BROWN COAL INNOVATION AUSTRALIA

Positioning brown coal for a brighter future

Oxygen-Blown Gasification of Victorian Brown Coals

Research and Technology Review

Authors

Daniel G Roberts[1], David J Harris[1], Sankar P Bhattacharya[2]

[1]CSIRO Energy Technology, Brisbane
[2]Monash University Department of Chemical Engineering

August 2014

Report prepared for Brown Coal Innovation Australia

Brown Coal Innovation Australia Limited
Suite 420, 1 Queens Road, Melbourne 3004, Australia
Tel +61 3 9653 9601 | Fax +61 3 9653 9026
Email info@bcinnovation.com.au | ABN 51 141 273 261

BCIA commissions research studies on topics of relevance and interest to its members. In 2013, BCIA commissioned CSIRO and Monash University to undertake a study on Oxygen Blown Gasification of Victorian Brown Coals. The report provided here is the result of that work.

Oxygen-blown gasification of Australian brown coals, particularly the coals found in Victoria, has been identified as a possible future high-efficiency technology route for power generation with integrated CO2 capture, and also for the generation of a range of value-added products (including liquid fuels, hydrogen, fertiliser etc).

Air-blown gasification of Victorian brown coals has been extensively studied from the late 1980s, when integrated gasification combined cycle (IGCC) was acknowledged as the most efficient strategy for the next generation of coal-fired power stations. This work was started by the SECV and has been continued by HRL, the Lignite CRC and Victorian universities. This activity complemented international RD&D activities undertaken by Rheinbraun, RWE, Lurgi, Uhde and others on German brown coals, as well as work on US low rank coals by EERC at the University of North Dakota and Southern Company, and more recent developments in China.

This BCIA member study has been undertaken to identify the opportunities and issues related to oxygen-blown gasification with Victorian brown coal, and to bring together the available information in a single report. It aims to help members to build understanding and achieve confidence in the potential for application of both generic and particular oxygen-blown gasification technologies to Victorian brown coal.

The report provides a technology and an R&D review, and has been informed where possible by interviews with international experts and the main technology vendors. The study examines the use of state-of-the-art oxygen-blown gasifiers in combination with Victorian coals. It identifies coal-specific issues that must be considered in relation to the choice of technologies, and pinpoints areas where there further R&D would be of benefit in advancing the use of such technology in a Victorian context.

BCIA September 2014

CSIRO ENERGY FLAGSHIP
www.csiro.au

Oxygen-Blown Gasification of Victorian Brown Coals

Research and Technology Review

Daniel G Roberts[1], David J Harris[1], Sankar P Bhattacharya[2]

[1]CSIRO Energy Technology, Brisbane
[2]Monash University Department of Chemical Engineering

August 2014

Report prepared for Brown Coal Innovation Australia

MONASH University

BROWN COAL INNOVATION AUSTRALIA

Citation

D G Roberts, D J Harris and S P Bhattacharya. *Oxygen-Blown Gasification of Victorian Brown Coals: Research and Technical Review*. CSIRO Report for Brown Coal Innovation Australia, August 2014.

Copyright and disclaimer

Important disclaimer

Contents

Executive Summary iii

1 Introduction and Background 1

1.1 Context 1

1.2 Scope 2

2 Overview of Gasification Technologies 3

2.1 Fixed Bed Gasifiers 3

2.2 Fluidised Bed Gasifiers 4

2.3 Transport Gasifier 5

2.4 Entrained Flow Gasifiers 6

2.5 Summary: Technology Implications for Victorian Brown Coals to Products 10

3 A Review of Some Recent Gasification Research into Victorian Brown Coals 11

3.1 Introduction 11

3.2 Australian Laboratory-Scale Studies 11

3.3 Bench Scale Fluidised Bed Research at EERC [29] 16

3.4 Pilot-Scale Transport Reactor Research at EERC 18

3.5 Pilot-Scale Studies in a High Temperature Winkler Gasifier (HRL) 23

3.6 Gasification Work by HRL Technology [31, 32] 26

4 Industry Survey 30

4.1 Coal Preparation, Handling and Feeding 30

4.2 Coal Gasification 31

4.3 Syngas Quality Issues 32

4.4 Case Study: Influence of Process Variables on Gasification of Victorian Brown Coals 33

5 Analysis 37

5.1 Issues facing O_2 Blown Gasification of Victorian Brown Coals 37

5.2 Research Gaps and R&D Requirements 38

5.3 Impact of Research Outcomes 42

5.4 Summary 43

6 Conclusions and Recommendations 44

6.1 Victorian Brown Coals to High Value Products 44

6.2 Recommendations 44

References 47

Acknowledgements 51

Appendix 53

Figures

Figure 1: Projected gasification capacity (in MW_{th} of syngas). Data from www.gasification.org (accessed February 2014). 1

Figure 2: International coal gasification capacity and planned growth, by region and product. Data from www.gasification.org (accessed February 2014). 2

Figure 3: (a) The Lurgi FBDB™ fixed-bed, dry-bottom gasifier [2] and (b) the BGL (Envirotherm) slagging gasifier (www.netl.doe.gov, accessed May 2014). 4

Figure 4: Fluidised bed gasifiers - (a) High temperature Winkler type (b) U-Gas type (www.netl.doe.gov, accessed April 2014) 5

Figure 5: Transport Gasifier (www.netl.doe.gov, accessed May 2014). 6

Figure 6: Examples of entrained flow gasifier technologies: (a) Shell, (b) GE, (c) MHI, (d) E-Gas, (e) Siemens [11]. 9

Figure 7: TRDU in the EERC gasification tower 18

Figure 8: Schematic of the filter vessel design with internal refractory, tube sheet, and shroud 21

Figure 9: Schematic of the HTW Process Development Unit [29]. 25

Figure 10: Schematic of the IDGCC process 27

Tables

Table 1: Characteristics of the leading commercial goal gasification technologies [3]. *More recently a down flow variant of this technology has been developed. 7

Table 2: Australian laboratory-scale experimental work at Monash University, Swinburne University, and the University of Adelaide. 14

Table 3: TRDU design and typical actual operating conditions used for US coals. 19

Table 4: Design Criteria and typical actual operating conditions for the pilot-scale HGFV. 20

Table 5: Particle size characteristics for the main gasification technology types (after [6] and [32]). 31

Table 6: Conditions and definitions used as the basis of the equilibrium process modelling discussed in this section. 34

Table 7: Issues matrix for the use of Victorian brown coals in oxygen-blown gasifiers, based on responses received from the international gasification community. 38

Table 8: Coal property impacts on gasifier design and operation [35]. ASU = air separation unit, AGR = acid gas removal unit. 42

Executive Summary

Victorian brown coals represent a significant, low cost energy resource that is traditionally utilised for power generation, albeit with low thermal efficiencies. There is an opportunity to develop a new 'coal to product' industry based on Victorian brown coals, using gasification combined with an appropriate syngas processing technology to produce hydrogen, chemicals, fertilisers, synthetic natural gas, or transport fuels, and/or as the basis of high efficiency power generation with integrated CO_2 capture. Oxygen blown gasification is the enabling technology of choice for all of these applications, yet there is very little research or industry experience in the use of Victorian brown coals in such technologies.

This report provides an overview of the leading gasification technologies in a coal-to-products context, focussing on their application in an oxygen-blown configuration and the important aspects of coal properties and behaviour that make particular feedstocks suitable for particular technologies. This report also gives an overview of the considerable R&D that has been undertaken in recent years on gasification of Victorian brown coal, most of which was performed in support of their use in air blown gasification or oxygen-enriched air blown gasification using fluidised bed gasifiers for efficient, reliable power generation.

There is some international experience with oxygen blown gasification of lignites for non-power applications. For example, the Great Plains Synfuels plant in the US gasifies lignite using oxygen-blown fixed bed gasifiers producing about 153 million cubic feet of synthetic natural gas each year, as well as CO_2 which is sent to EOR applications in Canada. Current expansion of the facility to produce 1,100 tpd of urea will be completed by 2017. Many of the hundreds of gasifiers operating in China are used to convert lignite to high value products such as methanol, fertilisers, chemicals, or synthetic natural gas. Particular challenges for the use of Victorian brown coal in similar applications arise from its unique set of properties and the lack of industrial experience or research supporting its use in oxygen-blown gasification systems.

A survey of international gasification industry and research experts undertaken as part of this work reiterated the significance of the unique properties of Victorian brown coal, suggesting that whilst international experience demonstrates that lignite-based coal-to-product projects are feasible, specific knowledge about the feedstock is required in order to be able to understand and manage a wide range of potential issues.

There were two underlying themes to their responses: the likelihood of increased temperatures arising from O_2 blown gasification (either locally in fluidised beds or overall in the case of slagging gasifiers) and the impact this might have on alkali release, gas cleanup, materials selection, mineral matter behaviour, and conversion performance; and the reduced overall gasifier and syngas volume, which has impacts on pre drying performance, fluidisation and transport, and gasifier design.

The responses also suggested that alternative technologies such as entrained flow, transport, or fixed bed gasifiers may be more suitable than fluidised beds for oxygen-blown gasification for coal-to-products applications. This introduces technology-specific issues which have not been considered for Victorian brown coals, such as fine particle behaviour at high temperatures and pressures, the ability of Victorian brown coals to form stable and tappable slags, the ability of Victorian brown coals and their chars to maintain a structurally sound and permeable fixed bed. There is also the potential for considering the use of Victorian brown coals in novel, non-slagging entrained flow gasifiers, although such technologies are not commercially deployed at industrial scales.

Given the air-blown (or oxygen-enhanced), power generation focus of previous gasification studies using Victorian brown coal, and the range of potential issues that may be faced in their use in oxygen-blown coal-to-products systems, this report has recommended some areas for coordinated, focused research in support of a coal-to-products industry in Victoria. These include:

- Coordinated R&D to develop a clear understanding of the gasification fundamentals of Victorian brown coals, generating transportable data that can be used to assess their suitability for a range of possible technologies including entrained flow, transport and fixed bed gasifiers. This should build on the fundamental work that has already been undertaken on these coals, by recognising that these technologies can utilise much wider ranges of particle size, temperature, pressure, and residence time than those usually considered for fluidised bed gasification.
- Coordinated R&D to provide insights into mineralogy and inorganic species transformation at higher temperatures than those experienced in fluidised bed applications, in particular addressing the release of alkalis, and to develop materials and technology solutions to their management. Particular emphasis here is on the role of higher temperatures potentially arising from O_2-blown gasification, and the possibility that Victorian brown coals will need to form stable, tappable slags.
- Considering the merit of a 'dry ash oxygen-blown entrained flow gasifier', in the context of the outcomes of the research activities recommended above. This would need to be based on a cost–benefit analysis based on some coal-specific gasification and process modelling work that incorporated aspects of coal conversion and mineral matter behaviour.

As well as building on existing work undertaken on Victorian brown coal gasification, these programs and research activities should build on the research undertaken in support of Australian bituminous coals in a range of gasification technologies. That work developed techniques and tools that are readily applicable to the assessment of Victorian brown coals for use in alternative technologies; they will be valuable in addressing many of the issues identified which are specific to Victorian brown coals. Similarly, any future work program needs to appropriately engage with international RD&D in this area. Research programs in Germany and the US, for example, are supporting their own modelling, pilot- and demonstration-scale research with collaborative fundamental studies, and links with Korean and Japanese applied research institutions offer access to pilot-scale facilities not readily available in Australia. To achieve research and demonstration outcomes in a timely fashion, engagement and collaboration with these groups (and others) will be required.

Clearly, international experience suggests that gasification of lignites for coal-to-products applications in Australia is technically feasible, given an adequate understanding of the performance of Victorian brown coals in oxygen blown gasification systems.

1 Introduction and Background

1.1 Context

Victorian brown coals represent a significant, low cost energy resource that is traditionally utilised for power generation with relatively low efficiencies. There is renewed interest in the assessment and development of alternative utilisation strategies for this vast resource. The low cost of Victorian brown coals and the international experience in gasification of low rank coals has seen much of this interest focus on their conversion via gasification to liquid fuels, hydrogen, and chemicals.

There is considerable international experience with coal gasification for chemicals and liquid fuels production, in particular in China and South Africa. World coal gasification capacity is projected to grow by up to 120% in the period 2013–2016, and increase by 250% out to 2020 [1]. Much of this growth will be in the gasification of coal to produce chemicals, fertilisers, gaseous and liquid fuels (Figure 1) and is largely due to the reliance of China on coal gasification as an energy feedstock (Figure 2). Feedstocks for this growth in gasification include anthracitic, bituminous, sub-bituminous and lignitic coals, as well as industrial waste streams such as petroleum cokes and various biomass materials.

Almost all of these coal-to-products systems are based on oxygen-blown gasification, where O_2 and steam are used as the gasifying agents. Whilst many first-generation integrated gasification combined cycle (IGCC) power generation plants used air-blown gasification for reliability, capital cost and efficiency reasons, oxygen blown gasification is now favoured for power generation applications incorporating CO_2 capture due to the favourable capital and operating cost impacts on downstream gas processing.

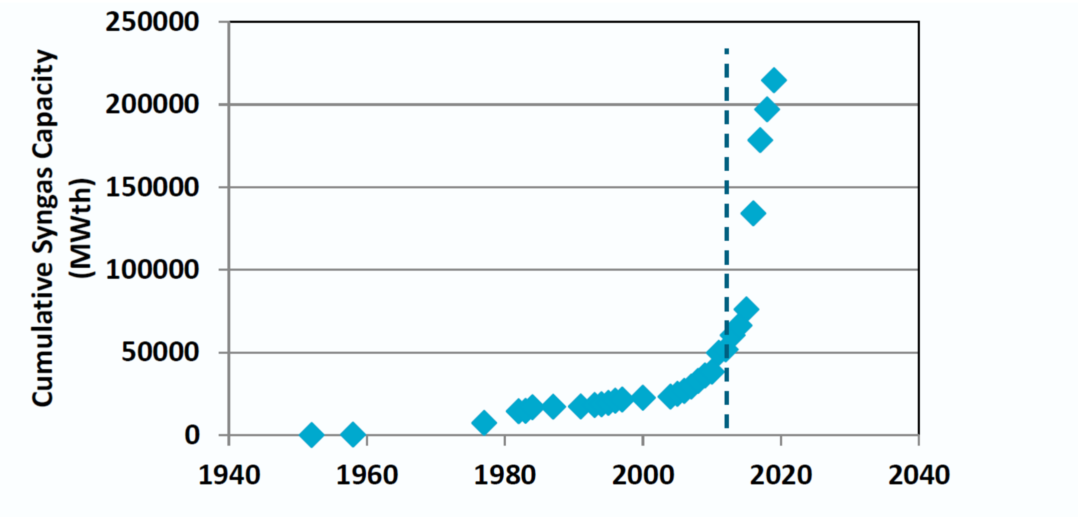

Figure 1: Projected gasification capacity (in MW_{th} of syngas). Data from www.gasification.org (accessed February 2014).

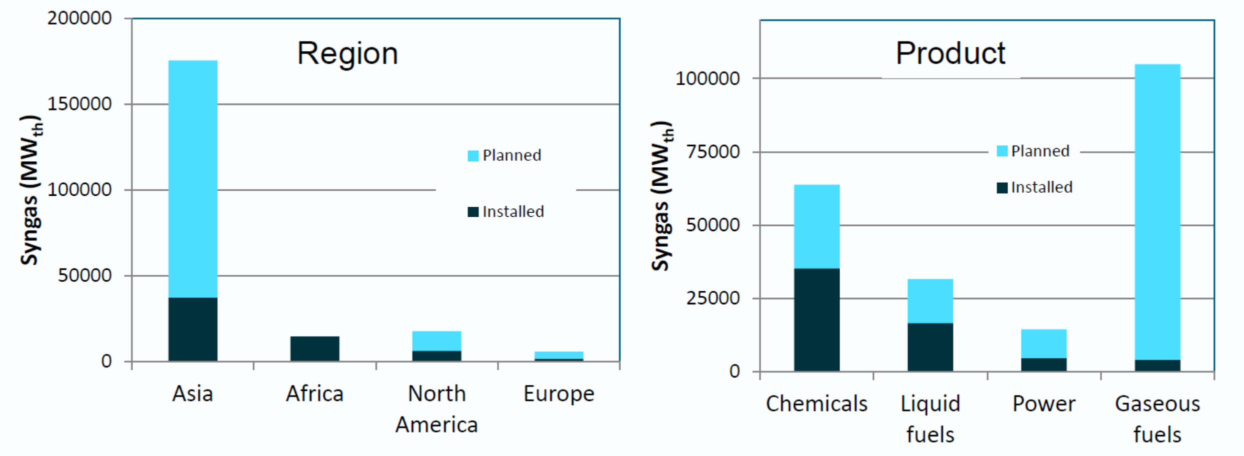

Figure 2: International coal gasification capacity and planned growth, by region and product. Data from www.gasification.org (accessed February 2014).

Air-blown gasification of Victorian Brown coals has been extensively studied from the late 1980s, when IGCC without CO_2 capture was identified as the most efficient strategy for the next generation of coal-fired power stations. This work was started by the SECV and has been continued by HRL, the CRC for Clean Power from Lignite, and Victorian universities (detailed in Section 3). This activity complemented international RD&D activities undertaken by Rheinbraun, RWE, Lurgi, Uhde and others on German brown coals, as well as work on US low rank coals by EERC at the University of North Dakota and Southern Company, and more recent developments in China.

It is likely that any viable proposal for the conversion of Victorian brown coals to hydrogen, chemicals, or liquid fuels will be based on an oxygen-blown gasification technology. The study of oxygen-blown gasification in relation to Victorian brown coals has not been as extensive as the studies of air-blown gasification. Our understanding of the combustion and gasification behaviour of these coals can provide us with some insights into the issues that may be expected under oxygen blown gasification conditions, and there is international experience with the oxygen blown gasification of lignites and other low rank coals that is relevant. However, the unique nature of Victorian brown coals (moisture content in particular) means that there remains considerable uncertainty as to the potential issues that may be experienced with their use in coal-to-products systems, and consequently the research requirements to support the development of new projects.

This report reviews the state of the art in terms of research and practical experience of oxygen blown gasification of lignites and Victorian brown coals, considering some of the key technology aspects of oxygen-blown gasification that may be important in the Victorian brown coal case, and provides some recommendations into the research and development activities that are required to support the deployment of gasification-based systems for the conversion of Victorian brown coals to high value products. Importantly, this work draws on relevant international experience as well as reviews of the scientific and technical literature, and the outcomes have been developed in consultation with leading international gasification experts.

1.2 Scope

This report focuses on the use of brown coals in oxygen blown gasification technologies, and specifically on issues that are expected to arise compared with their use in air blown systems. It considers these issues and provides some recommendations into R&D needs that could support the development of a Victorian brown coal to products industry in Australia. It is not the intention of this work to discuss all issues associated with gasification of Victorian brown coals; there is a significant body of work in that regard and many of the basic issues are reasonably well understood.

2 Overview of Gasification Technologies

Gasification is a flexible coal utilisation technology used as the basis for production of chemicals, liquid fuels, fertilisers, explosives and electricity around the world. Gasification converts coal to a syngas, which is predominately a mixture of carbon monoxide and hydrogen. Syngas is a precursor to a wide range of energy and chemical products: it can be combusted in a combined cycle turbine system for efficient production of electricity, fed into a Fischer-Tropsch plant for the production of liquid fuels, reformed to methane to provide synthetic natural gas (SNG), converted to methanol and used to produce gasoline, or used as a precursor for the production of a range of fertilisers, explosives and other chemicals. Most of these downstream processes are based on technologies that have long histories of development and improvement, requiring very little R&D to support their implementation into coal-to-products processes. This report will focus on the gasification aspect of these processes, the success of which depends strongly on coal properties and how they interact with the design features of gasifiers.

Gasification is suitable for a wide range of feedstocks, from waste streams and biomass materials to coals of all rank and quality. The variability in the properties of these feedstocks and the different requirements of the downstream processes mean that there is a range of gasification technologies, each variant having particular requirements in terms of feedstock properties and producing syngas of varying quality and composition. Of relevance to this report are the implications associated with the use of oxygen, rather than air, as a gasifying agent, and the technology features that have been developed in response to the different drivers for these: air is commonly used where cost-effective, reliable electricity is the product; oxygen is commonly used for the production of liquid fuels and chemicals.

This section gives an overview of the main technologies in use around the world, and provides some context for the traditional approaches to gasification of Victorian brown coal for power generation, and the likely implications of a shift towards gasification of these materials for the production of liquid fuels, chemicals, hydrogen, and others.

2.1 Fixed Bed Gasifiers

Fixed bed gasifiers operate in a manner similar to blast furnaces, where lump coal is fed from the top and air or oxygen (and therefore heat from partial combustion) is supplied from the bottom. Solids residence times are high (1–2 hours) and coal mineral matter is removed either dry (as in the Lurgi FBDB™ gasifier) or as a slag (as in the slagging BGL/Envirotherm technology). Dry-ash fixed beds usually have a rotating grate system at the bottom of the bed to facilitate removal of the ash. There are no moving parts at the bottom of the BGL gasifiers. These characteristics mean that fixed bed gasifiers are relatively easy to operate but have high maintenance requirements: this is why fixed-bed gasifier installations typically have two or more gasifiers (at least one idled for maintenance) as part of the operations. The Lurgi FBDB™ Mk Plus™ gasifier is the most recent offering from this technology suite, operating at higher pressures (up to 60 bar) and with greater throughputs.

Fixed-bed gasifiers have specific requirements of coal properties: structural stability of the slowly moving bed of coal and char is important, as is the ability for gas to permeate uniformly through the coal and char bed. The formation of fines, therefore, is not favourable as they reduce this permeability significantly. These gasifiers have relatively low throughput per unit, somewhat low degree of fuel flexibility and the tendency for the syngas to contain relatively high levels of methane, liquor, and tars. This makes them generally better suited to specific applications such SNG production than for large scale FT or IGCC power generation applications. Considerable scale and reliability, however, can be achieved through the use of banks of many gasifiers, such as the Sasol plant in South Africa which uses more than 80 Lurgi gasifiers in a parallel configuration.

Fixed bed gasifiers can be attractive for high moisture coals because the coal is dewatered and heated by the hot gas moving counter currently with the downward moving lump coal, resulting in low oxygen consumption. However, the use of lump coal immediately poses the problem of what to do with the fines that are usually present. Furthermore, the dirty gases leave the gasifier at temperatures below 500°C. This relatively low temperature and the presence of tars and liquor means that waste heat boilers (syngas coolers) cannot be used.

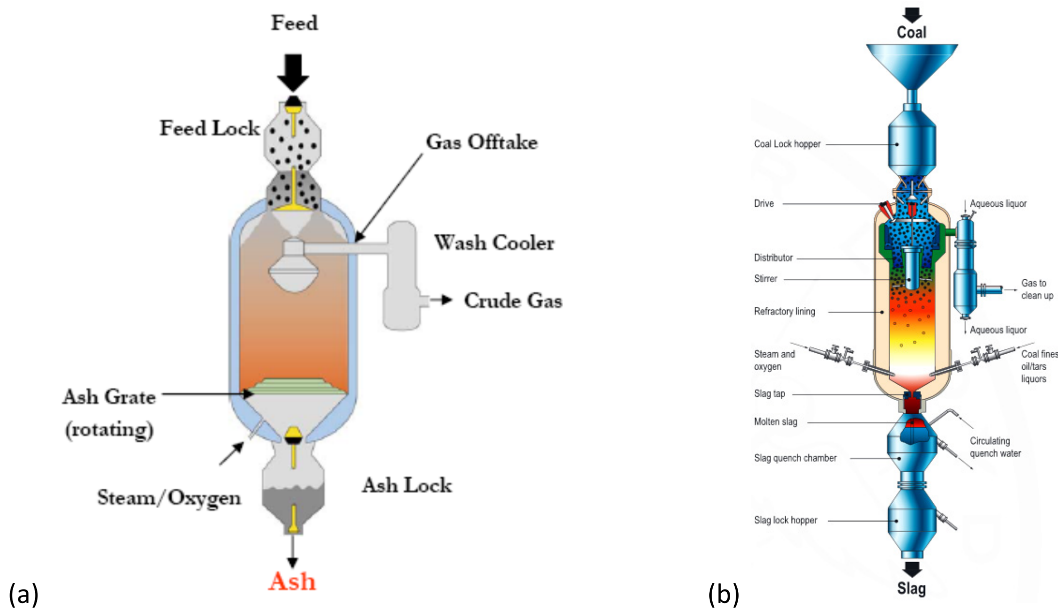

Figure 3: (a) The Lurgi FBDB™ fixed-bed, dry-bottom gasifier [2] and (b) the BGL (Envirotherm) slagging gasifier (www.netl.doe.gov, accessed May 2014).

The Great Plains Synfuels plant in the US gasifies lignite in an oxygen-blown dry-bottom fixed bed Lurgi gasifier producing about 153 million cubic feet of synthetic natural gas each year, as well as CO_2 which is sent to EOR applications in Canada. Current expansion of the facility to produce 1,100 tpd of urea will be completed by 2017, demonstrating the success of the operation as well as the flexibility afforded by gasification-based systems to respond to market changes. The Vresova IGCC plant in Czech Republic gasifies approximately 2000 tonnes per day of lignite, also using Lurgi fixed-bed dry-bottom gasifiers, to produce power in an IGCC configuration. Clearly lignites can be successfully gasified in fixed-bed technologies, provided that an adequate understanding of their structural and fragmentation properties shows them to be suitable.

2.2 Fluidised Bed Gasifiers

Fluidised bed gasifiers require coarse (1–10 mm) and dry coal (or biomass) particles in a bed fluidised by air or oxygen and steam. To minimise agglomeration and prevent defluidisation of the bed, operating temperature is usually kept below the ash softening temperature which for most coals is around 1000°C. The gasifiers are known to operate at atmospheric or higher pressures.

There are two variants of fluidised bed gasifiers that have been commercialised: High Temperature Winkler (HTW) and U-Gas gasifiers. The HTW gasifier is a circulating fluidised bed gasifier operating at 3–5 m/sec fluidisation velocity and pressure up to 30 bar. A mix of incoming feed, partially converted coal and dry ash constantly circulates inside the bed maintaining a constant temperature in the bed. To keep the bed fluidised and minimise agglomerates, a part of the mix is also constantly discharged from the bed. This discharge from the bed and low operating temperature also results in low carbon conversion (80-90%) in the gasifier. While Rhinebraun AG (now RWE) developed the process in 1926, ThyssenKrupp Uhde acquired the HTW technology in 2010.

The U-Gas gasifier is also a circulating fluidised bed gasifier, but with air/O_2 and steam injection at the conical bottom to improve the carbon conversion to about 95%. It can operate up to 1100°C, and large agglomerated ash is discharged from the bottom of the gasifier. The U-Gas gasifier was developed by the Gas Technology Institute in Chicago, while commercial licensing rights were acquired by Synthesis Energy Systems. As of 2013, three plants are known to be in operation at Hennan, Shandong and Inner Mongolia in China, all for chemicals production.

In air-blown mode, fluidised bed gasifiers are known to produce low-calorific value fuel gas (around 5 MJ/kg), while oxygen-blown mode operation will result in medium calorific value fuel gas.

Because of lower operating temperature, fluidised bed gasifiers are inherently more suited for reactive coals, such as brown coal. However, low carbon conversion does remain a problem due to low operating temperature.

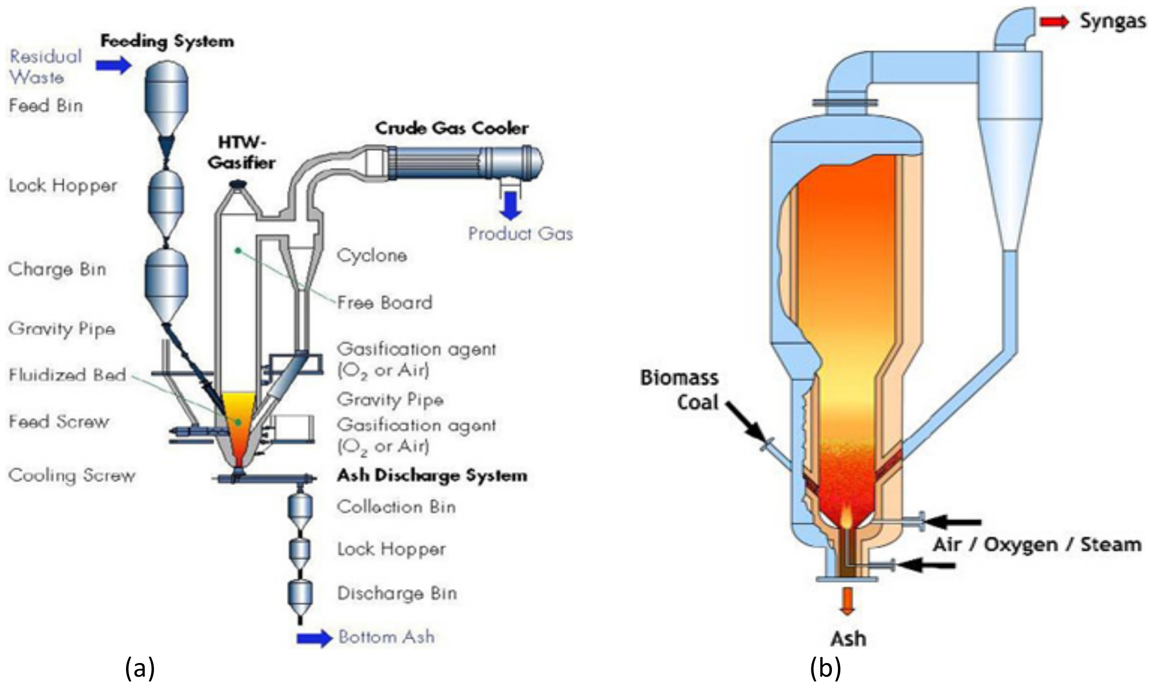

Figure 4: Fluidised bed gasifiers - (a) High temperature Winkler type (b) U-Gas type (www.netl.doe.gov, accessed April 2014)

2.3 Transport Gasifier

The transport gasifier (Figure 5) is also a circulating fluidised bed gasifier, but operates at higher velocity than HTW gasifier promoting better mixing between the coal and the reactants. The main body of the gasifier has two sections, a larger-diameter mixing zone, on the bottom, and a smaller-diameter riser section, on the top. The larger diameter of the mixing zone lowers gas velocity promoting solids mixing and consequently increasing solids retention time and therefore carbon conversion.

The transport gasifier can handle lower feed particle size compared to HTW gasifiers. Air or O_2 and steam addition at the bottom of the larger diameter mixing zone also improves carbon conversion. Due to low operating temperatures, the transport gasifier is also inherently more suited for reactive coals, such as brown coals and lignites.

The operating temperature of the transport gasifier is under 1000°C. Therefore calorific value of fuel gas produced is similar to that from fluidised bed gasifiers.

The transport gasifier technology has been developed by Kellog, Brown and Root (KBR) and Southern Company at the Power System Development Facility (PSDF) at Wilsonville, Alabama and the EERC at the University of North Dakota. This has formed the basis for the 582 MW Transport Reactor Integrated Gasification (TRIG) powered IGCC plant at Kemper county in Mississippi, due for start-up in late 2014. The gasifier will operate in air-blown mode for the production of power and fertiliser, as well as CO_2 for enhanced oil recovery. Designs are known to be available for oxygen-blown operation. Another plant is known to be under negotiation for construction in Dongguan, China.

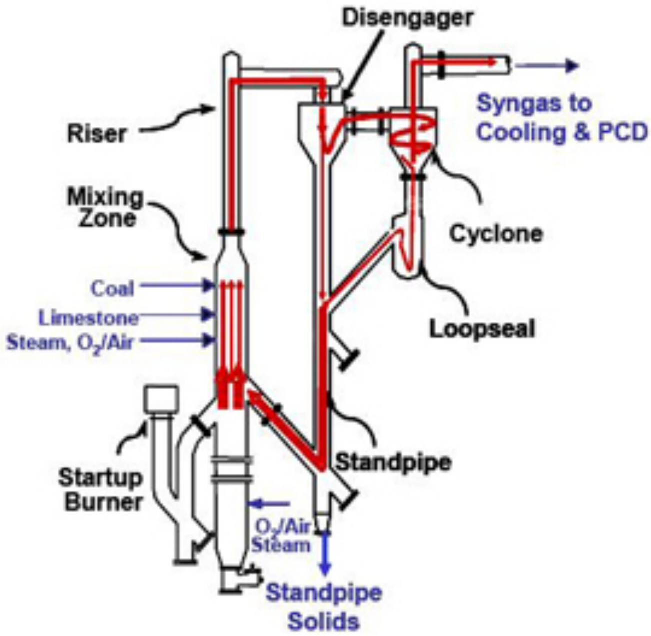

Figure 5: Transport Gasifier (www.netl.doe.gov, accessed May 2014).

2.4 Entrained Flow Gasifiers

Entrained flow gasifiers require pulverised coal at high pressures into a gasifier where temperatures and pressures are high (up to, and possibly over 1800–2000 K and 2.0–4.0 MPa) and residence times are low (usually less than 5 seconds). Due to these intense reaction conditions, entrained flow gasifiers offer high throughput and conversion for a wide range of feedstocks, making them the most common gasification technology for large-scale IGCC and coal-to-products applications (Table 1). Some example schematics of common entrained flow gasifiers are given in Figure 6.

The available commercial entrained flow gasification technologies are differentiated by particular combinations of feeding method and oxidant type, gasifier configuration, construction material, and mode of syngas quench. The impacts of these variations on fuel requirements and syngas quality (and therefore suitability for downstream applications) means that most technology vendors are continually exploring variants to their gasifier design and syngas processing configuration. For example, Shell now offers a partial quench system and Siemens are developing a radiant syngas cooler configuration to suit specific applications.

Technology	Stages	Oxidant	Feed	Configuration	Gasifier Wall
Shell, PRENFLO	1	O_2	Dry	Up-flow*	Water-wall
GE	1	O_2	Slurry	Down-flow	Refractory
CB&I E-Gas	2	O_2	Slurry	Up-flow	Refractory
MHI	2	Air	Dry	Up-flow	Refractory & Water-wall
Siemens	1	O_2	Dry	Down-flow	Water-wall

Table 1: Characteristics of the leading commercial goal gasification technologies [3]. *More recently a down flow variant of this technology has been developed.

Slurry-fed gasifiers (such as the GE and E-gas gasifiers) overcome issues associated with feeding powdered solids into pressure vessels and can operate at very high pressures; however, the increased reliability and decreased capital cost comes at the expense of a greater oxygen demand due to the increased thermal load. Refractory-lined slagging gasifiers (such as GE, E-Gas) are sensitive to the quality and quantity of the ash and slag, and are more susceptible to ceramic liner erosion and corrosion than water-wall (or membrane-lined) gasifiers. Membrane walled gasifiers (such as Shell and Siemens) require a protective slag layer to form, which is strongly dependent on the properties of the coal used.

Two-stage gasifiers (such as the MHI and E-Gas gasifiers) have two coal injection points: one in the 'combustion' stage, where heat is generated to melt the mineral matter and to drive the gasification reactions, and one in the second stage, where coal and char is 'gasified' using the heat and gaseous products from the combustion stage. The second stage also serves as a 'chemical quench', whereby the progress of the gasification reactions partially cools the syngas and stores this heat as chemical energy in the syngas. They consequently have greater cold gas efficiencies than single-stage gasifiers; however, this can be offset by higher rates of unconverted carbon and the possible production of some tar species (two-stage gasifiers often have a char recycling capability, which increases the total carbon conversion but also increases the capital cost).

Most entrained flow gasifiers are oxygen-blown, as the presence of significant amounts of N_2 is detrimental to the downstream chemicals and liquid fuels production processes for which most of these gasifiers were designed. Furthermore, for gasification-based IGCC power plants which are designed for integrated carbon capture and storage, oxygen blown systems are favoured for similar reasons. In oxygen-blown gasification, air is separated in an air-separation unit (ASU) and high purity O_2 (usually over 99%) is used as the oxidant, usually with steam to manage the temperature and enhance the production of syngas. There are significant capital and operating costs associated with operating an air-separation unit: the ASU can comprise up to 15% of the capital cost of an IGCC plant, and consume up to 20% of the power generated [4].

It is not common for air-blown gasifiers to be used in chemical and liquid fuel production processes. Air blown gasifiers are typically used in applications were lower cost is important, such as some IGCC applications. (The Nakoso IGCC plant in Japan, for example, was designed for high-efficiency power generation and was not initially designed for use with integrated carbon capture [5].) The greater gas volumes associated with air-blown gasification are significant: gasifiers must be larger, and downstream syngas cooling and cleaning plant must also be larger [6]. For IGCC applications, therefore, there is a trade-off between capital cost and operating cost and reliability.

The need for higher efficiencies and lower cost for gasification systems, particularly for application in the power generation sector, is driving new initiatives in gasifier design. Several new technology variants have emerged in recent years and these are at various stages of development and commercialisation. Some of the leading examples are indicated below.

Aerojet Rocketdyne is developing a high intensity, compact gasification technology aimed at significantly reducing the size and cost of commercial scale gasification systems. The technology builds on their rocket engine experience and comprises a high pressure dense phase dry feed system with rapid mixing via multiple fuel injectors. The gasification reactions proceed in a high velocity plug flow tubular reaction zone with advanced gasifier wall cooling system. The technology is currently undergoing pilot scale testing using an 18 ton/day test facility at the Gas Technology Institute at Des Plaines, Illinois while the high pressure dry solids feed pump is undergoing testing at the EERC at the University of North Dakota. Performance and design targets include 90% reduction in size and up to 50% reduction in cost of the gasifier unit [7].

There are several commercial scale gasification technology variants now reaching demonstration scale in China and these are expected to be deployed in future coal to chemicals and liquid fuels plants which are undergoing strong growth in that region [8]. The most mature of these is the 'Opposed Multi-Burner' (OMB) gasifier developed by the Institute of Clean Coal Technology (ICCT) at the East China University of Science and Technology [9]. This gasifier uses a coal-water slurry feed which is injected through four opposed fired burners at the top of the down-flow gasifier unit. A dry-fed variant is also under development. The gasifier also uses an internal water quench system which simplifies slag removal and gas cleanup. The Huaneng Clean Energy Research Institute (HCERI), formerly the Thermal Power Research Institute (TPRI), have developed a 2-stage up-flow entrained flow gasifier which is part of the Chinese Greengen project. Phase 1 of this project is now underway and plans include operation of a 400 MW IGCC demonstration project in 2015 [10].

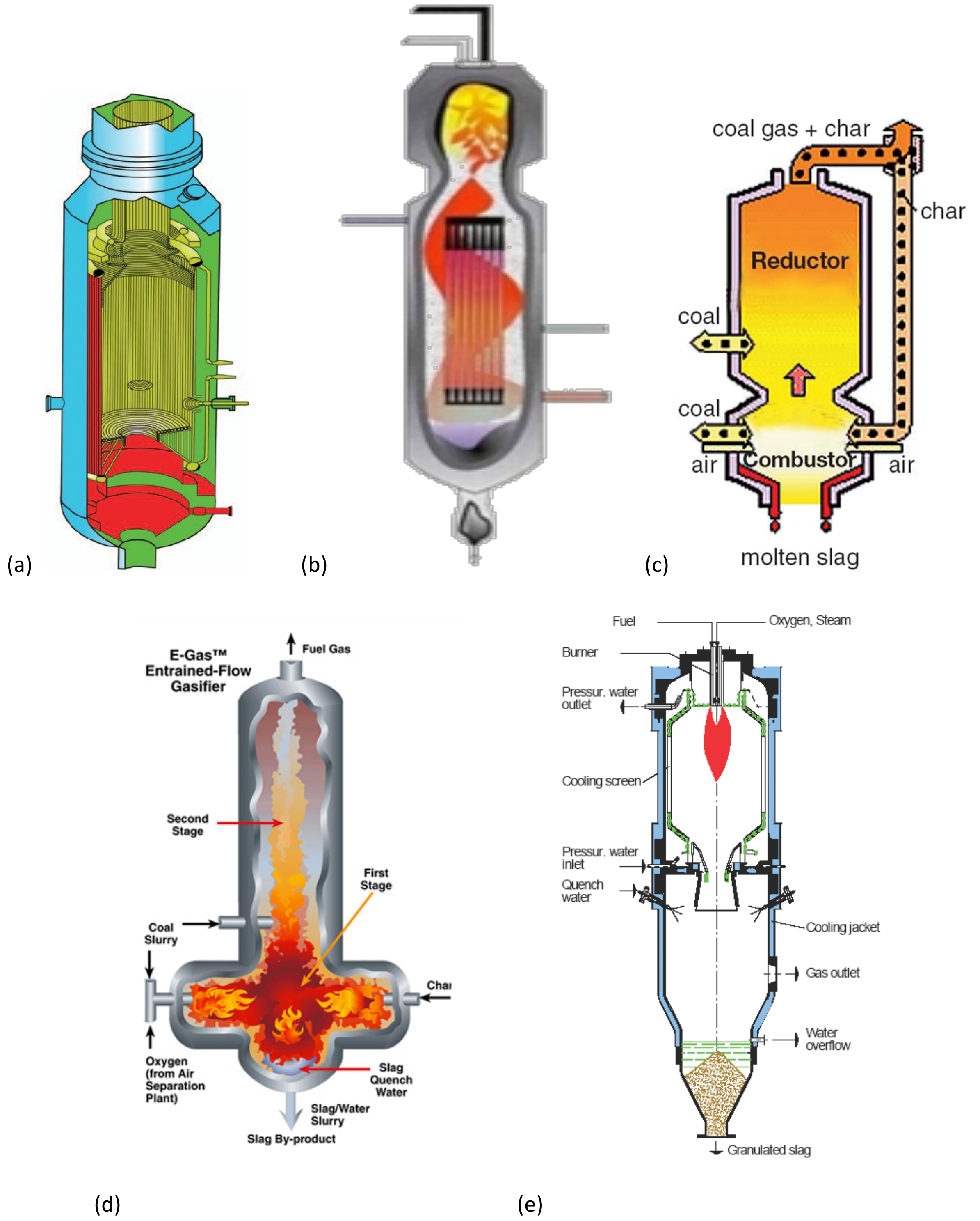

Figure 6: Examples of entrained flow gasifier technologies: (a) Shell, (b) GE, (c) MHI, (d) E-Gas, (e) Siemens [11].

2.5 Summary: Technology Implications for Victorian Brown Coals to Products

It is clear that there is a wide range of gasification technologies, in part as a response to the variety of feedstocks that are used in gasification applications and also due to the range of applications of the syngas produced. In terms of lignite gasification, fluidised beds are the most common technology type in use, with modern variants (such as the transport gasifier) designed to overcome some of the traditional issues associated with their use with lignite feedstocks (discussed in more detail in the next Section). There are also some successful large-scale applications of lignite gasification in dry-bottom fixed-bed gasifiers for the production of power and synfuels, and a rapidly increasing capacity of lignite use as feedstocks for fixed bed and entrained flow gasifiers in China for the production of chemicals.

For large-scale coal-to-products applications, there are considerable benefits from the use of oxygen blown as opposed to air-blown gasification. For projects using many bituminous and sub-bituminous coals the use of an air-blown entrained flow gasifier is supported by relevant industry and research experience, with only some specialised supporting work required to facilitate appropriate design and operating parameters. The same is true for lignite use in fixed bed gasifiers: the selection of a fixed-bed technology for the lignite-based projects mentioned in this section would have relied on a good understanding of the relevant properties of the feedstock, and therefore their suitability for use in a fixed bed system.

As we will see in the next Section, Victorian brown coals do not have this degree of industry and research experience for their use in entrained flow or fixed bed gasifiers. Furthermore, the technologies in which they are well-studied (air-blown bubbling fluidised beds) are not commonly used in an oxygen blown configuration for the production of fuels and chemicals, with most of the work being done in the context of reliable, high efficiency power generation (e.g see [12]).

There is considerable uncertainty, therefore, in the most appropriate technologies for gasification of Victorian brown coals under oxygen-blown conditions in coal-to-products applications. The next section will review some of the considerable research that has been undertaken into gasification of Victorian brown coals, which will be followed by some international industry and researcher insights into the issues faced by the Victorian brown coal industry in considering the potential for a Victorian brown coal-based coal-to-products industry.

3 A Review of Some Recent Gasification Research into Victorian Brown Coals

3.1 Introduction

Between 1994 and 2006, the CRC for Clean Power from Lignite carried out a considerable amount of research on pyrolysis and gasification of Victorian brown coals and South Australian lignites. The work involved both modelling and experimental work at laboratory and pilot plant scale at facilities of the CRC partners (Monash University, University of Adelaide and CSIRO) and external collaborators (HRL Limited and the Energy and Environmental Research Centre (EERC) at the University of North Dakota, USA). Most of the experimental work was carried out at low temperatures, up to 900°C, relevant to the fluidised bed or transport reactor pyrolyser or gasifier.

This section summarises some of this important work and its major findings. It is by no means intended to be a complete scientific review of all the available literature into the science of Victorian brown coal gasification (a good place to start for such information is [13]). Rather, the intention is to demonstrate the breadth and nature of the research that has been undertaken into gasification of Victorian brown coals, within the context of the scope of this report.

3.2 Australian Laboratory-Scale Studies

Considerable laboratory-scale experimental work of brown coal gasification was carried out at Monash University, the University of Adelaide, and Swinburne University of Technology, some of which has continued since the CRC was completed at Curtin University of Technology. These studies mainly focused on assessing alkali and alkaline earth metal (AAEM) emissions and their catalytic effects during pyrolysis and gasification of Victorian brown coals and South Australian lignites. Table 2 gives an overview of this work. Some highlights from the work are discussed in this section, noting that the experimental conditions used make many of the outcomes difficult to apply to O_2-blown gasification conditions.

Recent work at Monash University has included for the first time reactivity, gas evolution and ash viscosity studies during oxygen-blown entrained flow gasification of Victorian brown coal, Chinese lignites and Rhenish brown coal. Three such projects, funded through Brown Coal Innovation Australia (BCIA), have collaborative links with German universities (Karlsruhe), German research institute (Forschungszentrum Juelich GmbH) and industry (Mitsubishi Heavy Industries). A fourth project, also funded by BCIA, extends the entrained flow gasification work to catalytic synthesis of fuel gas to liquid fuel (dimethyl ether). These works include experimental and modelling based on a new atmospheric pressure entrained flow reactor (capable of working to 1600°C) built at Monash University.

This work is complementary to high pressure entrained flow studies of German lignite gasification being undertaken by CSIRO in Brisbane. This work [14-16] is being undertaken in collaboration with the Technical University Bergakademie Freiberg.

3.2.1 AAEM SPECIES DURING COAL PYROLYSIS AND GASIFICATION

The volatilisation of sodium (and other alkali and alkali earth metal—AAEM—species) during pyrolysis was extensively studied during the CRC program and beyond (e.g. see [17, 18] and the many subsequent references). During the gasification of coal at conditions characteristic of a fluid bed process, the sodium species formed will depend on the initial form of sodium present in coal, on gas atmosphere and on the initial forms of silicon present in coal. This dependence on the gas atmosphere is particularly apparent for organically bound sodium, with CO_2 atmosphere favouring the formation of sodium carbonate (Na_2CO_3) although oxygen levels and temperature–time histories make the ultimate fate of sodium complex.

The release behaviour of sodium is temperature- and heating rate-dependent. Under fast heating conditions, the volatilisation of sodium from raw and NaCl-loaded coal samples increased monotonically until almost total volatilisation occurred at 900°C. Under slow heating rate conditions, the volatilisation of Na from raw coal also increased monotonically although <20% of the total sodium was volatilised at 900°C. Sodium and chlorine did not show evidence of volatilisation together as NaCl molecules, as they show different trends in their volatilisation during pyrolysis.

The volatilisation of chlorine is highly dependent on temperature, starting as low as 200°C, and its behaviour is complex: for example, at temperatures higher than 600°C, it can interact with and be restablised in the char formed. Sodium bonded to the coal as carboxylates is less easily volatilised than sodium present as NaCl in the coal. The monovalent AAEM species (sodium) is more easily volatilised than the divalent species (Ca and Mg) when they all exist as carboxylates in brown coal. The volatilisation of the AAEM species as simple carboxylates may be an important mechanism for the release of the AAEM species from coal during pyrolysis, particularly at low temperatures (<600°C). Volatilisation of the AAEM species due to the direct breakage of bonds between the AAEM species and the char matrix at higher temperatures may also be another mechanism. The volatilisation of Na is intensified by an increase in interaction between the nascent char and volatiles. Interactions between nascent volatiles and char have been shown to increase the volatilisation of sodium at high temperatures. This is attributed to the ability of low molecular weight free radicals to displace monovalent sodium from the char.

The volatilisation of sodium from char during pyrolysis/gasification can reach a plateau due to the formation of a stable form of sodium. This lower 'retention limit' is independent of the level of loaded sodium in the coal. More sodium can be stabilised in the char at lower temperature compared to at high temperature: this is believed to be related to the level of oxygen in the char. Significant volatilisation of calcium and magnesium occurs during CO_2 gasification of coal. This contrasts to its stability in inert atmospheres. Calcium and magnesium did not show a great difference in volatility between inert and steam atmospheres.

Most of this fundamental work was carried out at low temperatures relevant to fluidised bed pyrolysis and gasification under air-blown conditions. While these studies provide a strong scientific foundation that can be useful for understanding the AAEM behaviour during low temperature stages of gasification, their usefulness for oxygen-blown, high temperature (>1000°C) gasification is likely to be limited.

3.2.2 DEVOLATILISATION AND REACTIVITY STUDIES

Under the Lignite CRC, two PhD projects investigated the kinetics of devolatilisation of Victorian brown coal in a drop tube reactor at elevated pressures. Yeasmin [19, 20] carried out experimental work to examine the effect of residence time, pressure and temperature during devolatilisation of Yallourn coal. Coal particles of 37–53 μm size were devolatilised at pressures of 100, 500 and 1000 kPa. The experiments were carried out at temperatures of 873, 1073 and 1273 K. Residence times were varied from 0.02 to 3 s. The effects of residence time, temperature, and pressures on the structural parameters were also studied. This work attempted to describe the devolatilisation behaviour with simple modelling expressions and also a more complex distributed activation energy model (DAE). In general the DAE model represents the experimental data reasonably well and expressions were able to be derived to describe the observed data.

Marney [21] extended Yeasmin's work to additional Victorian brown coals and to higher pressure (1500 kPa). The work examined mainly the tar evolution as a function of temperature and pressure. The experimental data were fitted with two established pyrolysis models – chemical percolation devolatilisation (CPD) model and functional group deploymerization, vapourization, and cross-linking model (FG-DVC). The CPD model was found to better predict the experimental tar yield.

Recent work at CSIRO has built on earlier studies into reactivity fundamentals of Victorian brown coal chars [22] to begin to characterise German lignites for their use in high pressure entrained flow gasification. This work has focussed on high pressure laboratory-scale studies into devolatilisation, char formation and reactivity [14], slag formation and flow behaviour [23] and high pressure studies of entrained flow gasification behaviour [24] and provides a useful foundation for the application of similar techniques to Victorian brown coals. These investigations have reinforced that such coals are highly reactive, and has revealed some important differences between these coals and bituminous coals in terms of the impact of process conditions (such as temperature and pressure) on volatile yields, char structures, and reactivity. The behaviour of mineral matter is also likely to require some detailed knowledge of its transformation under gasification conditions and how it may be managed through blending or fluxing.

Recent work at Monash University and CSIRO has included for the first time reactivity, gas evolution and ash viscosity studies during entrained flow gasification of Victorian brown coal, Chinese lignites and Rhenish brown coal. The Monash work, funded by the BCIA, has been at atmospheric pressure in a purpose-built entrained flow reactor. There is a clear need for extending these works through coordinated R&D to high pressure entrained flow gasification, linking to considerable related experimental and modelling work done using high rank coals (and more recently, German lignites) by CSIRO.

Table 2: Australian laboratory-scale experimental work at Monash University, Swinburne University, and the University of Adelaide.

Year	Coals &Size	Temperature	Pressure	Medium	Sample	Reactor	Key Findings:
2000 (see [25])	Lochiel Coal, South Australia 106-150 µm	650-850°C	Atmospheric	Steam, CO, CO_2, H_2	Containing 1% NaCl and 10% d.b. Si	Horizontal tube furnace	1. Under inert gas environment, Na transformed to Na_2CO_3 , and further reduced by the char to element sodium and evaporated. 2. Under a steam environment, the melting point temperature of sodium carbonate found to decrease.
2000 [26]	Bowman, South Australia Morwell,Loy Yang, Yallourn Char; 180-350µm	750-950°C	Atmospheric	Steam CO_2 O_2	0.28-0.3kg/hr	Fluidised-bed reactor	1. Bed temperature, oxygen concentration, particle size, moisture content and coal rank were found to influence the devolatilisation time. 2. The devolatilisation time was found to be directly proportional to the particle diameter t_v=Ad_p^n. 3. A new theoretical treatment to distinguish between heat transfer and chemical kinetically controlled regimes of coal devolatilisation has been used.
2005 (see [27]	Loy Yang, Yallourn coal: 0.5-2.0 mm	850°C	Atmospheric	Air Air/steam	7.2-8.7 kg/hr	Fluidised-bed Reactor	1. 21 vol% CO for air gasification, 21 vol% H_2 for air/steam gasification. 2. Air gasification only yielded syngas richer in CO compared with air/steam gasification
2002 (see [28])	NaCl-loaded, Na-exchanged and Ca-exchanged Loy Yang coal: 106-150 µm	Pyrolysis: 500-900°C Gasification: 900°C batch mode experiments	Atmospheric	Ar /CO_2 Ar /steam	1.0-2.0g	Fluidised-bed/fixed-bed reactor	1. The valency and the chemical/physical form of the AAEM* species in the coal can affect their volatilisation during pyrolysis. 2. Na present as NaCl in the coal could exhibit good catalytic activity during gasification. The differences in char structural changes between the two atmospheres also have a effect on reactivity.with steam atmosphere having a larger positive effect. 3. Longer exposure to temperature makes the char less reactive to subsequent gasification

Year	Coals &Size	Temperature	Pressure	Medium	Sample	Reactor	Key Findings:
2004	Loy Yang: 106-150 µm	500-600°C	Atmospheric	O_2 in Ar	10-390 mg/min	Fluidised-bed/fixed-bed reactor	1. Increased yields of HCN and NH_3 during gasification in Oxygen at 500°C. 2. During gasification, NO_2 is formed from NO via reactions with HO_2 radical.
2005	H-Form and Fe-loaded Loy Yang coal:106-150 µm	Pyrolysis: 670-870 K Gasification: 1070 K	Atmospheric	Steam	1.5-2.0g	Fluidised-bed/fixed-bed reactor	1. In the presence of iron species, the production of hydrogen during the gasification of chars from iron-loaded brown coal is greatly enhanced. 2. Both reduced-iron and magnetite finely dispersed in chars are strong catalysts for char gasification with steam.

Table 2 continued.

3.3 Bench Scale Fluidised Bed Research at EERC [29]

3.3.1 DESCRIPTION

As part of the Lignite CRC research program, an experimental program on gasification of Victorian brown coal was performed at the Energy and Environmental Research Centre (EERC), University of North Dakota. The experimental rig has a maximum capacity of 2 kg/hr, operating pressure up to 10 bar and temperature up to 1000°C. Pyrolysis and gasification tests of air dried Loy Yang coal particles undertaken over a range of temperatures (400–800°C) and two pressures (1 and 10 bar) at low fluidisation velocity of around 0.3 m/sec representative of bubbling fluidised beds. These tests had the following objectives:

- to obtain data on yield and composition of char, tar and gas under various conditions of pressure, temperature, and gasification medium in a fluidised bed using large particles (0.5–3 mm) of a low-rank coal.
- to determine the retention of sodium, chlorine, and sulfur in char as a function of pressure and temperature during pyrolysis/gasification of coal.
- to estimate the proportion of original coal energy associated with the char and the evolved gases.
- to evaluate the thermal efficiency, and concentration of tar, alkali and HCl vapour in the gas of an advanced PFBC (A-PFBC) process that the CRC were trying to assess at the time, using the test data from this study.

3.3.2 KEY RESULTS

Yield of Char, tar and gas during pyrolysis tests

- The char yield decreased with temperature from about 79% at 394°C to about 48% at 800°C during the atmospheric pressure tests. At 10 bar, the char yields were 82% at 404°C and 50% at 776°C.
- The tar yield was at a maximum at about 500°C. At atmospheric pressure the tar yield fell from about 15% to 10% as the temperature increased from 500°C to 800°C. At a pressure of 10 bar, the tar yield fell from about 12% to 3% over the same temperature range.
- The gas yield increased with temperature from about 8% at 400°C to about 46% at 800°C.

Yield of char, tar and gas during gasification tests

- The char yield varied from about 73% at 500°C to about 44% at 800°C during 1 bar tests. At 10 bar, the figures were about 42% at 500°C to about 27% at 800°e.
- The tar yield varied from about 14% at 500°C to about 8% at 800°C. At 10 bar, the tar yield rose from about 1% at 500°C to about 3% at intermediate temperatures before falling to about 1% at 800°C.
- The gas yield at 1 bar pressure ranged from 13% at 500°C to about 43% at 800°C. At 10 bar, the gas yields increased substantially to 56% and 72% respectively.

Composition of char and gas

A typical dry gas composition (including the incoming gas used for fluidisation and heating) for the gasification test is shown as follows:

- At 700°C: 5–6% H_2, 14–20% CO_2, 67–72% N_2, 4.5–6% CO, 1–3% CH_4, plus 1–2% unsaturated hydrocarbons.

- At 800°C: 9–13% H_2, 17% CO_2, 52–70% N_2, 8–12% CO, 1–5% CH_4, plus 1–2% unsaturated hydrocarbons

3.2.4 Energy content in char and gas (including tar)

- Pyrolysis tests: at atmospheric pressure, the char energy is 82% at 394°C and 54% at 800°C; at 10 bar the char energy is 85% at 404°C and 64% at 776°C.
- Gasification tests: at atmospheric pressure, the char energy is 80% at 467°C and 61 % at 800°C; at 10 bar the char energy is 50% at 404°C and 34% at 809°C.

3.2.5 Effect of solids residence time on yield and composition

- With the increase of solid residence from 56mins to 130mins, char yield decreased from 44% to about 38%, tar yield decreased from 2.8% to 0.75% and the gas yield increased from 53% to more than 60%.
- The H_2 and CO concentrations increased with residence time, and the CH_4 concentration decreased.
- There was a slight increase in carbon and a slight decrease in hydrogen and volatile matter at the longer residence time.

3.3.3 FURTHER ASSESSMENT OF THE DATA AND CONCLUDING COMMENTS

The study has generated data on the pyrolysis and gasification of large (~2 mm) low-rank coal particles over a range of temperatures and two pressures (1 and 10 bar) under pyrolysis and gasification conditions relevant to bubbling fluidised bed conditions. The data include the yield and composition of the char, tar and gas. These data allow the efficiency and gas phase concentration of alkali and tar to be estimated when used in one version of the A-PFBC process that was investigated at the time.

The salient features from the study are summarised below.

- The char yield decreased with temperature under both pyrolysis and gasification conditions. The gasification tests at 10 bar showed the char yield was about 34% at 700°C and 27% at 800°C. The energy content of the dry fuel gas is estimated to be in the range 3.5–4.0 and 3.5–4.6 MJ/kg respectively. The yield and SE of the gas was found to be adequate for an A- PFBC process with the carboniser operating at 800°C. At higher pressures the char yield would be decreased and the SE of the gas increased.
- The gas yield from the 700°C gasification test at 10 bar pressure was about 64% which is not sufficient to achieve a temperature at the topping combustor of 1270°C.
- A solids residence time of about 55 minutes appears to yield about 30% char yield at 800°C temperature for the particle size, coal and gasification condition used during the tests. To obtain the same yield using a smaller size of particles, it is expected that lower steam/coal ratio and shorter residence time will be required.
- During the process of pyrolysis and gasification, chlorine and sulfur were depleted preferentially to sodium. Under gasification conditions at 800°C and 10 bar, retention of Na, Cl, and S in char was found to be about 65%, 20%, and 30% respectively. However, the gas phase alkali concentration estimated from this data is an order of magnitude above the currently acceptable limits for gas turbine operation. It is concluded that low temperature carbonisation alone cannot limit the concentration of gas phase alkali to an acceptable level. To achieve this, separate means such as gas cooling and/or use of alkali sorbents will be required.
- The tar yield under pressurised gasification condition was low (well below <3%) and was not expected to be a problem for the hot gas filters.

The information generated during these tests were relevant to part of the A-PFBC process that the CRC were assessing at the time. The gaseous environment, fluidization velocity, particle size, and particle residence time used in the tests generated information that cannot be directly related to oxygen-blown, CO_2-rich, high temperature (>1000°C) gasification.

3.4 Pilot-Scale Transport Reactor Research at EERC

3.4.1 DESCRIPTION

This work was part of a collaborative project between the EERC and the CRC for Clean Power from Lignite. The project compared the gasification performance of U.S. and Australian lignites in two variants of fluidised-bed gasifiers: the transport gasifier and the high-temperature Winkler (HTW) gasifier, through short-duration (4–8 hr) tests under similar conditions of temperature and pressure.

Transport Reactor Development Unit (TRDU)

The TRDU has an exit gas temperature of up to 980°C, a gas flow rate of 325 scfm, and an operating pressure of 120–150 psig (8–10 bar). The TRDU system can be divided into three sections: the coal feed section, the TRDU proper, and the product recovery section. The TRDU proper, as shown in Figure 7, consists of a riser reactor with an expanded mixing zone at the bottom, a disengager and a primary cyclone and standpipe and dipleg under the cyclone for recycling the bed material back to the mixing zone. The standpipe is connected to the mixing section of the riser by an I-leg transfer line. All of the components in the system are refractory-lined and designed mechanically for 150 psig and an internal temperature of 1090°C (2000°F). Table 3summarizes the operational conditions used in the TRDU and performance obtained from testing of different US coals.

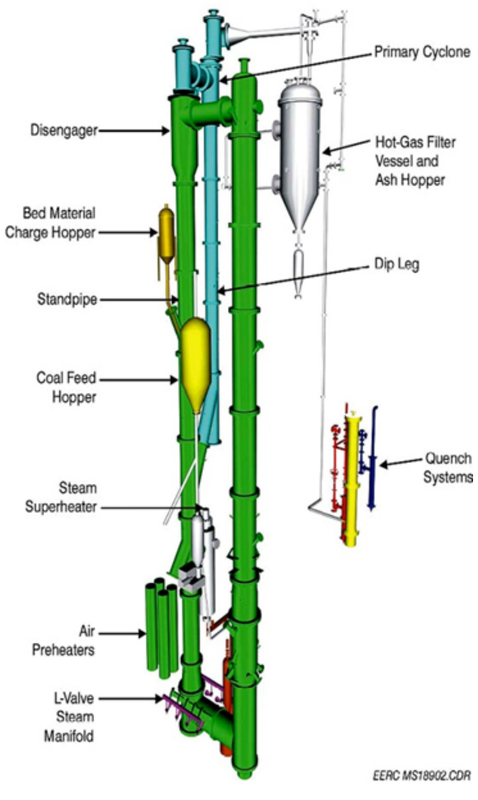

Figure 7: TRDU in the EERC gasification tower

Parameter	Design	P056 and P057	P056	P057
Conditions	Gasification	Gasification	Gasification	Gasification
Coal	Illinois No. 6	Wyodak	Illinois No. 6	SUFCo
Moisture Content, %	5	20	8.5	9.5
Pressure, bar	9.3			
Steam: Coal Ratio, lb/lb coal	0.34	0.29	0.39	0.14–0.41
Air: Coal Ratio, lb/lb coal	4.0	2.69	2.59	3.34–3.45
Ca: S Molar Ratio, sorbent	1.5	2	2	2
Coal Feed Rate, lb/hr	198	276.6	232.5	220
Mixing Zone, °C, av				920–950
Riser, °C, av				894–914
Standpipe, °C, av				828–860
Dipleg, °C, av				555–591
TRDU Outlet, °C, av				856–877
Carbon Conversion, %	>80	89	76	72–87
Carbon in Bed, %, Standpipe	20 to 40	6 to 15	6 to 15	5 to 20
Riser Velocity, ft/s	31.3	30	24	25–31
Standpipe Velocity, ft/s	0.1	0.4 to 0.5	0.45	0.4–0.45
Circulation Rate, lb/hr	3000	3000 to 6000	4000	2650–4200
HHV of Fuel Gas (actual), Btu/sef	100	62–75	61–113	52–75
(corrected), Btu/sef		105–117		93–130
Duration, hr	NA	179	41	118

Table 3: TRDU design and typical actual operating conditions used for US coals.

The premixed coal and limestone feed to the transport reactor can be admitted through three nozzles, which are at varying elevations. Two of these nozzles are located near the top of the mixing zone (gasification), and the remaining one is near the bottom of the mixing zone (combustion). During operation of the TRDU, feed is admitted through only one nozzle at a time. The coal feed is measured by a volumetric metering auger. Oxidant is fed to the reactor through two pairs of nozzles at varying elevations within the mixing zone. For the combustion mode of operation, additional nozzles are provided in the riser for feeding secondary air. Hot solids from the standpipe are circulated into the mixing zone, where they come into contact with the nitrogen and the steam being injected into the I-leg. This feature enables spent char to contact steam prior to the fresh coal feed. This staged gasification process into the mixing zone is controlled by the solids level in the standpipe and by the gas flow rates and distribution in the L-valve aeration nozzles.

The riser, disengager, standpipe, and cyclones are equipped with several internal and skin thermocouples. Nitrogen-purged pressure taps are also provided to record differential pressure across the riser, disengager, and the cyclones. The data acquisition and control system scans the data points every ½ second and saves the process data every 30 seconds. The bulk of entrained solids leaving the riser is separated from the gas stream in the disengager and circulated back to the riser via the standpipe. A solids stream can be withdrawn from the standpipe via an auger to maintain the system's solids inventory. Gas exiting the disengager enters a primary cyclone. Gas exiting this cyclone enters a jacketed-pipe heat exchanger before entering the hot gas filter vessel (HGFV). The cleaned gases leaving the HGFV enter a quench system before being depressurized and vented to a thermal oxidiser.

The quench system uses a sieve tower and two direct contact water scrubbers to act as heat sinks and remove impurities. All water and organic vapours are condensed in the first scrubber, with the second scrubber capturing entrained material and serving as a backup. The condensed liquid is separated from the gas stream in a cyclone that also serves as a reservoir. Liquid is pumped either to a shell-and-tube heat exchanger for reinjection into the scrubber or down to the product receiver barrels.

Hot Gas Filter Vessel

This HGVF is designed to handle all of the gas flow from the TRDU at its expected operating conditions. The vessel is approximately 48 in. i.d. and 185 in. long and is designed to handle gas flows of approximately 325 scfm at temperatures up to 980°C and 130 psig. The refractory has a 28 in. i.d. with a shroud diameter of approximately 22 in. The vessel is sized such that it could handle candle filters up to 1.5 m long; however, l-m candles were utilized in the 540°C gasification tests. Candle filters are 2.375 in. o.d. with 4-in.center line-to- center line spacing. The filter design criteria are summarized in Table 4, and a schematic is given in Figure 8.

Operating Conditions	Design	Actual
Inlet Gas Temperature	540–980°C	520–580°C
Operating Pressure	150 psig	120 psig
Volumetric Gas Flow	325 scfm	350 scfm
Number of Candles	19(1 or 1.5 meter)	13(1 meter)
Filter Face Velocity	2.5-10 ft/min	4.5 ft/min
Particulate Loading	<10,000 p.m.	<7,000 p.m.
Temperature Drop Across HGFV	<30 °C	<25 °C
Nitrogen Backpulse System Pressure	Up to 800 psig	250 to 350 psig
Backpulse Valve Open Duration	Up to 1 sec duration	½ sec duration

Table 4: Design Criteria and typical actual operating conditions for the pilot-scale HGFV.

The total number of candles that can be mounted in the current geometry of the tube sheet is 19. This enables filter face velocities as low as 2.5 ft/min to be tested using 1 m candles. Tests consisted of 200 hr hot-gas filter tests under gasification conditions using the TRDU with the filter operating at temperatures of 540–560°C and pressure of 120 psig. Higher face velocities would be achieved by using fewer candles.

The test program performed the first filter test at 540–560°C, 120 psig, and 2.75 ft/min face velocity. All subsequent testing was performed after removing six candles to increase the face velocity to approximately 4.0 to 4.5 ft/min at the same operating temperature and pressure. The openings for the six removed candles were blanked off. This program has tested an Industrial Filter & Pump (IF&P) ceramic tube sheet and is expected to enhance process efficiency. Gasification or combustion and desulfurisation reactions are carried out in the riser as coal, sorbent, and oxidant (with steam for gasification) flow up the reactor. Later tests also utilised a metal tube sheet manufactured with expansion cones to allow for thermal stresses. Since the metal tube sheet was installed, candle filter fail-safes from Westinghouse Science and Technology Center have also been tested.

The ash letdown system consists of two sets of alternating high-temperature valves with a conical pressure vessel to act as a lock hopper. Additionally, a natural gas burner attached to a lower inlet nozzle on the filter vessel can be used to preheat the filter vessel separately from the TRDU. The hot gas from the burner enters the vessel via a nozzle inlet separate from the dirty gas.

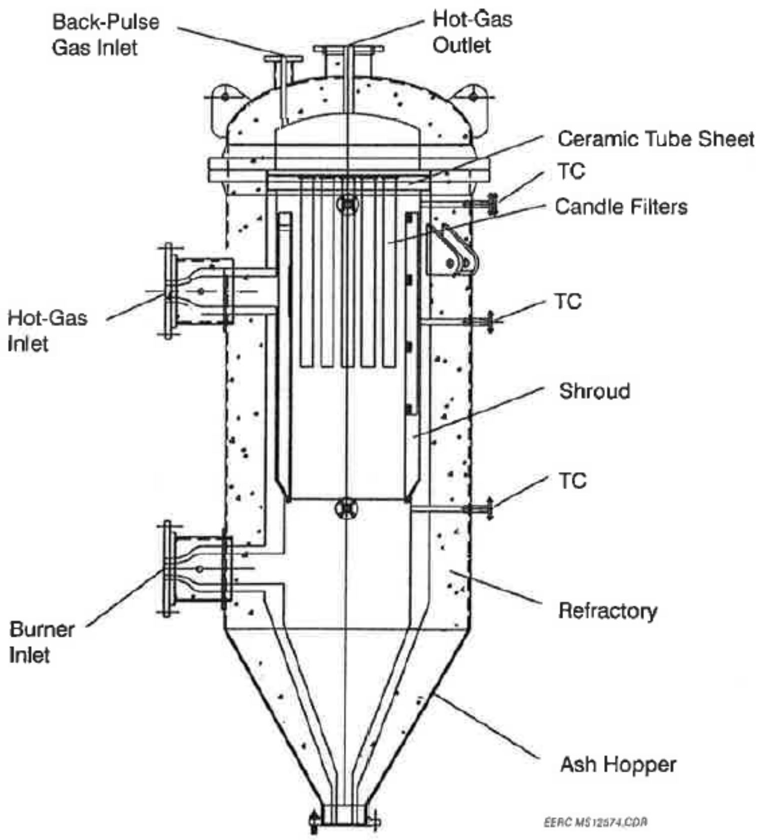

Figure 8: Schematic of the filter vessel design with internal refractory, tube sheet, and shroud

The high-pressure nitrogen backpulse system is capable of backpulsing up to four sets of four or five candle filters with ambient-temperature nitrogen in a time controlled sequence. The pulse length and volume of nitrogen displaced into the filter vessel is controlled by regulating the pressure (up to 800 psig) of the nitrogen reservoir and the solenoid valves used to control the timing of the gas pulse. Figure 7 also shows the filter vessel location and process piping in the EERC gasifier tower. Since the entire filter tests are to be completed in the 540–650°C range, a length of heat exchanger was used to drop the gas temperature to the desired range. In addition, sample ports both upstream and downstream of the filter vessel have been utilized for obtaining particulate and hazardous air pollutant (HAP) samples.

3.4.2 KEY RESULTS

TRDU North Dakota lignite air-blown gasification tests

The TRDU was operated at average temperatures ranging from 793–894°C at various air/fuel ratios and reactor velocities. The dry product gas produced was 4.2% to 6.5% CO and 7.1% to 9.2% H_2, 12.0% to 13.8% CO_2, and 0.9% to 1.4% CH_4, with the balance being N_2 and other trace constituents. The moisture in the fuel gas averaged 18% to 19%. The H_2S concentration ranged from 446 to 1088 ppm and averaged 850 ppm. Coal feed rates ranged from 302 to 492 lb/hr (137 to 223 kg/hr), and the gasifier pressure averaged 120 psig (8.6 bar). Calculated recirculation rates ranged from 950 to 3115 lb/hr (430 to 1412 kg/hr).

TRDU oxygen-blown gasification test using North Dakota lignites

The TRDU was operated at average temperatures ranging from 792° to 828°C at various air/fuel ratios and reactor velocities. The actual dry product gas produced was 4.7% to 7.4% CO and 12.7% to 20.8% H_2, 20.8% to 29.7% CO_2, 1.9% to 3.1% CH_4, and 0.20% to 0.35% ethane, with the balance being N_2 and other trace constituents. The moisture in the fuel gas exiting the transport reactor ranged from 45.9% to 55.7% under oxygen-blown conditions. The H_2S concentration ranged from 2000 to 3700 ppm and averaged 3370 ppm under full oxygen-blown operating conditions. The sulfur retention was less than 33% under these operating conditions.

TRDU Long duration gasification Test using a North Dakota lignite

TRDU Test P074 was conducted during the week of September 22 through September 28, 2003. This test generated 81 hours of coal feed with 65 hours of gasification data. Of this testing, 48 hours was in air-blown operation, and 17 hours was in oxygen-blown operation. The results show that after 2 days of operation on a North Dakota (Falkirk) lignite, potential low-melting point species such as potassium/sodium were not building up in the bed material.

TRDU Australian Brown Coal Gasification Tests

TRDU Test P075 tested the thermally dried Australian brown coals from the Loy Yang and Lochiel Mines over the week of December 1, 2003, through December 4, 2003. This test generated 59 hours of coal feed and 46 hours of gasification, including 33 hours of air-blown gasification and 13 hours of oxygen-blown gasification. The experimental data shows that the standpipe ash for the Lochiel was high in sodium, which would be consistent with the bed material agglomeration and deposition that was experienced with that coal. Besides that, the filter ash particle size data averaged approximately 24.6 µrn for the low-ash Loy Yang coal, while the filter ash for the high- ash Lochiel coal averaged 12.9 µrn.

Comparisons of Brown Coal/Lignite Gasification Testing

In total, five test campaigns utilizing the selected test coals were completed under enriched air- or full oxygen-blown conditions. During these tests, 335 hours of coal gasification with 69 hours of gasification completed on the Australian brown coal. In general, operation on the more reactive low-rank western coals has displayed higher carbon conversions and product gas heating values even when operating at lower reactor temperatures than comparable bituminous coal tests. The data suggests that removal of all of the fines had lower carbon conversion and less syngas heating value than the coals with the fines left in. The data also shows that these low-rank feedstocks provided similar fuel gas heating values; however, the brown coals had lower carbon conversions in general than the North Dakota lignite. For all fuels, the carbon conversion tended to increase and corrected dry product gas heating value decrease with an increasing oxygen/maf coal ratio.

3.4.3 CONCLUDING COMMENTS

The TRDU was modified to accommodate oxygen-blown operation that could produce power, chemicals, and fuel. These modifications consisted of changing the loop seal design from a J-leg to an L-valve configuration, thereby increasing the mixing zone length and residence time. In addition, the standpipe, dipleg, and L-valve diameters were increased to reduce slugging caused by bubble formation in the lightly fluidised sections of the solid return legs. A seal pot was added to the bottom of the dipleg so that the level of solids in the standpipe could be operated independently of the dipleg return leg. A separate coal feed nozzle was added that could inject the coal upward into the outlet of the mixing zone, thereby precluding any chance of the fresh coal feedback-mixing into the oxidizing zone of the mixing zone; however, difficulties with this coal feed configuration led to a switch back to the original downward configuration. Instrumentation to measure and control the flow of oxygen and steam to the burner and mix zone ports was added to allow the TRDU to be operated under full oxygen-blown conditions.

In total, five test campaigns have been conducted and the data compared for this particular comparative study. These tests were conducts under both air-blown and oxygen-blown conditions. During these tests, 335 hours of operation on low-rank coals such as North Dakota lignite and an Australian brown coal. Data from these tests indicate that the transport gasifier performs better on the lower-rank feedstock because of their higher char reactivity with the gasification reactions.

Test data indicated that these low-rank feedstock provided similar fuel gas heating values; however, the brown coals had lower carbon conversions in general than the North Dakota lignite. The high sodium levels in all of these coals led to lower operating temperatures in order to avoid bed agglomeration and deposition problems. This lower operating temperature resulted in lower than desired carbon conversions; however, the brown coal seemed to be more affected by the lower temperatures than the lignite, possibly due to its high thermal friability. Tests of a brown coal with fines removed suggested that removal of all of the fines resulted in lower carbon conversions and lower syngas heating value than the coals with the fines left in. For all fuels, the carbon conversion tended to increase and corrected dry product gas heating value decreased with an increasing oxygen/maf coal ratio. Comparable carbon conversions have been achieved at similar oxygen/coal ratios for both air-blown and oxygen-blown operation. The fuel gas under oxygen-blown operation has been high in hydrogen and carbon dioxide concentration since the high steam injection rate drives the water-gas shift reaction to produce more CO_2 and H_2 at the expense of the CO and water vapour. However, the high water and CO_2 partial pressures have also greatly retarded the reaction of hydrogen sulfide with the calcium based sorbents.

The TRDU tests generated key performance data on carbon conversion, fuel gas calorific value, and some information on pollutant gases in the temperature range 800-900°C at pressure up to 10 bar. While these results can be representative of low temperature dry ash gasification, low carbon conversion (around 75%) means higher temperature or longer residence times will be required to obtain high carbon conversion.

3.5 Pilot-Scale Studies in a High Temperature Winkler Gasifier (HRL)

A pressurised fluidised bed gasifier process development unit (PDU) was leased from HRL Ltd as part of the CRC research program. The facility was designed as a high temperature Winkler (HTW) unit, built and commissioned by the then State Electricity Commission of Victoria (SECV) in 1992, and used in their test program. It is capable of operating at pressures up to 10 bar, temperatures up to 1000°C, and feed rates up to 300 kg/hr of dried coal. As the PDU had not been operated for a number of years, it was re-commissioned by the CRC in August 2001 following three tests.

3.5.1 PROJECT OBJECTIVES

The objective of the project [30] was to provide data for the development of gasification based technologies using lignites, and for use in validation of gasifier mathematical and process models. The data are to be generated under both air-blown (air and steam as gasification agents) and oxygen-enriched air-blown conditions through short-duration (approximately 2–4 hours steady-state condition) and longer-duration tests. Coals to be used were pre-dried by evaporative drying.

The tests were to determine the following parameters for the existing gasifier configuration (char recirculation arrangement, air/steam entry) and to compare conversion data generated using laboratory scale instruments and rigs.

1. To determine the following with air/O_2 and steam as gasification agent for the current gasifier configuration (recirculation arrangement, air/steam entry at the bottom):

- Gasification yield and carbon conversion.
- Product gas composition: major gases H_2, CO, CO_2, O_2, CH_4, C_2H_6, C_3H_8, and trace pollutant gases, COS, HCl, HCN and NH_3
- Characteristics of condensate recovered from fuel gas: NH_3 concentration, TOC, Cl^-, $S^=$, Na^+, Ca^{++}, and Mg^{++} by various techniques.
- Alkali and tar formation
- Characteristics of product char (bed and filter)
- Elutriation, attrition and solid circulation rate
- Bed agglomeration – assessment and control
- Dust collection characteristics of the gas filter- as a function of filtration temperature

2. Examine the influence of inherent inorganics and added sorbents (Ca and Mg-based) on capture of sulfur and alkali in-bed and in gaseous phase

3. Development of strategies for added sorbents to control agglomeration and in-bed sulfur removal. These include identification and preparation (size) of sorbents, assessment of their performance, and establishing usage rate.

These parameters were to be assessed as a function of the following operating variables:

- coal type and coal preparation
- operating conditions (pressure, temperature, concentration of reactant gases, air/coal, steam/coal ratio (fluidisation velocity), filtration temperature)
- air and steam staging within the gasifier
- bed level

The emphasis was on obtaining an acceptable carbon conversion (nominally 85%) and product gas specific energy (4 MJ/kg after allowing for N_2 addition).

3.5.2 PLANT DESCRIPTION

The schematic of the PDU plant is depicted in Figure 9. In its original configuration, it consisted of an air blown gasifier based on the High Temperature Winkler (HTW) process. In 2002, HRL fitted its own O_2-enhanced system with a facility for oxygen injection up to level 3. The CRC decided to lease this system, and based on its tests, decided to retrofit oxygen and steam supply at freeboard level 4. Decision for supply of oxygen and steam (as reactants) in the freeboard (level 4) was taken following improvements in fuel gas composition observed in earlier tests with air injection at freeboard.

The system requirements for oxygen-enhanced gasification were identified in conjunction with Air Liquide, who were also the suppliers of nitrogen and nitrogen storage system for the PDU use. Air Liquide also supplied the oxygen tank and instrumentation associated with the supply system.

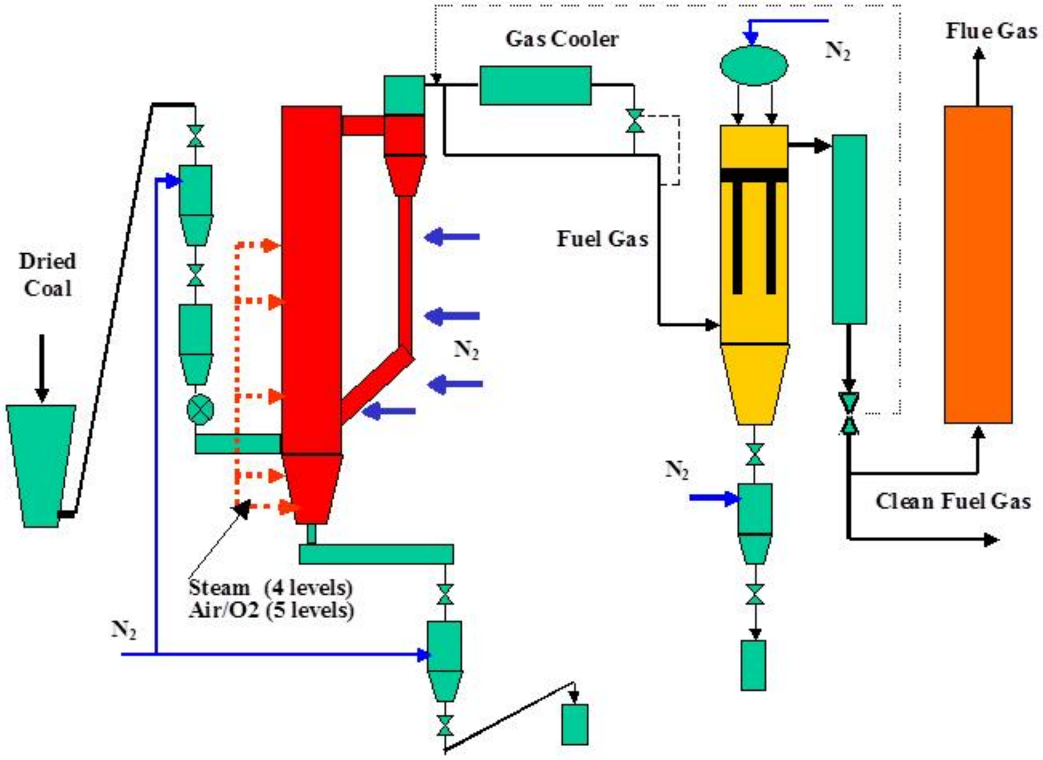

Figure 9: Schematic of the HTW Process Development Unit [30].

3.5.3 KEY RESULTS

Ten different fuels were tested during the test program. These included three Victorian coals (Loy Yang, Morwell and Yallourn), one mixed (80% Loy Yang and 20% Yallourn) coal, one briquetted mixed coal (Grus), one commercially procured char (also used during start-up), one char generated during the gasification of the Loy Yang coals, coal of one South Australian coal (Lochiel), and two North American lignites (Falkirk and Freedom).

A total of one hundred and fourteen tests were attempted representing total fuel feeding of about five hundred hours, of which three hundred hours were sampling period. Of these, five were commissioning tests; twenty of the remaining tests were abandoned at different stages due either to mechanical or electrical problems, or the coal being too fine or too moist for reliable and continuous feeding. Majority of the tests was of short duration about four hours of fuel feeding.

The test conditions ranged between 2–8 bar pressure and 750–900°C average bed temperature. Test environment was either 'air-blown' or 'oxygen-enriched air-blown' mode. Operating variables included pressure, average bed temperature, freeboard temperature, coal preparation (fine size selectively removed, hard briquetted coal), coal type, steam/coal ratio, oxygen/coal ratio and bed height.

Carbon-conversion ranged from 60% during the early stages of the program to 90% towards the end. However, the majority of the C-conversion figures were around 85%. The reason for the relatively low C-conversion initially was excessive bed drainage, which was managed by closely matching the feed rate with the gasification rate under the conditions employed. However, elutriation of C-rich fines from the bed and their loss from the system through the cyclone remained a major problem. These losses could be attributed to a high proportion of fines in the feed coal, the brittle nature of these coals (some of which had been stored for several years), and inefficient performance of the cyclone and the recirculation loop. A revised pulsing regime, based on the cold model tests, was employed during the PDU tests. This improved the C-conversion slightly, however the brittle nature of the Victorian brown coals, and the use of a single cyclone meant that there was scope for further improvement of C-conversion.

It was expected that carbon conversion would improve with the following:

- a narrower size distribution of the coal feed with little or no fines
- use of multiple efficient cyclones, and
- longer residence time (as in taller or commercial scale gasifiers, as well as gasifiers with expanded freeboard)

PDU-scale units require larger purge and pulse nitrogen gases compared to commercial-scale units. Also, per unit of heat input, the heat losses of PDU sized rigs are higher. After adjusting for purge and pulse gas, and heat losses appropriate for large units, the major gas constituents from Victorian and South Australian lignites were estimated to be as follows:

- Air-blown: 14-20% H_2, 11-18% CO, 2-3% CxHy, 8-15% H_2O, 40% N_2, 12-17% CO_2, LHV = 3.5-4.2 MJ/kg
- O_2-enriched blown: 22-26% H_2, 19-24% CO, 3-6% CxHy, 13-20% H_2O, 9% N_2, 17-26% CO_2, LHV = 6-8 MJ/kg

It is clear that an acceptable fuel gas LHV of 4 MJ/kg would be expected to be attained during commercial-scale gasification of these lignites.

Tar was not a problem in any of the tests. There was no sign of any tar deposition on the filter elements in the gas filter, or any tar in the condensate from the fuel gas during the sampling period.

During the tests, the fuel gas was cooled down to 400°C before being filtered of the dust. Based on the analysis, majority of the alkali in the coal was transferred to the bed char and filter dust, rather than to the fuel gas.

Based on the observations during the tests and analysis of agglomerates, it is recommended that the average bed temperature be limited to 900°C, while freeboard temperature can be allowed up to 950°C during commercial scale HTW gasification of the Victorian lignites. For gasification of Lochiel coal, these temperatures should not exceed 800°C and 850°C respectively. This is likely to ensure stable operation with manageable deposition.

3.5.4 CONCLUDING COMMENTS

Based on the test results, it was concluded that it would be difficult to obtain C-conversion in excess of 90% with Victorian and South Australian lignites on a consistent basis in fluidised bed gasifiers of HTW type, which require coarse particles as feed material. This is due to the friable nature of these coals which when dried generate fines. Fines lead to elutriation problems, but at the same time are also more amenable to gasification more quickly than coarse particles. It is, therefore, worthwhile assessing the gasification performance of these lignites in higher temperature gasifiers (which would convert carbon faster and also can use fine particles better) such as entrained flow gasifier or transport reactor gasifier.

3.6 Gasification Work by HRL Technology [31, 32]

In Victoria, a research program was initiated in 1989 by the State Electricity Commission of Victoria seeking ways of reducing cost of electricity and increasing conversion efficiency from brown coal fired power stations. Several technologies were investigated including Integrated Gasification Combined Cycle (IGCC), steam fluidised bed drying, hydrothermal dewatering and direct coal-fired turbine. From these investigations a process called Integrated Drying and Gasification Combined-Cycle (IDGCC) was developed.

3.6.1 THE IDGCC PROCESS

IDGCC used an air blown fluidised bed gasifier to convert brown coal to fuel gas. Because of its high moisture content brown coal must be dried before feeding it into a gasifier. The integrated drying concept used the hot fuel gas from the gasifier in direct contact with the raw coal under pressure for evaporating the water.

The raw coal is introduced into the dryer through a lock hopper system. The dried coal is separated from the gas at the outlet of the dryer and goes directly to the gasifier. The cooled and humidified gas is cleaned and sent to a gas turbine combined-cycle plant. Using air as the gasifying agent, the calorific value of the gas is very low, but it is acceptable for combustion in a gas turbine. By integrating the coal drying and gas cooling substantial cost savings are made whilst achieving high efficiencies (42% based on HHV) and low CO_2 emissions (810 kg/MWh sent out) through the combined cycle. The process is shown schematically in Figure 10.

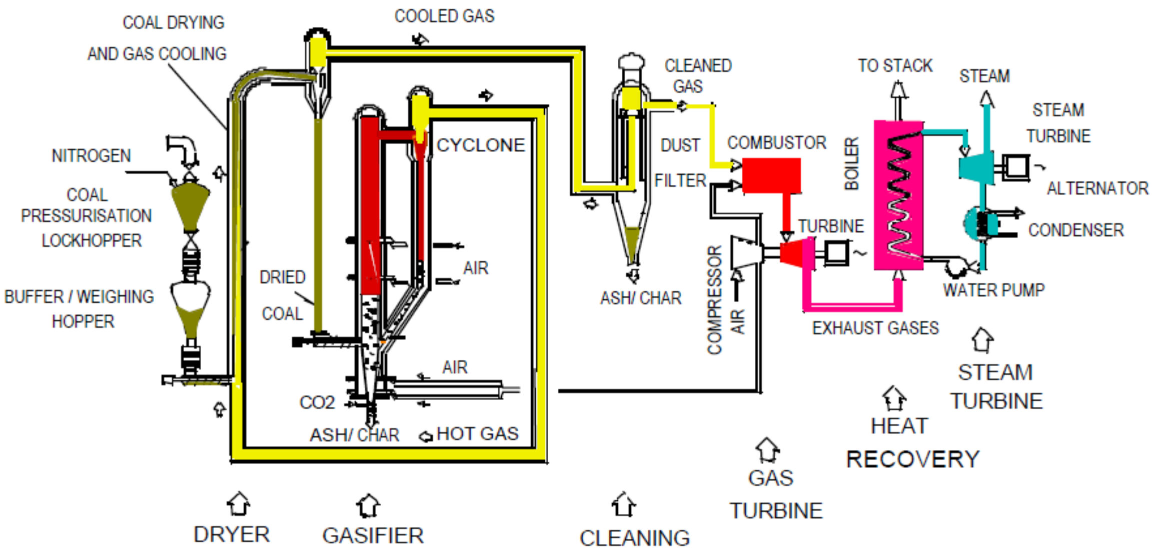

Figure 10: Schematic of the IDGCC process

The incoming raw coal feed is crushed and screened to about 10 mm top-size. The crushed coal is brought up to the process pressure of 25 bar through a system of lock hoppers and fed to the dryer by a screw feeder.

Inside the dryer the coal comes into direct contact with the hot fuel gas from the gasifier. The gas is cooled as the coal moisture is evaporated. The water vapour produced from drying the coal under pressure becomes part of the fuel gas, the fuel gas is cleaned and then sent to the gas turbine. The dried coal passes directly to the gasifier. There is no discharge to the atmosphere from the drier.

The fluidised bed gasifier operates at a temperature about 950°C with air plus some steam as the gasifying agent. Air is bled from the gas turbine compressor to supply the gasifier. This type of gasifier operates well with low-rank coals because of their high reactivity. The temperature is below the ash fusion point allowing dry ash removal from the bed. The hot gas leaving the gasifier at the top passes through a cyclone that returns most of the carryover dust back to the bottom of the gasifier.

The cooled gas leaving the coal dryer at a temperature of about 250C passes through a ceramic candle barrier filter which removes virtually all the remaining particulates from the gas stream. The filter elements are cleaned by reverse pulses of nitrogen. The dust from the filter is high in carbon, so the char can be combusted to raise extra steam for the combined cycle. Sulphur can be captured in the fluidised bed using calcium based additives or, if more stringent emission limits apply, additional hot gas cleaning or gas scrubbing can be included.

The gas is combusted in a gas turbine. The turbine output is higher than normal because of the steam added to the gas during coal drying. Some combustor modifications are necessary for the low heating value gas. The gas from the gas turbine goes through a heat recovery steam generator, which raises steam to drive a steam turbine. The steam cycle is also closely integrated with parts of the coal drying and gasification and char burning plant.

3.6.2 IDGCC DEVELOPMENT PROGRAM

HRL Technology Ltd conducted laboratory and pilot-scale research on key aspects of the IDGCC process including: raw coal feeding, pressurised drying, fluidised bed gasification, hot gas filtration and low-energy gas combustion. These systematic investigations included the following stages:

- Laboratory scale tests on coal gasification reactivity using pressurised thermogravimetry and ash deposit analysis
- Atmospheric pressure gasifier at 50 kg/h dry coal feedrate.
- Pressurised Gasifier at 300 kg/h dry coal feedrate, 10 bar.
- Pressurised gas combustion test rig, at 500 kg/h gas flowrate, 6 bar.
- Pressurised coal drying test rig at 1500 kg/h wet coal feedrate, 10 bar.
- Integrated gasifier, dryer and 5 MW gas turbine at 10,000 kg/h raw coal feedrate, 25 bar. This was stage 6 of the development program, the Coal Gasification Development Facility (CGDF)

3.6.3 CGDF DESIGN AND CONSTRUCTION

The Coal Gasification Development Facility was constructed at Morwell, in the Latrobe Valley in Victoria, commencing in September 1995. The facility was commissioned in July 1996.

The facility had a throughput up to 10 tonne per hour of raw coal, at the full pressure of 25 bar. This represented a process capacity of 10 MW output. An EGT Typhoon gas turbine of nominally 5 MW generating capacity operating in simple cycle mode was used. It dis not include the heat recovery steam generator or the steam turbine as these are already commercially proven technologies. The CGDF included the following key elements that needed proof of concept:

1. The pressurised coal feed system.
2. The pressurised coal drier.
3. The coal gasification unit.
4. The hot gas filtration unit.
5. Combustion of the coal gas in gas turbine.
6. An ammonia scrubber.
7. Sulphur absorption test rig.

When operating at the maximum coal feed rate, the gasification process produced more gas than could be combusted in the gas turbine. A separate flare stack was used to dispose of the excess gas. There were some periods when this flare was required to take the full gasifier output, while the gas turbine operated on auxiliary fuel. The gasifier/drier was in the main structure, with the gas turbine, exhaust stack and control building behind the structure. The height of the main structure was about 30 metres.

A range of coals was tested, concentrating mainly on Morwell coal from the Latrobe Valley. Each coal was tested initially in short run operation to obtain data over a range of operating conditions, with some extended runs to investigate longer-term effects such as ash fouling behaviour and dust filter performance.

3.6.4 CGDF OPERATION AND RESULTS

The plant achieved 85 runs between commissioning in June 1996 and the end of the test program in December 1997. Full operation of the integrated system, including combustion of the coal gas in the gas turbine was achieved after 14 runs, following the change-over of the gas turbine to dual-fuel combustors. During testing, the turbine was operated at full power output on coal gas, giving up to 5.2 MW compared to its site rating of 4.3 MW on liquid fuel. The generator was synchronised and connected to the national power grid for all the tests.

The plant was easy to start by preheating with nitrogen and then introducing char into the gasifier through a separate feed system, followed by the introduction of air and steam through the fluidising jets. Initially the gas turbine was operated on liquid fuel, with a water spray into the dryer inlet to control the coal gas temperature. Only a short time (several hours) was needed to reach steady operating conditions before introducing raw coal.

The gas quality produced was dependent on the amount and distribution of air and steam in the gasifier bed. Different settings were tested to determine the conditions needed produce gas with a heating value at the design level of 4.0 MJ/kg. Formation of ash clinkers in the bed was closely monitored since this was found to be potentially a problem with coals having ash with low fusion temperature.

The gasifier proved to be very stable and easy to operate. The fluidised bed, with its large particle residence time, could accept short term variations in coal feed rate and moisture content with little change in product gas quality. The integrated dryer operated well, giving the correct level of gas cooling with sufficient drying of the coal to give stable gasifier operation. The ceramic filter initially suffered some element failures due to operational problems but later it operated well with no further breakages and very effective dust removal. The ammonia scrubber was effective in removing ammonia from the product gas and reducing NOx from the turbine to low levels. Large reductions in sulphur emissions were demonstrated using an additive in the gasifier and also with a regenerable sorbent system.

Overall the CGDF testing plus the supporting research demonstrated that the IDGCC technology was technically feasible and the concept of integrating the drying with gasification was proven.

3.6.5 HRL'S IDG TECHNOLOGY

While the IDGCC technology was not commercialised, a variant of it – Integrated Drying and Gasification (IDG) technology - evolved. This IDG technology combines pressurised drying of high moisture fuel with the gasification of the dried fuel to produce synthesis gas.

In the IDG process, dried fuel is gasified using steam with air or oxygen to produce hot syngas. Hot syngas is used to evaporate the moisture present within the wet fuel. Drying of the fuel cools and humidifies the syngas. The cooled syngas is filtered to remove particulate matter before further processing. Combustion of the char and ash extracted from the gasifier and particulate filter is used to raise steam for use within the process.

Integration of the fuel drying with the gasification in this way minimises the requirements for fuel drying external to the gasification system and heat exchangers to cool the syngas. This reduces both capital and on-going costs.

Syngas from the IDG technology is readily transformed into a wide range of products using well established gas processing technologies. HRL has confirmed the suitability of IDG syngas for use within these technologies, including the removal of sulphur species and CO_2 from the syngas.

A 600 MW Dual Gas Demonstration Project was proposed using the IDG syngas in a combined cycle plant (IDGCC) for power generation. Works Approval for the 600 MW Dual Gas Demonstration Project was granted in 2012 with conditions. However, at the time of preparing this report, the project is on hold.

4 Industry Survey

A key component of this work is the gathering of input from industry and research organisations who have had some experience at utilisation of low rank coals (especially lignites) in gasification systems, and who are therefore well placed to consider possible implications for moving from air to oxygen blown gasification. Most of the responses received were obtained *pro bono* and the level of detail and the degree to which the information can be related to viability (both technical and economic) of particular technologies reflects this. Some of the people contacted were unable to participate due to the requirements for detailed confidentiality and pricing agreements.

The exception to this is the input from Maarten van der Burgt, an internationally-renowned gasification technologist with direct industry experience working on a range of gasification technologies. He now operates as an industry consultant advising industry (and researchers) on all aspects relating to the leading (and emerging) gasification technologies and their applications. Maarten provided direct responses to our questions, but also worked directly with the project team to assist with the interpretation and analysis of the issues with the view to developing some research priorities for this area.

The industry responses are arranged in this section according to the aspect of the process to which they are relevant. These are coal preparation, handling, and feeding; the gasifier; and downstream syngas cleaning and processing systems. Given that the focus of this work is on understanding the issues associated with a move from air-blown to oxygen-blown gasification, it is reasonable to expect that most issues will be expected to impact on the gasifier, with some on downstream syngas processes. Well-known feeding and handling issues are generally unaffected by a move to oxygen blown gasification, with a few exceptions as detailed below.

4.1 Coal Preparation, Handling and Feeding

In the context of issues associated with a move from 'air blown' to 'oxygen blown' gasification, it is reasonable to assume that the issues associated with preparing, handling, and feeding Victorian brown coals into air blown gasifiers will have considerable overlap with those expected in oxygen blown gasifiers. Most of these are related to the requirement (and impact of) different drying technologies and the levels to which moisture can be removed. These R&D needs and their cost implications are well understood and won't be discussed in particular detail here.

A key difference between O_2-blown and air-blown gasification is the significant reduction in syngas volume that results from the move to O_2-firing. This clearly has strong relevance to the gasifier and syngas handling systems (discussed below). However this reduction in syngas volume will have an impact on coal preparation, handling and feeding if the syngas is used in the drying or preparation process. There may be some R&D required to understand the impact of this reduction on drying efficiency, capital requirements, and overall process performance.

Slurry feeding was also identified in the responses as an issue worthy of research, as oxygen blown entrained flow gasifiers are generally suitable for feeding coal water slurries. However, for slurry-feeding Victorian brown coals, management of overall moisture levels (i.e. inherent moisture in the coal combined with waster required for slurrying) to allow effective slurry formation and gasifier operation is important and forms the basis of many of the R&D needs in this area. Integration of coal pre-drying with slurry formation is one option, as is the use of alternative slurrying media (e.g. heavy oil, liquid CO_2) to help with managing the moisture load of the system.

Development work should focus on a reliable and continuous feeding system for dried lignites, reflecting the particle size requirements of specific technologies (Table 5). Current experience suggests that a consistently continuous feeding of dried lignites (12–20% moisture) through lock-hoppers proved difficult at times, resulting in either significant "overflow" or "underflow" of coal feed relative to the set point in a gasifier. This has a flow-on effect on the temperature excursions, fuel gas quality and fouling or agglomeration in a fluidised bed.

Technology	Particle Size	Characteristics
Fixed-bed	Lump coal, 6–50 mm.	Limited acceptability of fines in dry-bottom gasifiers. Caking coals require stirrers.
Bubbling fluidised bed	Granulated coal, 6–10 mm	Friable or brittle coals lead to excessive fines (and carbon elutriation)
Transport	Pulverised coal, <400 μm	
Entrained flow	Pulverised coal, <100 μm	Can accept slurries

Table 5: Particle size characteristics for the main gasification technology types (after [6] and [33]).

4.2 Coal Gasification

The move from air-blown to oxygen blown gasification will be expected to have significant impacts on coal behaviour in the gasifier. Underlying themes in all the responses received were the impact of reduced syngas volumes on gasifier design and operation, the potential impacts of 'hotspots' or localised areas of high temperature (particularly relevant to fluidised bed gasifiers), and how these high temperatures might impact alkali release and the subsequent impact these species may have on different aspects of the gasifier including coal behaviour, refractory materials, and metal components.

In general, it was clear that the move to an O_2 blown operation, and the fact that this usually allows for a much smaller gasifier, was a positive as it provides the opportunity for up-front savings in capital and infrastructure requirements. In general, however, the related design requirements for the different gasifiers, and the effects on conversion behaviour and syngas volumes for the different technologies, are not well understood for Victorian brown coals. Issues relating to coal conversion behaviour (and the role of moisture), ash behaviour, and the impacts of these on overall gasifier efficiency will require good laboratory and pilot scale data to support gasifier and process model development.

Bubbling fluidised beds are expected to pose particular challenges with localised hot spots potentially arising from the significantly greater concentration of O_2 at the air inlets. These hot spots may lead to alkali vaporisation or agglomeration of the mineral matter in the coal particles. Agglomeration in a bubbling fluidised bed has significant impacts on operability and stability. Steam can be added to try and manage these temperature effects; however, knowledge of the fuel and technology specific requirements is needed to ensure that this does not adversely impact on the overall gasification process. This is particularly relevant to very high moisture coals such as Victorian brown coals.

Recirculating fluidised beds and transport gasifiers will be affected by the reduced syngas volume and also the low ash content—managing the 'solids inventory' and gas velocities were seen as issues that needed particular consideration. This is especially relevant for the transport gasifier (and entrained flow gasifiers which rely on char recycling systems, such as the two-stage entrained flow variants) given the importance of cyclone filtration to effective operation. CFD modelling tools that can accurately incorporate coal-specific behaviour in these technologies are required.

Fixed bed gasification has been used successfully to convert lignites to synfuels using oxygen blown gasification (e.g. the Great Plains Synfuels plant). Fixed bed technologies have very specific requirements for feedstock properties, in particular regarding coal and char strength, structure, and permeability. Whilst not a specific issue associated with moving from air to oxygen blown gasification, there is very little knowledge of how Victorian brown coals might perform within such requirements and therefore their suitability for this kind of technology. Associated with this is the tendency of chars to fragment, and the role of mineral matter around the oxygen/steam injection sites. Dry-bottom fixed-bed gasifiers have similar requirements to fluidised beds, and the formation of sticky ash or agglomerates is a challenge for effective ash removal. Slagging fixed beds have similar requirements to entrained flow gasifiers, in that the ash must melt and flow in a controlled manner at reasonable operating temperatures.

There is very little experience at gasification of Victorian brown coals in entrained flow technologies. Typically, entrained flow gasifiers operate in a higher temperature regime than fluidised bed or transport gasifiers, and many responses received identified the associated volatilisation of alkali species as a potential problem. Specifically, their role in refractory degradation (for refractory-lined gasifiers) and metal corrosion in the gasifier and downstream have the potential to significantly affect their usability in many technologies.

Slagging entrained flow gasifiers often require a minimum amount of mineral matter (as well, of course, of mineral matter that can melt and flow at operating temperatures). The low-ash nature of Victorian brown coals means that an increase in the mineral matter content of the feed will most likely be required for conventional entrained flow gasifiers. The amount of this increase is strongly feedstock- and temperature-specific, and will require careful consideration of the nature (chemistry, cost and preparation) of any additive and how it impacts ash chemistry and the ability for the ash to melt and flow appropriately. This may introduce new concepts to slagging gasifiers such as the recycling of tapped slag to increase the slag volume without unduly affecting slag chemistry.

Whilst not a commonplace technology, it was suggested that a non-slagging mode of entrained flow gasification may be suitable for these reactive, low-ash feedstocks. This is clearly a different approach to the conventional use of entrained flow gasification, offering considerable advantages in terms of gasifier materials and their ongoing maintenance. It takes advantage of the high reactivity of Victorian brown coal and offers the potential for high overall gasification efficiencies.

Such an approach, however introduces a range of potential issues and challenges that are not traditionally associated with entrained flow gasifiers. These include fouling of the gasifier and downstream infrastructure as well as the need for cleanup and removal of downstream particulates. The lower temperatures can also encourage the formation of methane, which is not normally considered a valuable syngas species for catalytic coal-to-products technologies, although the high moisture content of Victorian brown coals may affect the equilibrium content of the syngas favourably in this regard (see Section 4.4).

4.3 Syngas Quality Issues

From a coal-to-products perspective, the respondents agreed that the biggest advantage in moving from air to oxygen blown gasification is the reduction in syngas volume and the subsequent capital and operating cost savings associated with syngas processing. Certainly any system that has significant gas processing plant (i.e. coal to products, but also including power generation with CO_2 capture such as IGCC-CCS) will also benefit from this reduction in syngas volume and increased concentrations of gaseous species.

The single biggest issue identified from a syngas perspective was the link between oxygen blown gasification and higher temperatures (either overall, as in the case of slagging gasifiers, or localised in the gasifier, as in the case of many fluidised beds) leading to increased presence of alkali species in syngas. Increased alkalis has the potential to affect the downstream requirements, both in terms of material selection and longevity, but also in terms of processes required to protect subsequent downstream systems. In particular the use of radiant syngas coolers was seen as potentially troublesome. Gasifiers with water quench systems (which are likely to be seen as advantageous for coal to products as it complements the water-gas shift reactions) may also need materials that are able to withstand alkalis, and while it is not expected that the water quench process will remove all of these troublesome species, a simple water quench system could provide a cost-effective means of primary syngas conditioning and cleaning.

Interestingly, the formation of fume was raised as a potentially-important issue underpinning lignite utilisation at high temperatures. Fume formation arising from alkali-rich inorganic species, and its fate and interaction with syngas handling infrastructure, may require further understating as part of our management of alkalis in high temperature gasification systems.

The suggestion of non-slagging entrained flow gasification (as discussed) has impacts on gas cleaning requirements to ensure suitable syngas quality. A feature of slagging gasifiers is a reduced amount of fine particulates. Non-slagging gasifiers will have all of the mineral matter report as fly ash, and there will need to be plant in place to remove these particulates before the syngas processing steps. The more reducing conditions found in gasification will mean that our knowledge of fly ash from pf combustion of lignites may not be relevant, although some of the outcomes from pilot-scale testing of Australian lignites in the EERC system should provide some useful insights.

4.4 Case Study: Influence of Process Variables on Gasification of Victorian Brown Coals

4.4.1 INTRODUCTION

When assessing the suitability of particular coals for use in gasification technologies, it is important to understand the operating envelopes of the technology of interest and how these relate to the basic feed coal properties. Impacts of coal properties on likely syngas compositions and process mass and energy balances are basic requirement for both technology and coal selection, and for process design and specification. Moisture and ash content, for example, have direct impacts on plant size, capacity, configuration and operating strategies (this is discussed in more detail in Section 5.3). Issues arising from these aspects of plant design cannot be addressed through retrofitting or simple modifications to operating strategies once a plant has been installed.

As part of his contribution to the interpretation and analysis of this work, Maarten van der Burgt provided some preliminary scenario analyses of oxygen-blown gasification of Victorian brown coals. The outcomes of these simulations give us some preliminary insights into the impact of some gasification operating parameters such as temperature and pressure on syngas composition, and also provide some guidance as to the levels of drying that may be required for coal-to-products applications in specific technologies. By their nature, these early assessments are based on assumptions that the coals are able to be converted under the conditions selected—many of the research issues discussed in subsequent sections are required in order to achieve this.

4.4.2 SIMULATION PARAMETERS

Table 6 gives the conditions and definitions used as the basis of the equilibrium process modelling. These are not technology-specific, and have been designed to allow the lower temperature results to be applicable to fluidised bed gasifiers, and the higher temperature results to entrained flow gasifiers, for example.

The proximate and ultimate analyses of the coal used in this simulation are given in Tables A and B (see Appendix).

Conditions	
Temperature of predried coal to gifier	90°C
Temperature oxygen	200°C
Temperature steam moderator	300°C
Oxygen composition (%mole)	99 oxygen, 0.7 argon, 0.3 nitrogen
Transport gas	if not indicated otherwise 100 %mole CO2. 350 kg predried coal to the gasifier per actual m3 transport gas
COS	10% of total sulphur in raw gas leaving the gasifier
NH_3	350 ppmv in raw gas
HCN	350 ppmv in raw gas
Definitions	
Unconverted carbon	% of the carbon in the coal feed to the gasifier
Heat loss from gasifier:	% of the lower heat of combustion of the dried coal feed to the gasifier
Tons are	metric tons (1000 kg)

Table 6: Conditions and definitions used as the basis of the equilibrium process modelling discussed in this section.

4.4.3 OUTCOMES

Temperature

The effect of temperature is given in Table C (see Appendix). For the higher temperatures of 1300–1500°C a water-wall reactor was used with a heat loss of 2% and a 99% carbon conversion. For the lower temperatures of 900 and 1300°C an insulated refractory-lined wall with a heat loss of 0.5% and a 97% carbon conversion was used. The coal to the gasifier is predried to a water content of 20%.

As expected, lower temperatures show a lower oxygen consumption and a higher syngas yield. The lower temperatures are reserved for fluidised bed reactors and the higher temperatures for entrained bed reactors.

Only at temperatures of 1300°C and above is the sensible heat in the syngas theoretically sufficient to dry the coal from 60 to 20 %mass water.

Pressure

As shown in Table D (see Appendix) the effect of pressure is very low. The pressure of the gasification process will therefore be mainly determined by the upstream coal feeding system and/or by the downstream processes.

Because water slurry feeding is out for brown coals a pressure of over 30 bar is not recommended for the high transport gas requirement which increases proportional with the pressure.

Water content in the coal

As can be seen in Table E (see Appendix) the effect of the water content in the coal to the gasifier is of major importance in terms of oxygen consumption, syngas yield, and process efficiency. It also shows that the sensible heat in the gas leaving the gasifier is just sufficient to dry 40% of the water present in the as-received brown coal resulting in a 20 %mass water coal to the gasifier. This implies that the IDG approach of drying the pre-dried coal further by direct contact with the hot syngas is certainly an option.

Extreme drying of the coal to the gasifier in combination with low temperatures

In Table F (see Appendix) the results of some simulations are given for the combination of deeply dried coal to the gasifier in combination with low gasification temperatures. The conclusion is important for the choice of the gasifier. The results show that under all conditions studied no moderator such as steam is required for the gasification. Adding some moderator results in an additional thermal load on the gasifier. In order to maintain the temperature would imply burning valuable syngas with expensive oxygen and is therefore not an option. Such an operation where no moderator is required would mean that pure oxygen is contacted with the dried coal. In entrained gasifiers this can be managed but in fluidised bed gasifiers this would lead to locally very high temperatures and hence in agglomeration of the fluidised material because there is always some carbon present in the circulating ash.

It may be concluded from that the use of fluidised bed gasifiers is not very attractive for the gasification of Victorian brown coals with pure oxygen.

Choice of transport gas and moderator requirements

Three gases can in principle be used as transport gas: N_2, CO_2, and recycled syngas. In almost all dry-feed gasifiers nitrogen is used which is no problem when using oxygen as blast because it is co-produced with oxygen in the ASU. However, it inevitably leads to about 4 %mole nitrogen in the product gas as shown by comparing the gas composition in data columns 3 and 5 in Table C and columns 3 and 4 in Table F (see Appendix). Therefore in all other cases it has been assumed that CO_2 is used as transport gas of the coal. This is required when the synthesis gas is used for other purposes than power generation or ammonia synthesis. One of the reasons that in none of the examples in Tables C –F (see Appendix) a moderator was required is that the transport gas CO_2 is a powerful moderator. When using nitrogen as transport gas combined with a low gasification temperature and a very deep, and therefore probably not realisable, drying of the brown coal feed a small amount of moderator is required as shown in column 5 of Table F (see Appendix). Using cold syngas as transport gas is possible but not very realistic because somewhere between the entrance of the coal feed to the gasifier and the gasifier proper an inert gas is required between the oxidizing atmosphere and the syngas and the only gases available for this purpose are nitrogen and CO_2.

4.4.4 OTHER CONSIDERATIONS

Coal drying

Before gasifying a Victorian brown coal the coal has to be dried to preferably 20% moisture or less. Exergetically this drying is best accomplished with sensible heat of the lowest possible temperature and in a way that the evaporated water can be recovered. If alkali species in the hot gases cannot be removed before an eventual waste heat boiler an attractive option may be to use that sensible heat in the gas leaving the gasifier for partly drying the coal in a co-current direct contact drier as applied in the IDG process. As can be seen in the Tables C–F substantial drying is only possibly at relatively high gasification temperatures in combination with additional pre-drying by other means.

For IGCC power generation air gasification can be considered because in the gas turbine a low Btu gas is advantageous because it results in a low NO_X formation. Moreover air gasification results in the production of double the amount of gas per unit coal intake as the gas contains about 50 %mole nitrogen. Because the gas leaving the gasifier will have the same temperature as a gas produced by oxygen gasification in the same type gasifier, there is about twice the amount of sensible heat present in the gas. This implies that air gasification is almost mandatory for the IDG process because the bulk of the drying of the coal can be accomplished by injecting the slightly pre-dried coal into the gas leaving the gasifier.

Oxygen Purity

For most synthesis processes high purity oxygen (>99 %mole) is required in order to minimise nitrogen build-up during synthesis. In such cases CO_2 is used during pressurising and transport of the coal. This CO_2 is readily available from the CO-shift that is required for all bulk products: Fischer-Tropsch liquids, methanol, Synthol synthesis and SNG. The only exception is ammonia where up to 25 %mole nitrogen must be present in the synthesis gas. This implies that 95 %mole oxygen can be used and nitrogen, available from the ASU, is readily available for pressurizing and transport of the coal to the gasifier. The energy required for the ASU is 250 kWh/ton for 99.5 % pure oxygen and 175 kWh/ton for 95% pure oxygen [34]. This reinforces the notion that the ASU is the major parasitic power consumer in any gasification complex.

Waste Heat Recovery

With high ash melting point brown coals waste heat boilers can be used for power production. Exergy wise this is the best way to use the sensible heat in the hot gases leaving the gasifier. Quenching of the gas to a temperature of about 900^oC is required to convert the slag to a non-sticky dry material. In case of an entrained-flow slagging gasifier, a gas quench is required for optimum use of the sensible heat. A water quench can also be used but this should generally only be considered in case of a CO-shift downstream of the syngas cooler.

When the coals have an ash that is rich in alkali metals, syngas coolers are not recommended because of the inevitable fouling problems. This means that for the majority of Victorian brown coals the sensible heat in the gases leaving the gasifier can only be used for direct evaporation of water or for drying of coals with a high moisture content. A well known example of the latter is the IDG process. A direct water quench increases the water content in the syngas. In case a subsequent CO-shift is required it should be tried to keep the water in the gas during the removal of solids from the gas.

Although the raw syngas from partly dried brown coals has a relative high water content of 10–20% this is not enough for a subsequent CO-shift. For the economics of a brown coal gasification process in combination with a CO-shift it is essential to use a water quench or the IDG direct drying process. An expensive waste heat boiler is only attractive in the case of power generation. For brown coals with a low alkali content this may not be a problem. When gasifying an alkali rich coal it could be necessary to flux the coal with (a low cost) aluminosilicate sorbent that chemically react with the alkali species in the ash under reducing conditions [35].

Ash and Slag Management

In fixed bed and slagging entrained gasifiers the ash and slag can be readily removed from the gasification system. In fluidised bed gasifiers the ash is generally removed together with some unconverted carbon. Also in non-slagging entrained gasifiers the ash can be readily removed with one exception and that is when the hot syngas leaving the gasifier is used to (partially) dry the brown coal. In this case it is difficult to isolate the ash from the dried coal and hence ash can build-up in the gasifier system. This may be avoided by a cyclone upstream of the coal injection point. This cyclone will have to operate at temperatures of about 800-900^oC. To conserve all the sensible heat for drying in the gas leaving the gasifier a gas quench is mandatory. Then the heat available for drying remains unchanged although the hot gases have on average a few hundred degrees lower temperature.

Syngas Management

In most of the calculations reported in Tables C–F (see Appendix) the gases leaving the gasifier have a CO content of 50–60%mole and a hydrogen content of 25-–0 %mole whereas the yield of CO + H_2 is about 300000 Nm^3/1000 As Received (a.r). brown coal. Hence on average 200000 Nm^3 CO and 100000 Nm^3 H_2/1000 ton a.r. brown coal are produced. The water content in the 1000 ton a.r. brown coal amounts to 600 ton corresponding to 747000 Nm^3 steam/ 1000 ton a.r. brown coal. Theoretically 25–30 % of the water in the brown coal is required to shift all the CO to hydrogen. Only for the production of pure hydrogen and ammonia all the CO has to be shifted. For Fischer-Tropsch liquids and methanol only half of the CO has to be shifted and for SNG (methane) about 63%.

5 Analysis

5.1 Issues facing O_2 Blown Gasification of Victorian Brown Coals

The previous section has given an overview of some of the gasification industry and research community's perspectives on issues that might be faced by gasification of Victorian brown coals using oxygen-blown technologies. Some of these responses considered the existing technologies that are currently commonplace in oxygen blown gasification applications; others also considered new technology variants (such as non-slagging entrained flow gasification) that might be suitable for the low ash, highly reactive, alkali-rich brown coals of Victoria.

Clearly, the two aspects of reduced syngas volume and higher gasification temperatures are fundamental to most of the issues identified, both in the gasifier and in downstream systems. These include gas velocities and their impacts on gasifier performance, the formation of alkalis and their impact on gasifier and syngas processing systems, and a range of issues associated with ash stickiness, agglomeration, and slag formation and flow behaviour, for which there is little research or industry experience.

The relative importance of these issues is strongly dependent on the gasification technology of choice, and summarised accordingly in Table 7. Many of these issues are dependent on coal properties and coal behaviour under specific gasification conditions: the lack of understanding of these properties in the context of Victorian brown coals is translated to R&D needs in the next section. Some of these issues are not directly related to coal properties (for example the need for adequate syngas volumes for drying in particular technologies)—the research requirements here are in understanding the overall performance of systems based on different technologies as a function of different degrees of coal pre-treatment, syngas recirculation, etc.

In considering R&D needs to support the development of a Victorian brown coal to products industry, therefore, the following outcomes of the literature review and industry survey are important:

- Industrial-scale gasification of lignites is usually performed using fixed or fluidised bed gasifiers. More recently the growth of coal-to-products applications has seen fixed-bed and entrained flow technologies also deployed. These lignites, however, differ significantly from Victorian brown coals.
- Most literature R&D in the context of lignite gasification is in support of fluidised bed gasification and fixed bed gasification. Victorian brown coal gasification research is generally aimed at their use in air blown fluidised beds.
- Research addressing most of the issues raised in this work in terms of moving from these applications to O_2 blown applications is scarce.
- There is very little available industry experience or supporting research for entrained flow gasification of Victorian brown coals, and none for fixed bed gasification.
- Lack of R&D or industry experience in the areas of non-slagging entrained flow gasification (for any coal types, not just Victorian brown coals).

	Reduced syngas volume	Increased temperatures (localised or overall)	Other
Generic	Is their sufficient syngas in systems that rely on it for coal drying?	Increased alkali release and the impact this might have on coal performance, corrosion and degrading of gasifier components, gas cleaning, and GtL systems.	
Fixed bed		Dry bottom: agglomeration at hotspots impacting ash removal Alkali corrosion of moving parts associated with ash removal systems	All: Ability for Vic. Brown coals to form a supported and permeable fixed bed. Formation of fines. Slagging: ability for Vic. Brown coals to form tappable slags.
Fluidised bed	Ensuring bed fluidity whilst managing hot spot formation and requirements for steam addition	Agglomerate formation at hotspots. Significant issue affecting gasifier operability. Higher temperatures leading to alkali release (impacts on conversion?).	
Transport	Ensuring adequate transport of particles with reduced gas flow (whilst avoiding ash softening or agglomeration).	Managing steam addition to avoid ash softening and alkali release within the constraints of overall gasifier performance.	Low ash content and being able to manage the 'solids inventory' of the gasifier
Entrained Flow	None expected: slagging entrained flow gasifiers have been designed to operate under O2 blown conditions, reduced gasifier size incorporated into design.	Alkali release at slagging temperatures is expected to be high and create problems with refractories or metallic gasifier and downstream (syngas handling) components. Novel, non-slagging variants will need to manage steam and coal flows to avoid ash melting (this is a new concept for EFGs).	Existing slagging variants may have ash requirements above the levels of ash in VBCs. Vic brown coals may not be able to form a stable, tappable slag (either due to ash chemistry or low ash levels). Novel, non-slagging variants will have new requirements for gas cleaning, especially particulates (with different chemistry to pf combustion fly ash). Methane in syngas may be an issue.

Table 7: Issues matrix for the use of Victorian brown coals in oxygen-blown gasifiers, based on responses received from the international gasification community.

5.2 Research Gaps and R&D Requirements

There are some clear issues that need to be understood and addressed before Victorian brown coals can be effectively and reliably used in oxygen-blown gasification systems. In general, these knowledge gaps arise due to the lack of experience of using Victorian brown coals in technologies commonly used in coal-to-products applications, the increase in temperatures that oxygen-blown operation may lead to, and the decrease in syngas volume produced as a result of moving away from air-blown gasification. These manifest themselves in different ways depending on the gasification technology of interest.

The ability to be predictive about coal behaviour in a range of technologies relies on the integration of good quality, transportable data regarding gasification fundamentals with sound gasification and gasifier models, which incorporate the required technology-specific features. These models then feed into system and process modelling tools to compare different technology variants, the relative economics of systems based on these technologies, and consequently their 'pros and cons' as technology choices for coal to chemicals and liquid fuels applications based on specific feedstocks. For such process modelling to be of value, however, they will need to incorporate many of the outcomes of the research gaps identified below.

Pilot-scale testing is an important component of research supporting coal use in particular technologies. Such testing provides insights into coal suitability for specific technologies and validation of many of the research outcomes, yet rarely supports decision-making regarding other technologies. It is of most use, therefore, once laboratory work has identified particular technology variants to which coals are most suited. Victorian brown coals have been tested at pilot scale as part of the development of some coal-to-products projects; however the data from these tests are not available, and in any case, are not supported by coordinated laboratory investigations. Engagement and collaboration with international research groups and technology vendors will be required.

The rest of this section details some technology-specific research gaps and R&D requirements supporting the use of Victorian brown coals in coal-to-products applications.

5.2.1 OXYGEN BLOWN FLUIDISED BED GASIFICATION

As evident by the outcomes of the literature review section, fluidised bed gasification of lignites (including Victorian brown coals) has been the subject of considerable research in Australia and internationally. As discussed, most of this has been focussed on air-blown (or oxygen-enriched) gasification. There are some clear issues that have been identified in previous sections of this report, however, that remain to be addressed in the context of O_2 blown fluidised bed gasification.

These include:

- Understanding tendency for Victorian brown coals to form agglomerates around high temperature zones of O_2 injection in fluidised beds. This will rely on an understanding of mineralogy, phase chemistry, technology specific operating conditions, and CFD modelling outcomes incorporating coal conversion data to help manage steam injection rates.
- Understanding interactions between bed fluidity, gas velocities, and steam requirements for lower gas volume systems.
- Carbon elutriation. We have seen that fluidised beds already have significant issues with carbon elutriation arising from fines formation. Localised high temperatures and subsequent alkali release (and perhaps carbon annealing) may lead to less reactive chars and further compound issues regarding unburnt carbon in ash.

5.2.2 OXYGEN BLOWN TRANSPORT GASIFIERS

The transport gasifier technology is a relatively-new gasifier variant designed for air-blown gasification of low rank coals, and is intended to overcome some of the limitations of bubbling fluidised beds (in particular the low carbon conversion arising from fines elutriation). Research needs for oxygen blown gasification of Victorian brown coals in transport gasifiers are therefore similar to some for bubbling fluidised beds, although some aspects are believed to be less important due to inherent design principles of the transport gasifier. Research needs for the transport gasifier from a Victorian brown coal perspective must also include more general characterisation measurements and model applications to support the use of these coals in this relatively new technology.

Research gaps in this context are therefore:

- Measurement and modelling work using fundamental properties of Victorian brown coals (devolatilisation, conversion, mineral matter behaviour) to characterise them for use in the relatively-new transport gasifier. This will be important to understand the impacts of different degrees of drying on system performance and efficiency.
- The point above will also support studies matching steam addition requirements to mineral matter behaviour and coal conversion reactivity to ensure proper temperature management (and minimise alkali release and ash agglomeration issues).
- Understanding the impacts of low ash on technology requirements for particular solids loadings, and assessing the need for addition of material as part of the feed.
- Long duration (fully) oxygen-blown pilot-scale testing of Victorian brown coals in transport gasifier facilities, building on the work reported in the literature review section. This is particularly important to validate many of the research outcomes above, but also to generate important data to support the design of full-scale coal to products systems.

These research gaps will need to be addressed in collaboration (or at least consultation) with the technology vendor and the research scale facilities that exist in the US.

5.2.3 FIXED BED GASIFIERS

Fixed bed gasifiers are perhaps the oldest type of gasifier, and there is some modern industrial-scale experience at using fixed bed gasifiers for lignite-to-synfuels applications. There are, however, some important feedstock properties that make coals suitable for use in fixed bed gasifiers, and these are primarily related to strength and structure: coals must be strong enough to support the weight of the bed, whilst creating a sufficiently porous bed to allow reactant and product gas (and in the case of slagging fixed beds, the liquid slag) to flow as required. There is very little (if any) research into the use of Victorian brown coals in such systems.

Research gaps, therefore, in the context of Victorian brown coals include:

- Large-particle devolatilisation and char formation behaviour under slow heating rate conditions
- Understanding the porosity, structure, and strength of Victorian brown coals and their chars under such conditions
- Understanding of the fragmentation tendency of large particles of Victorian brown coals—as received and briquetted—and their chars formed under these conditions
- Application of 'intrinsic' gasification kinetics to large particles (where pore diffusion is significant over wide temperature ranges). This requires good quality laboratory data and reasonably-detailed insights into the structure and morphology of Victorian brown coal chars formed under these conditions
- Slag formation and flow behaviour (for slagging fixed beds).

5.2.4 ENTRAINED FLOW GASIFIERS

Whilst entrained flow gasification has been the technology of choice for many of the proposed Victorian brown coal to product projects, Victorian brown coal use in entrained flow gasifiers is not commonplace. There have been some project-specific investigations supporting their use in particular technologies; however, the fundamental data to allow more widespread application are not available, and in any case, are unlikely to be suitable to answer many of the R&D needs listed below.

R&D requirements for Victorian brown coal use in entrained flow gasifiers include:

- Studies of fine particle devolatilisation, char formation and reactivity behaviour, coal conversion and ash behaviour at the high heating rates, pressures, and temperatures found in entrained flow gasifiers (for Victorian brown coals).
- The integration of these data into wider process models that reflect coal-specific behaviour, to allow effects of different drying levels and technology variants to be assessed
- Consideration of the value of gasifying such a reactive feedstock at temperatures above the slag melting point. The outcomes of the first two points above, incorporated into a gasification modelling framework, is required here.

Following on from the last point, and building on some of the responses received from the gasification community, the development or adaptation of a novel non-slagging entrained flow gasifier is a potentially significant area of research which may be of value to the effective utilisation of Victorian brown coals. Consideration of the potential value of such a technology development will need to consider:

- A cost benefit analysis of the cheaper materials and lower operating costs associated with lower temperature gasification compared with the need for additional particle removal and gas cleaning, as well as the potential for formation of high levels of methane. Such an analysis will require outcomes of many of the research areas listed above.
- The impact of relatively-low temperatures on gasifier size and design (i.e. lower temperatures will require larger gasifiers). Again, this will require outcomes of fundamental studies of the gasification of fine particles of Victorian brown coals.
- Properties of gasification fly ash (which is expected to be distinct from combustion fly ash) from Victorian brown coals and the impacts on gas cleaning requirements
- Partitioning of the trace elements in brown coal into slag and gas phase

5.2.5 DOWNSTREAM OF THE GASIFIER

There are fewer issues expected downstream of the gasifier in a move from air blown to oxygen blown gasification for the production of chemicals and liquid fuels. We have discussed the benefits of oxygen-blown gasification in terms of capital and operating costs of the syngas cleaning and processing systems. Clearly, the role of some degree of temperature increase on the potential for enhanced release of alkali species during gasification is the main factor influencing downstream syngas processing research needs. We have also mentioned above the potential for needing to mange 'gasification fly ash' from novel, non-slagging entrained flow technologies.

Research gaps in this context, therefore, include:

- Development of materials resistant to corrosion and degradation from alkali vapours and fume. This will have applications in radiant syngas coolers, gas filtration systems, etc.
- Fundamental research into alkali behaviour at high temperatures (e.g. fume formation) and how this links to its reactivity with refractory and metal components.
- High temperature particulate removal systems (in particular for power generation systems with integrated CCS), in particular those suitable for alkali-containing gas streams
- Utilisation options for gasification ash and slag from Victorian brown coals
- Understanding of the limits of gas cleaning systems for alkali species, and therefore assessing impacts on current (i.e. solvent) and advanced (e.g. membrane-based) gas separation systems

5.3 Impact of Research Outcomes

A general theme in the outcomes of the review and industry survey work in this report is the need for the ability to understand Victorian brown coal performance in a range of different gasification technologies. This is driven by the unique properties of Victorian brown coal, and the degree to which that impacts the ability of related research on bituminous coals and other lignites to be applied to the Victorian brown coal case.

The importance of understanding the impact of coal properties was made clear during an EPRI coal workshop in 2009 whereby research needs in the context of gasification for IGCC were discussed, and linked to outcomes and learnings from international demonstration activities. The outcomes from this workshop provide some insights into research issues that, if left unaddressed, have the potential to impact significantly on the cost and operability of gasification-based systems (these discussions were particularly focussed on entrained flow gasification, but the implications can be applied to other technologies as appropriate). These are summarised in Table 8, which is based on a previous discussion with EPRI.

Coal Property or Analysis	Data/knowhow required for:
Total Moisture	Coal Receiving & Handling, Plant Water Balance
Surface Moisture	Coal Drying*, Bin & Chute Design (Plugging)
Inherent Moisture	Achievable Slurry Concentration for Slurry Feed, ASU, & General Plant Design**
Top Size, Size Distribution	Grinding/Milling Equipment**, Bin & Chute Design (Plugging)
Ash Content	Slag Removal System**, Ash Handling System*
Heating Value-As Received	Coal Receiving & Handling*
Heating Value-DAF Basis	General Plant Design and ASU*
Ash Trace Elements	Carbon Bed Design*
Proximate Analysis-VM & FC	Coal Reactivity for Coal Feed, Gasifier Size, Ash Handling & ASU**, Achievable Slurry Concentration (Coke) for Slurry Feed, ASU, & General Plant Design**
Special Reactivity Test	Coal Reactivity for Coal Feed, Gasifier Size, Ash Handling & ASU**
Ultimate Analysis – C,H,O,N	General Plant Design
Ultimate Analysis – S	AGR and SRU**
Ultimate Analysis – Cl	Brine Concentration**
Ash Composition – Majors	Slag Viscosity → Operating Temperature Selection for Gasifier Size, Ash Handling, ASU**, Syngas Cooler Fouling and Plugging, Flux**
Ash Fluid Temperature	Slag Viscosity → Operating Temperature Selection for Gasifier Size, Ash Handling, ASU**, Flux**

** = Extremely important-missing the range could severely limit plant capability or fuel options

* = Important but missing the range somewhat could probably be accommodated with reasonable design contingencies and/or by adjusting operating parameters for the affected system.

Table 8: Coal property impacts on gasifier design and operation [36]. ASU = air separation unit, AGR = acid gas removal unit.

Of particular importance in this regard was the impact of poor slagging behaviour of coals on the entire system operation. Most notable is the need to operate the gasifier at higher temperatures or with excessive fluxing to successfully manage the slag in the gasifier. This has direct implications on gasifier efficiency and on oxygen demand (and costs) and can directly limit plant capacity. Excessively high operating temperatures also affects plant life and maintenance requirements – both within the gasifier and in downstream gas cooling and cleaning systems. EPRI made the point that Australia had developed a leading reputation in the field of coal mineral matter assessment and slag flow behaviour and that this area was likely to be of continuing importance for the demonstration projects.

A striking point to emerge from this analysis is the potential impact of relatively fundamental coal properties on many of the process operations comprising the gasification (and, here, the wider IGCC system). Items marked by double asterisks (**) in Table 8 are particularly important as they may create issues that cannot be accommodated through simple changes to operating conditions and hence will become limiting factors for the fixed plant design. Items marked with a single asterisk (*) are also very important as managing these issues can incur significant costs and/or operating boundaries that can seriously affect plant capacity, efficiency and performance. These impact factors give some guidance as to the relative importance of the R&D needs discussed in this work in the context of Victorian brown coal use in gasification technologies for coal-to-products applications.

5.4 Summary

The majority of research needs in the context of a move from air blown to oxygen blown gasification relate to the performance of Victorian brown coals in new technologies or those previously not considered (such as transport gasifiers, fixed bed gasifiers, and entrained flow gasifiers) and in managing the impact of alkali release arising from the higher temperatures that are likely to be experienced. Hotspot formation and their impacts are also important for fluidised bed gasifiers, although some of the inherent issues with this technology type may mean that alternatives are more suitable for large-scale coal-to-products applications. The reduced volume of oxygen blown gasifiers and the reduction in the volume of syngas generated are features leading to reductions in capital costs; however, they will also affect the fluidisation or transport properties of fluidised beds, and possibly the effectiveness of any drying process that relies on this syngas.

There are very few publicly-available reports of pilot-scale testing of Victorian brown coals, with the exception of studies in the 1990s using an air-blown fluidised bed gasifier. Engaging with international research groups such as those in Germany, Korea, Japan and the US will allow more widely applicable pilot-scale testing of Victorian brown coals in specific technologies.

There exist laboratory and larger-scale techniques that have been used extensively to characterise and assess high rank coals for use in entrained flow gasifiers [37], and these have been shown to provide useful insights into the performance of coals in specific technologies [38]. It would be prudent to build on the outcomes of such bituminous-coal-based R&D [3, 39, 40] in any assessment of Victorian brown coals, and ensure that appropriate engagement is made with international R&D in this area (in particular in the US and Germany).

6 Conclusions and Recommendations

6.1 Victorian Brown Coals to High Value Products

Gasification-based systems offer efficient and flexible strategies for the conversion of a wide range of feedstocks (including Victorian brown coals) into high value products. There are international examples of lignites being gasified for the production of synfuels, and there exist project proposals in Australia for Victorian brown coals to be used in the production of liquid fuels and fertilisers.

One of the challenges with the development of gasification-based projects for conversion of Victorian brown coals is the lack of knowledge and understanding of the performance of these coals in the range of gasification technologies available. While R&D supporting their use in fluidised bed gasifiers is extensive, there are some issues associated with their use in these technologies that may make alternatives attractive. Furthermore, gasification for chemicals and liquid fuels production is usually based on an oxygen-blown gasification technology and the vast majority of research into Victorian brown coal gasification has been in support of air-blown systems.

There is very little available R&D that can be applied to assessing their suitability for use in fixed-bed, transport, or entrained flow gasifiers, or in the specification and design of such plant. It is even difficult to assess the impact of moving from air to oxygen in the operation of fluidised bed gasifiers, considering potential hotspot formation, bed fluidity, steam requirements, etc. This complicates technology selection and gasifier design, and increases the risk and cost of any such proposal.

Based on a review of the available literature and consultation with Australian and international industry and research specialists, this report details the range of uncertainties associated with the gasification of Victorian brown coals for coal-to-products applications. While the details are wide-ranging and technology-specific, underlying themes are:

- There are insufficient fundamental, transportable data regarding coal devolatilisation, char formation, char reactivity and ash/slag behaviour to allow a widespread assessment of the suitability of Victorian brown coals for use in 'non-traditional' technologies such as entrained flow, transport, or fixed bed gasifiers.
- The likelihood of increased temperatures—either overall (for slagging gasifiers) or locally (for fluidised beds)—introduces a range of potential issues related to alkali release and subsequent behaviour.
- The reduced gas volume of O_2-blown gasification compared with air-blown gasification can have impacts on pre-drying effectiveness, as well as on gasifier design and operability (design volume of entrained flow gasifiers, fluidity and transportability of fluidised bed gasifiers).

In support of the development of new opportunities for Victorian brown coals, and to provide a greater level of understanding of the role of coal performance in subsequent systems, a coordinated R&D program—including pilot-scale testing and demonstration—is required to address these issues.

6.2 Recommendations

This report has shown that an acceleration of the development of Victorian coal-to-products projects requires a better understanding of the performance of Victorian brown coals in a range of gasification technologies, in particular those operating in oxygen-blown configurations. This work has also distilled the information received from international industry and research experts and a review of the literature to highlight areas where targeted research and development will significantly advance the extent to which Victorian brown coals can be assessed for, and used in, these different gasification technologies.

It is recommended that a coordinated R&D program be undertaken to develop a clear understanding of the gasification fundamentals of Victorian brown coals, generating transportable data that can be used to assess their suitability for a range of possible technologies including fixed bed, entrained flow, and transport gasifiers. This work should build on the extensive R&D that has been undertaken in support of fluidised bed gasification, generating insights into aspects associated with use of pulverised and lump coal (as opposed to the 'granulated' particles used in fluidised beds), and the temperatures, pressures, and residence times relevant to these technologies.

Similarly, it is recommended that a coordinated R&D program be undertaken to provide insights into Victorian brown coal mineralogy and inorganic species transformation at higher temperatures than those experienced in fluidised bed applications, in particular addressing the release of alkalis, and to develop materials and technology solutions to their management. This work will need to build on the significant volume of work that has been undertaken in support of fluidised bed gasification of Victorian brown coals, whilst placing particular emphasis on the role of higher temperatures arising from O_2-blown gasification.

It is important to ensure that any R&D in support of Victorian Brown Coal gasification builds on the R&D outcomes from extensive Australian research supporting the use of bituminous coals in emerging gasification technologies, and the existing work studying gasification of Victorian brown coals. While the drivers and motivations for much of that work are different to those identified here, that work led to the development of laboratory infrastructure and test procedures that have been shown to be important in the quantification of coal gasification performance in real systems.

These outcomes all support the development of gasifier models which are able to integrate coal-specific performance into process models based on different gasification technologies. This is an important aspect to assessing coals for use in different technologies, and will provide an important input into techno-economic considerations of the most feasible products (such as methanol, H_2, synthetic natural gas, etc).

It is also recommended that relevant international experience be leveraged as appropriate. There are research groups in Germany and the USA (and, of course, elsewhere) actively researching lignite gasification at laboratory and pilot scale, with the view towards conversion of lignites to higher value products. Notwithstanding the fact that German and US lignites differ significantly from the brown coals of Victoria, cooperation and collaboration with research groups such as these will provide access to research infrastructure not available in Australia.

Some consideration should be given to the merit of a 'dry ash oxygen-blown entrained flow gasifier', in the context of the outcomes of the research activities recommended above. This would need to be a cost–benefit analysis based on some coal-specific gasification and process modelling work that incorporated aspects of coal conversion and mineral matter behaviour, allowing the reduction in capital and material costs to be offset against the requirements for particulate removal and management of ash slagging and fouling, and the impacts on syngas quality.

References

1. D J Harris. *Gasification and Syngas R&D: Underpinning clean and efficient energy products from fossil and renewable fuels*, 6th International Freiberg Conference on IGCC and XtL Technologies, Dresden, Germany (2014).

2. H Timmermann. *Mk Plus^{TM}: The Next Generation Lurgi FBDB^{TM} Gasification*, 5th International Freiberg Conference on IGCC & XtL Technologies, Leipzig, Germany (2012).

3. D J Harris and D G Roberts. *ANLECR&D Scoping Study: Black Coal IGCC,* CSIRO Report EP103810 Prepared for ANLECR&D (http://www.anlecrd.com.au/publications) (2010).

4. A Lowe, L Juniper, D J Harris and N Simento. *CCSD Coal Utilisation Compendium,* CRC for Coal in Sustainable Devleopment (2008).

5. Y Ishibashi and O Shinada. *First Year Operation Results of CCP's Nakoso 250 MW Air-Blown IGCC Demonstration Plant*, Gasification Technologies Conference, Washington DC (2008).

6. C Higman and M van der Burgt. *Gasification, 2nd Edition*. Gulf Professional Publications, Burlington, MA (2008).

7. A Darby. *Compact Gasification Development and Test Status*, Gasification Technologies Conference, Washington DC (2010).

8. A J Minchener. *Coal-to-oil, gas and chemicals in China,* (2011).

9. Z Zhou. *Opposed Multi-Burner Gasification: Development, Demonstration and Applications*, 5th International Freiberg Conference on IGCC & XtL Technologies, Leipzig, Germany (2012).

10. Industrial Info Resources. *Greengen - China's First IGCC demo Project 'Inaugurated'*. (2012).

11. M Gräbner and B Meyer. *Introduction of a Ternary Diagram for Comprehensive Evaluation of Gasification Processes for High Ash Coals*, 2011 International Conference on Coal Science and Technology, Oviedo, Spain (2011).

12. D J Brockway. *Power Generation Technologies for Low-Rank Coals*, Developments in Chemical Engineering and Mineral Processing **7(5/6)** 483-500 (1999).

13. C-Z Li. *Advances in the Science of Victorian Brown Coal,* Elsevier Ltd, Oxford, UK (2004).

14. D G Roberts, J Bachmann, B Garten, M A Kochanek and D J Harris. *Gasification Behaviour of Rhenish Lignite: Laboratory Characterisation*, 5th International Conference on IGCC & XtL Technologies, Leipzig, Germany (2012).

15. J Bachmann, B Garten, D G Roberts, M A Kochanek and D J Harris. *Gasification Characteristics of Rhenish and Victorian Lignites: Effects of Devolatilisation Conditions on Char Reactivity and Structure*, Second International Symposium on the Sustainable Use of Low Rank Coal, Victoria, Australia (2012).

16. M A Kochanek, D G Roberts, B Garten, S Russig and D J Harris. *A Systematic Study of the Effects of Pyrolysis Conditions on Coal Devolatilisation*, 2011 International Conference on Coal Science and

Technology, Oviedo, Spain (2011).

17. D M Quyn, H Wu and C-Z Li. *Volatilisation and catalytic effects of alkali and alkaline earth metallic species during the pyrolysis and gasification of Victorian brown coal. Part I. Volatilisation of Na and Cl from a set of NaCl-loaded samples*, Fuel **81(2)** 143-149 (2002).

18. D M Quyn, H Wu, S P Bhattacharya and C-Z Li. *Volatilisation and catalytic effects of alkali and alkaline earth metallic species during the pyrolysis and gasification of Victorian brown coal. Part II. Effects of chemical form and valence*, Fuel **81(2)** 151-158 (2002).

19. H Yeasmin, J F Mathews and S Ouyang. *Rapid devolatilisation of Yallourn brown coal at high pressures and temperatures*, Fuel **78** 11-24 (1999).

20. H Yeasmin. *Measurement and Modeling of Kinetics of Devolatilisation of Low-rank Coal at Elevated Pressures and Temperatures*. PhD Thesis, Monash University (1998).

21. D Marney. *Investigation of Pyrolysis of two Low-rank Coals at Elevated Pressures*. PhD Thesis, Swinbourne University (2002).

22. D J Harris and I W Smith. *Intrinsic Reactivity of Petroleum Coke and Brown Coal Char to Carbon Dioxide, Steam and Oxygen*, Proceedings of the Combustion Institute **23** 1185-1190 (1990).

23. A Y Ilyushechkin, D G Roberts, M Kaiser and D J Harris. *Evaluation of the slagging behaviour of Australian and German Low Rank Coals*, 6th International Freiberg Conference on IGCC & XtL Technologies, Dresden, Germany (2014).

24. C Schneider, D G Roberts, L N Fogliaresi, M J Langley, M A Kochanek and D J Harris. *High Pressure Entrained Flow Gasification Studies of Rhenish Lignite*, 6th International Freiberg Conference on IGCC and XtL Technologies, Dresden, Germany (2014).

25. D-K Zhang and A Poeze. *Variation of sodium forms and char reactivity during gasification of a South Australian low-rank coal*, Proceedings of the Combustion Institute **28(2)** 2337-2344 (2000).

26. D P Ross, C A Heidenreich and D K Zhang. *Devolatilisation times of coal particles in a fluidised-bed*, Fuel **79(8)** 873-883 (2000).

27. P J Ashman, A Kosminski, S Button and P Mullinger. *Gasification of Victorian lignite in a laboratory scale fluidised bed gasifier*, 5th Asia-Pacific Conference on Combustion (2005).

28. H Wu, D M Quyn and C-Z Li. *Volatilisation and catalytic effects of alkali and alkaline earth metallic species during the pyrolysis and gasification of Victorian brown coal. Part III. The importance of the interactions between volatiles and char at high temperature*, Fuel **81(8)** 1033-1039 (2002).

29. S P Bhattacharya. *Fluidized Bed Pyrolysis and Gasification Tests at the University of North Dakota Using Victorian Low-Rank Coal,* Report no 97021, CRC for New Technologies from Lignite (1999).

30. S P Bhattacharya. *Gasification Performance of Australian Lignites in a Pressurized Fluidized Bed Gasifier Process Development Unit Under Air and Oxygen-enriched Air Blown Conditions*, Process Safety and Environmental Protection **84(6)** 453-460 (2006).

31. A Campisi, *Pers. Comm.* (2014).

32. F Woskoboenko, T Johsnon, A Campisi, J Holden and S Hodges. *IDGCC and Fundamental Studies*, 7th Japan-Australia Joint Technical Meeting on Coal, Newcastle (1997).

33. S Ariyapardi, P Shires, M Bhargava and D Ebbern. *KBR's Transport Gasifier (TRIG^{TM}) - An Advanced Gasification Technology for SNG Production from Low-Rank Coals*, 25th Annual International Piitsburgh Coal Conference, Pittsburgh, PA (2008).

34. G Beysel and T Schueler. *The Proven Cryogenic Air Separation Process Adapted to the Needs of CCS (IGCC and Oxyfuel)*, 10th European Gasification Conference, The Netherlands (2010).

35. A Waindrich and M Müller. *Alkali removal at 1400°C under gasification conditions*, Fuel **116** 889-893 (2014).

36. N A Holt, *Pers. Comm.* (2005).

37. D G Roberts, A Y Ilyushechkin and D J Harris. *Linking Laboratory Data with Pilot-Scale Coal Gasification Performance. Part 1: Laboratory Characterisation*, Fuel Processing Technology **94(1)** 86-93 (2012).

38. D G Roberts, A Y Ilyushechkin, A Tremel and D J Harris. *Linking Laboratory Data with Pilot-Scale Coal Gasification Performance. Part 2: Pilot-Scale Testing*, Fuel Processing Technology **94(1)** 26-33 (2012).

39. D Harris. *Coal Performance in Gasification.* In: A Lowe, L Juniper*, et al.* (Eds.) CCSD Coal Utilisation Compendium, Australian Black Coal Utilisation Research Limited, (2008).

40. D J Harris and D G Roberts. *Coal Gasification and Conversion.* In: D Osborne (Ed.) The Coal Handbook - Towards Cleaner Production. Volume 2: Coal Utilisation, Woodhead Publishing, Cambridge, UK (2013).

Acknowledgements

The authors are grateful to Maarten van der Burgt who brought his considerable gasification knowledge and expertise to this project. Maarten's first-hand experience with a range of gasification technologies, and decades of experience in understanding coal behaviour in these technologies, has allowed the outcomes of this work to be interpreted in the context of real issues expected with gasification of Victorian brown coals in coal-to-products systems.

The authors would also like to thank the following people (in no particular order) for their time and effort in providing information used in the production of this report, either in response to our survey, during in-person meetings, or via email and telephone:

Simon Moongeun Jung and Yongjeon Kim, SK Innovation Pty Ltd (Korea)

Yongseung Yun, Institute for Advanced Engineering (Korea)

Arie Geertsema, Geert Tech LLC (USA)

Hartmut Spliethoff, Technical University of Munich (Germany)

Qianlin Zhuang, KBR (USA)

Christopher Higman, Higman Consulting (Germany)

Kevin Whitty, University of Utah (USA)

David Brockway, Research Advisory Committee BCIA (Australia)

Johan van Dyk, African Carbon Energy, formerly Sasol (South Africa)

Timothy Saunders, Aerojet Rocketdyne (USA)

Jason Laumb and Joshua Stanislowski, EERC North Dakota (USA)

Geoff Gay, TRUenergy

Anthony Campisi, HRL Technology Pty Ltd

The authors would also like to thank Tao Xu (Monash University) for his contributions to the literature review sections of this report.

Appendix

This appendix contains the tables of coal analyses and modelling results discussed in Section 4.4.

Table A: Proximate analysis used in the simulation

Proximate analysis	as received basis
Fixed carbon, mass%	18
Volatile matter, %mass	19
Moisture, %mass	60
Ash, %mass	3
Total, %mass	100

Table B: Ultimate analysis used in the simulation

Ultimate analysis	Daf basis
Carbon, %mass	68
Hydrogen, %mass	5
Oxygen, %mass	26
Sulphur, %mass	0.5
Nitrogen, %mass	0.5
Total, %mass	100.0

Table C: Effects of Temperature

Water content,% mass	20	20	20	20	20
Temperature, °C	900	1100	1300	1500	1300
Pressure, bar	30	30	30	30	30
Unconverted carbon, %	3	3	1	1	1
Heat loss from gasifier, %	0.5	0.5	2	2	2
A.R. Coal, ton	1000	1000	1000	1000	1000
Dried coal, ton	500	500	500	500	500
Transport gas (CO_2), ton	65	65	65	65	41 N_2
Oxygen (99%mole), ton	234	253	286	307	282
Moderator steam	0.00	0.00	0.00	0.00	0.00
Total in, ton	799	818	851	872	823
Raw product gas, ton	761	780	818	839	790
Unconverted carbon, ton	8	8	3	3	3
Ash/slag, ton	30	30	30	30	30
Total out, ton	799	818	851	872	823
Raw gas composition, %mole					
CO	50.15	49.84	49.12	48.14	47,60
CO_2	9.27	9.58	10.74	11.71	8,29
CH_4	0.00	0.00	0.00	0.00	0.00
H_2	29.72	26.81	23.36	20.85	25,49
H_2O	10.28	13.18	16.16	18.67	14,04
N_2	0.21	0.21	0.22	0.22	4.18
A	0.14	0.15	0.17	0.18	0.17
H_2S + COS	0.16	0.16	0.16	0.16	0.16
NH_3 + HCN	0.07	0.07	0.07	0.07	0.07
Total	100.00	100.00	100.00	100.00	100.00
Molecular mass, kg/kmole	20.77	21.28	22.07	22.63	21.34
Sensible heat raw gas, GJ	751	1031	1347	1664	1318
Energy required for predrying the a.r.coal, GJ/1000 ton	1351	1351	1351	1351	1351
Nm^3 CO + H_2 per 1000 a.r. feed	655758	629394	602202	573295	
Cold gas efficiency, LHV basis	83.5	80.4	77.3	73.8	77.6

Table D: Effects of Pressure

Water content,% mass	**20**	**20**	**20**
Temperature, °C	**1300**	**1300**	**1300**
Pressure, bar	**20**	**30**	**40**
Unconverted carbon, %	**1**	**1**	**1**
Heat loss from gasifier, %	**2**	**2**	**2**
A.R. Coal, ton	**1000**	**1000**	**1000**
Dried coal, ton	**500**	**500**	**500**
Transport gas (CO_2), ton	**43**	**65**	**86**
Oxygen (99%mole), ton	**284**	**286**	**288**
Moderator steam	**0**	**0**	**0**
Total in, ton	**827**	**851**	**874**
Raw product gas, ton	**794**	**818**	**841**
Unconverted carbon, ton	**3**	**3**	**3**
Ash/slag, ton	**30**	**30**	**30**
Total out, ton	**827**	**851**	**874**
Raw gas composition, %mole			
CO	**49.39**	**49.12**	**48.83**
CO_2	**9.93**	**10.74**	**11.55**
CH_4	**0.00**	**0.00**	**0.00**
H_2	**24.48**	**24.36**	**22.31**
H_2O	**15.58**	**16.16**	**16.70**
N_2	**0.22**	**0.22**	**0.21**
A	**0.17**	**0.17**	**0.17**
H_2S + COS	**0.16**	**0.16**	**0.16**
NH_3 + HCN	**0.07**	**0.07**	**0.07**
Total	**100.00**	**100.00**	**100.00**
Molecular mass, kg/kmole	**21.71**	**22.07**	**22.42**
Sensible heat raw gas, GJ	**1320**	**1347**	**1375**
Energy required for predrying the a.r. coal, GJ/1000 ton	**1351**	**1351**	**1351**
Nm^3 CO + H_2 per 1000 ton a.r. feed	**605638**	**602202**	**598796**
Cold gas efficiency, LHV basis	**77.6**	**77.3**	**77.0**

Table E: Effect of the water in the feed to the gasifier

Water content,% mass	5	10	15	20	30
Temperature, C	1300	1300	1300	1300	1300
Pressure, bar	30	30	30	30	30
Unconverted carbon, %	1	1	1	1	1
Heat loss from gasifier, %	2	2	2	2	2
A.R. Coal, ton	1000	1000	1000	1000	1000
Dried coal, ton	421	444	471	500	571
Transport gas (CO_2), ton	55	58	61	65	74
Oxygen (99%mole), ton	261	269	277	286	309
Moderator steam	0	0	0	0	0
Total in, ton	737	771	809	851	954
Raw product gas, ton	704	738	776	818	921
Unconverted carbon, ton	3	3	3	3	3
Ash/slag, ton	30	30	30	30	30
Total out, ton	737	771	809	851	954
Raw gas composition, %mole					
CO	62.45	58.01	53.56	49.12	40.26
CO_2	5.21	7.13	8.97	10.74	14.03
CH_4	0.00	0.00	0.00	0.00	0.00
H_2	25.04	24.63	24.07	23.36	21.46
H_2O	6.62	9.58	12.76	16.16	23.67
N_2	0.24	0.23	0.23	0.22	0.20
A	0.18	0.17	0.17	0.17	0.16
H_2S + COS	0.18	0.17	0.17	0.16	0.14
NH_3 + HCN	0.08	0.08	0.07	0.07	0.08
Total	100.00	100.00	100.00	100.00	100.00
Molecular mass, kg/kmole	21.71	21.82	21.94	22.07	22.34
Sensible heat raw gas, GJ	1113	1183	1261	1347	1557
Energy required for predrying the coal, GJ/1000 ton a.r. coal	1534	1480	1419	1351	1185
Nm^3 CO + H_2 per indicated tonnage dried feed	636293	626315	615039	602202	570589
Cold gas efficiency, LHV basis	82.1	80.7	79.1	77.3	73.0

Table F: Extreme drying of the coal to the gasifier in combination with low temperatures

Water content,% mass	**5**	**5**	**5**	**5**
Temperature, C	**800**	**900**	**1000**	**1000**
Pressure, bar	**30**	**30**	**30**	**30**
Unconverted carbon, %	**3**	**3**	**3**	**3**
Heat loss from gasifier, %	**0.5**	**0.5**	**0.5**	**0.5**
A.R. Coal, ton	**1000**	**1000**	**1000**	**1000**
Dried coal, ton	**421**	**421**	**421**	**421**
Transport gas (CO_2), ton	**54**	**54**	**54**	**35 N_2**
Oxygen (99%mole), ton	**209**	**217**	**225**	**222**
Moderator steam	**0**	**0**	**0**	**15**
Total in, ton	**684**	**692**	**700**	**693**
product gas, ton	**646**	**654**	**662**	**655**
Unconverted carbon, ton	**8**	**8**	**8**	**8**
Ash/slag, ton	**30**	**30**	**30**	**30**
Total out, ton	**684**	**692**	**700**	**693**
Raw gas composition, %mole				
CO	**65,36**	**64,77**	**64,22**	**59,84**
CO_2	**1,92**	**2,51**	**3,06**	**2,00**
CH_4	**0,00**	**0,00**	**0,00**	**0,00**
H_2	**30,72**	**29,91**	**29,01**	**31,42**
H_2O	**1,37**	**2,17**	**3,07**	**2,33**
N_2	**0.23**	**0.23**	**0.23**	**4.00**
A	**0.14**	**0.15**	**0.15**	**0.15**
H_2S + COS	**0.18**	**0.18**	**0.18**	**0.18**
NH_3 + HCN	**0.08**	**0.08**	**0.08**	**0.08**
Total	**100.00**	**100.00**	**100.00**	**100.00**
Molecular mass, kg/kmole	**20.23**	**20.45**	**20.68**	**19.96**
Sensible heat raw gas, GJ	**509**	**619**	**733**	**744**
Energy required for predrying the coal, GJ/1000 ton a.r. coal	**1534**	**1534**	**1534**	**1534**
Nm^3 CO + H_2 per indicated tonnage dried feed	**689304**	**679317**	**668976**	**671462**
Cold gas efficiency, LHV basis	**88.5**	**87.2**	**86.0**	**85.9**