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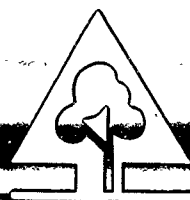
CHARCOAL FROM NEW SOUTH WALES SPECIES OF TIMBER

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FORESTRY COMMISSION OF N.S.W.

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**CHARCOAL FROM NEW SOUTH WALES
SPECIES OF TIMBER**

by

F. R. Humphreys, G. E. Ironside

Forestry Commission of New South Wales,
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INTRODUCTION TO THIRD EDITION

Since publication of the original work in 1974, interest in charcoal has been stimulated by the many conflicting issues of the age—the world fuel shortage; energy conservation; pollution and the environment. Insofar as charcoal is made from wood which would otherwise be wasted, the manufacture of charcoal adds to our total energy resource. The carbonising process, however, involves a nett loss of usable energy yielding a product with special properties. Thus, unless these special properties of charcoal are utilized, it cannot normally be regarded as an economic substitute for conventional fuels.

The second edition was substantially the same as the first edition. More prominence was given to the carbonising of the smaller fractions in mill residues and to biological uses, especially those associated with pesticides. The analytical data on ash contents have benefitted by recent research.

The Third Edition, this present work, arises due to the popularity of the previous works and contains, apart from minor revisions, the latest information from sources not previously studied.

Forestry Commission of New South Wales
1980

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INTRODUCTION

Wood charcoal is a form of amorphous carbon which is derived from incomplete combustion pyrolysis of wood. The term amorphous carbon covers a much wider group of substances than can be made from wood. It includes the various carbon blacks, cokes, coals and all other forms of carbon which are not crystalline. The term char is sometimes used for unactivated charcoals. However, it is probably best kept for the product of pyrolysed bones, sometimes referred to as "animal charcoal".

PRINCIPAL PHYSICAL AND CHEMICAL PROPERTIES

Density

Wood charcoal is a porous solid, the density of which varies directly as the density of the raw material used and with the method by which it is prepared. Three types of density can be used when referring to wood charcoal, namely, bulk, particle, and material density.

Bulk density. The bulk density of a material is that weight which can be packed into a container of a given volume. It varies with

- (a) the granule density of the charcoal,
- (b) the grading of the particles.

In the size grading 6–25 mm, bulk density of local hardwood charcoal is in the range 240–420 kg/m³.

Particle density. Particle density is the weight of a given volume of charcoal particles excluding the volume of free space between the granules. This can be determined by immersing granules in mercury which will not enter the pores at atmospheric pressure. This figure is a better measure of differences between charcoals than the bulk density, but is not as easy to determine. Typical figures for this density are 0.7–0.9 g/mL.

Material density. Material density is the weight of a unit volume of the solid substance (excluding the pore space) which makes up the skeleton of charcoal. Its determination requires a knowledge of the pore volume of the charcoal, and is obtained by measuring the volume of fluid (water, organic solvents, etc.) required to fill the pores. Pore space in ordinary unactivated charcoal may be as high as 1 mL/g (Kipling, 1956). The material density of wood charcoal is usually between 2.0 and 2.2 g/mL.

Pore Size

The absorbing capacity of various charcoals is related, not simply to the total pore volume, but to the volume available in pores of specific size. Pores have been classified by Dubinin (1955) into macro-pores, transitional pores and micro-pores. Macro- and traditional pores can be measured by forcing mercury into them under pressure but the micro-pores are more difficult to measure. It has been estimated that in charcoal with an absorbing area of 1500 m²/g, the macro-pores contribute only about 3 m³/g (Juhola and Wug 1949). Micro-pores are probably between 1 and 10 nanometres in diameter.

Moisture Content

Charcoal absorbs water vapour from the atmosphere after manufacture. Wet charcoal will dry to a satisfactory moisture level by exposure for a few hours in hot sunshine. (Queensland, 1942). Charcoal probably has an equilibrium moisture content but no reliable data on this property appear to be available. Some preliminary figures, which were obtained on one sample without temperature control, are contained in Forestry Commission of N.S.W. files and are as follows:

Relative humidity %	35	52	79	100
Moisture/100 parts charcoal oven dried at 150° C	2.69	10.38	12.18	20.74

No information is available concerning the analysis of the charcoal used. Information concerning carbon black (Perry, 1950) indicates that these figures may be high.

Specific Heat

The specific heat of charcoal is reported by Perry (1950) to be 1.013 kJ (kg K). Figures given by Schorger (1926) taken from old sources (Kunz, 1904; Weber, 1875) are set out in the following table.

Temperature ° C	Specific heat Cal/g/° C	Specific heat capacity kJ (kg K)
0— 23.5	0.1653	0.692
0— 99.2	0.1935	0.810
0— 223.6	0.2385	0.998
435	0.243	1.017
561	0.290	1.214
728	0.328	1.373
925	0.358	1.498
1059	0.378	1.582
1297	0.381	1.595

Electrical Resistance

The electrical resistance of charcoal is dependent on the carbonisation temperature. Charcoal carbonised at 600° C has a resistance in the region of 10⁶ ohms whilst the resistance of charcoal carbonised at 800° C is less than 1 ohm. (Bergström, 1954). Figures quoted by Schorger (1926) ex Herbst (1921) indicate the order of magnitude of increase in conductivity obtained by carbonisation at higher temperatures.

Temperature of carbonisation (° C)	Conductivity (mA)
700	0.004
1150	67
1200	210
1400	340

The specific resistivity for oak (*Quercus* sp.) carbonised in the temperature range 400–1100° C is depicted in Figure 1.

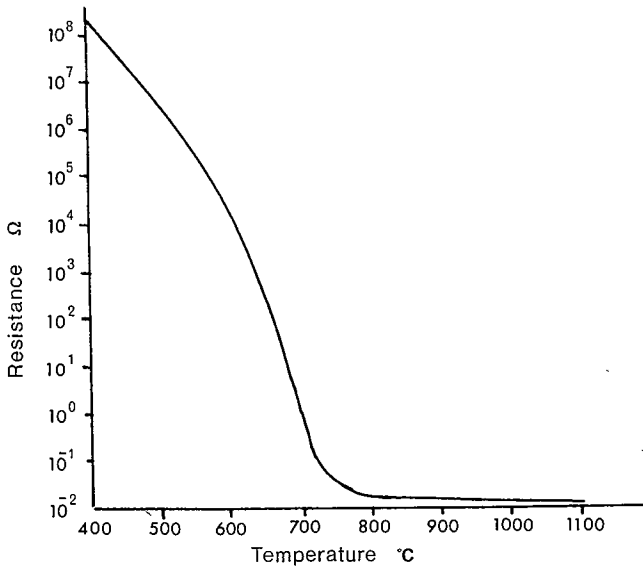


Figure 1. Electrical resistance of oak charcoal. (after Kishimoto *et al.*, 1951).

Calorific Value

The values given by Klason *et al.* (1910) for charcoal from various species are as follows:

Species	Composition			Calorific value
	C	H	O	kJ/g
Pine	82.5	4.0	13.5	32.18
Spruce	82.5	4.1	13.4	40.59
Birch	82.2	3.8	14.0	32.16
Beech	82.1	4.1	13.8	31.63

The mean calorific value for thirty samples made from Australian timbers (mostly eucalypts) reported by Almond *et al.* (1940) was 31.99 kJ/g (standard deviation 1.17). The elemental composition of these samples is unknown although proximate analyses were carried out. The samples were made in a number of ways and under various conditions.

Gregson (1941) reported a number of calorific values obtained for *Eucalyptus marginata* charcoal, the mean of which (excluding specially made charcoals) was 32.34 kJ/g (standard deviation 0.84). He showed that, for this species, a good correlation existed between the calorific value and the volatile matter content and gave an equation connecting these values. He supported this equation with data obtained from other species and by other analysts. The correlation was not as good in the latter case.

Comparing the calorific values of wood with other commercial fuels Humphreys (1956) gave the following data:

Fuel	Approx. calorific value kJ/g
Wood (dry)	19
Coal	28-33
Coke	28-30
Charcoal	29-30
Fuel oil	42-44
Kerosene	46

Identity

As the anatomical features of wood remain intact during carbonisation, charcoal specimens can often be identified using a good hand lens and a reference collection of authenticated charcoal specimens. Because of the brittleness of charcoal however, the usual wood sectioning techniques are totally unsatisfactory. For microscopic examination, a microscope with incident light attachments is required so that anatomical details of a solid piece can be viewed (Koeppen 1972).

Microtome sectioning of charcoal without shattering may be achieved by infiltrating the charcoal with polyethylene glycol and supporting the section during cutting with adhesive cellulose tape (Cousins 1973). McGinnes *et al.* (1971) described a technique for preparing samples for electron microscopy. The electrical resistivity of wood carbonised at 600° C or higher is sufficiently low to permit direct SEM viewing without metal coating. Exposure of sample planes by fracturing is preferable to microtoming (Beall *et al.* 1974).

Elemental Composition

The carbon, hydrogen and oxygen content of charcoal varies with the temperature at which it is made.

Data from Bergstrom and Weslen (1918) on the ratio of these elements in charcoal produced at different maximum temperature is given in the following table:

Distillation temperature (° C)	Composition of Charcoal			Yield (% charcoal/dry weight of wood)
	% C	% H	% O	
200	52.3	6.3	41.4	91.8
250	70.6	5.2	24.2	65.2
300	73.2	4.9	21.9	51.4
400	77.7	4.5	18.1	40.6
500	89.2	3.1	6.7	31.0
600	92.2	2.6	5.2	29.1
700	92.8	2.4	4.8	27.8
800	95.7	1.0	3.3	26.7
900	96.1	0.7	3.2	26.6
1000	96.6	0.5	2.9	26.8
1100	96.4	0.4	3.2	26.1

Ash

The ash content of wood charcoal is a function of the wood from which it is made and the yield. The amount and composition of the ash are quite significant factors in most forms of charcoal utilisation. Ash removal and clinkering are important when charcoal is used as fuel or in carbon bisulphide manufacture. In activated charcoal the composition of the ash can profoundly affect the absorbing properties of the material. A low phosphorus content is looked for in iron smelting.

The ash content of wood varies with the species and growing environment. Some overseas charcoal ash figures for unactivated charcoal, made at 400° C–500° C, indicate that a range of 0.8–5.0% ash can be expected for hardwood charcoal made from clean wood of a single species. Rather lower figures are found for most softwoods.

Moore (1940) has given a list of values for the ash content of a number of Queensland species. These figures show that while most of the eucalypts tested gave a charcoal with an ash content less than 2%, a few, namely *Eucalyptus crebra*, *E. paniculata*, *E. moluccana*, *E. microtheca*, *E. sideroxylon*, *E. tessellaris*, *E. populnea*, sometimes produced charcoal with ash contents over 2%. A number of other species, *Acacia cambagei*, *A. harpophylla*, *A. pendula*, *Casuarina glauca*, *E. luehmannii*, *Melaleuca leucadendron*, *Santalum lanceolatum*, *Syncarpia glomulifera*, *Tristania conferta* were found to have a high ash content (over 2%). In addition, a number of species were found to have an ash which was fusible below a temperature of 1300° C. These were *Tristania conferta*, *Callitris columellaris*, *Eucalyptus gummifera*, *Melaleuca leucadendron*, *Syncarpia glomulifera*.

Jaeger (1941) examined the ash content of some Tasmanian timbers in some detail. In most of these timbers, the ash content of the outer layer of charcoal made from green wood was high (greater than 1%), falling off rapidly to a constant value at the interior. This pattern was considered to be well established for eucalypts, as no exceptions were found in over 200 samples. Several *Acacia* spp., *Casuarina* spp., and *Nothofagus* spp. were shown to be similar. A number of other species, however, did not conform. Jaeger showed that although this effect was greater in the case of small diameter timber than large, the ash content of a whole limb was seldom more than twice that of the centre. The content of the heartwood of three different eucalypts, namely *Eucalyptus pulchella*, *E. obliqua* and *E. globulus*, was examined. These were taken from eight different localities and had diameters ranging from 80 mm to 1.2 m. The species mean was not affected greatly by locality. Unsound wood did not appear to have a higher ash value than sound wood. Bark was found to be much higher and more variable than wood, often being as high as thirty times or more that of the wood from the same species. Analyses indicate that the ash content of industrial charcoal will be about twice that expected from laboratory figures because of the inevitable inclusion of some free inorganic material and some bark in the charge.

Data on ash contents of charcoal, gleaned from N.S.W. Forestry Commission files, are given in Appendix A. The charcoals with high ash content are mainly from western dry country species or from species normally found on dry sites in localities of greater precipitation.

Assessment from different portions of the same tree shows that the ash content of sapwood is sometimes as much as an order of magnitude higher than that of heartwood. The ash content of bark is markedly greater particularly in the sappy inner bark.

Jaeger (1941) working on Tasmanian eucalypts reported the ash contents as follows:

	Ash % Heartwood range	Bark—typical value
<i>Eucalyptus pulchella</i>	0.1-0.5	19
<i>E. globulus</i>	0.1-0.8	14

Taking heartwood as unity, the ratio of ash in heartwood: sapwood: inner bark: outer bark could be of the order 1:10:100:10 though 1:4:30:4 is probably more usual. The ratio of sapwood to heartwood becomes less as a tree grows older (Bamber 1974), thus fast-grown trees from a lush situation will have a greater sapwood to heartwood ratio than those of the same species and size grown under adverse conditions (Bamber 1976).

The table in Appendix B summarizes analyses of ash of bark, sapwood and heartwood from mature trees (Lambert and Cramsie 1977) of the more important species grown in N.S.W.; in general, the ash reflects the nutrients level of the site on which the tree is grown. Osse (1959) noted that charcoal from eucalypts grown in acid soils had a higher phosphorus content than that from

eucalypts grown elsewhere. As charcoal yield may be as low as one fifth of the oven-dry weight of the original material, the percentage ash in the charcoal will increase in inverse proportion, but the composition will remain the same.

USES

Charcoal has a great variety of uses, some of which are of recent origin while others date back to the very dawn of civilization. It has a long history as a fuel and as a source of pure carbon for metallurgy, but more recently its use in the chemical industry, because of its carbon content and absorbent properties, has become extensive. It is also used in electrical industry. Some of the ways in which it can be used are listed below. It should be pointed out that many of these uses are encouraged by a low local price for charcoal or by the unavailability of other suitable material as well as by its suitability for the purpose.

Fuel

Barbeques	Incinerators
Cement (Earl 1974)	Laundries
Domestic	Meat and fish curing
Explosives	Restaurants
Foundries	Shipyards
Fruit growers	Tinning and plumbing
Furnace oil extenders (Hyne 1978)	Tobacco curing
Gas producers	

Metallurgy

Aluminium	Magnesium
Antimony—purified form	Mining
Armour plate	Molybdenum
Arsenic—purified form	Nickel
Case-hardening	Pig iron
Cobalt	Powdered iron
Copper, brass, bronze	Reduction of sulphates
Electromanganese	Silicon
Foundry moulds	Silver
Galvanising	Special alloys
Lead	Steel

Chemical

Activated carbon	Graphite
Black powder	Gunpowder
Brake linings	Magnesium chloride
Carbon bisulphide	Moulding resins
Carbon monoxide	Pharmaceuticals
Catalyst	Pigments
Catalyst carrier	Plastics
Decoloriser	Potassium cyanide

Chemical

Deodorant
Electrodes
Gas cylinders
Glass
Glue

Potassium oxide
Rubber
Sodium cyanide
Water filter

Biological

Charcoal lumps have provided a satisfactory growing medium for epiphytic orchids fed with organic fertilisers (Gemenis 1968) but salinity problems have been encountered by users of soluble inorganic nutrients. Charcoal has been used to prevent pollution of water in hydroponics and as a top dressing for bowling greens. Application of 500 g charcoal of 2-3 mm per m² of forest nursery soil doubled or trebled height growth of spruce (Beltram 1963). Fungal damage was lessened and ammonifying bacteria increased with the beneficial effects persisting over many years. Liberal application to seed beds, however, has had an inhibiting effect on germination and growth (Earl 1974). A finely powdered charcoal dip has been used to check 'bleeding' of poinsettia cuttings (Hellyer 1977).

Vantsis and Bond (1950) cite improved yields when charcoal had been incorporated in the growing medium, variously attributed to prevention of unfavourable pH through adsorptive capacity (Prianishnikov and Domontovitch, 1926), adsorption of toxins (Zinsadse, 1932), oxidation of toxins (Papadakis, 1941), improved aeration in sands (Gukova and Butkevich, 1941). They found improved growth of inoculated peas in sand culture, through better N fixation, with 2-4% wood charcoal of 0.5-2% activated charcoal in admixture, an effect attributed to adsorption of toxins or root secretions. Addition of charcoal had been observed to alleviate clover sickness (Rothamsted, 1946). Nodulation of clover plants was stimulated by addition of charcoal to the rooting medium due to adsorption of inhibitory compounds secreted by plants (Turner, 1955) or those resulting from microbial antagonism in the rhizosphere (Hely *et al.*, 1957). Incorporated in the soil, charcoal acts as a soil improver by increasing the cation exchange capacity (Puri *et al.*, 1958) (Puri and Mahojan, 1960) and when introduced as H charcoal (which is prepared by exposure to the air without special treatment) is useful in reducing alkalinity (Puri *et al.*, 1958).

Addition of 2-10% activated charcoal increases the availability of plant nutrients in phosphate rock and organic fertilizer materials such as blood meal and tankage (Eyster, 1954).

Charcoal has been employed in combating problems associated with pesticides in soils:

A slurry of activated charcoal on the roots of strawberry plants acts as a protective barrier against the residual herbicide simazine (Schubert, 1969).

Banding with activated charcoal protected row crop seedlings against pre-emergent herbicides such as simazine (Kratky and Warren, 1971) and nitralin (William and Romanowski, 1972). Similarly protected, grasses can be established relatively weed free for the production of high quality seed in the first seed crop (Lee, 1973).

Translocation of insecticide residues from soil into vegetable crops has been reduced by incorporation of charcoal (Lichtenstein *et al.*, 1971).

Charcoal is often included in commercial feed mixtures for pigs. It is sometimes recommended as a treatment for diarrhoea and as an adsorbent of gases and detrimental products in the gastro-intestinal tract. Though inclusion of charcoal in a well balanced diet for pigs would appear to have no significant effect (Totusek and Beeson, 1953), supplementing broiler finisher diets with 0.5% activated charcoal for 21 days before slaughter resulted in increased growth and increased proportion of Grade A carcass weight (Proudfoot *et al.*, 1971).

Deposits of the systemic organophosphorus insecticide ronnel in the stomach lining of sheep were greatly reduced by incorporation of 5% activated charcoal in the feed (Smalley *et al.*, 1971). Activated charcoal has also been used to adsorb pesticide residues from the digestive tract of cows, sheep and goats (Wilson and Cook, 1970) with subsequent elimination in the faeces. However, similar trials on poultry have had no significant effect on residue levels in eggs and body tissues (Foster *et al.*, 1972). The addition of phenobarbitol and charcoal briquettes to the dieldrin contaminated diet of hogs brought about a great reduction in the amount of dieldrin in the fat (Dobson *et al.*, 1971). Charcoal in briquette form is avidly sought and consumed by swine.

Emergency treatment of poisoning in animals may be accomplished by activated charcoal (Decker *et al.*, 1968) (Decker and Corby, 1970) (Phansalkar and Holt, 1968). Administration of activated charcoal one minute after poisoning was markedly more effective than 30 minutes after poisoning in reducing gastro-intestinal adsorption by dogs (Chin *et al.*, 1970). Activated charcoal can be administered at the rate of 5-50 g for small animals and 250-500 g for large animals (Szabuniewicz *et al.*, 1971). Activated charcoal is recommended as first aid treatment for white arsenic dust poisoning in humans (Fairey, 1976). Because of its broad spectrum of activity and exceedingly rapid inactivation of poisons activated wood charcoal is probably the most effective single measure in the first phase of therapy. Rather than in pill form, with its mucilaginous binding agent, the charcoal should be administered as a thick soup of fine powder stirred into water. Activated charcoal will also adsorb vitamins, digestive enzymes, amino acids and other valuable nutrients from the gut. Such losses, if continued, would seriously affect health but are of no importance in situations of acute poisoning (Holt and Holz, 1963).

Fine activated charcoal dust has been found to have a marked insecticidal effect (Majumder, *et al.*, 1959).

COMMERCIAL APPLICATIONS OF CHARCOAL

In Australia the main commercial uses for charcoal are in steel production and for fuel. It would appear that the demand for active carbon for air-conditioners could support a local venture.

Charcoal produced from Australian species is particularly useful in those applications which require low ash and high mechanical strength properties.

Carbon Bisulphide

Carbon bisulphide manufacture is essential for viscose rayon production. The charcoal requirements of a carbon bisulphide plant are at the rate of 0.25 tonne of charcoal per tonne carbon bisulphide, the carbon bisulphide being produced by the reaction of sulphur on red hot charcoal. The charcoal must be reactive to sulphur vapour, have reasonable structural strength, a low ash content, be of a suitable size and must contain as little hydrogen as possible. Hardwood charcoal is best, prepared for optimum reactivity at a temperature of not more than 500° C. (Brane and King, 1935). This temperature, however, does not seem compatible with recent volatile matter and fixed carbon specifications.

Carbon bisulphide is also used in the production of carbon tetrachloride, ammonium thiocyanate and thiourea-formaldehyde plastics. It is a solvent for sulphur, phosphorus and many waxes and fats.

Case-hardening Compounds

Case-hardening charcoal must be reactive, have high structural strength and be of a suitable size. Charcoal from hardwoods is preferred though charcoal made from coconut shells is also used. These charcoals are desired because of their high density and comparatively low burning rate.

The main function of charcoal in carburisation is to ensure a continuous supply of carbon monoxide to the work being carburised and to remove from the work the resultant carbon dioxide. It is necessary that the charcoal be in quite close contact with the work but also that the particles be of such a size as to permit free circulation of the gases. Too fine a charcoal would result in a high concentration of carbon dioxide, retarding carburisation. The charcoal size normally specified is about 8 mm and seldom larger than 12 mm.

In addition to the charcoal a catalyst, usually a carbonate which decomposes on heating, is required. This serves as the initial source of carbon dioxide which reacts with the heated charcoal to form the carbon monoxide necessary for the carburising action. The selection of specific carbonates depends on temperature and time of carburising. Less stable carbonates such as calcium and sodium carbonate evolve their carbon dioxide at lower temperatures than the more stable barium carbonate.

For high temperature carburising and deep case-hardening a stable carbonate is required. Generally a mixture of these three carbonates, calcium, sodium and barium, is used to take advantage of the carburising which occurs through a large temperature range. Sodium carbonate however is kept to a minimum as it attacks the alloy containers used in the process. Rate of carburisation depends on the percentage catalyst in the compound, up to 8%, after which little increase in rate occurs. As the process involves a considerable loss of catalyst it is necessary, however, to commence with a higher percentage.

A typical specification for a case-hardening compound is as follows:

Hardwood charcoal 85%

Sodium carbonate (soda ash) 2%

Barium carbonate (precipitated) 10%

Calcium carbonate (whiting) 3%

The exact percentages may vary to some extent with the carburising method used. The carbonates are usually added to the charcoal in a powdered condition. They may be introduced into the pores of the charcoal suspended in water, after which the resultant material is dried.

It is, however, considered by some workers that this carbonate/charcoal bond is too weak, resulting in high loss of catalyst. As this aspect of carburising operations is very important to the economy of the process the use of binding materials is usually warranted.

One such method is to coat the charcoal granules with a mixture of carbonates in molasses. Alternatively, powdered charcoal can be intimately mixed with catalyst and binder and pressed into tablets by machinery. Often coke, anthracite and other diluents may be used in the formulation of these compounds. Their function appears to be cost reduction rather than technical.

Metallurgical Charcoal

For metallurgy, charcoal must have excellent structural strength, absence of fines and low volatile content. In this respect the work of Hulisz (1970) is pertinent. Hulisz, experimenting with European species of beech, birch, hornbeam and pine with a moisture content of 1.5, 20 and 35% in various cross-sections from 10 to 200 mm square and lengths from 25-1000 mm, found that volatiles increased and mechanical properties of the charcoal decreased with increasing moisture content and size of wood. The effect of moisture content was particularly evident on mechanical properties when large pieces of wood were used. Araujo (1956) reporting on vegetable charcoal for blast furnaces in Brazil found that eight-year-old *Eucalyptus paniculata*, *E. punctata* and *E. citriodora* yielded charcoal of satisfactory strength. Working on *E. robusta* he found that older trees provided stronger charcoal, the compressive strength of that from 8 and 25 years old being 22 and 36 kg/cm² respectively.

Collet (1956) found a straight line correlation between fixed carbon per unit of carbonised material and age of the eucalypt tree. Under Brazilian conditions it was concluded that the economical age of eucalypts for the production of metallurgical charcoal lay between 8 and 12 years.

Further requirements are good reactivity, minimum carbon content of 80% and ash content of less than 1.5% with as low a phosphorus content as possible.

The higher cost of charcoal and its low load-bearing strength, compared with metallurgical coke, limit the use of charcoal in metallurgy to special products or special situations.

Fuel Charcoal

Charcoal is used directly in foundries, barbecues etc. and indirectly for gas production. As a domestic or industrial fuel it should be well fired at not less than 350° C.

Ward (1959) stated that the average carbonising temperature should be above 440° C for at least one hour for good quality charcoal. So that it neither smokes nor flames when burned, the volatile content should be less than 24% and the fixed carbon 75% or more (United States, 1957). Ash content and composition

are unimportant. It should be neither too hard, when it is difficult to ignite, nor too crumbly, and of a suitable size distribution. For domestic barbecues, lump charcoal is usually preferred to briquettes. Lump is easier to ignite and burns down more quickly to the glowing bed needed for cooking. Briquettes tend to burn long after the typical picnic is completed (Simmons, 1957).

Producer gas—Charcoal is the preferred source of producer gas for use in internal combustion engines. Considerable numbers of static and mobile producer gas units were employed during World War II but were soon dispensed with when adequate petrol supplies became available. Whilst a producer gas unit had the benefit of economy and operated on a local source of fuel it suffered from the following major disadvantages:

Bulky and dirty fuel supply which too easily absorbed water and was not amenable to automatic handling systems.

Cumbersome producer units requiring extra maintenance.

Short run between refuelling (150-300 km).

Slow and finicky starting procedure.

Loss of power in engine of 40-50%.

In the making of producer gas a limited quantity of air is drawn or forced through a bed of red-hot fuel such as charcoal. The oxygen in the air combines with carbon from the charcoal to form carbon monoxide which is the main constituent of producer gas. At the same time water vapour in the atmosphere reacts with the carbon to form a mixture of hydrogen and carbon monoxide, both of which are combustible. In the cylinder of an internal combustion engine the carbon monoxide and hydrogen react with oxygen of the air to form carbon dioxide and water.

Charcoal from dense hardwoods is preferred for use in producer gas units as the greater fuel weight per hopper load provides a greater range. It should be of good mechanical strength, evenly graded and free from dust and fines which clog the filters. The preferred sizes of lumps vary with the design of the unit but lie in the range 6-36 mm. It should be black, dry, shiny and with a metallic ring, firm to the touch and breaking sharp and clean. Unburnt wood and under-carbonised samples should be avoided as they give rise to tars. A suitable sample should burn with a short bluish flame, free from smoke or odour.

The total ash content should not exceed 3% and moisture content should not exceed 7% (Savard and Coudreau, 1956).

Charcoal Briquettes and pellets—Briquettes may be made by binding charcoal fines with starch, tar or bitumen in the presence of water.

A typical specification requires:

100 kg charcoal

15-30 kg tar/bitumen

1 kg fuel oil

30 kg water (Stamm and Harris, 1953)

In the U.S.A. starch is favoured as a binder despite the low wet strength of the resultant briquettes. The usual proportions using starch as a binder are:

73% charcoal bound by
4% starch in
23% water by weight (Simmons, 1964)

These briquettes may also include waxes for quicker lighting or sawdust to reduce costs and impart a woody tang to barbecued meat (Earl, 1974).

For briquettes hardwood charcoal is preferred. It should be clean to minimize abrasion in the plant. The briquettes may be formed by compression or extrusion after which they are thoroughly dried, care being taken to keep the temperature below ignition point by mixing fresh air with the heated air. (Haig, 1958). Where tar or bitumen has been used as a binder a secondary heat treatment in the region of 500° C for 15 minutes is required after drying to drive off excess volatiles.

Apart from chicken and pig feed, briquettes constitute the main outlet for charcoal fines. They are cheaper to handle, transport and store than lump charcoal and there is less deterioration in handling. Briquettes are usually preferred by restaurants and dining car operators who wish to keep a fire burning more or less continuously (Simmons, 1957). The cost of briquetting however, is not inconsiderable. An American schedule for a one tonne per hour briquetting plant, which is regarded as minimum capacity, ran as follows:

Briquette press with paddle feeder

Hammermill

Charcoal feeder with surge hopper

Paddle mixer

Vertical fluxer

Starch feeder of pump

Briquette drier

Boiler—30 hp—100 kPa gauge pressure

Conveyors

Bagging machine

Building 18 m × 36 m with 6 m clear height

\$US 150,000–\$200,000 at 1961 prices. Double capacity with extra investment of \$80,000. (United States, 1961).

Charcoal fines can be compacted with a wide range of binding materials as pellets or sticks of high density and mechanical strength. Other materials may be incorporated to promote a reaction within a process or to provide special atmospheres (Kelley, 1980).

Activated Carbon

The ability of ordinary charcoal to absorb gases and impurities is greatly diminished by the presence of high-boiling hydrocarbon tars adhering to the carbon. By processes known as 'activation' much of the hydrocarbon is removed

creating a vast network of molecular capillaries and thus increasing and improving the absorptive power of the charcoal. The product, activated charcoal, has a wide range of uses in:

- (a) liquid purification where low density, frequently finely ground, soft charcoals are employed, and
- (b) gas and vapour adsorption for which high density hard types are preferred, usually in granular form. (FPRI Laguna, 1965).

Activation is achieved by pyrolysis or by controlled oxidation. Further heating of commercial charcoal drives off a proportion of the volatiles resulting in a degree of activation. Should such heating be carried out in the presence of air the temperatures should be kept between 400° and 600° C.

More usually however heating is carried out in the presence of steam or carbon dioxide in the temperature range 700° –950° C for a period of from 15 minutes up to several hours. Greater reaction time results in carbon with greater adsorptive powers; as the process results in a loss of carbon as well as the undesirable hydrocarbons, yields decrease with extended process time.

Yanai (1962), in a laboratory study applying steam activation to charcoal from mixed waste wood, found that yield was directly proportional to the hardness of the charcoal and that both of these were inversely proportional to the degree of activation. Mixing soft and hard charcoals accelerated activation.

In some processes the source material may be mixed with a chemical agent and carbonised at 400° –700° C. Suitable agents include calcium chloride, magnesium chloride, zinc chloride, phosphoric acid, sulphuric acid, sodium phosphate and dolomite. On a laboratory scale Satonaka and Tanaka (1975) obtained a 55% yield of activated carbon from sawdust of oak (*Quercus mongolica* var. *grosseserrata*). Ten grams of 70% phosphoric acid were added to 2 g sawdust which was then heated at 190° C for four hours. Ninety per cent of the phosphoric acid was recovered by four successive washings.

Apart from wood and charcoal, source materials used for the production of activated carbon include bagasse, bituminous coal, blood, bones, coconut shells, kelp, peat and pulpmill waste. Different source materials and activation techniques influence the properties of the activated carbon (Hassler, 1958): in highly specialised processes activated carbon from one particular source of material and activation technique may be the only acceptable medium. For each use a carbon must be selected with the desirable structural properties and the peculiar affinity for the adsorption of these impurities found in the material to be treated (Stamm and Harris, 1953).

The production of activated charcoal is highly specialised and requires both heavy plant investment and large raw material supplies (United States, 1961).

MANUFACTURE OF CHARCOAL

The reactions which lead to the production of charcoal from a carbohydrate-containing substance, such as wood, cannot be described in detail. An outline of the process however can be given: As wood is heated, water, both free and bound, is given off; this process continues until the wood has reached a temperature of

about 160° C. Very little chemical decomposition takes place until about 200° C but above this temperature and particularly after 275° C a rapid chemical decomposition takes place resulting in the formation of charcoal and the evolution of acrid smoke. The smoke consists of gases, such as carbon dioxide, carbon monoxide, hydrogen and hydrocarbons, and condensable vapours including tars, pyroligneous acids (acetic, formic, etc.), oils, alcohols, ketones, water and a large number of minor compounds.

For general charcoal manufacturing purposes the wood is allowed to reach a temperature of about 400° C. Mitigation of smoke nuisance and air pollution by stack gases from kilns may be achieved by use of an afterburner (Olson, 1959) (Hartwig, 1971).

The Primitive Stack

In its most primitive form charcoal production was undertaken in a wide stack or pit. The billets were piled as closely as possible leaving an open space in the centre to serve as a chimney.

The pile, once completed, was covered with turfs or adhesive soil except for the central chimney and a number of draught holes near ground level. Fire was started by igniting dry kindling at the base of the central chimney after which the rate of combustion was controlled by regulating the size of the draught holes and chimney by turfs and/or sand. Constant attendance was required to stop all flare-ups through displacement of the cover which rested on a diminishing support. Once smoke production became thin and greyish blue carbonising was complete and all holes were sealed, extinguishing the fire. After a period of cooling the charcoal was ready for use.

It will be readily appreciated that, although little capital outlay was required, this technique finds little favour today. It was highly labour intensive, the yield was unduly low owing to uncontrolled burning whenever the cover was displaced and the product was inevitably contaminated with sand, earth and grit.

Earthen Beehive Kiln

As the inefficiencies of the open stack technique came to be appreciated, earthen beehive kilns were developed and remained the standard method for centuries. These provided a greater degree of control over production and eliminated much of the contamination. Heat losses, too, were less and thus yields higher. These kilns required frequent maintenance, principally in the closing of cracks in the structure, and in all but very dry regions required a weatherproof roof. Capital cost was relatively high per unit of output.

In more recent times carbonising has been done mostly in closed pits, small portable kilns, larger permanent kilns and retorts. Basically the first three differ little from the open pit of our ancestors—they merely eliminate or reduce the deficiencies.

Closed Pit

In New South Wales the wood carbonising industry has always been primitive. Closed pit burning has been the method usually adopted.

The closed pit was only slightly less crude than the early pit kiln method. Typically a pit of 3.5 m × 1.5 m × 1.5 m with battered sides would be excavated and lined with brick or corrugated iron. At one end pipes of 150–200 mm diameter would be installed, supplying air at a low level. After charging, all but the two ends would be covered with corrugated iron sheeting and kindling previously placed at the bottom end remote from the air inlets would be ignited. Once properly alight the opening at the fired end would be covered and the top covering sealed at the edges with sods or sand. The rate of carbonisation was then controlled by adjustment of the smoke gap close to the air inlet pipes. Once carbonisation was complete, all openings were sealed and the charged allowed to cool.

The main advantage was low capital cost. The chance of contamination by mineral matter was almost certain and spoiling of the fires or the product by inundation high. As a reverse draught was achieved, there was less tendency for charcoal to burn to ash before carbonisation of the remaining wood was complete.

Portable Kilns

Subsequent to an investigation in 1938 by Howarth and Muir on the prospects of charcoal production from New South Wales forests, small portable kilns were used extensively during World War II. Being portable, they could be moved to available supplies of raw materials, reducing haulage of heavy, low value wood. As the combustion area was fully enclosed, contamination was reduced to a minimum provided care was taken with sand joint and opening sealants. Draught control was simplified by properly designed venting. As these kilns were constructed of sheet steel heat losses were considerable, but this was not entirely disadvantageous as the cooling period was reduced and thus turn-round accelerated.

Lighting takes place with all apertures open to provide sufficient oxygen. With direct draught kilns carbonisation follows without difficulty. With down draught kilns reversal of the draught is done slowly and requires close supervision; the kiln cannot be left to itself until the down-draught is working perfectly.

For maximum yield the charcoal must be burned at a low temperature and the part of the charcoal already produced must not be allowed to burn. This requires admission of the minimum of air needed for carbonising and depends on the skill of the operator in regulating vents. By traditional methods this is gauged by the amount, appearance and smell of the smoke and by the feel of the heat at various parts of the cladding. Frequent attention is required to guard against leakages and wind changes which can lead to unpremeditated flare-ups and possible explosions.

Completion of carbonisation must be precisely assessed so that the process can be stopped at the right time. Premature closure can result in unburnt brands and delay results in burning of part of the charcoal; the correct time is judged more by colour and smell of the smoke rather than by the appearance of fire at the vents.

On completion of carbonising, all air inlets are opened to induce flash up, sometimes referred to as "refining", if a further degree of tar removal is required. The temperature rises rapidly with copious production of dark smoke. After some thirty to sixty minutes the smoke reduces, becoming clear, marking the end

of flash up, whereupon the inlets are closed and the charge allowed to cool. Where a number of portable kilns are operated together a limited degree of mechanisation can be achieved with a crane (Younotsey, 1941).

A typical timetable for a portable kiln of 5-6 m capacity is as follows:

(a) Assembly and loading of kilns	3 hours
(b) Lighting and carbonisation	20-27 hours
(c) Cooling of kiln	7-15 hours
(d) Unloading	3-15 hours
	<hr/>
	TOTAL 33-60 hours

As much of this constitutes slack time, the usual practice is to operate kilns in batteries to keep labour fully employed.

Generally portable kilns do not exceed 10 m³ capacity and are most efficient when wood of less than 120 mm diameter is carbonised. In the United States there are fixed kilns of up to 400 m³ capacity. Owing to cooling time, the largest kilns do not necessarily provide the greatest daily average output. In New South Wales however, no medium or large scale distillation plant has yet been installed, although such a plant has often been contemplated.

For small scale consumption in remote areas, charcoal can be produced in a kiln improvised from a 200 litre oil drum.

The bottom of the drum is first removed by cutting round the inside of the rim. After unscrewing both plugs two more holes of similar dimension should be made equidistant from these plug holes. Two small holes should be made just below the rim of the bottom (open) end and opposite each other. The drum, open end up, is then placed on two 25 mm pipes and a small fire lit in the base of the drum.

Once this fire is well alight the drum may be closely packed with billets. A slow compact fire can be maintained by control of air inflow at the base and by hammering of the billets or shaking of the drum. From time to time the charge may be topped up with short billets.

When the drum is full of charcoal the base should be replaced and held in place with a steel skewer passed through the small holes below the rim.

The drum may now be upturned and allowed to stand until smoking ceases, whereupon the holes should be sealed by metal plates damped with sand or soil and the base banked up to exclude air.

With adequate sealing combustion should cease overnight and the drum may be emptied the following morning (D.W.T., 1941).

Masonry Kilns

In the U.S.A., the most popular masonry kilns are the rectangular cinder-concrete block kilns, similar in appearance to a one-car garage. The blocks are usually 200 mm × 460 mm × 200 to 300 mm thick and may be made to the

following specification: 220 kg cinders; 100 kg limestone screenings; 50 kg 3mm screened limestone aggregate, 50 kg Portland cement. Water/cement ratio of about 0.9. Blocks should be moist-cured (Simmons, 1957). The most trouble-free, economical and efficient are made with single walls laid with lime mortar. Smoke leaks during coaling demonstrate the occurrence of cracks which should be sealed immediately with lime slurry to prevent subsequent burning (United States, 1961). Attempts to make the kiln walls self-sealing, by means of double walls with a layer of sand between, have proved unsuccessful owing to continued settling of the sealant forcing the walls apart. Instead of temporarily sealing the entrance during the burning by means of blocks, steel plate doors are now used. These are frequently large enough to permit the use of a light truck for charging and discharging. During the burn the edges of the doors are sealed with mineral wool and mortar. The kiln roof is normally of galvanized iron laid horizontally and sealed in place with a covering of sand. The galvanized iron is supported internally by a framework of iron piping suspended from external rafters. Progress of carbonisation is controlled by draught inlets in the side walls at floor level, proceeding from the kindling area at the door to the flue. When carbonisation approaches floor level at the back wall the draught inlets are closed, but the chimney is left open until smoking ceases, a matter of 1-2 hours. The chimney is then sealed to prevent further combustion and the possibility of explosion. The kiln may be opened for removal of the product at 77° C or less (United States, 1961).

Simmons (1964) reported that installation of mechanical control of air supply eliminated the variables and disadvantages of natural draught. Reduction in partially carbonised brands towards the bottom of the charge was particularly marked.

By igniting the charge with a gas or oil-fired torch, Lane (1960) reduced ignition time from 1-2 hours using dry kindling, to a matter of minutes. He found adequate initial combustion was more certain, labour was reduced and the valuable kiln space otherwise needed for kindling could be filled with utilisable material. By arranging ignition and air entry at one central point with multiple chimneys more even kiln temperatures were attained, control was easier and carbonising time was reduced by 40%.

Ward (1959) working on *Acer saccharum* found that the amount of retained volatiles depends on temperature of carbonisation and the length of time the charcoal is held at this temperature, volatiles decreasing with an increase in either temperature or time. There is a tendency therefore for volatiles to be greater towards the bottom of a fixed kiln.

Closer control requires instrumentation, a pyrometer being the most useful. A simple inexpensive pyrometer and thermocouple installation was developed by Peter (1956). The pyrometer consists of a D.C. microammeter range 0-25 with 2,200 ohms resistance fitted with a special scale for direct reading of kiln temperatures. The thermocouples were made from iron paired with constantan wire with asbestos insulation and stainless steel overbraid. For wiring diagram see Figure 2.

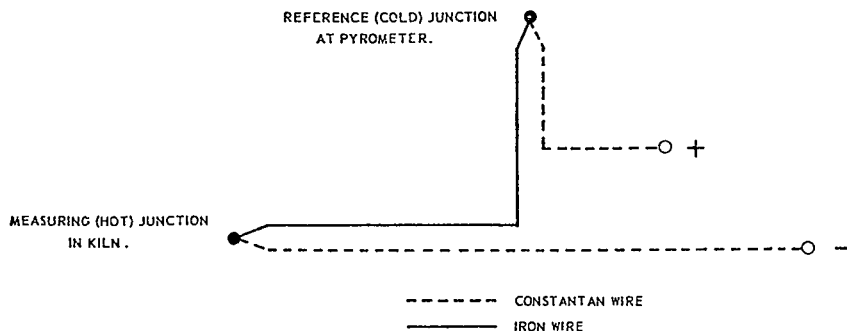


Figure 2. Wiring diagram for pyrometer (ex Peter, 1956)

The extreme end of the thermocouple wire, at the point where the temperature is to be read, has the insulation stripped for 50 mm back from the end and the two wires are twisted together and welded at the tip.

For a nine cord cinder-block kiln (external measurements 3 m × 3 m × 6 m) five thermocouples provide adequate control. Three are placed crossways at the centre of the kiln close to the roof and two are placed vertically at the centre of the kiln near the chimney, one about 1.5 m from the floor and the other 0.6 m.

Once the operator *knows* the temperatures in various parts of his kiln he is more able to optimise yields of the quality desired.

Most newer masonry kilns of larger size are built of poured concrete, being cheaper and quicker to make and requiring fewer skilled men in construction.

Large permanent kilns permit much closer control of carbonisation, cleaner working conditions and therefore a cleaner and better product. A much higher degree of mechanisation is possible, particularly with regard to the charcoal which can be unloaded, crushed, graded and bagged with little manual labour.

Larger kilns involve a greater cooling time more especially when the structure is well insulated. Attempts to accelerate cooling appear to have met with some success:

- (a) By circulating the inert gases left in the kiln after carbonisation through a heat exchanger, cooling time was reduced from six to three days (Simmons, 1964).
- (b) By water spraying from 480° C intermittently for four hours down to 90° C using 3 m³ of water for 0.85 tonne charcoal, cooling time was reduced from 60 hours by natural radiation to 13 hours (Ward and Lane, 1960). Care is needed in the application of this method if explosions and degrade of the product through waterlogging are to be avoided.

Retorts

Although retorts for charcoal production were first introduced into England in 1783 when improved charcoal was wanted for gunpowder, their advantages have been slow to find general favour. Vertical, insulated steel retorts give higher yields, shorter operation cycles, more uniform and higher quality charcoal for

less manpower per tonne of charcoal produced than do any of the kilns. Retorts lend themselves to the collection of volatiles for use as a further source of energy or for fractionation into commercial products such as methyl alcohol, acetic acid and pitch.

Modern retorts consist of upright steel cylinders, adequately insulated externally, in which carbonisation takes place in a matter of hours instead of days. On completion of carbonisation the charcoal is allowed to cool to 200° C whereupon it is dumped into large steel drums (of about 0.25 m³ capacity) which are sealed with a tight cover. In those drums the charcoal cools for a few days with the cover in place and then for several days with the cover removed. The charcoal is then tipped out for use or for packaging.

Vertical Kilns—Although described as 'retorts', in their simpler form such retorts are vertical kilns from which it is possible to remove, by gravity, a portion of carbonised wood from the base at intervals and top up with fresh wood from above, through the chimney. (See Figure 3.)

Of the true modern charcoal retorts two are worthy of separate mention: the Cornell and the Lambiotte.

The Cornell retort employs an outside source of heat, usually an oil burner, a blower and thermostatic controls. There is close and complete control of carbonisation and a uniform high yield of charcoal of any specific quality required. Batteries of Cornell retorts are used at sawmills for conversion of slabwood which, after being cut to 300–400 mm lengths, is delivered by conveyor belt to the top of the retorts during the working day. Each retort can contain the coarse residue from the production of about 7 m³ of sawn timber. The normal practice is to commence the burn in the evening after mill close-down, leaving the battery under the surveillance of the nightwatchman. On completion of the burn, after some 6–8 hours, the retorts automatically shut down and are allowed to cool ready for unloading in the morning.

A feature of the Cornell retort is that the gases are circulated in a reverse direction, down through the charge by means of blowers and thence to the external burner where their combustion supplements the fuel oil (see Figure 4). As the volatile gases and tars burn almost completely in the burner, little odour is produced by the retort during combustion, but a potential user should take cognisance of local clean air requirements.

The Lambiotte (SIFIC) process uses wood cut into one metre lengths and up to 200 mm diameter or more (Lambiotte, 1952). The wood is added to the top of the vertical retort (about 20 m high) through a barrel type valve and the charcoal is removed by a rotary valve at the bottom. The wood is heated to 500° C by non-condensable wood gas which passes counter-current through the retort.

When in operation, heated wood gases enter the retort, heat the charge, and then are led off to the condensers together with volatile matter from the wood distillation. The condensable material is removed and a portion of the non-condensable gases is passed under slight pressure into a heat exchanger, where it is heated by combustion of the remainder in a furnace. This gas then passes from

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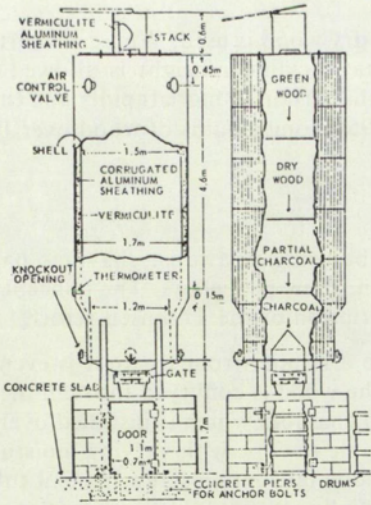


Figure 3. Thomas retort (ex Simmons, 1964)

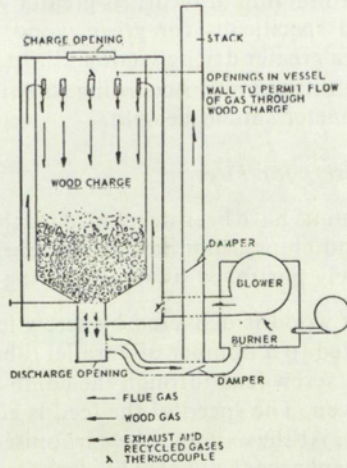


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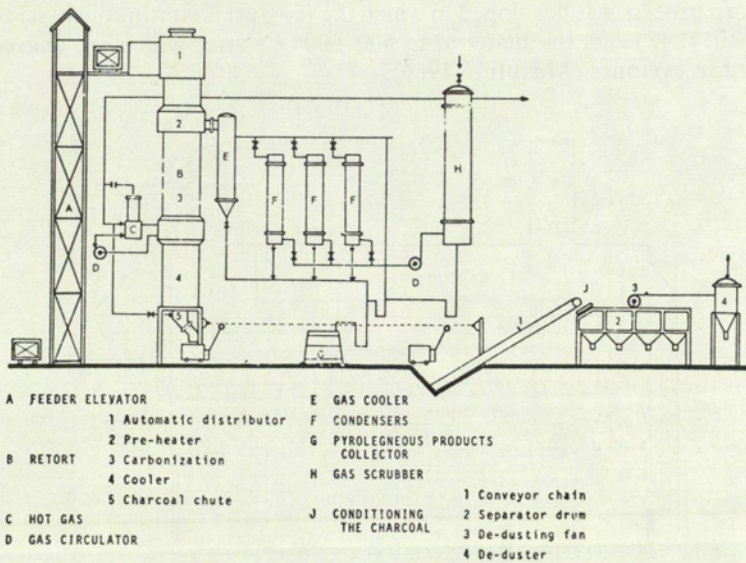


Figure 5. Lambiotte retort (ex Savard and Coudreau, 1956)

The only Lambiotte retorts in Australia are at Wundowie, some 60 km east of Perth, Western Australia, where, with their output supplemented by horizontal trolley-fed batch-type wood distillation retorts, they operate at the centre of an integrated land clearance, sawmilling, iron and steel industry with charcoal and refined distillates as by-products.

Daily production of retorts is greater when dry wood is used. Where a retort is designed specifically for green wood a greater cylinder height is allowed to provide a greater drying section. Short lengths carbonise more rapidly and thus increase throughput. According to Aries (1954) long lengths of wood over 100 mm diameter should be split.

Carbonisers for Fires

Several units have been developed for the carbonising of sawdust, shavings, bark and wood chips using horizontal tubes with screw propellers. The concept is adequately portrayed by the following description of the Thomsen retort.

The raw wood is delivered by screw feed to a hopper from where it is evenly distributed to a number of parallel tubes. The wood is conveyed through these tubes by screw feed through the combustion chamber which is installed over a dutch oven. The speed of the feed is adjustable to cope with varying moisture contents. At the exit end the carbonised residue falls into a screw fed exit tube where the charcoal is cooled by steam and partially activated (Dargan and Smith, 1959).

Initially the dutch oven is fuelled by wood for several hours bringing the temperature up to about 500° C, but once carbonisation commences the volatiles are fed back to the oven to sustain this temperature without any further supplementary source of heat. (See Figure 6).

In Japan a process was developed in which the sawdust is continuously screw-fed into a still that heats the material to 500–600° C, after which the charcoal is collected in cyclones (Mitsufuji, 1966).

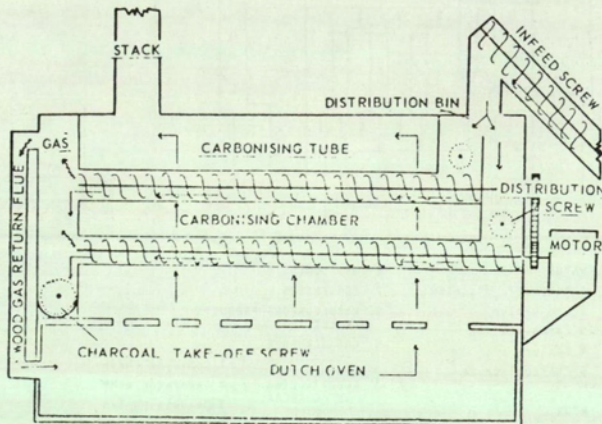


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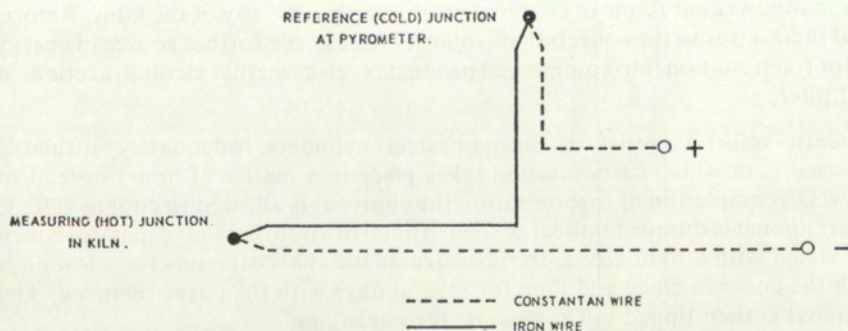


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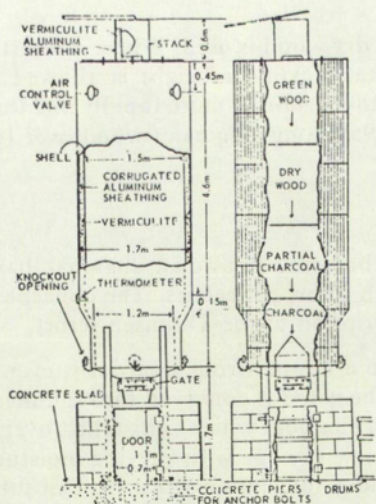


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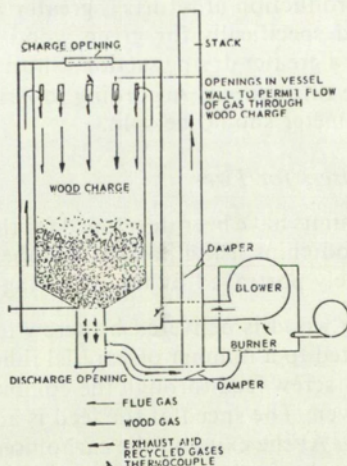


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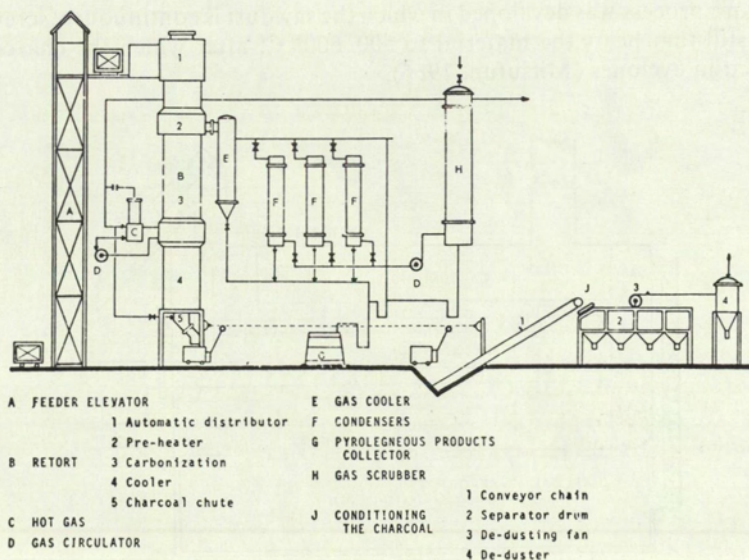


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Several units have been developed for the carbonising of sawdust, shavings, bark and wood chips using horizontal tubes with screw propellers. The concept is adequately portrayed by the following description of the Thomsen retort.

The raw wood is delivered by screw feed to a hopper from where it is evenly distributed to a number of parallel tubes. The wood is conveyed through these tubes by screw feed through the combustion chamber which is installed over a dutch oven. The speed of the feed is adjustable to cope with varying moisture contents. At the exit end the carbonised residue falls into a screw fed exit tube where the charcoal is cooled by steam and partially activated (Dargan and Smith, 1959).

Initially the dutch oven is fuelled by wood for several hours bringing the temperature up to about 500° C, but once carbonisation commences the volatiles are fed back to the oven to sustain this temperature without any further supplementary source of heat. (See Figure 6).

In Japan a process was developed in which the sawdust is continuously screw-fed into a still that heats the material to 500–600° C, after which the charcoal is collected in cyclones (Mitsufuji, 1966).

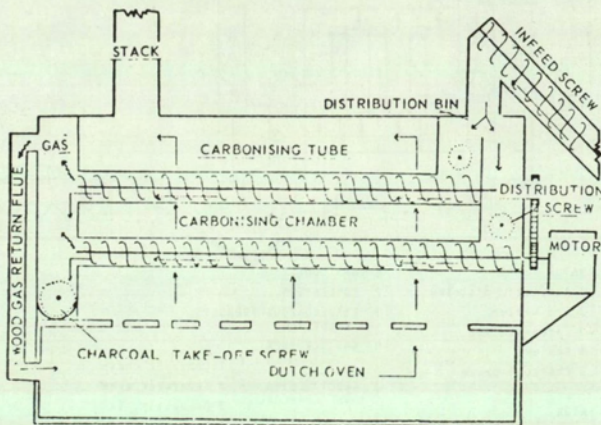


Figure 6. Thomsen retort
(ex Simmons, 1964)

Charcoal has been produced on a pilot scale in a reactor containing a fluidized bed of incandescent charcoal. The fluidizing medium consisted of pre-heated air and recycled wood gas. On entry to the reactor the sawdust was carbonised almost immediately and recovered via overflow pipes or from the hot product gases, in which it was entrained, by cyclone (see Figure 7). Charcoal yields at 15–22% of dry wood were low but further energy recovery may accrue from the flue gases (Kilburn and Levelton, 1963).

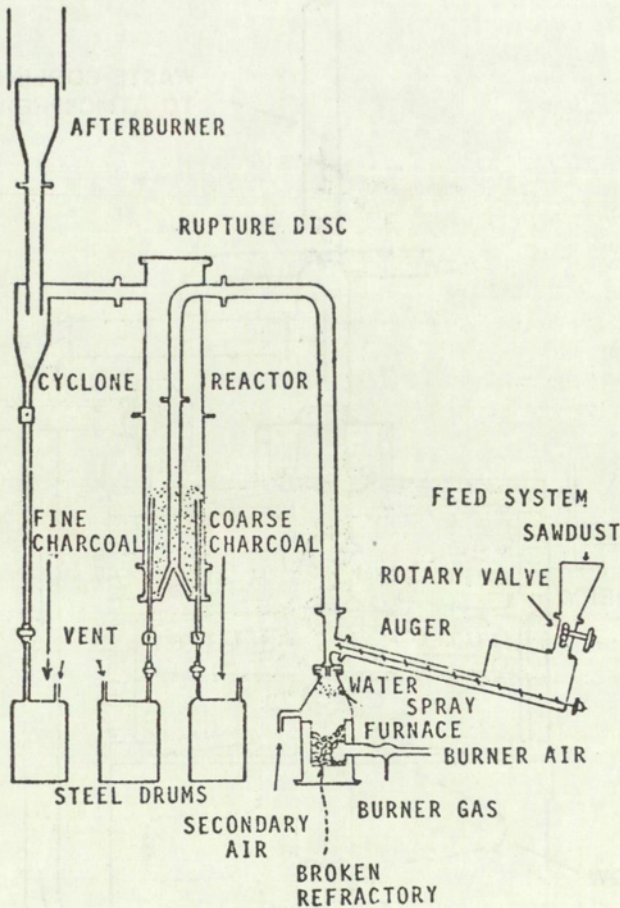


Figure 7. Pilot scale fluidized bed reactor
(ex Kilburn and Levelton, 1963)

Herreshoff multiple hearth furnaces are used for 8 000 hours per annum, continuous process carbonising of sawdust and wood or bark, hogged or chipped to <math><13\text{ mm}</math>. The furnaces are available in two sizes; the smaller has four circular hearths, 6.6 m in diameter, one above the other; the larger has six hearths, 7.6 m in diameter. These units are rated to produce 0.9 t and 1.8 t per hour respectively; but yield is dependent on moisture content of input; the larger unit can produce 2.3 t.p.h. from 40% moisture feed but only half that when moisture is 60%. The

raw material is conveyed continuously to the top where it drops through ports into the top hearth. A central, vertical shaft, rotating at about 1-2 r.p.m., drives arms with rabbling ploughs which move the material spirally across the hearth, passing from hearth to hearth by dropholes placed alternately at the centre and periphery. (See Figure 8.)

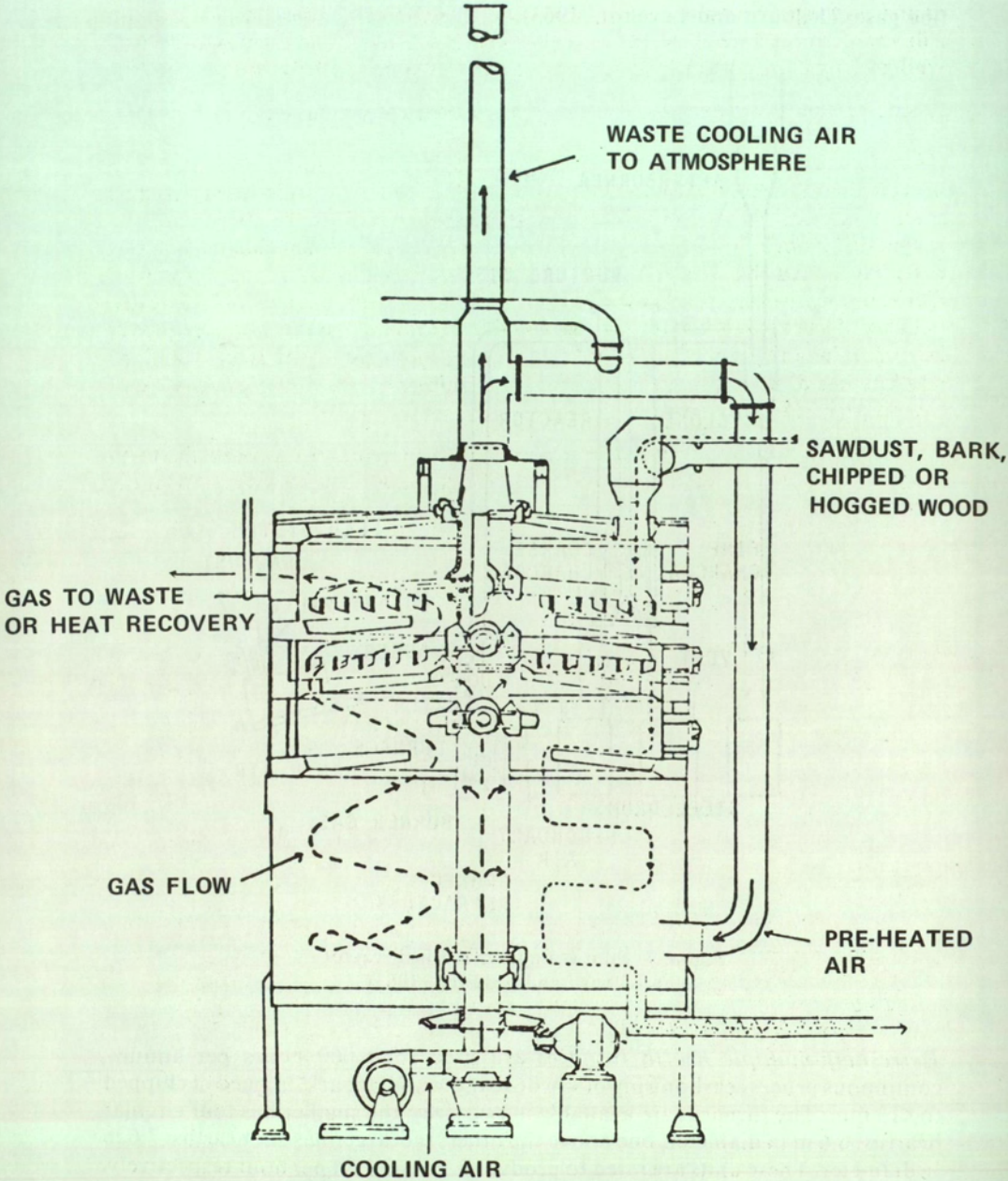


Figure 8. Herreshoff multiple hearth furnace

As the material passes through the carboniser, it is progressively dried, heated and eventually carbonised at a temperature, in the range 480–760° C, which can be automatically controlled by adjustment of infeed rate and air flow to the hearths. The volatile gases produced pass upward through the furnace counter-currently to the material flow and are discharged at the top of the furnace. They may be burnt to waste in refractory lined stacks at the top of the furnace or used as an energy source in a separate installation. The charcoal is discharged through a drophole at the base of the furnace whence it is cooled by water spray to 200° C whilst being transported by screw conveyor (Gallagher, 1969) (Reinks, 1976).

A similar concept is employed by BSP Envirotech Systems Inc.

Aldred horizontal continuous carboniser is depicted in Figure 9. The standard unit comprises a pair of horizontal kilns with a concrete brick-lined furnace. Each kiln consists of a gas-tight insulated jacket fixed at the drive end and suspended from all units to accommodate thermal dimensional change. The raw material is fed by hopper onto a split-run variable speed moving bed. Carbonisation takes place on the upper bed in a zone heated by controlled delivery of hot gasses from the furnace. At start up supplementary fuel is required, but once incandescent temperature is reached adequate heat is provided by combustion of pyrolysis gases, with surplus energy available for pre-drying of raw material (Kelley, 1980).

The carbonised material drops to the lower level and is conveyed mechanically to exit at the same end as the input. Further cooling under controlled conditions is then required.

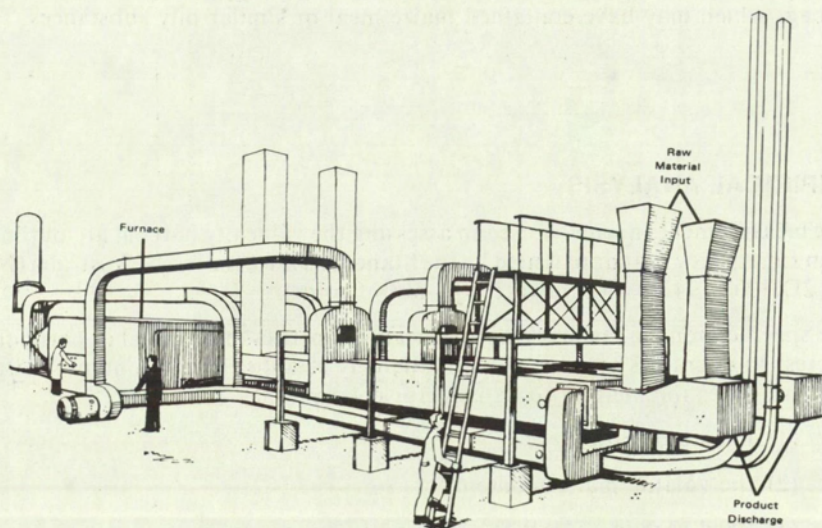


Figure 9. Aldred horizontal continuous carbonising unit.

With a raw material of coarsely granular form, moisture content of 10% and bulk density of 350 kg/m^3 , the standard unit is rated to process some 13 000 t.p.a. yielding approximately 4 000 t of charcoal fines.

Spontaneous Combustion

Charcoal is slowly oxidised by the air at normal storage temperatures. As the reaction is exothermic it tends to raise the temperature and thus increase the readiness of the charcoal to combine with oxygen. In large stacks the temperature can reach ignition point whereupon spontaneous combustion occurs.

Ignition point varies with the final carbonisation temperature and is particularly low for charcoals finished at $400\text{--}450^\circ \text{C}$. These can be stabilised by the addition of water when carbonisation is complete. Once the temperature has dropped to 200°C , air is introduced and this, diluted with steam, cools and 'settles' the charcoal in a few hours.

Alternatively stabilisation can be effected by exposure to the atmosphere in thin layers. Storage in this manner for eight days at 20°C or for a few days at 90°C renders the charcoal safe for transportation in bulk (Savard and Coudreau, 1956).

According to von Schwartz (1926) other causes of spontaneous ignition of charcoal are:

- (a) redrying of moistened charcoal,
- (b) powdering of charcoal,
- (c) presence of fats and oils.

Phillips (1940) warned against the use of damp or greasy jute bags and the re-use of bags which may have contained maize meal or similar oily substances.

EMPIRICAL ANALYSIS

The measurements normally used in assessing the value of charcoal are outlined in an Emergency Standard issued by the Standards Association of Australia (No. (E) 2D.3002-1942) (withdrawn 1959—out of print).

The specification makes reference to certain properties of charcoal of particular interest to operators of gas producers, namely cleanliness, tar content, shatter test and states the method to be used for determining—

- (1) moisture content
- (2) the volatile matter content
- (3) fixed carbon
- (4) ash.

Moisture Content:

When charcoal is taken hot out of the carbonising apparatus, it is free of water. However, exposure to the atmosphere at normal temperature results in the rapid adsorption of water until it comes to equilibrium with the prevailing atmospheric moisture conditions.

Volatile Matter:

The volatile materials evolved during the pyrolysis of wood vary with the stage the process has reached. Initially water vapour and carbon dioxide are the principal constituents. As pyrolysis proceeds the CO/CO₂ ratio increases, as does the hydrocarbon content. In charcoal which has been properly made at 400° C most of the polymerising reactions which produce tarry matter would have been completed but, as outlined by Garten and Weiss (1957), important changes proceed up to temperatures in excess of 1 000° C. There is always some volatile matter in charcoal because it is not pure carbon but a complex structure involving chemically bound oxygen and hydroxyl radicals. But once the basic structure of charcoal has been formed by pyrolysis at a certain temperature, further rises in temperature probably result in the expulsion mainly of CO, CO₂ and water. Because of this the volatile matter content as determined by the standard test can be quite high even though the charcoal contains, or forms, only a negligible quantity of tar. Conversely, commercial lots of charcoal produced under poor conditions but having a reasonably low volatile matter content could yield considerable quantities of tar when tested because of the presence of partially formed charcoal in admixture with charcoal exposed to a high temperature.

The volatile matter content of charcoal produced at 400° C is in the region of 15–20% (Beglinger, 1947). This is the usual temperature attained in retorts. Conaghan (1940) carbonised sawdust from various species at 350, 400, 450, 500, 590, 700, 800, 950° C and concluded that the volatile matter content of charcoal is a function of the temperature at which it is made, reaching a very low figure with temperatures above 750° C. He found the relationship between volatile matter content and the temperature of carbonisation to be linear between 310° C and 750° C. No differences could be established between species as only one replication was used at each experimental level. Hanley and Pearce (1945), using Western Australian species, obtained similar results to those of Conaghan, as did Jaeger and Johnson (1941), working with Tasmanian species. The latter, however, found volatile matter was also a function of the time the charcoal had been exposed to the carbonising temperature. The existence of this time factor is a possible explanation of the lower volatile matter content of commercial kiln and retort production compared with what may be expected from laboratory data and is the probable explanation for the differences between Conaghan's findings and those of Jaeger and Johnson. Conaghan's data itemised in Appendix C, were used as a basis for Figure 10.

Fixed Carbon

The fixed carbon content of charcoal is equal to the weight of charcoal remaining after heating at 950° C in accordance with the standard specification, less the ash content. However, as has been noted, charcoal made at this temperature still has a significant oxygen and hydrogen content. Carbons prepared at a high

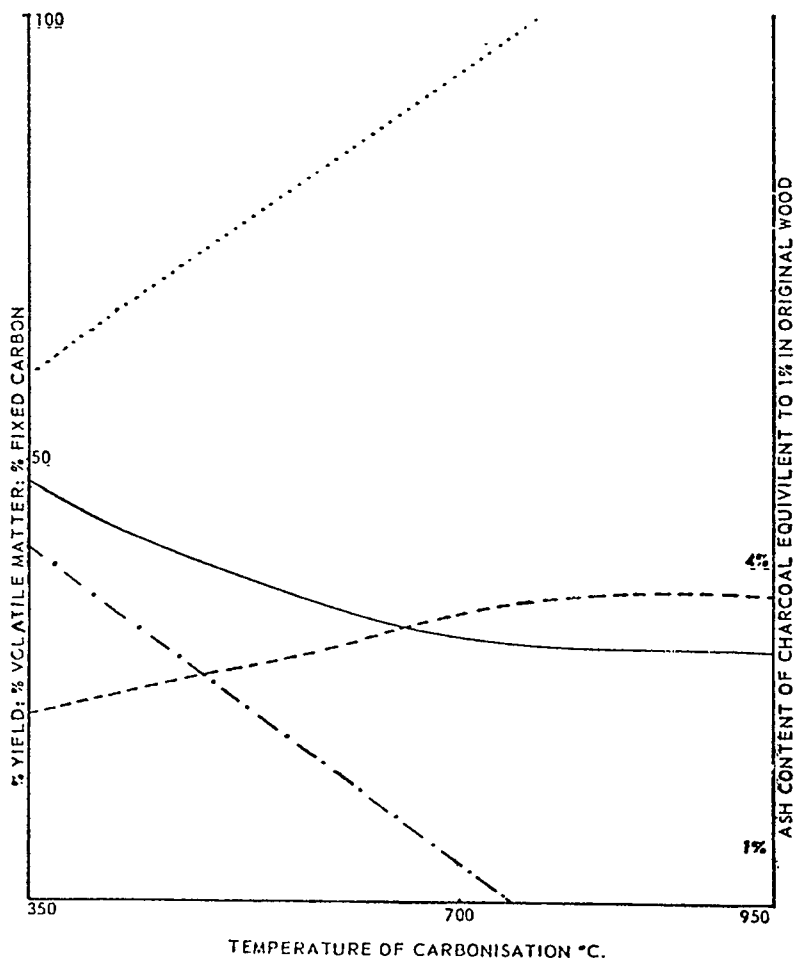


Figure 10.

temperature ($>700^{\circ}$ C) have properties quite different from those prepared at the usual temperature. Garten and Weiss (1954) working with sugar chars, have postulated that these changes are due to a transition from aromatic structure, having the characteristics of a hydroquinone, to an olefine quinonoid structure. Riley (1939) has shown that the crystallites have a graphite structure, the size of which increases with the temperature of carbonisation.

The fine crystalline charcoal from a number of species obtained at $>800^{\circ}$ C was found to resemble graphite in its anti-friction properties (Kiselev, 1971).

From Figure 10 it can be seen that charcoal produced at 700° C is almost as high in carbon as it is possible to obtain without the expenditure of excessive amounts of energy.

The purity and degree of refining of charcoal could be determined by measuring the contact electrical resistance. Kishimoto *et al.* (1951) made an experimental meter using a 0.005 milliamper pivot type ammeter able to measure resistance of 10^8-10^{-1} ohm.

FACTORS AFFECTING YIELD

As could be expected from the nature of the raw material and the processes involved in making charcoal a number of factors have an important effect on the yield. They are:

- Moisture content of wood
- Species, particularly the ash content
- The temperature of carbonisation
- The type of plant used
- Catalysts.

Moisture Content of Wood

The yield expressed as a percentage of the raw material input is directly related to the latter's moisture content. This is because all the free water present in the wood must be removed before pyrolysis commences. This water takes no part in the pyrolysis itself and can only be removed from the wood in the carboniser's plant very inefficiently. Fuel consumption is therefore high. If the yield is calculated on the basis of charcoal freed from dust and very small pieces, the excessive checking associated with a wet charge would tend to further decrease the yield.

With dried wood however, more careful control is needed in order to avoid explosions. Wood with less than 20% moisture content is liable to coal too rapidly with excessive temperatures. Too rapid coaling at high temperatures usually results in crumbly charcoal easily broken into small pieces and fines (United States, 1961).

By debarking soon after felling the carboniser can not only speed up drying but also removes:

- inorganic contamination incurred by felling and extraction,
- tissue with a high ash content,
- tissue which forms a very friable, dusty, charcoal.

Further drying can be done by open stacking or by judicious use of flue gases, but stringent safety precautions are necessary to avoid fire and explosions. With retorts a taller cylinder may be used to assist drying of green wood prior to carbonisation. Throughput of retorts is reduced when green wood is habitually used.

Drying of billets prior to carbonising has a marked effect on yield per charge and the time taken for a burn—hence throughput. Ward (1959A), comparing the carbonising of green wood (62% moisture content) with material air-dried to 35% moisture content, found that pre-drying achieved a 40% reduction in carbonising time and an 11% increase in yield (from 26.4% to 29.3% based on the over-dried weight of the charges). In a retort such as the Lambiotte increased moisture content causes not only an increase in heat consumption, but also an increase in energy consumption for the circulation of the gases (Lambiotte, 1952).

Species

The effect of species on yield of charcoal has been studied by many workers (Klason, *et al.*, 1910), (Jaeger, 1940), (Conaghan, 1940), (Hanley and Pearce, 1945). Of particular relevance is the work of the last three as it deals in each case with Australian species, mostly eucalypts. Yields obtained by Conaghan are given in Appendix D. The range of results shown here is quite considerable and may represent real differences between species in this regard. Unfortunately, as with other reported work, there are no replicated results on one species carbonised under the same conditions and by the same method, and so it is impossible to establish the significance of the results. Experienced operators are of the opinion that species has an important effect on the yield at the temperatures normally used.

Petroff and Doat (1978) observed that the products of pyrolysis seem to be linked with the chemical composition of the wood: a high lignin content is reflected in a higher charcoal yield.

This finding is in agreement with Brito and Barrichelo (1977) who examined ten species of *Eucalyptus* growing in Brazil. High volume yields of charcoal are to be got from species with high lignin content and high basic density. For superior chemical properties such as high fixed carbon, low volatiles and ash, woods with high lignin content should be preferred.

Species differ as to the condition of the wood likely to be received by charcoal manufacturers (rot, borer attack, bark, etc.) and also in their ash content. These would cause differences in yield. Operators also tend to consider yield on a kiln charge basis and this is often looked upon as a weight yield on the basis of certain volume of wood. Viewed in this way the heavy, dense species give a much better yield than light weight woods. The heavy dense timbers have the added advantage of producing a hard, clean, dense charcoal, which is the type most suitable for the majority of applications.

The Temperature of Carbonisation

Appendix D gives the yield of charcoal at various temperatures or different species reported by Conaghan (1940); the Table (Elemental Composition) shows the yield of charcoal as reported by Bergstrom and Wesslen (1918). Their figures are of the same order as Conaghan's, but in the lower bracket. It is clear from these and other figures commonly available that the yield of charcoal is, as would be expected, adversely affected by an increasing temperature of carbonisation. From this point of view, therefore, the lowest possible temperature which produces a satisfactory product should be used. For CS₂ production where a high fixed carbon is required a carbonising temperature in the region of 600° C is probably necessary. For household charcoal this is clearly unnecessary, and lower temperatures should be used.

Type of Plant

The plant used to make charcoal can be divided into kilns and retorts of various types. Kilns use part of the wood charged as a source of heat to raise the temperature of the kiln to the exothermic temperature (+275° C). Retorts on the

other hand are heated externally. A number of fuels can be used for this purpose including the volatile products from the carbonising stage of charcoal manufacture. There is a greater yield from a retort than a kiln for the same amount of charged wood of equal moisture content. However, if wood is used as a fuel for external heating then the nett yield will be somewhat less for the retort system, compared with the kiln system, because the heat transfer to the charge in the retort is not efficient in the former case. Internal gas-circulating processes are more efficient than either and give a higher overall yield.

Catalysts

Kishimoto (1959) studying the effect of certain inorganic chemicals on yield of charcoal, found that NH_4Cl increased yields by 15–30%, producing charcoal of excellent hardness and density about equal in quality to that obtained by normal methods. A “small amount” of NH_4Cl sublimes (at 339°C) and adheres to the uncarbonised, cooler wood, eventually diffusing to all the wood in the kiln. In the final stages refining (i.e. flash up) is commenced earlier than usual with draught outlet twice as large as usual.

ECONOMICS OF CHARCOAL PRODUCTION

The general price level and demand for charcoal are beyond the control of the individual entrepreneur. During the war of 1939–45, with strict limitations on the movement of fossil fuels from overseas, there was an upsurge in demand for charcoal leading to a proliferation of small producers who were able to flourish. Cessation of hostilities led to a rapid decline in demand and subsequently in supply, with local production apparently reaching its nadir about 1970. A renewed interest in charcoal was stimulated by the world energy crisis of 1973, yet in straight economy terms charcoal is uncompetitive with the wood from which it is made.

Energy must be expended to dry the wood and bring it up to the temperature required to start the exothermic reaction. The gaseous products of this reaction normally represent a further loss in energy. Further application of energy may be required to render these gases less objectionable environmentally. The end product has special properties but these have been achieved with about 50% loss of energy content. Unless its special properties are utilised, charcoal cannot, therefore, be regarded as a substitute for normal fuels.

Assuming adequate demand at an economic price level the profitability of a carbonising venture can be greatly affected by attention to the following factors:

- (a) Cost of raw material
- (b) Capital cost of plant
- (c) Yield
- (d) Distance from world markets.

Cost of Raw Material

The raw material may have a positive or negative cost as the sum of the following:

- (1) Royalty or stumpage
- (2) Felling, debarking, cross-cutting and splitting if necessary
- (3) Extraction
- (4) Storage and drying
- (5) Transport to site.

Stumpage is usually a payment to the land owner interrelated with (2), (3) and (5) above. Sometimes, however, stumpage is negative and the owner of the timber may be induced to pay the charcoal burner to remove otherwise valueless wood to facilitate silvicultural or agricultural operation. Similarly a sawmiller may find it advantageous to pay a carboniser to remove his residues rather than install his own incinerator or anti-pollution measures.

Wood of high basic density is generally of more value to the carboniser as it yields a greater throughput and higher density charcoal—a point worthy of note by the silviculturalist. Weight of wood fibre/ha/annum rather than m³/ha/annum should be the criterion.

Stumpage will be less where there is no alternative outlet for low grade wood, e.g. as chips for pulp.

Felling costs would not occur where sawmill residues are being used. This advantage, however, may be offset to some extent by the relatively higher ash content of bark and sapwood excluding the product from certain markets.

Debarking is necessary only where a high ash content is unacceptable. As bark slows down drying of the wood debarking is preferable where pre-drying is to be undertaken.

Crosscutting can be minimised where stacking is done by hand as in the war-time portable kilns. Cutting into 300–400 mm lengths facilitates mechanical charging of the kiln providing, by rough and tumble methods, a nett loading equal to careful hand piling of long lengths (Simmons, 1964). Shorter lengths dry more rapidly but this advantage must be balanced against increase in sawing costs and waste in sawdust.

Splitting may be advisable with large diameter material but the cost may be more than offset by the relative ease of debarking and handling in extraction.

Extraction costs are least where the greatest concentration of homogeneous utilisable material occurs on land with easy gradients accessible to modern transport and equipment.

Storage and drying of timber involves double handling, rental of suitable land and lock-up of capital for up to 18 months if air-drying is contemplated. As the disadvantages, however, of carbonising green wood are considerable, pre-drying of the charge is generally reckoned to be worthwhile.

Capital Cost

Primarily the choice lies between being labour or capital intensive. Charcoal burning is an arduous, dirty and uncomfortable occupation—turnover of labour is liable to be high and extra help frequently unobtainable. Except where the intention is to use 'cheap' family labour or own labour at 'no-cost' one is likely to opt for a system involving a considerable capital outlay amortised over a number of years against the cost of the product. With a quarter century lapse in recruitment charcoal burning tends to be a dying occupation; the more primitive the kiln the greater the degree of skill required by the burner to produce an acceptable product. Wages rising faster than charcoal price are further inducement to automatic controls and mechanical aids.

In comparing the cost of a capital item with the potential saving in wages in an inflationary era the following formulae are useful:

$$\text{Cost of capital item over economic life} = \text{original cost} \times 1.0P^n$$

Where P = rate of interest entrepreneur must pay

n = economic life of plant in years.

$$\text{Cost of labour over economic life of plant} = W \frac{(1.0R^n - 1)}{1.0R - 1}$$

Where W = current annual wage including direct overheads

R = expected annual rate % of wage inflation

n = economic life of plant in years.

e.g. by expending \$25,000 on plant with a life of 10 years an entrepreneur, who would have to pay 10% on his capital, could reduce his labour requirement by one worker whose current wage cost including direct overheads amounts to \$5,000 p.a. Assuming wages to inflate at 8% p.a. over the period, is the extra capital outlay worthwhile?

$$\begin{aligned} \text{Total capital cost} &= \$25,000 \times 1.10^{10} \\ &= \$64,900 \end{aligned}$$

$$\begin{aligned} \text{Total labour cost} &= \$5,000 \times \frac{(1.08^{10} - 1)}{1.08 - 1} \\ &= \$72,500 \text{ i.e. } \$7,600 \text{ more than capital above.} \end{aligned}$$

If, over the ten year period concerned ancillary costs of the plant such as insurance and maintenance are like to total less than \$7,600 the extra plant is the appropriate choice.

Yield

Yield is important in its relationship to—

input,

capital employed,

labour requirements.

Once a carbonising plant has been established it is in controlling yield that the burner can most influence his profitability. In any one charge it is desirable that the wood used should be as uniform as possible—in species, cross-section and moisture content. If billets of widely different burning characteristics are carbonised together, charcoal yields will be lower with a higher proportion of ash and/or unburnt brands (D.W.T. 1941).

The lower the carbonising temperature the higher the yield, therefore carbonising carried out at temperatures higher than that required to meet the specification reduces yield without compensating advantage.

Higher temperatures, too, are likely to shorten the life of the plant.

Yield in relationship to manpower can be improved by—

- choice of carbonising units,
- automatic controls,
- mechanisation in handling.

A battery of kilns operating in rotation provides fuller use of manpower than would a single kiln of the same total capacity. Retorts and vertical kilns lend themselves more readily to mechanical handling at all stages.

Automatic controls eliminate the need for many stand-by duties, relieving personnel for more active tasks and in particular minimising the need to employ skilled men outside normal working hours. More even carbonising temperatures can be obtained providing greater yields of the required specification.

The application of some ingenuity in handling can reduce labour requirements considerably. With fixed kilns the use of a front-end loader and conveyor belts can cut out most of the heavy work. With continuous or batch operated retorts the material need not be manhandled from the time it goes into the cross-cut saw until the bagged product is ready for despatch.

Large pieces of charcoal used to be broken with a mallet and then sieved by hand. A sheep foot roller would be more likely today for lump, followed by automatic grading to size on an inclined vibratory screen, delivering lumps straight into bags which would be weighed automatically

For briquetting comminution is normally carried out by a hammermill. Pressure rollers are not considered advisable owing to the danger of rise in temperature, leading to ignition.

Distance from World markets

Transportation costs and hence the nett price to the large producer in particular are affected by distance from world markets but remoteness can be of advantage to the small operator catering to a purely local demand. Under these conditions transportation operates as a buffer between him and possibly more efficient large scale operations elsewhere.

POTENTIAL MARKETS

Charcoal may be marketed locally as lump or briquette mainly for recreational uses either bulk through wholesalers or direct to industrial users such as animal feed compounders, horticultural sundries merchants and middlemen packagers or direct to retail outlets such as petrol service stations, hardware stores, garages and departmental stores. These retail outlets require frequent and systematic delivery of a well packaged product of apparently high quality. A producer selling direct to such outlets can expect to incorporate the wholesaler's costs and margins in his own price structure—frequent comparatively small deliveries to retail outlets over a wide area are not without cost!

Export sales can be negotiated directly by a large producer, but are more normally arranged through a wholesaler, merchant or import/export agency specialising in the commodity and/or geographical area.

A market survey in Georgia, U.S., revealed that 80% of charcoal sales were made in the summer months May through September. Sales by producers were:

Direct to retailer	..	..	..	..	..	..	48-53%
Through wholesalers and brokers	..	..	..	..	..	..	40-46%
To commercial trade	..	..	..	..	..	..	4- 5%
To industrial users	..	..	..	..	..	..	2%

Of retailer trade sales breakdown of sales by outlets was:

Supermarkets	..	..	..	..	..	..	75%
Convenience shops	..	..	..	..	..	..	20%
Hardware stores and filling stations	..	..	..	..	..	..	5%

Total sales had been rising at 8-15% per annum (13.8% over the previous 15 years). Per capita consumption amounted to 2.5 kg per annum (Cheung and Clipton, 1971), large by N.S.W. standards, but indicative of potential. The marked seasonal nature of demand could be of advantage to local producers wishing to export to the northern hemisphere.

TECHNICAL SPECIFICATIONS

Specifications for Charcoal in 1973

	Barbecue fuel	Activated carbon	'Metallic silicon'	Pig iron	Carbon bisulphide
Maximum m.c. %	.. 10	10-15	10	5	20
Maximum VM %	.. 24	25	10-15	7	5
Maximum ash %	.. not important	2	2	0.5	3
Minimum F.C. %	.. 75	60	83-88	87.5	81
Size	.. .. lump	dust 0.25-0.85 mm	lump 30 mm up	lump	lump
Bulk density	.. ..	0.15-0.20			
Final carbonisation temperature required *	500° C	500° C	600° C	700° C	700° C

* No allowance made for time factor—prolonged heating could result in specification being met with lower temperature.

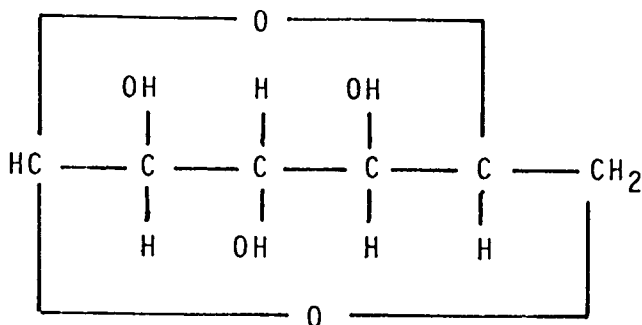
Reaction to S at 1200° C is important to some specifiers, e.g. for 'metallic silicon' and carbon bisulphide. One specification for 'metallic silicon' requires a maximum 8% Al₂O₃ and 20% Fe₂O₃ in ash, but neither of these are likely to present any difficulty to local producers.

SOME CHEMICAL ASPECTS OF CHARCOAL FORMATION

Wood charcoal always contains an appreciable amount of hydrogen and oxygen. Despite the fact that it is called a form of amorphous carbon, it very seldom contains as much carbon as anthracite. Some of the oxygen plays a decisive role in determining the chemical behaviour of activated charcoal.

Earlier workers in this field were generally mindful of increasing the productivity of the wood distillation industry and were particularly concerned with the chemical by-products produced in the distillate. The most important contributions to the explanation of the mechanism of the pyrolysis of wood were made by studying separately the pyrolysis of its three major constituents, cellulose, hemicellulose and lignin. This work has been outlined by Goos (1952) and Wenzl (1956).

Cellulose



By heating purified cellulose to 200–300° C under vacuum, Pictet and Sarasin (1918) obtained levoglucosan.

If glucosan is heated further it decomposes to form acetic acid, acetone, phenols and water. It can also repolymerise at 240° C. Levoglucosan has been definitely shown to exist in the water soluble tar from plant scale carbonisation of beech wood (von Wacek and Wagner, 1937) but generally very little appears to be formed when wood is carbonised at any temperature.

Cellulose pyrolysis produces no appreciable quantity of methanol. Acetic and other acids of this series are always found.

Hemicellulose—Pentosan

The hemicellulose from hardwood consists largely of pentosans whereas that from softwood often is predominantly hexosans. The products of the pyrolysis of pentosans are naturally more distinctive than those of hexosans. It is well established that pentosans give higher yields of acetic acid and acids of this series than either cellulose or lignin, and that they are the least heat stable of the three. Merritt and White (1943) found that wood heated at 210° C lost 77.5% of the pentosans originally present while only 23.5% of the cellulose was lost.

Furfural, which can easily be produced by the treatment of pentosans with 12% HCl, is not produced in great amount by pyrolysis of wood, possibly because it enters into secondary reactions or because pentosan molecules break down into simpler compounds under these conditions, and the furan ring is not formed or if formed readily decomposes.

Lignin

Experiments in the pyrolysis of lignin have established that this is the source of the phenols and phenolic ethers which have been isolated from the products of wood distillation.

Lignin has been shown to be the primary, if not the sole, source of methanol in wood distillation (Klason, *et al.*, 1909, 1910).

Mitchell *et al* (1953) studied the effect of heat on the properties and chemical composition of Douglas fir wood as well as the major components. The temperature used ranged from 110° C to 300° C in both an open and closed system. The results they obtained led them to concur with the opinion of Runkel and Wilke (1951) that the hydrolysis of the carbohydrates occurs first, followed by the condensation of the products formed, into insoluble materials. This is supported by the following:

hemicellulose decomposes before cellulose;

decomposition is greater in a closed system than in an open system at these temperatures;

the dimensional stability of wood is improved after heating at these temperatures. This could be due to the decomposition of the hygroscopic hemicelluloses and other carbohydrates.

Stamm (1956) concluded from his work on thermal degradation of wood that it is greater in the presence of air than in its absence, but that it is greater in a closed system than in a system from which the volatiles are removed. This he considered to be due to the build up of acids in the closed system, these acting as catalysts in the hydrolysis. It is also greater under steaming conditions than in the absence of water vapour. He found the hemicellulose degrades four times as fast as wood, cellulose at about the same rate and lignin at about half the rate.

Stamm (1956) also found that the thermal degradation of wood and its separate components follows a first order reaction. He established that the activation energies for degradation reactions were twice as high in the presence of water vapour as in its absence.

Wright and Hayward (1951) investigated the kinetics of the thermal decomposition of wood. They studied small sections of two species (western red cedar and western hemlock) introduced into an atmosphere of nitrogen at three temperatures, 500, 700, 900° C. They found that, for cubical pieces, the reaction was approximately of the half order and, for discs, it was of zero order. For cubes the rate constant was directly proportional to the specific surface and to the temperature and the proportionality constants were the same for both species of wood. It is possible, by using their method, to estimate the time required to produce charcoal at a given temperature for dry wood of a given size dropped into an inert atmosphere at that temperature. They also showed that the reaction was faster along the grain than across it.

Garten and Weiss (1957), in a review of activated carbon, described the process of charcoal formation as follows:

“The polymerization process that accompanies charring is the result of dehydration. although it is impossible to describe the reactions in detail, it is likely that double bonds arise from the elimination of water as in the production of acrolein by heating glycerol. Polymerization of these vinyl groups might occur as well as polymerization by condensation reactions between hydroxyl groups of different molecules and by aldol condensation. Subsequent heating will result in the aromatization of some of the double bonds. In the low temperature stages of charring, small aromatic nuclei will form amid large heterocyclic structures. The latter will undoubtedly contain ether-oxygen produced by condensation of hydroxyl groups. In a char,

lactone groups could arise from further oxidation. At higher temperatures lactones decompose to yield CO_2 , and the process of dehydration and dehydrogenation to give double bonds is facilitated. This could account for the well known fact that the size of the layer planes of carbon increases rapidly when the temperature of activation is increased above $650\text{--}700^\circ\text{C}$. The process of aromatization must also be accompanied by the elimination of much of the heterocyclic oxygen, resulting in a considerable gain in resonance energy. It is only when the temperature becomes sufficiently high for the elimination of such oxygen atoms that the aromatization process can proceed rapidly. The early stages of aromatization are probably associated with the production of chromenes as intermediates . . . the concentration of chromenes as sugar carbon is a maximum for an activation temperature in the region of 700°C the temperature at which the growth of the layer planes begins to accelerate rapidly.

The temperature at which the charcoal is made is clearly of considerable importance in determining the characteristics and analysis of the final product. It is of course, not the only factor, the presence of O_2 , CO_2 , steam or pretreatment with chemicals such as ZnCl_2 being necessary to give to the charcoal those characteristics which are required in activated carbon.”

However for most uses to which charcoal is put, temperatures higher than 600°C may prove detrimental.

APPENDIX A

Species	Common Name	% Ash in Charcoal	Range	No. of Samples
<i>Acacia aneura</i>	Mulga	1.2		1
<i>A. cambagei</i>	Gidgee	6.7	6.4-1.7	3
<i>A. cunninghamii</i>	Curracabah	1.2	0.6-1.4	5
<i>A. decurrens</i>	Green wattle	1.1		6
<i>A. dealbata</i>	Silver wattle	0.7		1
<i>A. harpophylla</i>	Brigalow	6.7	5.8-7.7	2
<i>A. pendula</i>	Myall	6.2	4.9-7.5	2
<i>Angophora costata</i>	Smooth-barked apple	1.5		1
<i>Callitris columellaris</i>	White cypress pine	1.7		1
<i>C. endlicheri</i>	Black cypress pine	1.9		2
<i>Casuarina glauca</i>	Swamp sheoak	1.7		1
<i>C. luehamannii</i>	Bull oak	3.0	0.6-4.3	7
<i>C. littoralis</i>	Black sheoak	1.0		6
<i>C. torulosa</i>	Rose sheoak	2.6		
<i>Eucalyptus acmenioides</i>	White mahogany	0.7	0.4-0.9	3
<i>E. alba</i>	Poplar gum	1.5		1
<i>E. albens</i>	White box	1.5		2
<i>E. amygdalina</i>	Black peppermint	0.2		6
<i>E. camaldulensis</i>	Red river gum	0.7	0.6-0.8	6
<i>E. crebra</i>	Narrow-leaved red ironbark	1.6		1
<i>E. delegatensis</i>	Alpine ash	0.3		6
<i>E. eugenioides</i>	White stringybark		0.2-1.6	5
<i>E. fibrosa</i> ssp. <i>fibrosa</i>	Broad-leaved red ironbark	0.5	0.3-0.6	3
<i>E. globulus</i>	Tasmanian blue gum	0.6		6
<i>E. grandis</i>	Rose gum	0.9	0.5-1.3	4
<i>E. gummifera</i>	Red bloodwood	0.7	0.1-1.9	4
<i>E. macrorhyncha</i>	Red stringybark	1.5		1
<i>E. maculata</i>	Spotted gum	1.4	1.1-1.9	8
<i>E. melanophloia</i>	Silver-leaved ironbark	0.9		1
<i>E. melliodora</i>	Yellow box	2.6		1
<i>E. microcorys</i>	Tallowwood	0.9	0.5-1.6	6
<i>E. microtheca</i>	Coolibah	3.1	1.8-6.5	5
<i>E. moluccana</i>	Grey box	2.6	0.9-4.7	6
<i>E. obliqua</i>	Messmate	0.3		7
<i>E. ovata</i>	Swamp gum	0.5		6
<i>E. paniculata</i>	Grey ironbark	1.5	1.0-2.2	7
<i>E. pilularis</i>	Blackbutt	0.6	0.1-2.1	8
<i>E. populnea</i>	Bimble box	2.5		2
<i>E. propinqua</i>	Grey gum	1.0	0.8-1.5	4
<i>E. pulchella</i>	White peppermint	0.3		6
<i>E. punctata</i>	Grey gum	0.3		1
<i>E. racemosa</i>	Scribbly gum	0.4		1
<i>E. regnans</i>	Mountain ash	0.4		6
<i>E. resinifera</i>	Red mahogany	0.8	0.5-1.5	7
<i>E. saligna</i>	Sydney blue gum	0.9		1
<i>E. tereticornis</i>	Forest red gum	0.6	0.5-0.8	5
<i>E. tessellaris</i>	Carbeen	2.2	2.0-2.4	2
<i>E. trachyphloia</i>	Brown bloodwood	0.4	0.2-0.5	4
<i>E. umbra</i> ssp. <i>carnea</i>	White mahogany	0.2		1
<i>Melaleuca leucadendron</i>	Broad-leaved tea-tree	2.0	1.4-2.5	2
<i>Pinus taeda</i>	Loblolly pine	1.5	0.9-2.0	4
<i>Syncarpia glomulifera</i>	Turpentine	3.0	2.1-3.5	3
<i>Tristania conferta</i>	Brush box	2.5		1

Appendix B. Inorganic content of bark, spawood and heartwood (ex Lambert and Cramsie, 1977) O.D. 105° C basis.

Botanical Name	Common Name	% Ash	% Si	ppm											Portion
				P	Ca	Mg	K	Na	Al	Fe	Mn	Zn	S	Cl	
<i>Callitris columellaris</i>	White cypress pine	4.93	1.020	65	16 500	555	1 815	135	145	200	25	7	340	425	Bark
		0.84	0.134	30	2 986	292	398	47	32	27	58	6	650	220	Sapwood
		1.00	0.197	7	3 217	435	270	18	27	13	52	3	450	280	Heartwood
<i>Ceratopetalum apetalum</i>	Coachwood	3.23	0.488	110	9 950	1 050	2 865	155	540	25	475	16	420	415	Bark
		0.87	0.099	45	3 200	235	800	175	85	25	45	6	n.a.	180	Sapwood
		0.81	0.125	40	1 930	370	110	220	50	30	25	12	n.a.	265	Heartwood
<i>Eucalyptus agglomerata</i>	Blue-leaved stringybark	1.28	0.235	70	3 470	570	700	340	35	45	165	5	n.a.	1 400	Bark
		0.22	0.005	165	420	280	880	230	15	25	30	6	n.a.	400	Sapwood
		0.03	trace	3	270	60	5	25	30	30	2	7	n.a.	n.a.	Heartwood
47 <i>E. andrewsii</i>	New England blackbutt	1.55	0.217	135	3 400	1 270	1 575	505	80	20	450	4	n.a.	1 070	Bark
		0.23	0.021	80	300	240	375	135	25	20	30	4	n.a.	265	Sapwood
		0.07	0.010	3	180	95	10	20	4	15	1	5	n.a.	n.a.	Heartwood
<i>E. andrewsii</i> ssp. <i>campanulata</i>	New England blackbutt	0.85	0.132	85	1 520	460	1 250	415	55	55	75	6	n.a.	960	Bark
		0.16	0.004	50	250	190	350	200	15	30	50	4	520	265	Sapwood
		0.06	0.001	5	150	40	75	10	9	80	2	3	n.a.	405	Heartwood
<i>E. blaxlandii</i>	Brown stringybark	0.68	0.118	105	940	260	880	650	35	30	50	1	n.a.	1 405	Bark
		0.30	0.075	70	215	90	420	140	10	15	15	7	n.a.	225	Sapwood
		0.02	trace	3	105	255	30	25	25	25	0	3	n.a.	n.a.	Heartwood
<i>E. camaldulensis</i>	River red gum	9.65	1.768	385	32 150	2 765	4 185	1 060	130	70	415	15	n.a.	2 455	Bark
		0.49	0.004	155	675	220	1 858	303	20	38	83	5	n.a.	910	Sapwood
		0.07	trace	14	235	100	53	33	8	18	7	4	n.a.	n.a.	Heartwood
<i>E. cameronii</i>	Diehard stringybark	1.28	0.283	30	2 630	330	1 025	298	295	140	75	170	2	n.a.	Bark
		0.36	0.017	100	600	235	880	265	40	25	45	8	n.a.	560	Sapwood
		0.05	0.004	21	60	110	30	30	6	2	6	3	n.a.	n.a.	Heartwood
<i>E. con-sideniana</i>	Yertchuk	0.72	0.110	65	1 040	690	1 100	255	65	5	65	3	n.a.	1 220	Bark
		0.17	0.021	105	160	230	550	160	20	15	50	6	n.a.	265	Sapwood
		0.04	trace	4	40	70	15	50	6	40	2	3	n.a.	5	Heartwood

Appendix B. Continued.

Botanical Name	Common Name	‰ Ash	‰ Si	ppm											Portion
				P	Ca	Mg	K	Na	Al	Fe	Mn	Zn	S	Cl	
<i>E. cypello-carpa</i>	Mountain grey gum	4.59	0.861	110	13 450	1 220	2 670	1 045	50	40	770	8	n.a.	4 755	Bark
		0.66	0.051	285	640	530	1 710	295	25	100	70	7	n.a.	935	Sapwood
		0.15	0.004	75	380	170	70	110	25	85	5	8	n.a.	425	Heartwood
<i>E. dalrym-pleana</i>	Mountain gum	5.07	0.856	110	14 540	1 420	4 050	830	75	30	1 765	5	n.a.	4 915	Bark
		0.51	0.034	325	640	470	110	125	25	50	90	8	n.a.	275	Sapwood
		0.18	0.006	145	330	240	100	160	35	20	2	20	n.a.	290	Heartwood
<i>E. deanei</i>	Round-leaved gum	22.88	5.524	190	68 790	2 560	5 050	55	285	70	1 345	5	n.a.	1 830	Bark
		0.52	0.066	135	700	440	1 050	100	35	20	55	4	n.a.	360	Sapwood
		0.05	0.001	8	270	110	120	10	5	15	3	3	n.a.	n.a.	Heartwood
<i>E. delegatensis</i>	Alpine ash	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Bark
		0.17	0.012	40	400	170	150	105	40	30	30	5	n.a.	515	Sapwood
		0.20	0.033	4	370	125	250	65	6	55	15	4	n.a.	n.a.	Heartwood
<i>E. fastigata</i>	Brownbarrel	1.53	0.242	200	3 510	600	1 700	830	50	50	50	9	n.a.	1 370	Bark
		0.32	0.028	120	320	120	800	330	25	30	15	8	n.a.	500	Sapwood
		0.02	0.001	10	80	70	25	25	8	40	2	2	n.a.	40	Heartwood
<i>E. fibrosa</i> ssp. <i>fibrosa</i>	Broad-leaved red ironbark	3.32	0.716	70	9 650	1 570	650	135	50	85	215	5	n.a.	2 045	Bark
		0.18	0.016	40	560	1 180	500	75	25	20	35	3	n.a.	90	Sapwood
		0.38	0.021	15	500	290	100	40	10	65	45	4	n.a.	10	Heartwood
<i>E. globoidea</i>	White stringybark	0.71	0.085	45	2 100	140	400	770	115	75	45	17	n.a.	1 340	Bark
		0.38	0.039	70	570	190	800	300	20	65	25	8	n.a.	750	Sapwood
		0.04	trace	5	200	10	25	35	25	70	2	4	n.a.	15	Heartwood
<i>E. grandis</i>	Rose Gum	8.30	1.687	115	29 060	1 090	1 400	1 270	60	45	230	5	990	2 665	Bark
		0.41	0.024	95	660	220	1 050	370	15	30	30	5	n.a.	775	Sapwood
		0.27	0.026	15	660	220	350	160	15	40	15	5	410	290	Heartwood
<i>E. gummifera</i>	Red bloodwood	0.94	0.103	65	1 980	470	1 150	590	20	20	25	6	640	1 470	Bark
		0.45	0.056	55	350	400	50	410	30	30	25	4	500	855	Sapwood
		0.14	0.019	3	270	160	120	65	15	30	3	3	n.a.	60	Heartwood

Appendix B. Continued.

Botanical Name	Common Name	% Ash	% Si	ppm											Portion
				P	Ca	Mg	K	Na	Al	Fe	Mn	Zn	S	Cl	
<i>E. intermedia</i>	Red bloodwood	1.03	0.152	30	4 400	420	4 900	2 395	25	30	55	6	n.a.	2 505	Bark
		0.28	0.025	100	310	190	750	105	15	30	20	5	n.a.	355	Sapwood
		0.04	0.001	4	150	50	100	20	10	20	1	7	n.a.	65	Heartwood
<i>E. laevopinea</i>	Silvertop stringybark	0.84	0.090	85	2 050	370	1 000	620	65	50	255	5	810	1 390	Bark
		0.27	0.013	85	410	180	650	235	25	35	25	5	n.a.	365	Sapwood
<i>E. macrorhyncha</i>	Red stringybark	0.03	trace	20	260	80	50	20	15	20	2	3	n.a.	15	Heartwood
		0.79	0.105	65	1 540	185	2 040	20	12	10	95	2	900	1 625	Bark
<i>E. maculata</i>	Spotted gum	0.31	0.032	113	448	160	675	40	25	125	15	10	n.a.	895	Sapwood
		0.07	0.008	9	103	60	138	28	6	10	2	4	n.a.	n.a.	Heartwood
<i>E. melliodora</i>	Yellow box	7.11	1.282	165	24 550	2 070	2 900	480	60	20	455	22	870	2 595	Bark
		0.70	0.111	95	1 730	320	750	175	20	40	50	7	770	510	Sapwood
<i>E. microcorys</i>	Tallowwood	0.98	0.181	8	2 810	740	250	145	20	35	78	10	410	1 105	Heartwood
		5.47	1.412	120	9 450	3 400	2 800	45	115	25	800	14	n.a.	8 205	Bark
<i>E. muellerana</i>	Yellow stringybark	0.43	0.043	75	860	350	850	30	25	20	75	8	590	365	Sapwood
		0.60	0.245	9	280	140	25	20	6	20	5	4	n.a.	20	Heartwood
<i>E. muellerana</i>	Yellow stringybark	3.16	0.606	100	9 380	2 300	655	75	85	180	8	810	1 700	n.a.	Bark
		0.49	0.077	86	630	160	900	255	70	80	35	5	n.a.	580	Sapwood
<i>E. obliqua</i>	Messmate	0.14	0.004	4	580	270	30	30	8	20	2	5	n.a.	85	Heartwood
		0.78	0.146	165	1 220	160	450	965	95	135	20	3	n.a.	2 050	Bark
<i>E. pitularis</i>	Blackbutt	0.44	0.014	15	1 110	390	850	340	15	115	15	7	510	600	Sapwood
		0.01	trace	15	330	30	8	30	35	105	2	4	n.a.	10	Heartwood
<i>E. pitularis</i>	Blackbutt	1.11	0.166	110	2 110	360	1 300	1 195	50	50	110	5	950	2 360	Bark
		0.35	0.009	110	460	290	850	415	25	50	35	6	750	995	Sapwood
<i>E. pitularis</i>	Blackbutt	0.06	0.001	5	110	50	50	45	15	35	2	6	370	30	Heartwood
		1.17	0.188	45	2 620	940	800	510	70	55	230	5	430	1 195	Bark
<i>E. pitularis</i>	Blackbutt	0.33	0.039	85	400	240	500	320	30	60	25	5	n.a.	425	Sapwood
		0.08	0.002	6	175	70	150	115	20	35	3	3	n.a.	190	Heartwood

Appendix B. Continued.

Botanical Name	Common Name	% Ash	% Si	ppm											Portion
				P	Ca	Mg	K	Na	Al	Fe	Mn	Zn	S	Cl	
<i>E. piperita</i> ssp. <i>urceolaris</i>	Sydney peppermint	1.59	0.283	70	2 310	1 325	1 060	1 350	70	25	550	5	n.a.	5 150	Bark
		0.39	0.053	100	295	170	850	350	15	60	40	7	n.a.	645	Sapwood
		0.08	trace	14	165	50	190	90	14	40	4	4	n.a.	125	Heartwood
<i>E. propinqua</i>	Grey Gum	10.88	1.551	405	43 900	3 100	1 550	1 495	140	25	2 620	5	n.a.	5 435	Bark
		0.37	0.038	90	680	200	650	200	25	35	80	11	n.a.	345	Sapwood
		0.14	0.028	8	320	90	20	60	7	35	2	3	n.a.	2 720	Heartwood
<i>E. radiata</i>	Narrow-leaved peppermint	1.45	0.232	90	2 510	890	1 750	1 020	115	55	160	6	n.a.	1 690	Bark
		0.51	0.048	115	790	320	1 000	305	25	185	30	7	n.a.	210	Sapwood
		0.08	0.002	6	460	30	60	55	45	165	0	10	n.a.	105	Heartwood
<i>E. saligna</i>	Sydney blue gum	9.19	1.208	185	32 030	1 700	3 250	1 955	125	75	330	8	1 660	2 615	Bark
		0.43	0.056	100	550	250	900	215	15	50	15	9	660	440	Sapwood
		0.07	0.002	5	280	60	100	60	10	25	4	4	340	65	Heartwood
<i>E. sideroxylon</i>	Red ironbark	1.48	0.319	95	3 110	830	1 040	25	85	60	200	5	1 200	1 555	Bark
		0.44	0.019	80	750	215	1 480	100	20	40	60	11	n.a.	770	Sapwood
		0.05	trace	8	345	45	75	30	7	20	4	8	n.a.	n.a.	Heartwood
<i>E. sieberi</i>	Silvertop ash	0.45	0.034	50	810	260	590	270	30	35	15	9	870	910	Bark
		0.28	0.008	95	470	180	550	340	20	85	275	4	510	510	Sapwood
		0.10	trace	15	370	140	50	85	20	55	3	4	n.a.	165	Heartwood
<i>E. smithii</i>	Gully peppermint	1.37	0.171	125	3 430	630	2 000	715	0	40	70	4	n.a.	1 315	Bark
		0.77	0.106	145	1 000	360	1 000	940	25	170	90	11	n.a.	1 290	Sapwood
		0.03	0.001	7	260	20	85	155	15	80	8	8	n.a.	385	Heartwood
<i>E. viminalis</i>	Manna gum	6.41	1.058	215	22 400	3 720	1 600	150	95	35	570	4	n.a.	2 410	Bark
		0.72	0.033	900	730	800	1 150	215	30	30	60	4	n.a.	1 160	Sapwood
		0.71	0.021	145	190	870	70	190	40	60	15	6	n.a.	680	Heartwood
<i>E. woollsiana</i> ssp. <i>microcarpa</i>	Grey box	9.28	1.912	225	29 170	2 980	2 900	15	75	40	950	15	n.a.	3 390	Bark
		0.49	0.066	90	500	445	1 100	15	45	20	120	7	n.a.	390	Sapwood
		0.79	0.142	10	3 055	165	115	10	10	30	30	4	n.a.	n.a.	Heartwood

Appendix B. Continued.

Botanical Name	Common Name	% Ash	% Si	ppm											Portion
				P	Ca	Mg	K	Na	Al	Fe	Mn	Zn	S	Cl	
<i>Pinus radiata</i>	Radiata pine	1.21	0.203	75	3 446	270	961	120	309	88	64	12	710	170	Bark
		0.37	0.035	43	752	211	809	53	40	51	67	10	530	100	Sapwood
		0.28	0.029	13	725	291	321	35	14	32	59	9	360	125	Heartwood
<i>Syncarpia glomulifera</i>	Turpentine	0.87	0.276	56	938	189	446	197	21	40	29	4	860	400	Bark
		0.65	0.164	103	455	228	818	264	19	38	21	5	430	820	Sapwood
		0.55	0.230	7	142	71	56	21	2	52	6	4	n.a.	205	Heartwood
<i>Tristania conferta</i>	Brush box	3.20	0.821	98	7 023	732	1 861	179	59	45	87	18	4 830	1 420	Bark
		0.92	0.205	72	1 438	358	1 164	185	19	58	20	7	1 080	1 365	Sapwood
		0.97	0.180	8	1 746	590	658	1 011	11	57	7	5	380	2 960	Heartwood

n.a. = not analysed.

Appendix C. % volatile matter at various carbonisation temperatures. (ex Conaghan, 1940)

Species	Common Name	Temperature of carbonisation ° C							
		350	400	450	500	590	700	800	950
<i>E. umbra</i> ssp. <i>carnea</i>	White mahogany	41.0	37.5	32.2	25.7	17.5	5.2	0.5	
<i>E. gummifera</i>	Red bloodwood	38.0	35.3	28.8	24.0	15.5	4.5	0.4*	0
<i>E. eugenioides</i>	White stringybark	41.9	35.9	31.0	26.5	16.5	5.2	-	-
<i>E. moluccana</i>	Grey box	41.2	33.4	30.4	25.5	18.5	6.0	1.9*	0
<i>E. maculata</i>	Spotted gum	40.0	31.3	28.6	23.9	16.0	3.0	0.5*	0
<i>E. paniculata</i>	Grey ironbark	39.0	34.4	29.0	23.5	14.2	4.4	-	-
<i>E. pilularis</i>	Blackbutt	41.0	39.0	31.0	25.3	16.9	5.4	0.5*	0
<i>E. resinifera</i>	Red mahogany	40.0	36.3	31.0	25.0	16.2	4.4	0.5*	0
<i>E. camaldulensis</i>	River red gum	39.4	35.8	31.0	26.0	16.7	4.4	-	-
<i>E. saligna</i>	Sydney blue gum	40.4	37.8	30.0	24.9	15.8	4.1	0	0
<i>E. siderophloia</i>	Ironbark	38.0	32.8	28.0	22.7	15.0	3.8	0	0
<i>E. tereticornis</i>	Forest red gum	39.3	32.6	30.0	24.8	16.7	4.1	0	0
<i>E. punctata</i>	Grey gum	41.2	39.0	30.0	25.1	18.8	5.2	0.5*	0
<i>E. crebra</i>	Narrow-leaved red ironbark	40.3	37.0	30.3	24.9	15.7	4.2	0.3*	0
<i>Melaleuca leucadendron</i>	Broad-leaved tea-tree	36.7	31.2	27.0	21.7	13.7	5.7	1.7*	0
Mean		39.8	35.3	29.9	24.6	16.2	4.6	0.5	

* Conaghan considered volatile matter at carbonisation temperature of 800° C to be nil; he attributed the figures listed to experimental error.

Appendix D. % yield charcoal at various carbonisation temperatures. (ex Conaghan, 1940)

Species	Common Name	Temperature of carbonisation ° C							
		350	400	450	500	590	700	800	950
<i>E. umbra</i> spp. <i>carnea</i>	White mahogany	46.9	44.2	40.7	37.1	33.4	29.1	27.7	27.6
<i>E. gummifera</i>	Red bloodwood	45.5	43.6	39.6	37.1	33.5	29.5	28.3	28.2
<i>E. eugenioides</i>	White stringybark	44.2	40.4	37.6	35.3	31.1	27.3	26.0	25.9
<i>E. moluccana</i>	Grey box	50.5	44.7	42.8	40.0	36.6	31.9	30.5	30.0
<i>E. maculata</i>	Spotted gum	47.1	41.2	39.5	37.1	33.7	29.8	28.4	28.3
<i>E. paniculata</i>	Grey ironbark	40.3	37.5	34.5	32.2	28.8	25.9	24.8	24.7
<i>E. pilularis</i>	Blackbutt	45.9	44.5	39.2	36.2	33.0	28.6	27.3	27.1
<i>E. resinifera</i>	Red mahogany	48.2	45.6	41.7	38.6	34.7	30.3	29.1	29.0
<i>E. camaldulensis</i>	River red gum	49.7	46.8	43.6	40.7	36.2	31.5	30.1	30.1
<i>E. saligna</i>	Sydney blue gum	49.9	47.9	42.6	39.8	35.4	31.1	29.8	29.8
<i>E. siderophloia</i>	Ironbark	48.2	44.3	41.5	38.6	35.2	31.1	29.9	29.9
<i>E. tereticornis</i>	Forest red gum	50.8	45.6	43.9	40.9	36.9	32.2	30.8	30.8
<i>E. punctata</i>	Grey gum	52.2	50.2	45.0	41.0	37.8	32.4	30.9	30.7
<i>E. crebra</i>	Narrow-leaved red ironbark	49.1	46.5	41.9	39.0	34.8	30.7	29.4	29.4
<i>Melaleuca leucadendron</i>	Broad-leaved tea-tree	41.8	38.6	36.3	33.9	30.8	28.0	26.8	26.6
Mean		47.4	44.1	40.7	37.8	34.1	30.0	28.7	28.5

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 Fig. 6—SC 7770; Figs 7-8—SC 7771; Fig. 9—SC 7769.