

THE CHARACTERISTICS OF AUSTRALIAN COALS AND THEIR IMPLICATIONS IN COAL LIQUEFACTION

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INTRODUCTION

In Australia, coal represents, in energy terms, over 97% of the country's non-renewable fossil fuel based energy resources, yet indigenous oil which barely represents 1% of these resources, together with imported oil, supply over 50% of the energy demand with much of this from the transport sector. This situation, catalyzed by the OPEC oil embargo in 1973, has led to strong and sustained interest in the prospects for producing liquid fuels from the abundant coal resources. The reserves of recoverable fossil fuels (1) and the present pattern of energy demand in Australia (2) are shown in more detail in Tables 1 and 2, respectively.

LOCATION, GEOLOGY AND GENERAL CHARACTERISTICS OF AUSTRALIAN COALS

The geographical distribution of Australia's coal resources is shown in Fig. 1. New South Wales and Queensland possess large reserves of black coals in the Sydney and Bowen Basins, respectively, adjacent to the eastern seaboard. Significant deposits of bituminous coals are also known to occur in remote areas in South Australia at Lake Phillipson in the Arckaringa Basin and at currently inaccessible depths (2000-3000 m) in the Cooper Basin (3,4). [An estimated 3.6×10^6 million tonnes in the latter].

Large reserves of brown coals occur in Victoria with smaller deposits in New South Wales and South Australia.

Whereas the majority of the black coals in the northern hemisphere, including the USA and Europe, were formed during the Carboniferous age, the black coals of Australia are, in the main, Permian. The latter include the coals from the two major basins - the Sydney and the Bowen - and also large deposits in the Galilee Basin (Queensland), at Oaklands (N.S.W.), Lake Phillipson (South Australia) and Collie (West Australia) as well as the deep coal in the Cooper Basin (South Australia). These Permian coals, together with counterparts in India, South Africa, Antarctica and South America, are referred to as Gondwana coals after the hypothetical super-continent which subsequently broke up into the continents and sub-continents mentioned above (5).

The climatic conditions prevailing in the Permian during the formation of these Gondwana coals were different from those for the Carboniferous coals of North America and Europe. As a result of a cooler climate with alternating dry and wet periods, and of the consequent difference in the original plant materials, the conditions of accumulation, and the slower rate, and prolonged duration of sinking, the Australian (and other Gondwana) Permian coals differ in many respects from the Carboniferous coals of the northern hemisphere. Thus for the former coals, seam thickness tends to be greater, vitrinite content lower, semi-fusinite content higher, mineral matter content high and sulphur content generally low; the ash derived from the mineral matter is usually refractory with high fusion temperatures. These coals occur in seams near the surface, and at depth.

The Australian Permian coals vary widely in rank (maturity) and type (vitrinite content) from the Oaklands (N.S.W.) coal at 72% (dry ash-free basis) carbon, a hard brown coal (6), at one extreme - though high volatile bituminous coals such as Galilee (Queensland) coal at 77% carbon, 16% vitrinite; Blair Athol (Queensland) coal at 82% C, 28% vitrinite; Liddell (N.S.W.) coal at 82% C, and >70% vitrinite, - to low volatile bituminous such as Peak Downs (Queensland) at 89% C, 71% vitrinite,

and Bulli seam (N.S.W.) 89% C, 45% vitrinite.

In addition to the Permian coals there are occurrences of Mesozoic and Tertiary coals in Australia. Mesozoic coals occur in small basins in South Australia, Tasmania, New South Wales and Queensland and vary in rank from brown to bituminous. Perhaps the most notable occurrences in the present context are the Wallon coals in the Clarence-Morton basin in Queensland, e.g. Millmerran sub-bituminous coal (78% carbon, vitrinite plus exinite ~90%).

The most significant Tertiary coals are represented by the vast brown coal deposits in Victoria, particularly in the Latrobe Valley. These brown coals with 68-70% carbon, occur in very thick seams (up to 200 meters) under shallow cover (<30 meters). These coals differ from the Tertiary brown coals of North America in that they have a much lower ash yield and significant amounts of the ash-forming inorganic constituents are present as cations on the carboxylic acid groups which are a characteristic of low rank coals.

COAL CHARACTERISTICS AND THEIR EFFECTS IN LIQUEFACTION PROCESS

The wide variation in Australian coals in rank, type and inorganic impurities and the significant differences between these coals and those from the USA and elsewhere, emphasize the need for detailed understanding of how specific coal characteristics influence liquefaction reactions and the properties of the liquid product. The heterogeneity and variability of coals make them a complex feedstock on the one hand and presents major challenges to efforts to identify and quantify those parameters of most significance. However, until this is achieved the application of a process developed and optimized on a coal, or similar coals, from one region to coals in another region is fraught with danger. In recognition of this, research is in progress in a number of laboratories in Australia to elucidate the chemistry of Australian coals in relation to their liquefaction. This encompasses both black and brown coals and liquefaction via pyrolysis, non-catalytic hydrogenation (solvent refining) and catalytic hydrogenation. The results obtained in these studies are informative but some give rise to more questions than answers. In the remainder of this paper selected highlights from these Australian studies will be presented and discussed.

EFFECTS OF PETROGRAPHIC COMPOSITION AND RANK

It is possible to produce some liquid hydrocarbons from most coals during conversion (pyrolysis and hydrogenation, catalytic and via solvent refining) the yield and hydrogen consumption required to achieve this yield can vary widely from coal to coal. The weight of data in the literature indicate that the liquid hydrocarbons are derived from the so-called 'reactive' macerals, i.e. the vitrinites and exinites present (7,8,19). Thus, for coals of the same rank the yield of liquids during conversion would be expected to vary with the vitrinite plus exinite contents. This leads to the general question of effect of rank on the response of a vitrinite and on the yield of liquid products; and, in the context of Australian bituminous coals, where semi-fusinite is usually abundant, of the role of this maceral in conversion.

A number of research projects in Australia are being addressed to these questions. The Australian Coal Industry Research Laboratories (ACIRL) have been approaching the question through a study of the conversion behaviour of a selected range of Australian bituminous coals under non-catalytic solvent refining conditions (9,10). The Commonwealth Scientific and Industrial Research Organization (CSIRO) is considering the question with regard to pyrolysis (11) and catalytic hydrogenation (12) of bituminous and brown coals, with support from studies of the behaviour of individual maceral types during conversion with the aid of petrographic techniques (12).

Experimental data published recently by Cudmore (10) for eight Australian bituminous coals, reproduced in Fig. 2, show a good direct linear correlation between conversion (to gas + liquids), under non-catalytic hydrogenation conditions

using tetralin as vehicle, and the vitrinite plus exinite contents over the range 40 to 80% for coals in the rank range where the mean maximum reflectance (R_0 max.) of the vitrinite varies from 0.43% to 0.68%, i.e. for carbon content over the range of about 75% (dry ash-free) to about 82%. This encompasses the sub-bituminous coals and high volatile bituminous coals. However, for coals where R_0 max. is greater than 1.47% the yield was markedly lower than might otherwise have been expected from the vitrinite plus exinite contents (refer Fig. 2). The information in Fig. 2 would further suggest that the rank effect in decreasing conversion yield increases rapidly with increase in rank from R_0 max. 1.47% to 2.64%, i.e. carbon (dry ash-free basis) 88% to >90%. This, of course, leaves open the question of where the decrease in the conversion of the vitrinite (+ exinite) starts in the rank range 83 to 88% carbon.

An implication of Cudmore's data (10) for the sub-bituminous and high volatile bituminous coals is that the semi-fusinite appears to contribute little to the conversion products, otherwise the apparent dependence of yield on the vitrinite (+ exinite) content would not be so linear.

The whole question relating to the possible role of semi-fusinite is receiving the attention of Shibaoka and his associates in the CSIRO (12). Although the project is still at an early stage, direct observations on the changes occurring in semifusinite-rich coal grains during conversion under a wide variety of conditions suggest that the possible contributions of this maceral in conversion cannot be ignored although further work is required to define the nature and magnitude of such contributions.

Studies initiated by the author while still with CSIRO (13) seek to throw light on the role of the various macerals by studying the conversion, under catalytic hydrogenation conditions, in tetralin as vehicle, of maceral concentrates from a high volatile bituminous coal. Some preliminary results, given in Fig. 3, show conversions as almost complete for the hand picked vitrain (>90% vitrinite) from a high volatile bituminous coal (Liddell seam N.S.W., 83.6% carbon and 43% volatile matter both on a dry ash-free basis). However, it is evident that the conversion of the 'whole' coal increases rapidly with increase in hydrogen pressure (under otherwise similar conditions - batch autoclave, 4h. @ 400°C). This could suggest either that conversion of the vitrinite is suppressed by other components in the coal, particularly at the lower pressures, or more likely, that other macerals are participating to an increasing extent as the hydrogen pressure increases.

Consideration of the latter results in relation to those of Cudmore (10), discussed above, emphasise the need for caution when generalising on the influence of coal characteristics on conversion. Indeed, it would appear that the absolute and relative contribution of the various petrographic components is dependent on the process conditions which include, inter alia, the hydrogen potential.

The petrography of brown coals differs from that of black coals and is less well developed. However, evidence is mounting that brown coals can vary significantly, even within the same seam, and that these variations may effect their conversion behaviour. The Victorian Brown Coal Development Commission has initiated studies in this area (with advice from the German Democratic Republic). No results are available as yet.

THE EFFECT OF ELEMENTAL COMPOSITION

It is well established that for any coal the so-called reactive macerals, vitrinite and exinite, are richer in hydrogen than the inert macerals. Therefore, since the conversion of coals to liquid fuels involves the production of lower molecular weight products having atomic hydrogen to carbon ratios in the range 1.7 to 2 compared with <1 for most coals, it is of interest to consider the effect of the hydrogen content, or alternatively the hydrogen/carbon ratio on the conversion of coals to liquid and gaseous fuels under a wide range of conditions.

Pyrolysis

In this context it is relevant to consider initially the effect of hydrogen contents on tar yields during pyrolysis (carbonization). This is particularly so, since, in all coal conversion processes little happens until the coal is at a temperature above that where active thermal decomposition normally sets in. In other words, all coal conversion processes may be regarded as pyrolysis under a variety of conditions which determine the nature of the primary decomposition and the reactions which follow.

Fig. 4 represents a plot of the atomic H/C ratio versus tar yields obtained by the former CSIRO Division of Coal Research for a wide variety of Australian coals during low temperature (600°C) Gray-King carbonization assays (14) over several years. This figure shows that, despite a wide variation in rank and inorganic impurities, there is a significant linear correlation between the tar yield and the atomic H/C ratio. A variety of factors may account for the scatter - the empirical nature of the assay, wide variations in the ash yield and nature of the ash (see below), weathering of the coal, the multitude of analyses involved and the long time span over which the results were accumulated.

The steep dependence on hydrogen content of the tar yields obtained during the low temperature (500°C) fluidized bed carbonization of 14 Australian coals, ranging in rank from 72% to -89% (dry ash-free basis) carbon content, is clearly demonstrated in Fig. 5 (15,16).

In current CSIRO investigations into the production of liquid fuels via the flash pyrolysis of selected Australian coals (11) the importance of the hydrogen content, or more precisely the atomic H/C ratio of the coal with regard to the total yield of volatile matter and tar, has been demonstrated also. This is shown in Fig. 6 (20) together with the reproduction of the correlation line for the low temperature Gray-King Carbonization assay transferred from Fig. 4. Also included are data obtained for one USA bituminous coal (Pittsburgh No. 8) and one lignite (Montana). The former coal plots consistently with the Australian bituminous coals for both the volatile matter and tar yield; but whereas the raw Montana lignite, together with the raw Australian brown coal, are consistent with the bituminous coals for total volatile matter yield, the tar yields from the lignite and brown coal fall significantly below those to be expected from Fig. 4 for bituminous coal with similar atomic H/C ratios with one exception - a low ash sample of Loy Yang brown coal. The reason for the 'deviation' is considered in the next section of the paper.

Hydrogenation

Cudmore (13) in his studies of the non-catalytic hydrogenation (solvent refining) of six Australian coals has indicated that the conversion systematically increases as the atomic H/C ratio of the coal increases over the range 0.60 to 0.85. This is shown in Fig. 7 (10) which also includes data for the catalytic hydrogenation of six Canadian coals (17). These results, together, indicate the importance of the hydrogen contents of coal in general for both non-catalytic and catalytic hydrogenation.

With regard to the implications of the elemental composition (ultimate analysis) of Australian coals, brown coals (lignites) call for special attention by virtue of their high oxygen contents (as high as 30%). During hydrogenation of brown coals it is usually considered that significant amounts of hydrogen are consumed in the elimination of oxygen as water and that this places these coals at a disadvantage because the cost of hydrogen is a significant factor in the economics of conversion. White has recently considered oxygen balances in the catalytic hydrogenation of some Australian brown coals (18). This study indicates that, whereas the overall conversion, under comparable conditions, is higher for brown coals than for bituminous coals studied, the yield of hydrocarbon liquids is higher for the latter; but, surprisingly, the hydrogen consumption in the primary conversion is actually lower for the brown coals than for any of the bituminous

coals studied (H/C in range 0.57 to 0.72). Further, the results show that the present hydrocarbon liquid yield (dry ash-free basis) per cent of hydrogen consumed is actually as high, or higher, for a low ash yield (0.5%) brown coal (H/C = 0.81) by comparison to the bituminous coals studied. Indeed, the evidence suggests that much of the oxygen (~30%) is eliminated as carbon monoxide and carbon dioxide.

EFFECT OF INORGANIC CONSTITUENTS

Despite much speculation on the possible effects of the inorganic ash-forming constituents in a coal on its behaviour during conversion, there is still no clear understanding on the subject. It is generally suspected that where pyrite is present in a coal this is converted to pyrrhotite under the conditions of coal hydrogenation and can act as a catalyst (19). The effectiveness will, of course, be dependent on how the pyrite is disseminated through the coal including the maceral association; this may be the cause where no significant effect has been noted (8). In the majority of Australian coals the sulphur, and hence pyrite, content is very low and hence the possibility of a catalytic effect from pyrite is negligible. As mentioned earlier, Australian bituminous coals tend to be high in mineral matter. This consists primarily of aluminosilicate minerals (20). To prepare most coals for use as a feedstock in conversion these will need to be processed in a coal preparation plant to reduce the ash yield. Otherwise reactor throughput in terms of effective coal feed rates, are adversely affected and excessive ash can 'blind' added catalysts and cause other operational problems. Since aluminosilicates are the basis of cracking catalysts, the mineral matter in the coal might well act in this way and be either to the advantage or disadvantage of the conversion process.

A project initiated by the author when with CSIRO has, as one of the objectives, the study of effect of the mineral matter in selected Australian coals during catalytic hydrogenation (13). The initial approach has been to compare, under otherwise identical conditions, the conversion behaviour of a coal sample before and after demineralization. Some very preliminary results are shown in Fig. 8 for a sample of Liddell seam coal (ash yield 7.35% air dried basis; volatile matter 43.2% and total sulphur 0.48% dry ash-free basis) before and after demineralization to reduce the ash yield to 0.5%. Fig. 8 shows the effect of temperature on the total conversion and yield of bitumen, (i.e. residue from atmospheric and vacuum distillation to 210°C of the hydrogenation product) during batch catalytic (a commercial Co-Mo on alumina catalyst) hydrogenation using tetralin as solvent. The main effect of the mineral matter appears to be to give an increased scatter in the experimental data with regard to total conversion. This is also evident, but to a lesser degree, in Fig. 3 where the effect of pressure on total conversion for the same coal is indicated.

Since the scatter of experimental points for total conversion is both above and below the curve for the demineralized sample, it is not possible to assign the behaviour to either catalyst blinding or enhanced catalytic effects. With regard to the yield of 'bitumen' (Fig. 8), the bias on the high side in yield could be interpreted to suggest that some catalytic effect was exhibited by the mineral matter. Obviously further studies of this type are required to determine the nature of the effects, if any, of the aluminosilicates in Australian bituminous coals on the response of these coals during conversion.

Australian brown coals are of special interest with regard to the possible influence of the inorganic constituents during pyrolysis and hydrogenation. In the low ash yield Australian brown coals, a considerable proportion of the inorganic ash-forming constituents are present as cations associated with the carboxylic acid groups in the coal (21,22,23). Studies in CSIRO have shown that the nature and amount of the cations can exert marked effects on the behaviour of the coal during thermal decomposition (pyrolysis). In particular, Schafer (24) has shown that the presence of cations facilitate the elimination of the oxygen during pyrolysis in a manner that is still not understood. This could have interesting and practical implications for hydrogenation which remain to be investigated.

In the USA, observations with North Dakota lignites have suggested that sodium associated with the carboxyl groups have a beneficial catalytic effect with regard to the quality of the liquid product (8). Further, the superiority of CO-steam over hydrogen in the 'non-catalytic' hydrogenation of lignite has been attributed again to the catalytic effects of alkali and alkaline earth metals present on the coal (25) which are known to be effective catalysts in the carbon-steam and carbon monoxide-steam reactions. It has been suggested that the hydrogen generated accordingly in-situ is more effective since it probably passes transiently through the reactive 'nascent' hydrogen-form and avoids the need to dissociate the strong bond in molecular hydrogen.

The ability to exchange cations on the carboxylic acid groups in brown coal (26) has led to interest into the effectiveness of transition metals exchanged onto the carboxyl groups as catalysts. This aspect was first looked at by Severson and his colleagues in North Dakota with negative results (27). However, the matter is now being re-examined in Australia in the context of Victorian brown coals. Careful studies in this area could well help contribute to the better understanding of the role of the catalyst in coal hydrogenation, e.g. does it facilitate the direct transfer of hydrogen from molecular hydrogen in the gas phase, or in solution, to the fragments derived from the thermally decomposing coal? or does it simply facilitate in the regeneration of the hydrogen donor capacity of the 'solvent'?

It is appropriate to conclude this section by reference to one aspect of the CSIRO flash pyrolysis project involving, again, brown coals. Here, it has been shown (28) that the presence of cations on the carboxyl groups strongly suppresses the tar yield obtained during rapid pyrolysis, although the total conversion to volatile products appears to be unaffected. For example, a sample of raw Gelliondale (Victoria) brown coal having a 7.2% (dry basis) ash yield, yielded 12% (dry ash-free basis) of tar during flash pyrolysis but, when this coal was acid washed 0.7% (dry basis) ash yield, the tar yield increased to 20% (dry ash-free basis). Further reference to Fig. 6 shows that the latter tar yield now plots with the bituminous coals with reference to the effect of the atomic H/C ratio. Similarly a second brown coal sample (Loy Yang) which, as recovered from the seam, has a very low ash yield (0.4% dry ash-free basis), and most of the carboxyl groups in the acid form, plots with the bituminous coals in Fig. 3; however, when the sodium-salt is produced from this coal before flash pyrolysis the tar yield is almost completely suppressed.

It is interesting to speculate on the significance these observed effects of the presence of cations on the carboxylic acid groups in brown coals. It would appear that the cations either inhibit the tar forming reactions in some way or else cause the tars, once formed, to break down to more volatile components with no solid residue since the total volatile matter yield is independent of whether the carboxyl groups are in the salt- or acid-form. The former possibility appears to be more plausible which, in turn, implies that the tars are formed from lower molecular weight precursors by reactions which are blocked by the presence of a cation, or cations, on the carboxyl groups. The clue to the detailed explanation perhaps resides with the observations, already mentioned, of Schafer (24) on the effects of cations associated with carboxyl groups on the oxygen elimination reactions during the thermal decomposition of brown coals.

Further detailed studies in this area are obviously needed to resolve the chemistry involved. Such pyrolysis studies supplemented by hydrogenation experiments with acid-form and salt-form brown coals offer promise of resolving the precise role of pyrolysis in the hydrogenation of these coals and of how the ash-forming cations participate in the hydrogenation reactions. For example, how does the presence of the cations effect the hydrogen consumption? A question that needs also to be considered in the context of the observations of White (18).

CONCLUDING REMARKS

The first part of this paper has shown that Australian black and brown coals differ significantly in a number of respects from coals of similar ranks from North

America and elsewhere in the northern hemisphere. The rest of the paper then proceeded to indicate the progress being made to determine how the characteristics of Australian coals influence their conversion to volatile and liquid products during pyrolysis and hydrogenation.

The results presented and discussed here for on-going investigations on Australian black coals indicate strongly that, over a rank range up to about 83% (dry ash-free) carbon, the vitrinite and exinite contents and overall, the atomic hydrogen-to-carbon ratio are the important parameters with regard to total volatile and liquid yields during pyrolysis and hydrogenation of such coals. In these respects there appears to be no major differences relative to northern hemisphere coals. The strong dependence of conversion on atomic H/C ratio suggest that the subtleties of variation in chemical composition or structure with change in rank are of secondary importance. Also the near linear dependence of conversion yields on the atomic H/C ratio further suggest that the effects of the mineral matter in the Australian black coals may be secondary.

The results mentioned for Australian brown coals raise many interesting questions concerning the effect of coal characteristics on conversion during pyrolysis and hydrogenation. These relate to the similarity of the behaviour of the acid-form brown coals with the black coals in terms of the effect of the atomic H/C ratio on conversion during pyrolysis; the suppression of the tar yield when the carboxyl groups are in the salt-form; and the elimination of oxygen during the primary hydrogenation without the involvement of hydrogen. Again, within the limitations of the investigations mentioned, there is no reason to believe that the effects observed should be unique to Australian brown coals.

To conclude, it is emphasised that many of the results discussed relate to on-going investigations and need confirmation on other coals. Also, many of the effects mentioned relate to the overall conversion. In coming to grips with the effects of coal characteristics, attention must be given to the quality as well as the quantity of liquid products obtained during conversion; as well as to the rate at which the conversion occurs under various conditions. These aspects, which have not been considered in this presentation, call for careful experimentation where the emphasis is not on maximising conversion but on careful control of experimental conditions with termination of experiments at only partial conversion.

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TABLE 1: AUSTRALIA'S FOSSIL FUEL ENERGY RESOURCES (1)

<u>Resource</u>	<u>Quantity</u> (Demonstrated)	<u>Specific Energy</u> (10^{18} Joules)	<u>(Percentage)</u>
Black Coal*			
In Situ	36.30 x 10^9 t	1040	69.8
Recoverable	20.26 x 10^9 t	580	58.9
Brown Coal			
In Situ	40.93 x 10^9 t	400	26.8
Recoverable	39.00 x 10^9 t	380	38.6
Crude Oil and Condensate			
In Situ	49.00 x 10^9 bb1	29.7	1.99
Recoverable	20.70 x 10^9 bb1	12.4	1.26
Natural Gas + LPG			
In Situ	545 x 10^9 m ³	21.0	1.40
Recoverable	327 x 10^9 m ³	12.6	1.28
Total			
In Situ		1,685.7	100
Recoverable		1,145.0	100

*Demonstrated + Inferred in situ black coal resources are estimated to be 5600×10^{18} J with 55% recoverable - inferred resources of crude oil and natural gas are relatively minor representing only 1% and 8%, respectively, of the demonstrated resources.

TABLE 2: PATTERN OF AUSTRALIAN USE OF FOSSIL FUELS 1974-75 (2)

Total primary energy demand 2512×10^{15} J consisting of:
coal 1035×10^{15} J; oil 1318×10^{15} J; natural gas 159×10^{15} J

	<u>% of Fuel Type</u>	<u>% Total Primary Energy</u>
<u>Coal</u>		
Electricity generation	61	26)
Iron and steel	25	10) 42
Other	14	6)
<u>Oil</u>		
Transport*	61	32)
Fuel oil	15	8) 52
Other	24	12)
<u>Natural Gas</u>		
Electricity generation	20	1)
Other	80	5) 6

*Includes fuel oil for bunkering

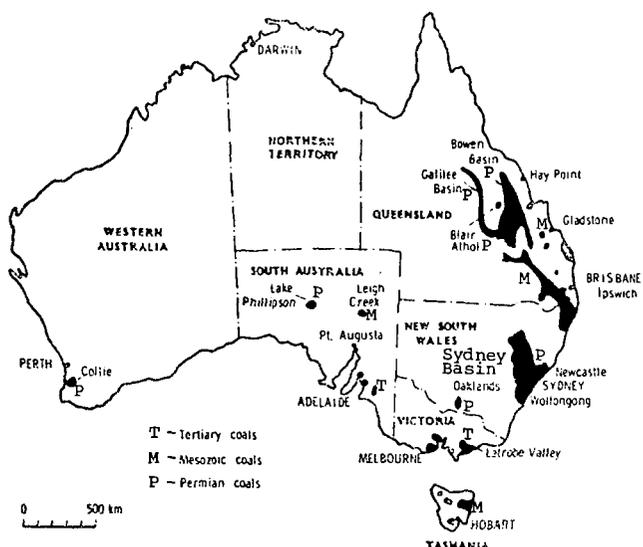


FIG.1. AUSTRALIAN COALFIELDS (3)

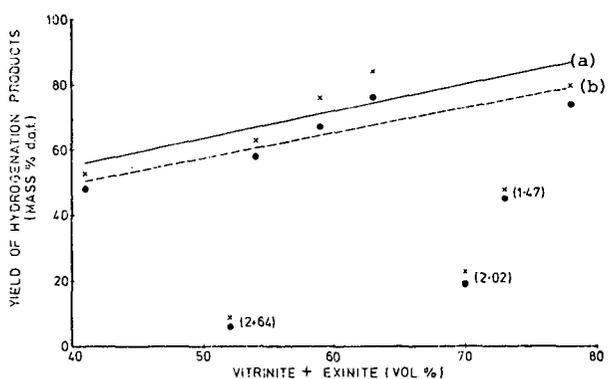


Fig.2. Non catalytic hydrogenation - Product yields versus vitrinite + exinite content. Curve (a) total conversion (x) (b) extract (●) (11)
 Note: Lines (a) & (b) relate to rank range R_0 max. 0.43 - 0.68%. Values in parenthesis refer R_0 max. for higher rank coals.

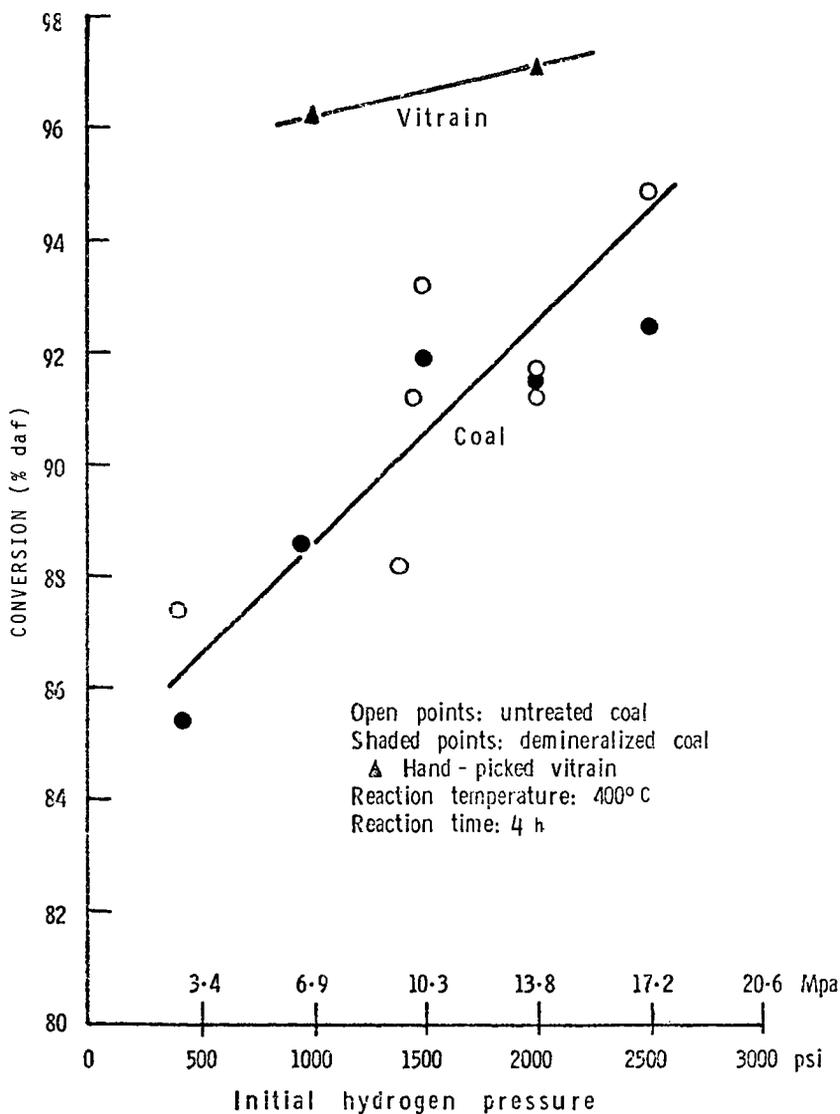


FIG. 3. EFFECT OF HYDROGEN PRESSURE ON CONVERSION OF LIDDELL COAL (13).

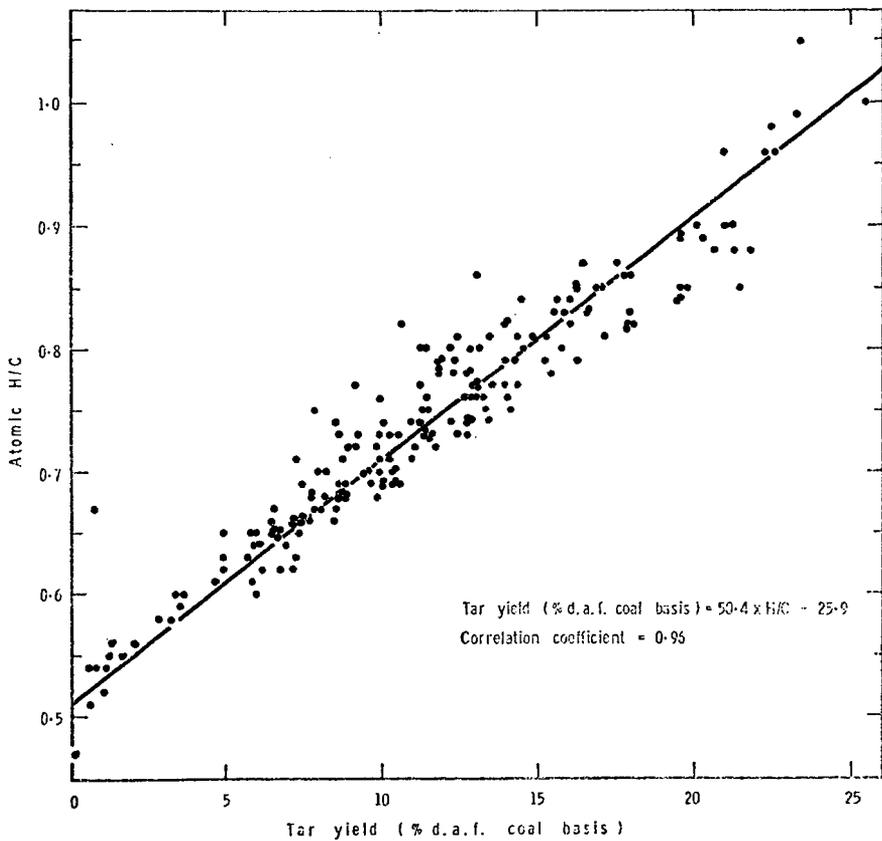


FIG.4 DEPENDENCE OF TAR YIELD, DETERMINED BY LOW-TEMPERATURE GRAY-KING CARBONIZATION ASSAY, ON ATOMIC HYDROGEN-TO-CARBON RATIO FOR A WIDE RANGE OF AUSTRALIAN COALS (14)

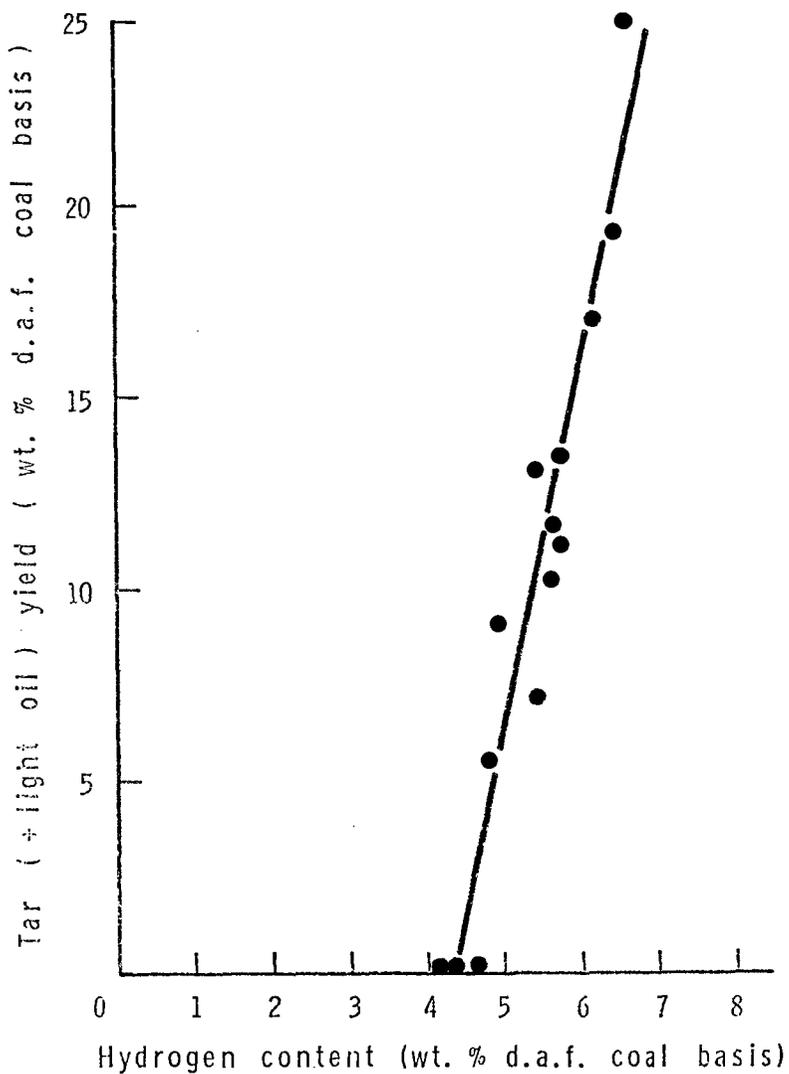


FIG. 5. DEPENDENCE OF TAR YIELDS FROM LOW TEMPERATURE (500°C) FLUIDIZED-BED CARBONIZATION ON HYDROGEN CONTENT FOR SOME AUSTRALIAN COALS (15,16)

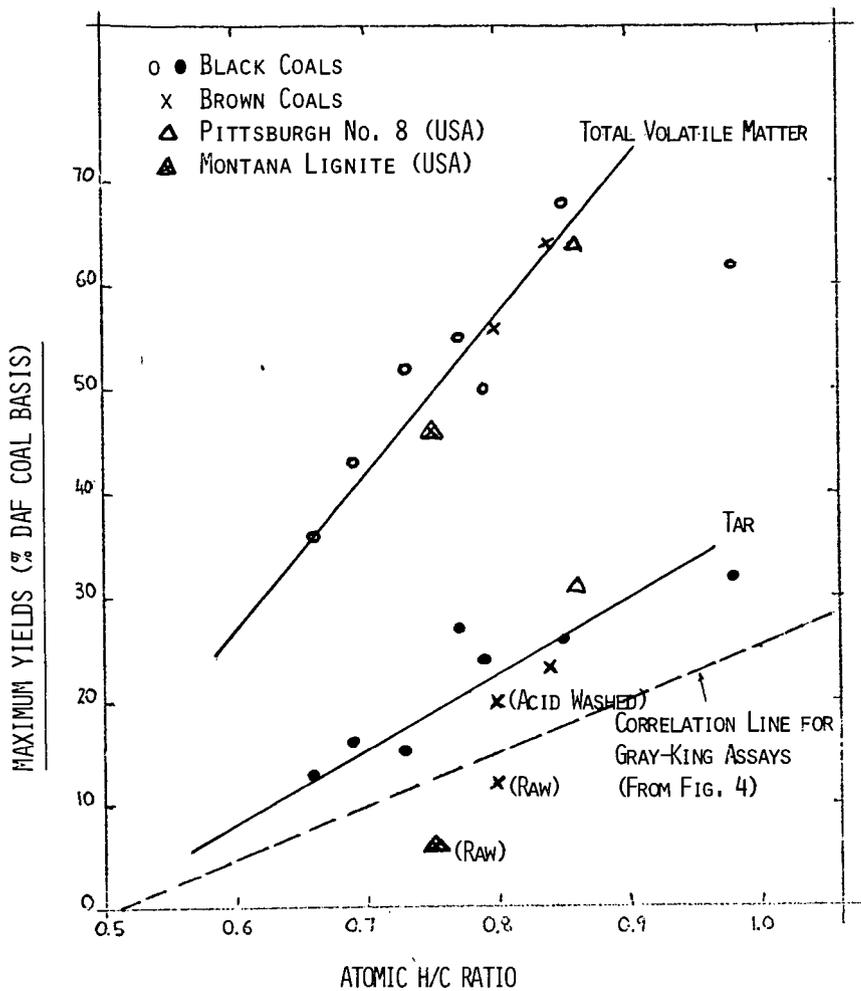


FIG. 6. DEPENDENCE OF MAXIMUM TAR YIELDS AND CORRESPONDING TOTAL VOLATILE MATTER YIELDS DURING FLASH PYROLYSIS ON ATOMIC HYDROGEN-TO-CARBON RATIO FOR SOME AUSTRALIAN AND USA COALS (11,27)

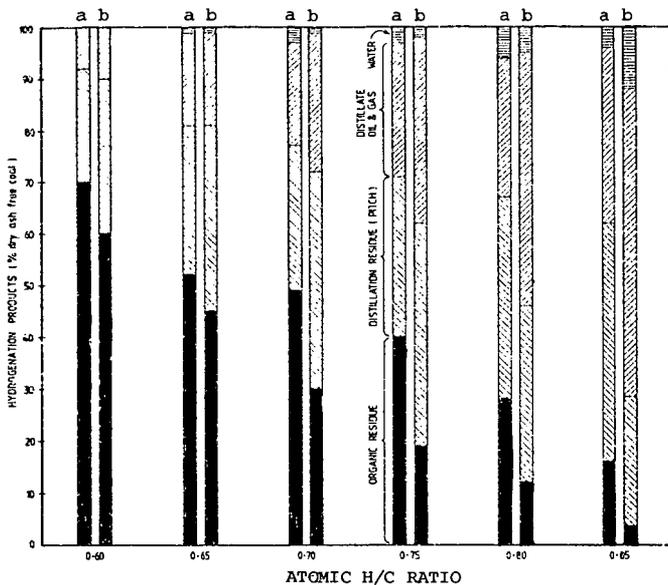


Fig. 7. Dependence of yields of hydrogenation products on the atomic hydrogen-to-carbon ratio.
 (a) Australian coals - non catalytic conditions (10)
 (b) Canadian coals - catalytic conditions (17)

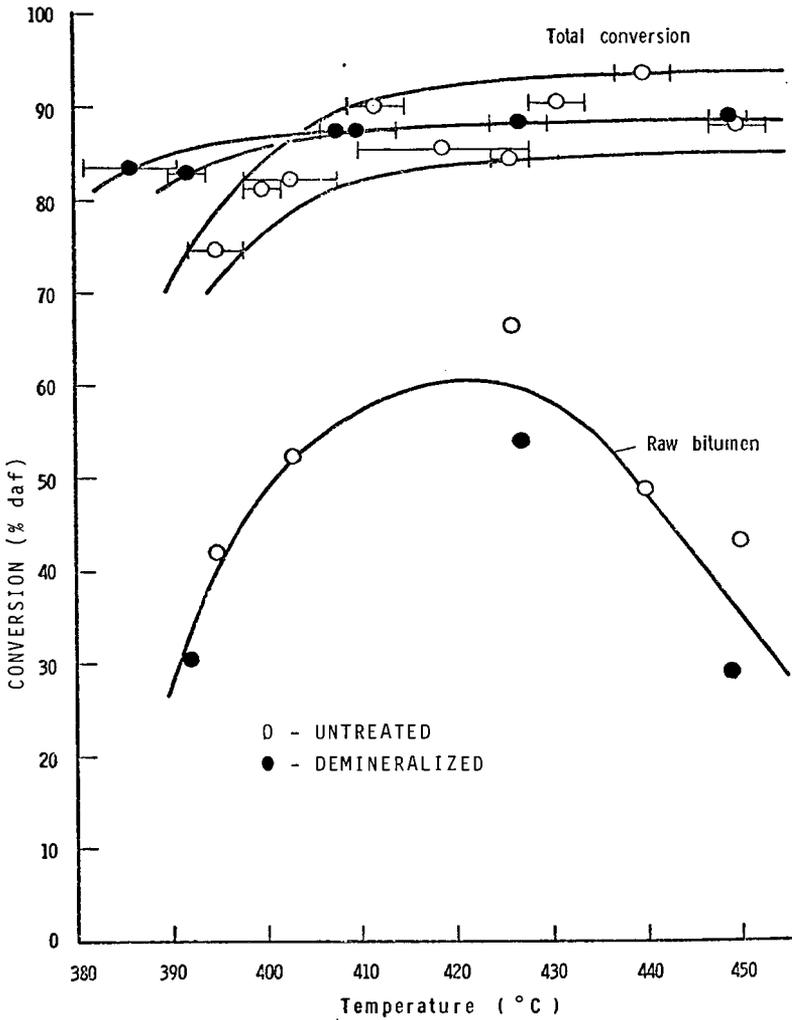


FIG. 8. EFFECT OF TEMPERATURE ON CONVERSION OF UNTREATED AND DEMINERALIZED LIDDELL COAL (13)
 (300 ml autoclave, 6.9 MPa, 4 h)