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CALORIFIC VALUES AND COMBUSTION CHARACTERISTICS OF SOUTH AFRICAN GROWN FUELWOODS

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for NATIONAL PROGRAMME FOR ENERGY RESEARCH

EXECUTIVE SUMMARY

The objective of this project is to determine calorific values of a range of South African grown fuelwoods. A secondary objective is to develop a technique for assessing the flammability or combustion characteristics of different fuelwoods.

Much anecdotal evidence exists on the relative quality of fuelwoods, but no objective measure is available to compare the combustion characteristics of various species. This information is of use to afforestation programmes for fuelwood production for underdeveloped rural areas, as well as industrial processes for energy recovery from wood residues.

The most commonly used parameters for comparing alternative fuels are calorific or heat values. The distinction between gross (high) and nett (low) calorific values at constant pressure or volume are discussed.

One hundred and fifteen (115) sets of samples, each consisting of heartwood and sapwood, were supplied to the Energy Research Institute by the South African Forestry Research Institute. They include 108 different species; 7 species from different sites were duplicated. A summary of the results obtained is shown below:

CALORIFIC VALUE OF SOUTH AFRICAN GROWN TREE SPECIES

	No of Samples	Range MJ/kg	Mean MJ/kg	Variance
All woods	230	18,34-22,49	19,80	
Heartwood	115	18,34-22,49	19,88	0,41
Sapwood	115	18,83-21,09	19,73	0,41
Hardwood	86	18,77-20,97	19,70	
Softwood	13	20,07-21,25	20,43	

The most obvious conclusion which may be noted from the reported values is that the calorific value of wood, on an oven dry mass basis, varies surprisingly little. Because calorific value varies within such

narrow limits, it is not a good indicator of the usefulness of a tree species as a fuel. This is further borne out by the results obtained from the 7 duplicated species tested, for the determinations within a species were found to vary by 0,43 - 1,53 MJ/kg, which is nearly equal to the range of variation between all the different species examined. Thus the variation within a single species, allowing for differences of ages and site, is as significant as that between different species.

Although the main focus of this project was to document calorific values of South African grown fuelwood species, there was also the requirement to develop an appropriate measure of flammability or combustibility but without, at this stage, undertaking experimental combustibility tests on a full range of tree species.

The fundamentals of wood combustion are described. The thermogravimetric method for the determination of combustion characteristics of fuels is well known and widely used. This method enables the determination of the rate of mass loss during combustion, reactivities and activation energies for different fuels.

An experimental rig has been developed at the Energy Research Institute, for a parallel research project on reconstituted fuels, which will enable the combustion of small particles under controlled conditions to be studied. The results from three fuelwood species are described in order to demonstrate the usefulness and potential of this method. Marked differences in mass loss rates and reactivities were observed.

It is concluded that calorific value is not important in the choice of species for fuelwood production. In practice, other factors such as growth rate, plantation siting, moisture content, density and type of combustion system used are far more important.

The need still exists, however, for an objective measure of the worth of tree species as fuelwood. It has been argued that the most fruitful research direction would be a fundamental investigation into the combustion characteristics of different wood species under controlled conditions. An experimental rig has been developed which has indicated the usefulness of looking at such parameters as rate of mass loss during combustion, reactivity and activation energy. What remains to be done is the experimentation with very many more wood samples using this technique and for the data obtained to be correlated with

anecdotal and field information on fuelwood preferences so as to validate this approach as being useful for ranking fuelwood species. This information can then be related to silvicultural factors which are important in the selection of suitable fuelwood species.

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1. INTRODUCTION

1.1 Project objectives

This project aims to determine calorific values of a range of South African grown fuelwoods. A secondary aim is to develop a technique for assessing the flammability or combustion characteristics of different fuelwoods.

1.2 Background rationale

Much anecdotal evidence exists on the relative quality of fuelwoods, but no objective measure is available to compare the combustion characteristics of various species. This information is of use to afforestation programmes for fuelwood production for underdeveloped rural areas, as well as industrial processes for energy recovery from wood residues.

In underdeveloped areas, such as parts of South Africa, the predominant fuel is wood which is used to meet basic household energy requirements for cooking and heating. The demand for wood in many areas exceeds the supply from natural woodland with the result that supplies are often transported in from elsewhere and wood has become a commodity for sale. In order to meet the growing demand for fuelwood adequately , it is imperative that new plantations and woodlots be established.

What laboratory measurement should be used to objectively rank different tree species according to their desirability as a fuelwood? The most commonly used parameters for comparing alternative fuels are calorific or heat values. Up till now, very little data have been published on the calorific values of South African grown fuelwood species. The question arises as to whether calorific value is also an important parameter in the selection, pricing and combustion of fuelwood, and what other combustion related phenomena should be investigated?

This study aims to report the calorific values measured for a range of tree species, indigenous and exotic, occurring naturally or cultivated in South Africa. It looks critically at the usefulness of calorific measurements of fuelwood; the fuelwood preferences of rural users are

noted; and some of the other important factors in the selection and use of suitable fuelwood species are discussed. Finally, some preliminary results of fuelwood reactivity as a measure of combustibility are reported and recommendations made concerning future work in this area.

2. CALORIFIC VALUE MEASUREMENTS

2.1 Some definitions

Calorific value is one of the key factors to be taken into consideration when evaluating fuels. It has a bearing on the selection and pricing of fuels and for the design of combustion technologies.

All naturally occurring fuels are organic; being composed principally of the elements carbon, hydrogen and oxygen together with smaller amounts of sulphur and nitrogen. They may also contain traces of other elements. In addition, solid fuels may contain varying amounts of ash and moisture which do not contribute to the release of energy when the fuel is combusted. Combustion is simply an exothermic reaction in which one of the reactants is oxygen. Energy is released at varying rates depending on the conditions of temperature and pressure at combustion and on the final products of the reaction.

If different fuels are to be accurately compared, then it is important that the release of energy always be measured in the same way. For example, the quantity of heat produced by the combustion of hydrogen will depend on whether the the water formed is in the vapour or liquid state; more heat will be produced in the latter case because of the latent heat which is released when water vapour condenses. Since most fuels contain hydrogen and many also contain moisture, water is often one of the products of combustion. Consequently, the distinction between water in the vapour and the liquid states is of primary importance in defining how the energy released by the combustion of a fuel is to be measured.

The unit of measurement generally used to express the potential quantity of energy released by a substance on burning is the heat value or calorific value, determinations of which are made under certain standard conditions - usually by explosive combustion in a bomb calorimeter under an initial pressure of 23 to 37 atm. at constant volume (British Standard BS 526:1961).

Two standard calorific values need to be defined; the high or gross calorific value, in which all the water formed by combustion is condensed to the liquid form; and the low or nett calorific value, which is less by the latent heat of evaporation of the water.

In addition to this, it is usual to define heat values both at constant pressure and at constant volume. In practice, most fuels are combusted under conditions of constant atmospheric pressure, and calorimetric measurements on gaseous fuels are also usually made under these conditions; but since complete combustion of solid and liquid fuels requires higher pressures, calorimetric measurements on these fuels are always carried out at constant volume in a bomb calorimeter.

The definition of calorific value determined in a bomb calorimeter is given in BS 526:

> The gross calorific value at constant volume of a solid or liquid fuel is the number of heat units measured as being liberated per unit quantity of fuel burned in oxygen in a bomb under standard conditions in such a way that the materials after combustion consist of the gases oxygen, carbon dioxide, sulphur dioxide and nitrogen, liquid water in equilibrium with its vapour and saturated with carbon dioxide, hydrochloric acid in solution and solid ash.

The gross calorific value at constant pressure may be calculated from the following formula which assumes that the gaseous reactants and products behave as ideal gases.

$$E_{hp} - E_{hv} = 0.01\ RT\ (.5H/2 - O/32 - N/28)$$

where E_{hp} = gross calorific value at constant pressure
E_{hv} = gross calorific value at constant volume
R = universal gas constant
T = isothermal reaction temperature in Kelvin
H = per cent hydrogen in fuel by mass
O = per cent oxygen in fuel by mass
N = per cent nitrogen in fuel by mass

However, the correction is generally only of the order of 20 kJ/kg which is about 0,1% of the gross calorific value of oven dried wood. Furthermore this correction is practically cancelled out by the adjustment (in the opposite direction) of E_{hv} to atmospheric pressure to approximate the actual conditions under which most fuels combust. For most solid and liquid fuels these corrections are ignored and gross calorific value at constant volume measured in a bomb calorimeter approximates gross calorific value at constant pressure as the difference will not exceed 0,12 MJ/kg for solid and liquid fuels or 0,5 MJ/m^3 for gaseous fuels (Bialy, 1979, p 10).

The heat or calorific value which corresponds most closely with the conditions under which a fuel is burnt in practice is the low heat value or nett calorific value (at constant pressure) as water in the combustion products will usually be in the gaseous state. The difference between the gross and nett calorific value is simply the latent heat of evaporation of the water at the reference temperature and either at constant volume or pressure. The nett calorific value may be deduced from the gross calorific value and the composition of the fuel in terms of moisture and hydrogen (which will combust to water).

Thus for solid and liquid fuels:

$$E_{hp} - E_{lp} = 0.01\ L\ (H/2 + W/18)\ \ kJ/kg$$

where E_{hp} = gross calorific value at constant pressure
E_{lp} = nett calorific value at constant pressure
L = molar latent heat of water at 25 °C and constant pressure = 44 kJ/mol
H = percentage by mass of hydrogen in fuel
W = percentage by mass of water in fuel

Thus $E_{lp} = E_{hp} - 220\ H - 24\ W$ kJ/kg

Conventionally, moisture content is expressed on a dry basis (m%)

then $W = 100m/(100+m)$

and if h is the hydrogen percentage of the moisture-free fuel

then $H = 100h/(100+m)$

Hence the nett calorific value E_{lp} at a moisture content m will be

$$E_{lp}(m) = (100\ E_{hpo} - 22h - 2.4m) / (100+m) \quad MJ/kg$$

where E_{hpo} = gross calorific value of oven-dried fuel

As will be shown later, for wood, E_{hpo} = 20 MJ/kg on average and h = 6%, whence

$$E_{lp}(m) = (1868-2,4m)/(100+m) \quad MJ/kg$$

Thus the nett calorific value of moisture free or oven-dried wood is on average 18.7 MJ/kg and decreases with increased moisture content.

Calorific value varies significantly with moisture content. Freshly harvested wood contains a generally large, but variable proportion of water (anything from 30% to a few hundred percent). The moisture content of air dry wood is much less, generally between 10 and 20 %, and depends mainly on the temperature and the humidity of the surrounding atmosphere. The equilibrium moisture content increases with increasing humidity but decreases with increasing temperature. A fuel with a moisture content of m% will have a gross calorific value which is approximately a fraction 100/(100+m) times that of the same fuel in the oven dried condition. At a typical air dried moisture content of 15% (d.b.) the average gross calorific value of wood is 17,4 MJ/kg.

2.2 Experimental method

A waterless COALAB CP400 automatic bomb calorimetric system conforming in general to BS 526:1961 was used. The apparatus is microprocessor controlled and takes approximately 12 minutes to complete a gross calorific value measurement.

One hundred and fifteen (115) sets of samples, each consisting of heartwood and sapwood, were supplied to the Energy Research Institute by the South African Forestry Research Institute. They include 108 different species; 7 species from different sites were duplicated. The samples measured not less than 20x2x1 cm in size. They were generally obtained from a radial section through the tree stem and were free

from pith, bark, blue stain and rot. From them, test samples of approximately 0,5 gm were prepared, oven dried and stored with silica gel in sealed moisture free containers.

Calorific measurements were made on two or more test samples from the heartwood and sapwood of each species. The difference between measurements for each sample set were less than .15 MJ/kg, i.e. an experimental variability of less than 1%. The values reported in Table 1 are the average of these readings and represent gross calorific values for oven dried wood. Reported calorific values from the literature have been included as a comparison, although only a few values are available and most are of species which have been cultivated abroad.

Density values (at 10% moisture content) and shrinkage factors on drying are also included (van Vuuren et al, 1978). These were used to calculate calorific values on a volumetric basis (for oven dried wood).

TABLE 1

No.	SPECIES	Gross CALORIFIC VALUE MJ/kg			REPORTED CV	DENSITY (10%MC)	SHRINKAGE	DENSITY (Dry)	CV.	SOFTWOOD/
		SAPWOOD	HEARTWOOD	AVERAGE	(MJ/kg)	(kg/m³)	volume	(kg/m³)	MJ/m³	HARDWOOD
33	Abies religiosa	20.45	19.69	20.07		470	9.0	440	8841	S
108	Acacia caffra	19.61	20.00	19.81		1060	9.2	994	19689	H
146	Acacia davyi	18.92	19.65	19.29		820	17.9	793	15289	
143	Acacia dealbata	19.17	19.35	19.26						
144	Acacia decurrens	19.30	19.72	19.51	19.47					H
109	Acacia karroo	18.69	18.85	18.77		890	18.5	862	16185	H
145	Acacia mearnsii	19.05	19.39	19.22						H
11	Acacia melanoxylon	19.15	19.49	19.32		670	10.0	630	12173	H
12	Acacia sieberana	19.28	19.46	19.37		650	10.0	611	11841	H
147	Acacia tortilis	20.78	21.17	20.97						H
110	Acacia tortilis	18.95	19.94	19.44		890	13.1	846	16450	H
13	Agathis robusta	20.46	19.97	20.22		480	7.4	447	9044	S
14	Agathis robusta	20.41	20.18	20.29		400	7.5	373	7568	S
56	Albizia adianthifolia	19.96	19.83	19.90		560	9.3	525	10452	H
57	Anthocleista grandiflora	19.88	19.74	19.81		610		555	10985	
34	Apodytes dimidiata	19.74	19.66	19.70		790	15.2	757	14903	H
58	Araucaria angustifolia	20.24	20.19	20.22	20.09	460	9.1	431	8718	S
111	Berchemia zeyheri	19.52	19.62	19.57						
59	Breonadia salicina	21.09	21.81	21.45						
15	Bridelia micrantha	18.99	18.99	18.99		650	10.8	613	11640	H
35	Burkea africana	20.31	21.13	20.72		820	10.4	772	16000	H
36	Canthium mundianum	19.56	20.41	19.99		850	16.0	816	16317	H
37	Canthium obovatum	19.66	19.76	19.71		930	13.3	885	17437	H
112	Canthium obovatum	18.83	18.90	18.87		930	13.3	885	16690	H
38	Cassine peragua	19.21	19.21	19.21		800	12.9	760	14599	H
1	Casuarina cunninghamii	19.63	20.04	19.84	19.98	850	15.0	813	16134	H
39	Cedrela toona	19.91	19.94	19.93		310	12.2	578	11521	H
60	Cedrus libani	20.19	20.54	20.37		530	12.0	502	10221	S
16	Celtis africana	19.55	19.35	19.45		760	12.9	722	14042	H
40	Ceratonia siliqua	19.47	19.36	19.42						
17	Cinnamomum camphora	20.08	20.48	20.28		510	12.2	483	9801	H
107	Colospermum mopane	19.58	21.19	20.39		1090	10.8	1028	20954	H
61	Croton sylvaticus	19.16	19.18	19.17		580	11.0	547	10491	H

TABLE 1 (cont)

No.	SPECIES	Gross CALORIFIC VALUE MJ/kg SAPWOOD	HEARTWOOD	AVERAGE	REPORTED CV (MJ/kg)	DENSITY (10%MC) (kg/m³)	SHRINKAGE volume	DENSITY (Dry) (kg/m³)	CV. MJ/m³	SOFTWOOD/ HARDWOOD
18	Cryptomeria japonica	20.00	20,49	20.25	22.67	350	8.7	328	6634	S
62	Cupressus lusitanica	20.21	20.60	20.41		470	9.0	440	8988	S
63	Cupressus torulosa	20.01	22.49	21.25		510	9.3	478	10167	S
41	Curtisia dentata	19.34	18.34	18.84		900	16.8	867	16329	H
154	Dichrostachys cinerea	19.60	20.12	19.86						
42	Diospyros whyteana	19.14	19.17	19.16						H
114	Dombeya rotundifolia var. rotundifoli	19,37	19.29	19.33		870	14.4	831	16059	H
64	Erythrina lysistemon	19.20	18.80	19.00		320	6.7	298	5654	H
65	Eucalyptus agglomerata	19.85	19.91	19,88						H
133	Eucalyptus camaldulensis	19.78	19.60	19.69	19.74	930	24.7	921	18139	H
66	Eucalyptus capitellata	19.40	19.31	19.36		890	15.4	853	16507	H
2	Eucalyptus citriodora	19.81	19.35	19.58		1000	14.9	957	18230	H
43	Eucalyptus deanii	19,54	19.76	19.65						H
67	Eucalyptus delegatensis	20,25	20.83	20.54		750	29.0	755	15508	H
19	Eucalyptus fraxinoides	19.46	18.92	19.19		690	15.4	661	12689	H
135	Eucalyptus globulus	19.64	19,07	19.35	20.72	900	24.1	890	17215	H
3	Eucalyptus grandis	19.82	19.69	19.76		615	16.8	592	11700	H
136	Eucalyptus macarthurii	19.76	19,70	19.73		860	28.1	863	17018	
4	Eucalyptus maculata	19.53	19.51	19,52	19.04	830	15.4	795	15526	H
7	Eucalyptus maidenii	19.56	19.68	19.62		910	13.9	867	17020	H
20	Eucalyptus microcorys	20.09	19,94	20.02	19.54	880	16.5	847	16944	H
21	Eucalyptus moellerana	19.60	19.59	19,60		780	15.0	746	14626	H
137	Eucalyptus nova anglica	19.67	19.61	19.64						
68	Eucalyptus obliqua	19.55	19.90	19.73		720	16.9	694	13682	H
22	Eucalyptus oreades	19,43	19.38	19.41		670	15.7	643	12472	H
5	Eucalyptus paniculata	19.67	19.68	19.68		1070	19.8	1041	20491	H
6	Eucalyptus punctata	19.67	19.78	19,73		1010	17.4	975	19226	H
23	Eucalyptus quadrangulata	19.06	19.01	10,04		980	21.8	961	18287	H
78	Eucalyptus rummeryi	19.41	19.65	19.53		990	16.4	952	18593	H
140	Eucalyptus sideroxylon	19.65	19.59	19.62		1020	14.3	974	19103	H
24	Eucalyptus smithii	19.90	19.34	19.62		860	23.8	849	16661	H
141	Eucalyptus tereticornis	19.48	19.49	19.48	22.12	960	22.1	942	18357	

TABLE 1 (cont)

No.	SPECIES	Gross CALORIFIC VALUE MJ/kg SAPWOOD	HEARTWOOD	AVERAGE	REPORTED CV (MJ/kg)	DENSITY (10ZNC) (kg/m³)	SHRINKAGE volume	DENSITY (Dry) (kg/m³)	CV. MJ/m³	SOFTWOOD/ HARDWOOD
115	Faurea saligna	20.46	20.41	20.44		1040	11.3	982	20076	H
44	Ficus sycomorus	19.52	19.48	19.50	18.60	480	8.5	449	8757	H
8	Gmelina arborea	20.71	20.79	20.75	19.61	470	8.3	439	9118	H
45	Goniona kamassi	20.02	20.29	20.16		880	18.0	851	17157	H
10	Grevillea robusta	20.59	20.04	20.32	20.40	600	9.8	564	11455	H
46	Halleria lucida	19.55	19.58	19.57		770		700	13699	
156	Heteropyxis natalensis	19.86	19.91	19.89						
47	Ilex mitis	19.30	19.44	19.37		600	12.3	569	11017	H
48	Jacaranda mimosaefolia	20.13	19.93	20.03		530	8.8	496	9942	H
49	Kirkia acuminata	19.54	19.45	19.50		540	7.2	503	9808	H
132	Leucaena leucocephala	18.99	19.74	19.36						
31	Liquidambar styraciflua	19.32	19.24	19.28	19.89	630	15.4	604	11640	H
30	Lophostemon confertus	20.14	20.01	20.08		890	10.8	839	16849	
50	Maytenus acuminata	19.45	19.05	19.25		930	17.2	897	17265	H
120	Maytenus heterophylla	19.56	19.33	19.44		740	7.0	689	13392	
51	Maytenus peduncularis	19.60	19.99	19.80		1000	16.0	960	19014	H
52	Melia azedarach	19.45	19.03	19.24	20.90	600	12.2	569	10939	H
69	Ocotea kenyensis	19.64	19.61	19.63						H
124	Olea capensis subsp. macrocarpa	19.53	19.15	19.34		1020	19.1	990	19150	H
25	Olea capensis subsp. macrocarpa	19.77	20.62	20.20		1020	16.8	982	19837	H
53	Olea europaea subsp. africana	20.71	19.95	20.33		1080	13.7	1029	20915	H
125	Olea europaea subsp. africana	19.64	21.89	20.76						H
26	Parinari curatellifolia	19.79	19.86	19.83		710	10.1	668	13242	H
127	Peltophorum africanum	20.00	19.93	19.97		710	8.5	664	13263	H
32	Pinus patula	19.94	20.90	20.42		450	9.7	423	8633	S
9	Pinus roxburghii	20.75	20.18	20.47		510	10.0	480	9815	S
70	Platylophus trifoliatus	19.50	19.31	19.41		530	11.6	501	9726	H
71	Podocarpus falcatus	20.58	20.22	20.40		540	9.4	507	10338	S
72	Podocarpus latifolius	20.77	20.76	20.77		560	10.2	527	10943	S
73	Populus Xcanescens	19.46	19.42	19.44		480	11.5	454	8821	H
27	Ptaeroxylon obliquum	21.00	21.11	21.06		1030	10.3	970	20416	H
158	Pterocarpus angolensis	19.44	19.67	19.55						H

TABLE 1 (cont)

No.	SPECIES	Gross CALORIFIC VALUE MJ/kg SAPWOOD	HEARTWOOD	AVERAGE	REPORTED CV (MJ/kg)	DENSITY (IOZHC) (kg/m³)	SHRINKAGE volume	DENSITY (Dry) (kg/m³)	CV MJ/m³	SOFTWOOD/ HARDWOOD
74	Pterocarpus angolensis	20.23	21,52	20,88		440	3.7	405	8454	H
28	Quercus palustris	19.20	19.49	19.35		720	14.9	689	13324	H
54	Quercus sp.	19.43	19.28	19.36	19.75					H
75	Rapanea melanophloeos	19.11	19,37	19.24		740	16.6	712	13701	H
128	Rhus lancea	19.85	20.49	20.17		1040	13.0	988	19934	H
129	Rhus leptodictya	19.58	19.64	19.61						H
104	Rhus leptodictya	20,11	21.23	20,67						H
105	Schotia brachypetala	19.80	20.88	20,34		800	8.0	747	15198	H
29	Sequoia sempervirens	20.00	20.98	20.49	21.29	460	9.1	403	8260	S
106	Spirostachys africana	19.86	21.62	20,74		970	8.5	908	18822	
76	Strychnos decussata	19,79	20.21	20,00		890	16.4	856	17117	H
159	Syzygium cordatum	19.57	19.54	19.55						H
103	Terminalia sericea	19.96	19.97	19.97		870	10.6	820	16369	H
77	Trema orientalis	19.42	19.32	19.37	19.49	440	9.5	413	8001	H
131	Ziziphus mucronata	19.62	19.71	19.66		800	13.6	762	14977	H
160	Ziziphus mucronata	19,17	18.66	18.92						H

2.3 Discussion of results

The most obvious conclusion which may be noted from the reported values is that the calorific value of wood, on an oven dry mass basis, varies surprisingly little. This is shown in the table below.

Table 2 : Summary of Gross Calorific Measurements of South African Grown Trees

	No of Samples	Range MJ/kg	Mean MJ/kg	Variance
All woods	230	18,34-22,49	19,80	
Heartwood	115	18,34-22,49	19,88	0,41
Sapwood	115	18,83-21,09	19,73	0,41
Hardwood	86	18,77-20,97	19,70	
Softwood	13	20,07-21,25	20,43	

These findings are confirmed by other researchers. Harker et al (1982) review 791 reported calorific values of wood and give an average value for all woods as 19.96 MJ/kg, for hardwood - 19.73, and for softwood - 20.82 MJ/kg. They also reported that 90% of observed calorific values of different wood species lie between 18 and 21 MJ/kg, but that the observed spread of calorific values is 15 to 25 MJ/kg. Standard deviation was 1,06 MJ/kg.

This relatively small range can be partially accounted for by the remarkably small variation in the elemental composition of wood, where carbon is generally 49-50%, hydrogen 6%, oxygen 43-44% and nitrogen, sulphur and ash 0,5-1%. Using Seyler's formula, which determines calorific value in terms of the constituent elements of coal and peat, and which reads as follows (Bialy, 1979):

$$E_{hv} = 1624\ H + 518{,}5\ C + 1{,}05\ O^2 - 17860 \quad KJ/kg$$

where H, C, and O are the percentages of hydrogen, carbon, and oxygen respectively (all expressed on a dry, mineral free basis and assuming that there is no sulphur present but that the nitrogen content is 1%), one obtains a calorific value of 19,5 MJ/kg for wood. This is remarkably close to average calorific values which have been measured for wood.

The slight difference between the average softwood and hardwood values may be accounted for by variations in the proportion and calorific values of the five main wood constituents - resins, cellulose, hemi-cellulose, lignin and mineral matter. The presence of resins, which have calorific values between 35 and 40 MJ/kg, has a marked effect on the gross calorific value of wood. Softwood species such as pine have a higher resin content and thus slightly higher calorific value than hardwood. However, pine is not regarded highly as a fuelwood because it burns too rapidly, and does not make good coals. Formation of the latter may depend more on hemi-cellulose content which is generally higher in hardwoods (35%) compared with softwoods (28%) (Bialy, 1979).

Because calorific value varies within such narrow limits, it is not a good indicator of the usefulness of a tree species as a fuel. This is further borne out by the results obtained from the 7 duplicated species tested (table 3), for the determinations within a species were found to vary by 0,43 - 1,53 MJ/kg, which is nearly equal to the range of variation between all the different species examined. Thus the variation within a single species, allowing for differences of ages and site, is as significant as that between different species.

Table 3 : Gross calorific measurements of tree species from different sites (MJ/kg)

Species	Site One	Site Two	Difference
Acacia tortilis	20,97	19,44	1,53
Canthium obovatum	19,71	18,87	0,84
Olea capensis spp. macrocarpa	20,2	19,34	0,86
Olea europaea spp. africana	20,76	20,33	0,43
Pterocarpus angolensis	20,88	19,55	1,33
Rhus leptodictya	20,67	19,61	1,06
Ziziphus mucronata	19,66	18,92	0,74

Harker et al (1982) also report that trials on two species of timber conducted at the Tropical Products Institute in the UK have shown that the variation in gross calorific value between different trees of the same site is greater than the variation obtained from material taken from different parts of the same tree. Furthermore the large variation

in calorific value between these trees and the small standard deviation observed for the reported values of different species suggests that the calorific value determinations for wood are of limited value. As most tree species have a gross calorific value within 5% of 20 MJ/kg (oven-dried), this value is good approximation for nearly all fuelwoods.

It is clear from the above that other combustion parameters must be examined if we are to arrive at an objective measure or ranking of fuelwood species.

3. FUELWOOD COMBUSTIBILITY

Although the main focus of this project was to document calorific values of South African grown fuelwood species, there was also the requirement to develop an appropriate measure of flammability or combustibility but without, at this stage, undertaking experimental combustibility tests on a full range of tree species.

3.1 Theory of wood combustion

Wood combustion takes place in the following stages: driving of moisture from the wood, pyrolysis of volatile constituents, combustion of the volatiles and combustion of the char.

When wood burns, approximately 80% (by mass) burns as volatiles and 20% burns as fixed carbon (char) (Brame, 1961). For a wood particle Wagoner and Winegartner (1973) observed that the volatiles and char do not burn simultaneously since the expanding hot flue gases prevent air reaching the char. However in a hearth or woodburning stove where the wood pieces are relatively large, it is possible for char and volatiles to combust at the same time.

Many of the gases produced during combustion have high ignition temperatures; for example, H_2 - 540 °C ; CO - 600 °C ; and CH_4 - 650 °C.

A general, but pioneering, model of spontaneous and forced wood combustion was developed by Bramford and Crank (1946). They investigated temperatures and rates of decomposition inside sheets of wood of varying thicknesses. In spontaneous combustion, using oven dried wood of different thicknesses, they found that the core temperature was always approximately 480 K when spontaneous combustion could take place. The temperature of the wood then rose linearly until it reached 600 K, after which combustion occurred rapidly until 740 K, at which temperature all the volatiles had been released. They also found that spontaneous combustion occurred only when the rate of evolution of volatiles had reached a minimum value of $2{,}5 * 10^{-4}$ g.cm^{-2} sec^{-1}. The evolution rate then increased rapidly, depending on the thickness of the wood and the diffusivity of the evolved gases, until completion of combustion.

Later studies dealt with wood combustion by analysing the two main stages and their associated mechanisms.

Pyrolysis

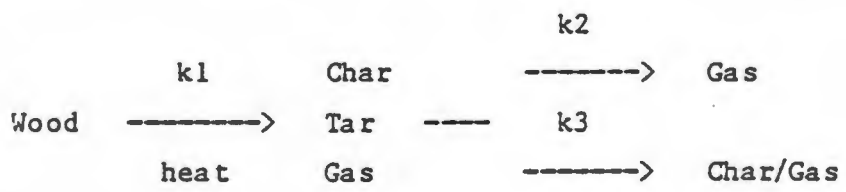
Pyrolysis refers to the release of the volatile constituents from the wood, and generally takes place at temperatures between 500 and 775 K. (Simmons, 1983, p13).

The mechanisms involved in pyrolysis include;

a) Convective and radiant heat transfer from the hot gaseous atmosphere to the wood. This is referred to as external heat transfer.

b) Heat transfer inside the wood particle. Before decomposition this is mainly conduction, but once pyrolysis begins the volatile production may result in convective heat transfer to the surface (Kansa, 1977).

c) Pyrolysis reaction. A large number of reactions take place during pyrolysis, some of which are endothermic and others exothermic. These reactions have been broadly grouped into two stages; primary and secondary pyrolysis.



Primary pyrolysis is endothermic whereas secondary pyrolysis is responsible for the heat release. Whether reaction two or three take place in secondary pyrolysis, depends on the permeability of the wood. In perpendicular grain orientation, reaction three is favoured due to the slow permeation of the volatiles and tar, and is associated with char build-up. In parallel grain orientation, reaction two is favoured.

Generally the pyrolysis reaction is represented by a first order Arrhenius equation:

$$\frac{dm}{dt} = C_r . \exp^{(-E_a/R.T)} .(1-m)$$

where C_r = rate constant (time^{-1}), E_a = activation energy (J/mol), R = gas constant, T = temperature (K) and m = mass of volatiles as a fraction of total volatiles at total conversion (Zaror:1981).

d) Diffusion of the volatiles through the wood; and

e) Diffusion of the volatiles to the combustion air.

Char combustion

The char burn-off is the final stage of wood combustion. Although char represents only 20% of the total mass of the wood, it requires 50-74% of the total burn time (Simmons, 1983, p 149). Simmons found that char combustion was purely diffusion controlled. He also did some measurements of surface temperatures of the burning char particle.[1] At a free stream Reynolds number of 265, the surface temperatures were between 1226 K and 1409 K, depending on the free stream temperature (which was varied from 900 to 1200 K) and the type of wood (pine and oak were used).

Comparing the combustibility of different species

It is clear from the above that the processes of moisture release, pyrolysis, volatile and char combustion are dependant to some extent on the physical characteristics of the wood. One approach might be try to analyse the physical structure of wood and derive a series of indices which would serve to rank fuelwoods.

The chemical composition of wood also affects the combustion process. The main chemical constituents of wood - cellulose, hemicelluloses and lignin - begin breaking down at temperatures above 250 °C. Cellulose and hemicellulose yield most of the volatile products and only 8 - 15% of the char. However 50% of the lignins form char (Zaror and Pyle, 1981). The proportion of these compounds varies greatly from one wood species

[1] Using an optical pyrometer.

to another and these variations contribute to the reasons for differing combustibility between tree species.

But it is difficult to define precisely which chemical and physical properties of wood species determine their suitability as fuel and the literature does not provide any definite measure for ranking fuelwoods. All that is available is anecdotal information based on experience (see Appendix A). From observations in the field a good fuelwood was described as a hardwood that burnt without cracking or spitting and formed a large quantity of char which then burnt for a prolonged period of time (Poynton, 1984).

A more fruitful approach is to study the processes of wood combustion itself and to characterize these processes for different species in order to rank fuelwoods. The thermo-gravimetric which yields decomposition profiles during combustion is well known and widely used. A modification of this method, where the reactor temperature is kept constant, enables the determination of the rate of mass loss during combustion, reactivities and activation energies for different fuels.

An experimental rig has been developed at the Energy Research Institute, for a parallel research project on reconstituted fuels, which will enable the combustion of small particles under controlled conditions to be studied. The experimental equipment and procedures are outlined below. No provision was made in the current project to undertake extensive combustion analyses on a wide range of samples. The results from three fuelwood species are described in order to demonstrate the usefulness and potential of this method.

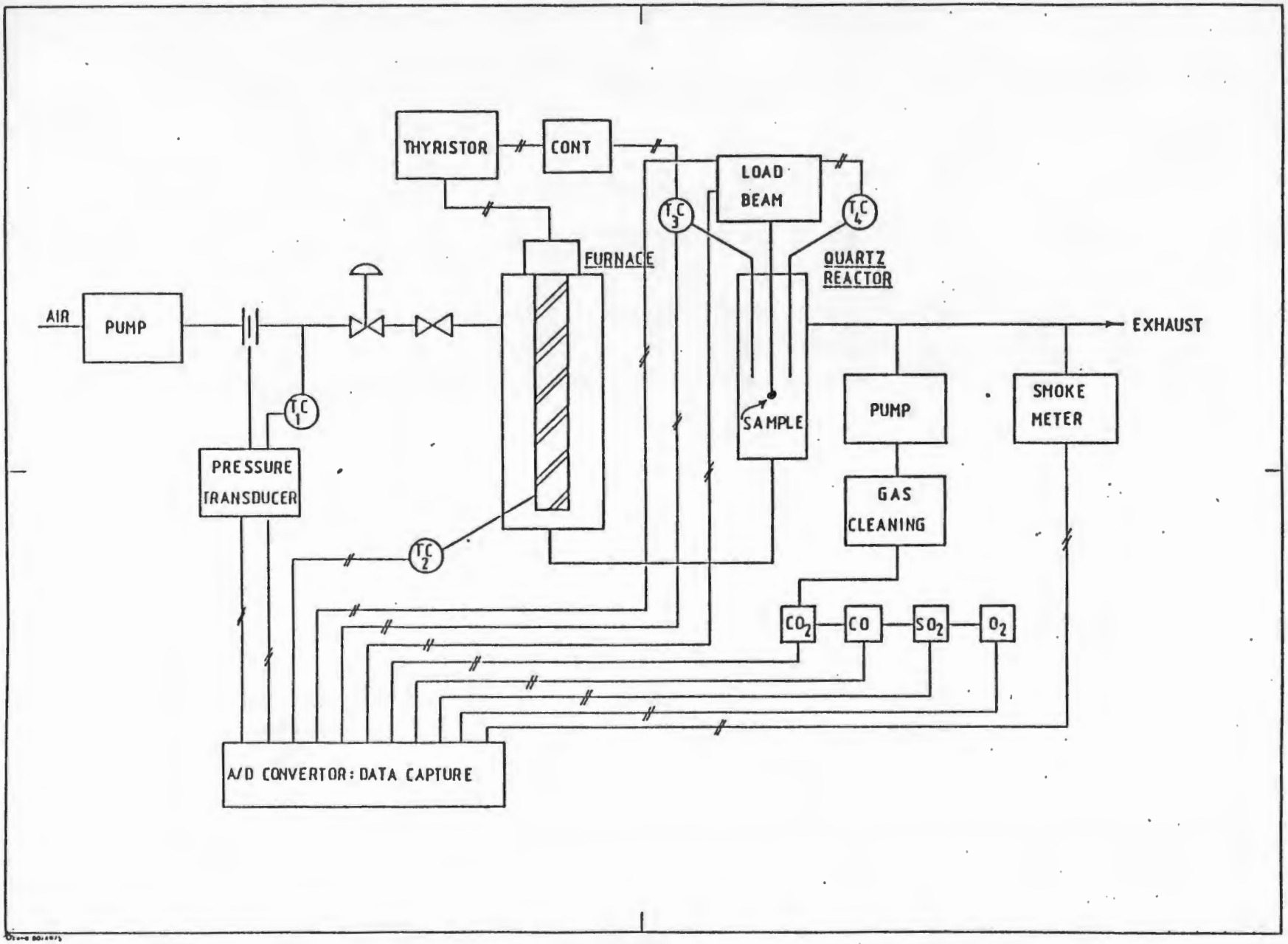


FIGURE 1 : ERI experimental rig for thermo-gravimetric combustion analysis

3.2 Experimental apparatus

The apparatus which was developed by Jim Petrie of the Energy Research Institute is illustrated in Figure 1.

Combustion air is blown through a furnace where it is heated to a required temperature which is regulated by a microprocessor controller. The heating element is a spiral silicon carbide form, with electrical power supplied to it via a bank of thyristors. From here it passes through a quartz reactor where combustion and decomposition of the sample takes place. A portion of the exhaust gases is drawn off for analysis of carbon dioxide, carbon monoxide and flue gas oxygen. The solid fuel sample is suspended in the quartz reactor from a load beam which monitors the mass loss during combustion. Two thermocouples are positioned in the reactor in the proximity of the sample. This provides a measure of gas film temperatures. Electronic signals from the thermocouples , load beam and gas analysers are digitised via an A/D board in a microcomputer. Software has been written to store and manipulate the data" (Petrie and Baldwin, 1987).

3.3 Experimental method

"Fuel samples were prepared as 14 mm sided cubes and suspended from a stainless steel rod in the reactor using nichrome wire, either wrapped around the sample or inserted through a hole drilled through the middle of the cube. Air flow to the reactor was permitted once the data capture system had been initialised. The sudden change in mass measurement due to the introduction of air was taken to be the effect of drag on the particle. A similar estimation on the drag on the ash remaining at the end if the experiment was performed so that mass measurements during combustion could be compared for drag effects by interpolating between these two values.

"The mass of the particle and the gas concentrations were recorded until constant mass signified the completion of combustion. The combustion period was divided into two phases, viz., devolatilsation and char combustion. The end of the former was determined as the time after which there were no more yellow flames (in all cases it was assumed that ambient furnace temperature was high enough, and gas residence times long enough to support ignition of volatiles).

"The final mass of the particle was determined from the average of the last ten values recorded. From this recorded mass (ash plus wire support), the combustible mass of the sample, at each time interval, was determined. A normalised value was calculated by dividing by the original sample mass. Because of the marked differences in devolatisation and char combustion profiles, their resolution was conducted separately. The overall mass loss profile was prepared and the time derivative of this mass loss curve yielded the reactivity of the sample" (Petrie and Baldwin, 1987).

The apparent rate of reaction for the devolatisation and char combustion phases can be derived from this data and hence the apparent rate constant may be calculated. The rate constant varies with temperature according to the Arhennius equation and using experimental data from different controlled temperature runs, the activation energy may be derived in the usual way. A worked example is included in Appendix B.

3.4 Some initial results

Rate of mass loss and reactivity curves for two different wood species, combusted under similar conditions, are shown below. Colophospermum mopane and Cryptomeria japonica were selected as representing very dense, good, and very lightweight, bad, fuelwood species respectively. The marked differences are readily apparent, with the japonica exhibiting rapid devolatisation and poor char combustion compared with the mopane. It would appear that this technique might be fruitfully employed to differentiate between different potential fuelwood species. At the time of writing this report no further experimental runs had been conducted under different temperature conditions and no activation energies could be derived for these two species. A number of experiments, at different temperatures, were performed for pine and a worked example of the derivation of activation energy for that species is shown in Appendix B.

FIGURE 2

COMPARISON OF MASS LOSS CURVES FOR TWO WOOD SPECIES

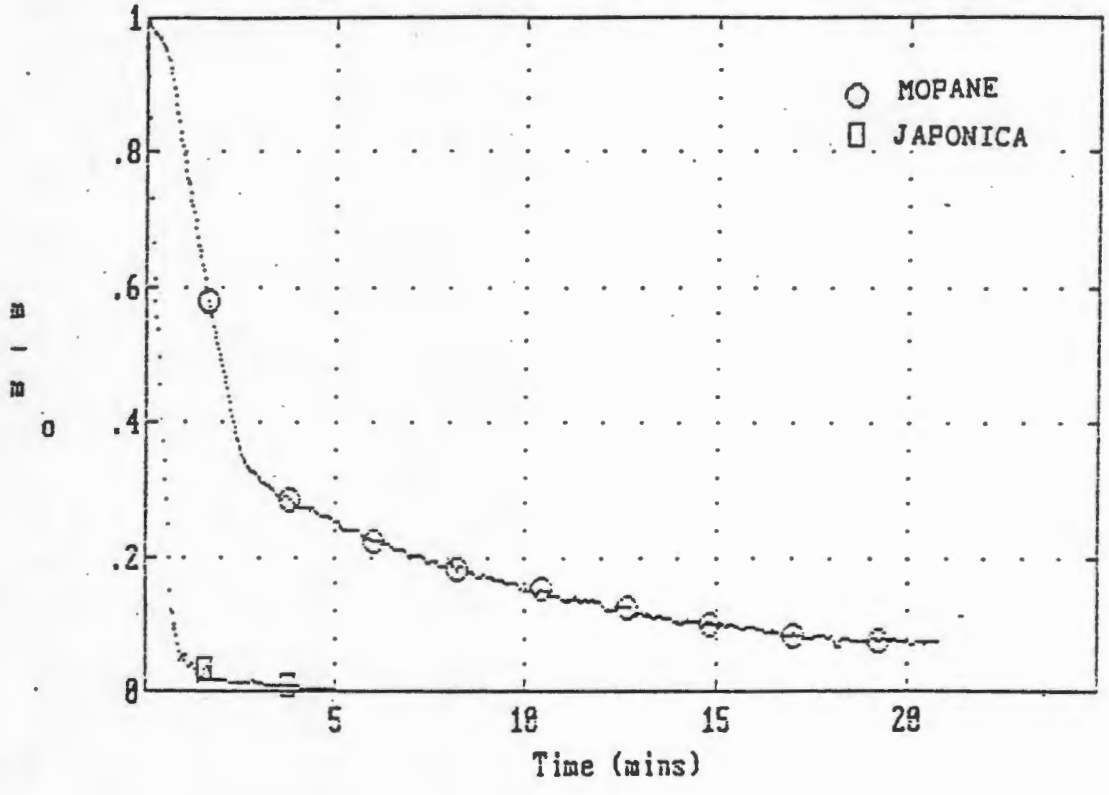


FIGURE 3

REACTIVITY AND MASS LOSS PROFILES

Date: 17/12/86
Fuel: Colo. Mopane
Test No.: 1
Free Stream
Temperature: 587 C
629 C
Velocity: 1.57 m/sec
Key
○ Mass (g)

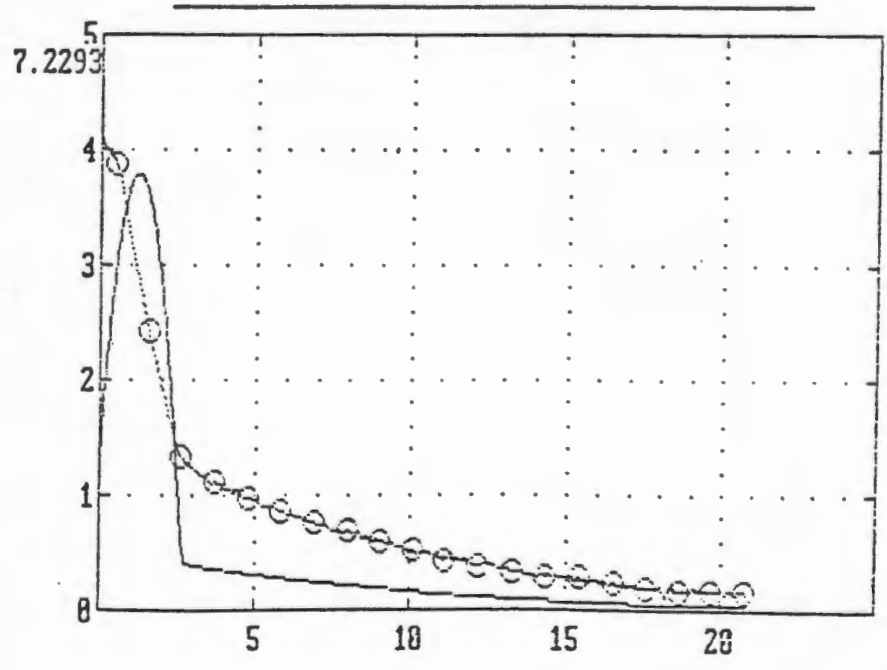
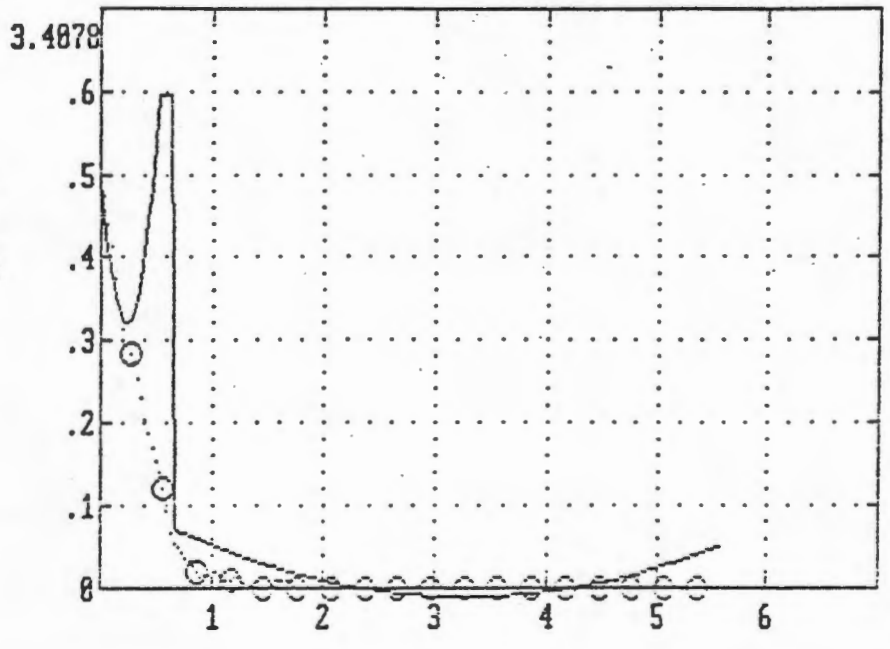


FIGURE 4
REACTIVITY AND MASS LOSS PROFILES

Date: 18/12/86
Fuel: Japonica
Test No.: 1
Free Stream
Temperature: 681 C
650 C
Velocity: 1.61 m/sec
Key
○ Mass (g)



4. CONCLUDING DISCUSSION

Calorific value is not important in the choice of species for fuelwood production. In practice, other factors such as growth rate, plantation siting, moisture content, density and type of combustion system used are far more significant.

The need still exists, however, for an objective measure of the worth of tree species as fuelwood. It has been argued that the most fruitful research direction would be a fundamental investigation into the combustion characteristics of different wood species under controlled conditions. An experimental rig has been developed which has indicated the usefulness of looking at such parameters as rate of mass loss during combustion, reactivity and activation energy. What remains to be done is the experimentation with very many more wood samples using this technique and for the data obtained to be correlated with anecdotal and field information on fuelwood preferences so as to validate this approach as being useful for ranking fuelwood species. This information can then be related to silvicultural factors which are important in the selection of suitable fuelwood species.

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APPENDIX A

FUELWOOD PREFERENCES

Rural households generally possess a very detailed local knowledge of the natural flora and have different vernacular names for the most subtly different tree species. They also have very definite preferences for different species depending on the use to which the wood is to be put. Eberhard (1986) studied energy consumption patterns in 6 villages in South Africa: Lujiko, near the Fish River valley in the Ciskei, Manzimahle, Clarkebury and Nkanga in the Transkei, Cottondale in the eastern Transvaal and Mokumuru near Bochum in the north-west Transvaal. Fuelwood preferences in these areas is shown in Table 2.

Most of the species noted are gathered primarily for fuel, although some are also used for the construction of kraals and fences. There is also a definite aversion to burning certain tree species, e.g., in Mokumuru, the Marula (Sclerocarya caffra), the Mogorogoro (Strychnos spinosa), the Morekuri (Spirostachys africana) because of its smell, the Mmilo (Vangueria infausta), and the Mogale (because, if burnt, it is believed that if burnt cows will produce bull calves only.

Gandar (1983b) also reports that certain species are avoided for fuelwood. It is believed, for example, that the burning of Euclea spp causes strife in the family while Vangueria infausta and Diospyros lycioides are believed to attract lightning. Spirostachys africana and Euphorbia tirucalli are generally only burnt outside because of their unpleasant or toxic smoke.

Expressed preferences are clearly linked to the local availability of particular species. For example, those households which indicated a liking for pine resided in areas which are dependent in large measure on plantation wood being trucked into the village.

Data from other areas is also of interest here. Liegme (1983) reports that in her area of study in Gazankulu, Colophospermum mopane and Combretum apiculatum were regarded as the best fuelwood species and that these were also the two which were most often used. Other species also mentioned as producing good firewood were Combretum imberbe and Acacia nigrescens. Altogether, 42 species were found to be used for fuelwood in her study area, but 3 species made up 77% by weight of the wood collected and 8 species over 90%.

Cunningham (1984) reports that the main fuelwood used in the Ingwavuma district, situated on the Maputaland coastal plains in Northern Kwazulu/Natal, are Sclreocarya caffra, Dialium schlecteri, Strychnos madagascariensis, Acacia burkei, Syzigium cordatum, Terminalia sericea, Trichilia emetica, Albizia adianthifolia and Macaranga capensis.

Gwaitta-Magumba (1983) writes that the preferred species in Swaziland are Acacia nigrescens (umkhanga) and A. davyi (umgambe).

Kgathi (1984) reports that traders who collect fuelwood in the Kaneng District of Botswana and sell it in Gaborone prefer Combretum imberbe and C. apiculatum. Less desired fuelwood species are Acacia karoo, A.erubescens, A.tortilis, and Dichrostachys cinerea.

Finally, Gandar (1983b) states that preferred species at Mahlabatini in Kwazulu are Maytenus heterophylla, Acacia nilotica, combretum apiculatum, Acacia nigrescens, A. tortilis, A. caffra, Ziziphus mucronata, Dichrostachys cinerea, Cassine transvaalensis, Berchemia zeyheri (this is a royal tree and generally protected), Acacia karoo, Olea africana, and Acacia robusta.

All the preferred fuelwood species reported above are hardwoods and many have dense timbers. The density of a wood determines to some extent the rate of release of volatiles and the degree to which good coals are formed, a dense wood usually making a longer lasting fire which gives off heat at a steadier rate. Households probably assess the rate of wood consumption primarily in terms of volumes rather than mass. Preferred fuelwood species are hence comparatively dense because they contain a greater quantity of energy per unit volume than lighter woods. Calorific value expressed in volumetric terms may thus be a more meaningful indicator of the desirability of a tree species for use as fuelwood.

% Households Listing Tree Species In Top Five Preferences

Villages	Manzimahle			Nkanga		Mokumuru
Species	Lujiko		Clarkebury		Cottondale	
Acacia karroo	8	-	24	100	-	10
(Umnga - (Xhosa), Mooka (N Sotho) or Mimosa)						
Combretum apiculatum	-	-	-	-	2	97
(Mohweleri (N Sotho) or Xikukutso (Tsonga))						
Acacia mearnsii	-	79	2	9	-	-
(Wattle)						
Eucalyptus spp.	-	6	78	-	10	-
(Gum)						
Scutia myrtina	-	-	44	73	-	-
(Ubobo or Sipingo)						
Ptaeroxylon obliquum	12	-	-	72	-	-
(Umthathi or Sneeze)						
Acacia burkei or robusta	-	-	-	-	-	63
(Mokgwa)						
Cussonia paniculata	-	-	-	-	-	50
(Motshe or motshetse?)						
Dalbergia obovata	-	-	-	45	-	-
(Uzungu)						
Pinus spp.	-	-	40	-	15	-
(Pine)						
Grewia lasiocarpa	-	-	-	36	-	-
((U)hlolo)						
Combretum imberbe	-	-	-	-	6	33
(Mmondzo - Tsonga, Motswere - N Sotho)						
Acacia tortilis	-	-	-	-	-	30
(Moswana or mosu)						
Aloe spp.	-	-	29	-	2	-
Rhus lancea	-	-	-	27	-	-
(Umhlakotshane)						

% Households Listing Tree Species In Top Five Preferences						
Villages		Manzimahle		Nkanga		Mokumuru
Species	Lujiko	Clarkebury		Cottondale		
Olea europaea spp. africana (Umnquma or Olive)	20	-	-	9	-	-
Maytenus heterophylla (Umqaqoba)	20	-	-	9	-	-
Schotia brachypetala (Molope)	-	-	-	-	-	20
Turraea floribunda (Umvuma)	-	-	-	18	-	-
Calodendrum capense (Umbaba)	-	-	-	9		-
Zanthoxylum capense (Umnungu mabele)	-	-	-	9	-	-
Combretum erythrophyllum (Modibo or Moduba)	-	-	-	-	-	3
Strychnos innocua (Nkwakwa)	-	-	-	-	2	-
Dichrostachys cinerea (Ndzenga (Tsonga) Moretshe (N Sotho))	-	-	-	-	8	-
Diospyros mespiliformis (Ntoma)	-	-	-	-	2	-

APPENDIX B

DETERMINATION OF COMBUSTION ACTIVATION ENERGY FOR PINE CHAR SAMPLE.

Wood reactivity data, obtained via a thermal balance reactor, can be used to determine fundamental combustion parameters such as the activation energy associated with the combustion of wood char. The numerical value of this "observed" activation energy should provide valuable information on the relative worth of various fuel wood species.

There are a number of assumptions implicit in this type of overall analysis. These are enumerated below. It should, however, be stressed that, in a more rigorous analysis, most, if not all of these, would be substantiated either by experimental measurement, or by making use of physical property correlations available in the open literature. This sample calculation serves only to outline the principles involved in this type of analysis.

Firstly, it is assumed that volatile release rate was fast compared to char combustion, and that volatile combustion and char combustion could be treated as consecutive, non interfering phenomena. For this analysis, the onset of char combustion was determined by the change in slope of the mass loss curve plotted as a function of time, and in all cases corresponded to between 20% and 30% of the original sample mass.

Secondly, no attempt has been made to resolve film diffusion and chemical limitations, nor to distinguish between reaction limitations at the char particle surface, and any intra particle diffusional constraints. The activation energy so derived is thus a "lumped" value. This is best explained as follows:

The specific reaction rate, R_a, is given by

$$R_a = k_c C_s^n \qquad [1]$$

where k_c is the intrinsic chemical rate constant, but includes a factor to account for intra particle diffusion.

C_s is the surface concentration of oxygen

and n is the true order of reaction.

The intrinsic activation energy, E_A, is determined from the value of k_c, assuming an Arrhenius dependence.

The surface concentration of oxygen is an unknown. Rewriting the expression for specific reaction rate in terms of the oxygen concentration gradient, gives

$$R_a = k_g (C_g - C_s) \qquad [2]$$

and further, for a first order reaction (a not unrealistic assumption), combining the above two equations gives

$$R_a = k_c k_g C_g / (k_c + k_g) \qquad [3]$$

From this expression, a pseudo rate constant, K, given by

$$K = k_c k_g / (k_c + k_g) \qquad [4]$$

is derived. An "observed" activation energy for char combustion can be derived from this effective rate constant, according to

$$K = A \exp(-E/RT) \qquad [5]$$

Depending on the relative importance of film mass transfer, chemical kinetics, and intraparticle diffusion, this pseudo rate constant, K, may approximate the true chemical rate constant, and the observed value of the char activation energy, so derived, approach the true intrinsic value. The intricacies of this type of analysis are not unwieldy, but go beyond the current requirement of fuelwood comparison. A comprehensive analysis is required if it is important to consider the combustion of various wood species in a range of combustion hardware, where temperatures and air velocity profiles may extend beyond the ranges covered in this investigation.

The specific reaction rate for char combustion, given by

$$R_a = K C_g \qquad [6]$$

is determined from the time rate of mass loss for the char species, assuming, in addition, that these pine chars burn at constant density (taken as 400 kg/m^3).

For the reaction

$$C + O_2 \Rightarrow \text{combustion products}$$

the specific rate of reaction can be related to the molar flux of oxygen by

$$R_a = - 1/S_A \frac{d N_A}{d t} \qquad [7]$$

where N_A is moles of oxygen reacted, and S_A is outer surface area of the unreacted char particle (which varies as the unreacted core shrinks with time).

The molar flux of oxygen (by stoichiometry) can be expressed in terms of carbon mass loss, to give

$$R_a = - 1/S_A \frac{d}{d t} (4/3\pi\rho r^3/MW) \qquad [8]$$

The instantaneous char particle radius, r, is, for particles of constant density, related to instantaneous particle mass according to

$$(r/R_o)^3 = (m/m_o) \qquad [9]$$

where R_o and m_o refer to initial particle radius and mass respectively. Expressing S_A in terms of particle mass, i.e.

$$S_A = 4\pi R_o^2 (m/m_o)^{2/3} \qquad [10]$$

and rewriting the expression for specific reaction rate, gives

$$R_a = \frac{-(R_o \rho / 3MW) \frac{d (m/m_o)}{d t}}{(m/m_o)^{2/3}} \qquad [11]$$

In other words, the apparent specific reaction rate for char combustion can be found from a plot of char reactivity versus normalised mass raised to the power 2/3.

This is the approach adopted here. A number of experiments were performed with pine samples in the temperature range of 600 °C to 850 °C. In all cases the combustion atmosphere was held constant at 21% oxygen.

Once the specific reaction rate for char combustion has been determined as a function of temperature, according to equation 11, a plot of the log of the specific reaction rate versus the inverse of the combustion temperature yielded a value for the "observed" char activation energy. Experimental data is shown in the accompanying table (A1).

The calculated value of E is 15,1 kJ / mol. This value is higher than one consistent with film mass transfer dominating, and indicates some intra-particle diffusional limitations.

TABLE A1.

PINE CHAR COMBUSTION IN AIR

EXPERIMENTAL PARAMETERS.

BULK GAS TEMP (K)	SLOPE	SPECIFIC RATE (kmol / s / m^2)
880	0.0132	0.0012
884	0.0167	0.0015
887	0.015	0.0013
1006	0.0121	0.0017
1014	0.0203	0.0013
1079	0.0237	0.0021
1105	0.0203	0.0018

The slope (column 2) refers to the plot of char reactivity versus char mass according to equation 11, and is equal to

$3\ MW\ R_a / (R_o \rho)$.

No allowance was made for the difference between char surface temperature and gas film temperature. In practice, this measurement would be made directly by non intrusive thermometry.

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CALORIFIC VALUES AND COMBUSTION CHARACTERISTICS OF SOUTH AFRICAN GROWN FUELWOODS

FINAL REPORT

A A EBERHARD

APRIL 1988