas	stoi.mix	(g/g)	(m³/kg)	(g/g)	(kJ/g)	effic.
Inputs and outputs (g/h)	Feed (M_F)	1.00																										
	Water (M_W)	-0.39	1.00																									
	Air (M_A)	0.46	0.08	1.00																								
	Gas (M_{PG})	0.53	0.05	0.81	1.00																							
	Solids (M_{SR})	0.54	0.17	0.07	0.08																							
	Liquids (M_{LR}	0.03	0.61	0.20	0.33	1.00																						
Mass balance		0.06	0.11	0.00	0.53	0.47	1.00																					
Residence time		0.38	-0.04	0.92	0.76	0.07	-0.05	1.00																				
Gasification rate (g/min)		0.76	-0.26	0.57	0.77	0.23	0.39	0.53	1.00																			
Equivalence ratio (ER)		-0.50	0.46	0.52	0.28	0.17	-0.07	0.53	-0.18	1.00																		
Net water formation, %		0.24	-0.69	-0.09	0.06	0.09	0.30	-0.03	0.33	-0.33	1.00																	
Temperatu (°C)	T_I	0.02	-0.13	-0.08	0.10	0.23	0.36	-0.10	0.15	-0.11	0.39	1.00																
	T_{II}	0.09	-0.53	-0.35	-0.16	-0.14	0.22	-0.31	0.00	-0.44	0.58	0.82	1.00															
	T_{III}	0.22	-0.75	-0.35	-0.21	-0.21	0.07	-0.32	0.09	-0.56	0.72	0.40	0.84	1.00														
	T_{IV}	0.21	-0.79	-0.30	-0.22	-0.34	0.00	-0.25	0.05	-0.51	0.73	0.32	0.74	0.98	1.00													
	T_V	0.45	-0.44	0.34	0.31	-0.22	-0.05	0.36	0.41	-0.09	0.26	-0.18	0.05	0.29	0.39	1.00												
Gas compositi (%)	H_2	-0.06	0.08	-0.13	-0.01	-0.11	0.21	-0.24	0.04	-0.04	-0.19	-0.16	-0.04	-0.06	-0.09	0.24	1.00											
	N_2	-0.22	0.26	0.06	0.01	0.24	0.00	0.12	-0.23	0.24	-0.05	0.05	-0.16	-0.18	-0.21	-0.37	-0.80	1.00										
	CO	0.30	-0.72	-0.04	-0.14	-0.55	-0.27	-0.02	0.16	-0.32	0.36	-0.03	0.33	0.48	0.56	0.37	0.29	-0.72	1.00									
	CH_4	0.61	-0.44	0.11	0.21	-0.07	0.00	0.11	0.53	-0.46	0.33	0.13	0.25	0.31	0.41	0.28	0.07	-0.47	0.44	1.00								
	CO_2	-0.10	0.75	0.06	0.20	0.61	0.29	0.00	0.09	0.17	-0.44	0.08	-0.24	-0.41	-0.55	-0.12	0.28	-0.08	-0.58	0.00	1.00							
Std gas relative density		-0.26	0.81	-0.03	0.09	0.55	0.27	-0.10	-0.07	0.24	-0.53	-0.01	-0.32	-0.51	-0.62	-0.20	0.36	-0.04	-0.63	-0.19	0.97							
HHV (MJ/Nm³)	Product gas	0.29	-0.52	-0.08	-0.06	-0.43	-0.07	-0.12	0.22	-0.33	0.22	-0.09	0.23	0.31	0.41	0.41	0.69	-0.94	0.87	0.52	-0.25	1.00						
	Stoi mixture	0.31	-0.60	-0.05	-0.07	-0.47	-0.14	-0.07	0.23	-0.33	0.28	-0.04	0.28	0.38	0.48	0.41	0.55	-0.90	0.95	0.54	-0.35	0.98	1.00					
Air:feed ratio, g/g		-0.29	0.65	0.54	0.28	0.39	-0.01	0.36	-0.14	0.81	-0.45	-0.11	-0.46	-0.59	-0.58	-0.16	0.11	0.17	-0.37	-0.49	0.31	-0.31	-0.34	1.00				
Gas:feed ratio, m³/kg		-0.23	0.68	0.39	0.52	0.58	0.58	0.22	0.08	0.60	-0.32	0.09	-0.30	-0.49	-0.56	-0.19	0.25	0.13	-0.53	-0.41	0.53	-0.31	-0.40	0.79	1.00			
Gas:feed ratio, g/g		-0.44	0.45	0.39	0.52	0.33	0.50	0.41	0.05	0.81	-0.18	0.08	-0.27	-0.45	-0.47	-0.11	0.09	0.21	-0.44	-0.38	0.33	-0.33	-0.37	0.60	0.79	1.00		
Gas:feed ratio, kJ/g		0.02	-0.40	0.31	0.44	-0.26	0.35	0.34	0.36	0.29	0.30	0.09	0.15	0.12	0.22	0.42	0.49	-0.56	0.51	0.22	-0.21	0.60	0.59	0.05	0.19	0.46	1.00	
Liquid:gas ratio, g/g		-0.27	0.64	-0.33	-0.27	0.71	0.14	-0.44	-0.15	-0.05	-0.11	0.22	-0.07	-0.15	-0.31	-0.56	-0.06	0.19	-0.50	-0.11	0.58	-0.38	-0.42	0.16	0.26	0.00	-0.55	
Cold gas effic, %		-0.24	0.14	0.37	0.52	0.09	0.47	0.37	0.21	0.62	-0.04	0.09	-0.11	-0.28	-0.24	0.14	0.49	-0.37	0.07	-0.05	0.22	0.26	0.21	0.43	0.62	0.81	0.83	1.00

Appendix 5.3

The influence of particle size distribution and bulk density on down draft gasification processes and products

Feedstock	Run time (min)	Bulk density (kg/m^3)	Inputs flow rate (g/h)			Outputs flow rate (g/h)			Mass balance (%)	Residenc time (s)	Gasificat rate (g/s)	Specific gas. rate (g/s/m^2)	Hearth load (m/s)	ER	NWF	Average run temperatures (°C)				
			Feed (M_F)	Water (M_W)	Air (M_A)	Gas (M_{PG})	Solids (M_{SR})	Liquids (M_{LR})								T_I	T_{II}	T_{III}	T_{IV}	T_V
A.dealbata (NB)	61	181	13814	1388	26160	35309	1703	2258	94.9	3.6	2.95	237	0.846	0.298	6	172	389	694	792	657
A.dealbata (NB,S_C)	87	173	13241	1759	24240	35366	1174	3791	102.8	3.3	3.50	280	0.850	0.288	15	348	502	-	809	730
A.dealbata (NB,S_F)	40	166	16151	2146	22740	33754	2468	3626	97.1	3.1	3.45	276	0.815	0.221	9	106	253	-	528	612
E.globulus (NB)	136	243	11522	1436	20100	29779	881	2578	100.5	2.7	3.03	243	0.713	0.274	10	291	501	804	874	718
E.globulus (NB,S_C)	92	232	14777	2161	23640	35539	1435	4187	101.4	3.2	3.72	297	0.853	0.251	14	363	537	-	851	758
E.globulus (NB,S_F)	78	227	14292	1995	22380	33638	1345	4117	101.1	3.1	3.52	282	0.814	0.246	15	134	318	-	714	692
E.nitens (NB)	100	208	13253	2015	23040	34099	1292	3551	101.7	3.1	3.47	277	0.813	0.273	12	246	444	-	860	752
E.nitens (NB,S_C)	110	192	11383	1746	24060	33350	878	3222	100.7	3.3	2.97	237	0.803	0.332	13	323	519	-	871	750
E.nitens (NB,S_F)	78	182	11820	1798	22320	31565	1250	3308	100.5	3.1	2.93	235	0.764	0.297	13	112	278	-	678	683

S_C - Sieved wood chips, coarse (> 19 mm screen)

S_F - Sieved wood chips, fines (< 19 mm screen)

Appendix 5.4

The influence of feedstock particle size distribution on gas composition and gasification ratios

Feedstock	Bulk density (kg/m^3)	Gas composition (%)					Gas quality			Air: dry feed (g/g)	Gas: dry fed (m^3/kg)	Gas: dry feed (g/g)	Gas: dry feed (kJ/g)	Reaction liq. dry feed (g/g)	Total liq.: dry gas (g/g)	Cold gas efficiency
							Relative density	Heat value MJ/Nm^3								
		H_2	N_2	CO	CH_4	CO_2		Pure gas	Stoich. mixtu							
A.dealbata (NB)	181	9.5	60.2	20.4	1.9	7.9	0.954	4.750	2.269	2.16	2.78	2.56	10.53	0.06	0.064	59
A.dealbata (NB,S_C)	173	9.4	57.6	21.5	1.9	9.6	0.963	5.039	2.309	2.01	2.82	2.67	11.44	0.15	0.107	66
A.dealbata (NB,S_F)	166	8.6	57.2	22.9	2.2	9.1	0.959	5.028	2.358	1.66	2.37	2.09	8.90	0.09	0.107	51
E.globulus (NB)	243	11.5	55.1	21.1	2.1	10.1	0.967	5.294	2.364	1.89	2.71	2.58	11.77	0.10	0.087	67
E.globulus (NB,S_C)	232	11.0	54.0	22.0	2.5	10.5	0.964	5.386	2.409	1.77	2.57	2.41	10.89	0.14	0.118	63
E.globulus (NB,S_F)	227	10.9	54.1	23.9	2.3	8.9	0.957	5.602	2.456	1.73	2.49	2.35	11.07	0.15	0.122	64
E.nitens (NB)	208	10.5	56.2	20.8	2.2	10.4	0.965	5.060	2.331	1.93	2.75	2.57	10.90	0.12	0.104	60
E.nitens (NB,S_C)	192	10.1	58.2	20.7	1.8	9.3	0.961	4.824	2.289	2.29	3.05	2.93	11.78	0.13	0.097	65
E.nitens (NB,S_F)	182	11.0	56.7	21.4	2.1	8.9	0.957	5.188	2.358	2.11	2.86	2.67	11.51	0.13	0.105	64

S_C - Sieved wood chips, coarse (> 19 mm screen)

S_F - Sieved wood chips, fines (< 19 mm screen)

Appendix 5.5

Correlation between properties of liquid condensate and other gasification parameters

		pH	Electrical conductivity	Turbidity	COD (ppm)
Run time (min)		0.22	-0.48	-0.19	-0.10
Basic density (kg/m^3)		-0.07	-0.39	-0.10	0.18
Ash content (%)		0.39	0.39	0.07	0.08
Volatile matter content (%)		-0.36	-0.37	-0.01	-0.30
Fixed carbon content (%)		0.32	0.36	0.00	0.31
Organic solvent soluble extractives (%)		-0.05	0.14	0.22	-0.23
Total extractives content (%)		-0.08	0.13	0.24	-0.26
Feed HHV (Mj/kg)		-0.20	-0.15	0.14	0.39
Bulk density		0.17	-0.23	-0.06	0.15
Feed moisture content (%)		0.49	-0.59	-0.13	-0.24
Bark (%)		0.44	0.35	0.14	-0.09
Inputs and outputs flow rate (g/h)	Feed (M_F)	-0.28	0.58	0.19	0.32
	Water (M_W)	0.53	-0.56	-0.11	-0.21
	Air (M_A)	0.42	0.41	0.11	-0.11
	Product gas (M_{PG})	0.30	0.52	0.14	0.04
	Solid residues (M_{SR})	0.02	0.17	0.19	0.30
	Liquid residues (M_{LR})	0.50	-0.56	-0.03	-0.21
Mass balance (%)		0.01	0.04	0.11	0.20
Residence time (s)		0.45	0.40	0.07	-0.24
Gasification rate (g/s)		-0.05	0.49	0.14	0.30
Specific gasification rate (g/s/m^2)		-0.05	0.49	0.14	0.30
Hearth load (m/s)		0.32	0.58	0.10	0.04
Equivalence ratio (ER)		0.57	-0.31	-0.07	-0.38
Net water formation (NWF, %)		-0.53	0.45	0.12	0.17
Average run temperatures (oC)	T_I	-0.47	0.10	-0.20	-0.06
	T_{II}	-0.60	0.34	0.00	0.06
	T_{III}	-0.45	0.38	0.05	0.16
	T_{IV}	-0.56	0.45	0.24	0.14
	T_V	0.37	0.61	0.25	0.03
Average gas composition (%)	H_2	0.11	0.32	0.20	0.31
	N_2	0.19	-0.45	-0.19	-0.27
	CO	-0.44	0.52	0.13	0.22
	CH_4	-0.51	0.40	0.19	0.28
	CO_2	0.58	-0.48	-0.07	-0.19
Gas quality	Std relative density	0.58	-0.49	-0.09	-0.17
	Product gas HHV (MJ/Nm^3)	-0.35	0.51	0.18	0.30
	Stoich mixture HHV (MJ/Nm^3)	-0.39	0.52	0.14	0.27
Gasification ratios	Air to dry feed (g/g)	0.63	-0.33	-0.02	-0.28
	Gas to dry feed (m^3/kg)	0.64	-0.38	-0.03	-0.23
	Gas to dry feed (g/g)	0.59	-0.35	-0.09	-0.36
	Gas to dry feed (kJ/g)	-0.21	0.61	0.14	0.15
	Reaction liquid to dry feed (g/g)	-0.53	0.45	0.12	0.17
	Total liquid to dry gas (g/g)	0.32	-0.69	-0.09	-0.22
pH		1.00	0.15	-0.01	-0.22
Electrical conductivity			1.00	0.13	-0.04
Turbidity				1.00	-0.19
COD (ppm)					1.00

Appendix R.1

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