Industrialisation of underground coal gasification in South Africa and the commercial optimisation of the Theunissen UCG project

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Thesis accepted in fulfilment of the requirements for the degree *Doctor of Philosophy in Chemical Engineering* at the North-West University

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PREFACE

Overview of the document

This manuscript is prepared for examination and submitted in completion of the author's Doctoral studies at the North-West University. The preface contains an overview in abstract form of the thesis submitted for examination.

General details regarding the published papers and presentations are given along with the papers in this thesis. The papers included in this thesis were published in various journals and conference proceedings, each specifying its own formatting and style. These papers are included "as is" and it should be noted that no changes were made to the content thereof.

The preface and appendices includes signed statements, acknowledgements and consent to publish from each co-author. The deliverables arising from each study are discussed and a conclusion of the thesis is provided.

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Submitted in completion of the Author's degree

Doctor of Philosophy (Chemical Engineering)

at the Faculty of Engineering at North-West University.

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AUTHOR'S DECLARATION

I, Johan Francois Brand, hereby declare before a Commissioner of Oaths:

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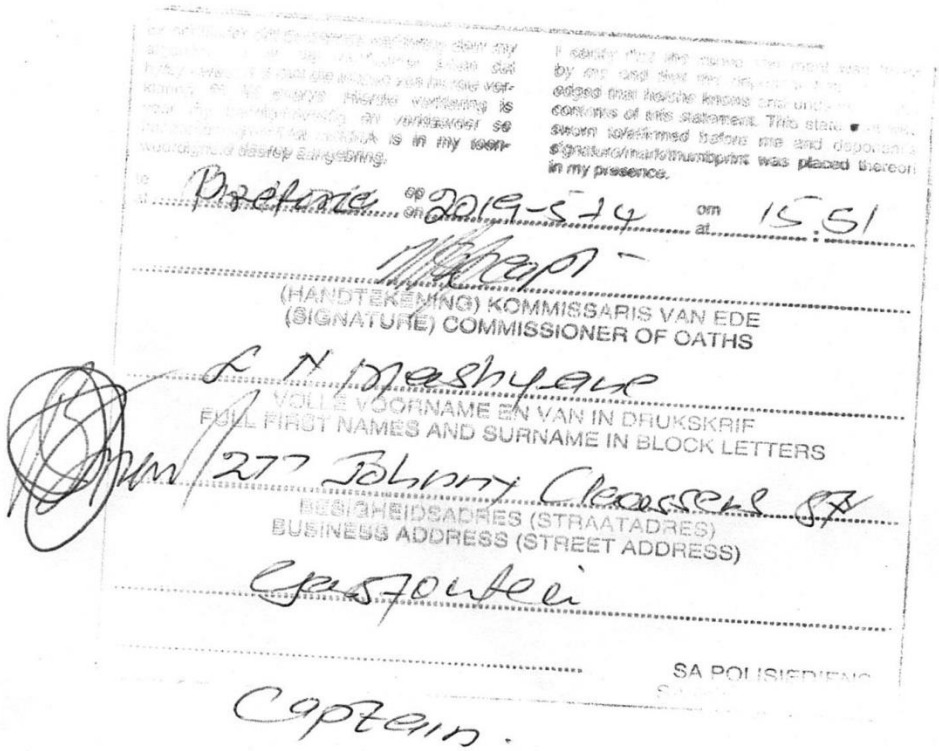

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ABSTRACT

South Africa faces long-term energy challenges, such as energy access and affordability; diminishing reserves of coal; environmental concerns; balancing the electricity grid whilst incorporating an increasing proportion of variable renewable energy sources; mounting environmental liabilities caused by defunct mining operations, and fluctuating exchange rates and their influence on energy commodity prices.

Underground coal gasification (UCG) is an advanced clean coal technology that offers a breakthrough solution to the country's energy challenges as UCG has the capacity to cost-effectively liberate vast domestic coal resources that currently cannot be economically exploited using traditional mining technologies. The technology offers flexibility in terms of coal types and load size, making it the ideal renewable energy compliment. By managing the gasification agent and operational conditions, it is possible to achieve a wide range of desired compositions and control the quantity of gas produced.

Johan Brand and his late partner teamed up as African Carbon Energy (Pty) Ltd ('Africary') to initiate UCG-based electricity production by aligning it with the government's request for independent power producers and coal-to-liquids. Africary promotes the implementation of UCG with several UCG projects immediately ready and awaiting financial close. All Africary projects utilise commercially available gas clean-up and chemical process systems, including the processing of by-products for marketable commodities, thereby preventing environmental pollution.

A concept study for integrating UCG with a mini-GTL system in a unique poly-generation configuration was presented. The process consists of two parallel gasifiers, operated on different agents, making the UCG, coal to liquids (CTL) and power generation tightly linked and interdependent, but reducing both cost and emissions. In addition, UCG offers a lower capital investment compared to conventional underground mining and surface gasification due to the removal of the surface gasifier and coal mine operations. The gas clean-up systems will remove undesirable components from each gasifier and blend the cleaned syngas for H_2:CO ratio control and provide the implementation of carbon capture and sequestration.

The latest study provide optimised process flow and reduces complexity to provide own use electricity and about 2 000 barrels of oil per day (bbl/day) diesel and 200 ton/day liquefied natural gas (LNG) at a capital cost estimate of about $ 350 million and operating cost of around 28 $/bbl (in 2017 $ terms).

Keywords:

South Africa, underground coal gasification, UCG, industrialisation, CTL, electricity.

DELIVERABLES FROM THIS STUDY

Paper Title	UCG Pilot Study in Secunda South Africa - The Experimental Design and Operating Parameters for the Demonstration of the UCG Technology and Verification of Models.
Authors	J.F. Brand.
Document type	Conference Paper and presentation
Journal	Proceedings of the 25th Annual International Pittsburgh Coal Conference, PCC - Proceedings. p. 17.
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ISBN	189097725X 9781890977252
DOI	NA

Paper Title	Groundwater Monitoring During Underground Coal Gasification.
Authors	J.C. van Dyk, J.F. Brand, C.A. Strydom and F.B. Waanders.
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Copyright	Copyright 2017. IEA Clean Coal Centre.
DOI	NA

Paper Title	Applying Spontaneous Adiabatic Test Procedure to Determine CO_2 Gasification Reactivity and Kinetics of Coal UCG Applications.
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NOMENCLATURE

AGR	acid gas removal
ASU	air separation unit
bbl	barrel of oil
bbl/day	barrel of oil (or its equivalent) produced per day
CBM	coal bed methane
CCGT	combined-cycle gas turbine
CCS	carbon capture and sequestration
CF2	Clean Fuels 2 program initiated by the DOE of SA
CO	carbon monoxide
CO_2	carbon dioxide
CRIP	controlled retraction injecting point
CTL	coal-to-liquids
CTX	coal-to-X, (X = power, chemicals, liquids or gas)
DOE	Department of Energy of South Africa
FT	Fischer-Tropsch
GTL	gas-to-liquids
GW	gigawatt or 1000 megawatt
H_2	hydrogen
IGCC	integrated gasification combined cycle
IPP	independent power producer
kV	kilovolt
kW	kilowatt
kWh	1 kW for 1 hour
LNG	liquefied natural gas
MW	megawatt
Nm^3/hr	a normal (at ISO conditions) cubic meter per hour
OCGT	open cycle gas turbine
ppm	parts per million
R	Rand (the currency of South Africa = ZAR)
$	Dollar (the currency of the United States of America)
SA	South Africa
SAMREC	The South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (the SAMREC Code)
SAUCGA	South African Underground Coal Gasification Association
SNG	substitute (or synthetic) natural gas
tcf	trillion cubic feet
TUCG	Theunissen underground coal gasification (a project developed by Africary)
UCG	underground coal gasification
ULSD	ultra low sulphur diesel (with less than 10 ppm sulphur)
VRE	variable renewable energy

1 INTRODUCTION

In a 2018 publication contribution, it was emphasised that South Africa was facing long-term energy security challenges, brought about by a myriad of factors that are somewhat uniquely exacerbated compared against the global context [1]. Long-term energy security challenges for South Africa (SA) became paramount due to factors like energy access and affordability; dwindling reserves of coal (the primary bulk energy source); mounting environmental concerns (especially regarding coal and nuclear energy generation); balancing the electricity grid whilst incorporating an increasing proportion of variable renewable energy (VRE) sources; mounting environmental liabilities caused by defunct mining operations, and lastly, but by no means less important, fluctuating exchange rates and their influence on energy commodity prices.

Underground coal gasification (UCG) is an advanced clean coal technology and correctly managed it offers a breakthrough solution to the country's energy challenges as UCG has the capacity to cost-effectively liberate vast domestic coal resources that currently cannot be economically exploited using traditional mining technologies.

South Africa signed the Paris Agreement on climate change in 2015, which was developed under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). At the same time the country has a commitment to increasing the population's access to affordable electricity. UCG arises as an economical and clean solution during a period of energy transition where consumers of fossil fuels are under pressure to reduce emissions significantly to comply with international climate change commitments.

UCG offers a considerable degree of flexibility in terms of different types of coal and load design, making it the ideal gas load-following method to compliment VRE. By managing the gasifying agent and operational conditions, it is also possible to achieve a wide range of desired compositions and control the quantity of gas produced. Commercially available gas clean-up and chemical process systems enable the processing of any by-products produced during the UCG process, resulting in marketable commodities and, by the same token, preventing environmental pollution.

1.1 Benefits and Advantages of UCG

UCG has considerable environmental benefits. The syngas is generated deep underground inside the coal seam, while the ash in the coal mostly stays in the seam. The cold gas efficiency of UCG is about 80% [2], meaning that roughly 80% of the energy in the mined coal can theoretically be extracted as fuel in the syngas, making UCG a very efficient mining process. Another major advantage is that storing areas for ash, waste and discard materials (inevitable in the case of traditional coal processing units) are virtually non-existent with the use of UCG. The UCG mining system coupled with efficient power production also requires

much less water, and all process water is cleaned and any steam produced is reused as an agent in the gasification process.

At the same time, no people are required to work underground, which offers safety benefits. UCG is not just more efficient and safer, but also offers the following advantages:

1. UCG is a technology that transforms coal into gas and may be operated on an "as-needed-basis" to become the ideal partner to VRE when utilised for load-following and peak shaving.
2. UCG can be combined with a large-scale combined-cycle plant to reach energy efficiency exceeding 55% compared to the current 35% efficiency obtained in sub-critical pulverised fuel boilers[3].
3. Gasification produces less particulate emissions, thus the process requires minimal ash handling, and there is little or no leaching of trace elements from ash when UCG is operated correctly [3].
4. Only one-quarter of South African coal reserves are economically and technically recoverable with current conventional mining methods [4]. UCG can economically monetise un-mineable coal that would otherwise be lost to the country's economy. Pershad, *et al*. provides a map (see Figure 1) showing that UCG offers access to much more coal situated in 7 out of the 9 provinces [1] and therefore new distributed projects can be located in economically depressed areas of South Africa.
5. UCG deployment can create new high-value jobs in the drilling, gas processing, and gas utilisation and maintenance industries.
6. No chemicals are injected into the UCG process as only air (or O_2) and water or CO_2 is required for gasification and technologies for CO_2 removal (for capture and re-use) are well matured.
7. Fracking is not required and no fracking chemicals are injected during UCG [5].
8. The UCG syngas is already in a form that can be further monetised to liquid chemicals or fuels, or the syngas can be separated to obtain basic chemicals such as hydrogen, carbon monoxide, and methane. See Chapter 8.
9. The form of sulphur present in the syngas allows for the economic recovery of elemental sulphur which can form part of the chemicals portfolio. This is further discussed in Chapters 7 and 8.

1.2 UCG development in South Africa

UCG is not new to SA as the government-owned power entity Eskom initiated a technology scanning study as far back as April 2001 [6]. By Nov 2002 they had highlighted the potential of clean coal technology at Majuba Colliery and then completed a pre-feasibility study by

December 2003. Simultaneously Sasol initiated a UCG development study lead by Johan Brand. A detailed site characterisation study confirmed the potential for Eskom and by July 2005 Eskom's research and development department launched the pilot project implementation with the successful commissioning of a 5 000 Nm^3/hr gasifier on 20 January 2007 and by 31 May 2007 the first electricity was generated from UCG gas [5].

Sasol was about two years behind Eskom but did catch up and completed a Secunda pilot project to final execution stage in 2008; however, the economic recession of 2008 necessitated placing the Sasol UCG pilot project on hold. Meanwhile, the Eskom project initiated the construction of a 7-kilometre steel pipeline to link the gas produced with Majuba Unit-4 (completed in March 2010) and co-firing of UCG gas into Majuba commenced [5]. From a research and development perspective Eskom demonstrated the following [1]:

1. UCG can provide cost-competitive fuel for future power generation. It can derive this fuel from local, unused coal resources shielded from international market forces.
2. Eskom has qualitatively proven that the technology works and is able to extract value from one of the most geologically complex coalfields in South Africa.
3. The Eskom Board supports the technology, but due to Eskom's current financial constraints, a partner will be sought to further commercial development.

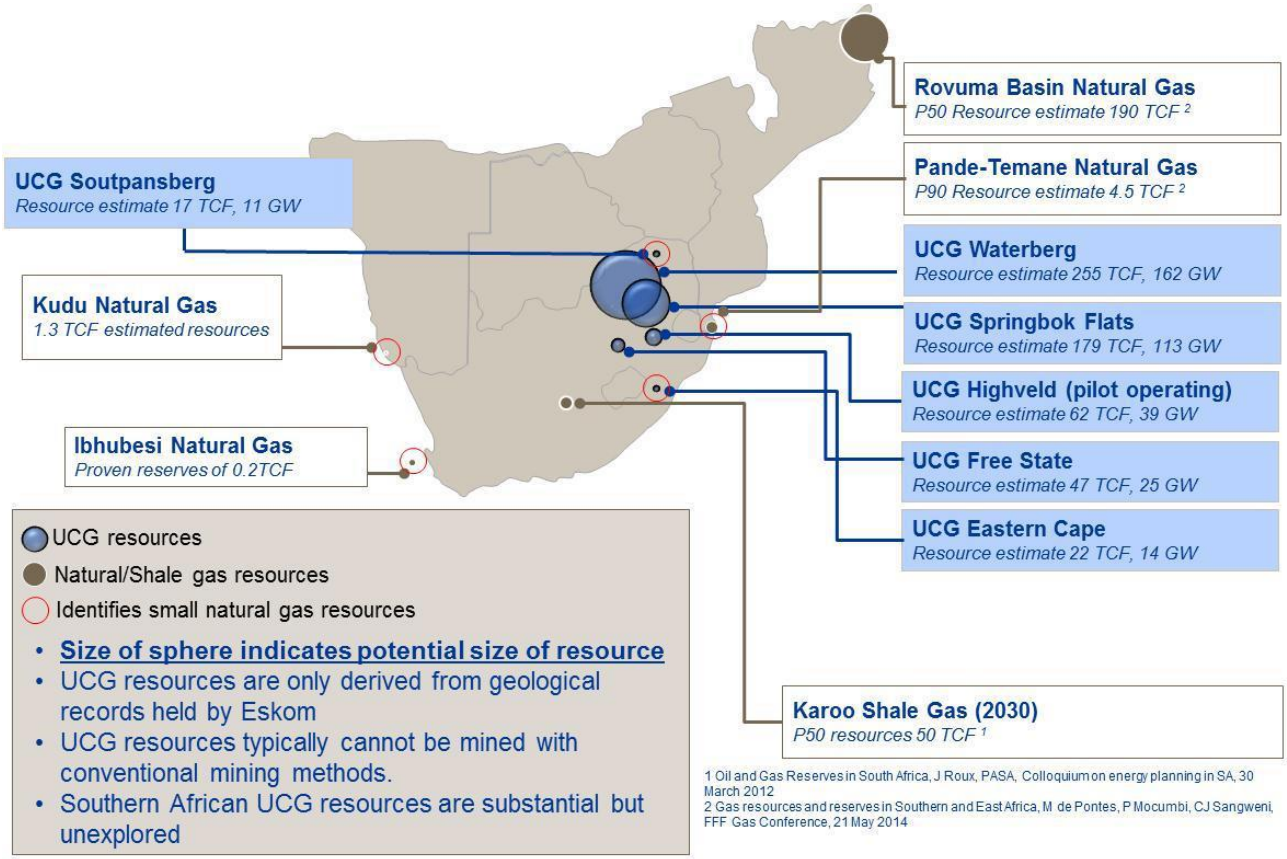

Figure 1 7 out of 9 SA provinces have coal suitable for UCG. UCG provides > 400 tcf local gas opportunity [1].

The design for a 140 MW open-cycle gas turbine (OCGT) demonstration plant for Majuba was completed and the environmental application (EIA) commenced in 2015. Eskom's UCG

indicative development indicated that a full-scale 2 100 MW project was further contemplated to monetise the coal that is currently left fallow at and around Majuba Colliery [5].

SA is facing an energy crisis where its net maximum generation capacity of ± 42 GW (85% coal-based) is characterised by an ageing fleet that underperforms environmentally against the new legislation. About 75% of Eskom's capacity is outdated and set to be decommissioned, starting in 2020 (see Figure 2). The average energy availability factor (EAF) of the ageing Eskom fleet fell below 80% [7] in 2017, leaving a growing economy with almost zero operating margin and renewed load shedding and increased future risk thereof. Eskom is also set to decommission several old power stations that will have reached the end of their economic life in the next decade.

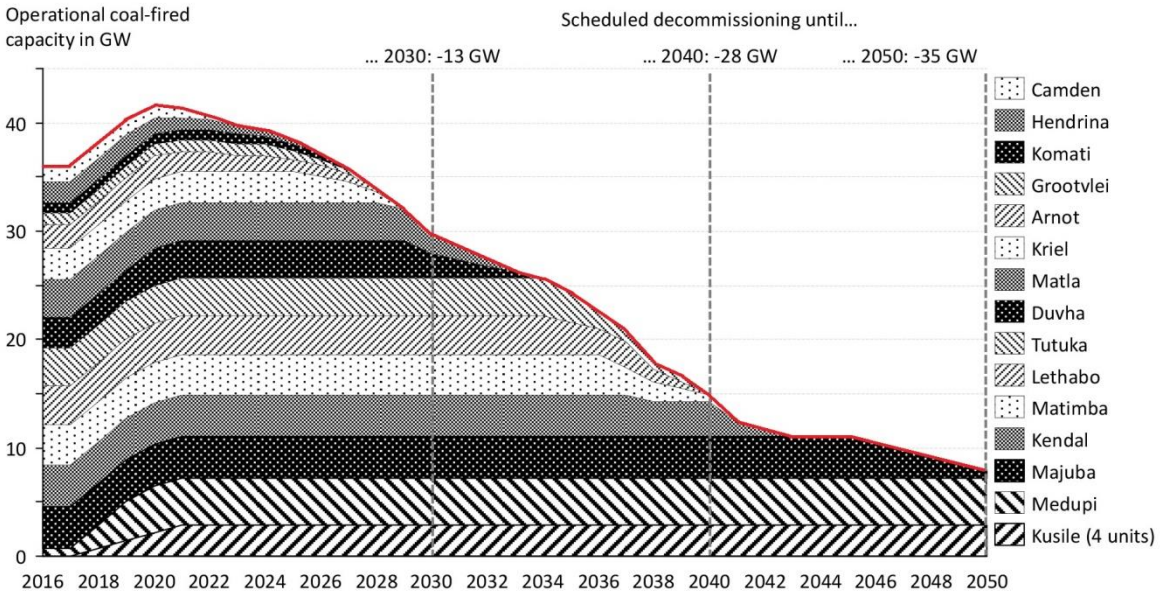

Figure 2 South Africa is scheduled to decommission 28 GW of coal power plants by 2040 [8].

The decommissioning of 28 GW of coal power capacity requires the integration of up to 60% industrial scale VRE penetration by 2040. To compensate for variability [9] South Africa requires a substantial increase in energy storage or fast ramping OCGT and flexible combined-cycle gas turbine (CCGT) implementation (at an estimated cost of incorporation at an additional 0.48 R/kWh [10] above and beyond the price of power generation). This is because the conventional Eskom base-load coal power stations cannot attain the quick ramping rates required to follow the VRE supply fluctuations. For example, Kendal power station ramp rate is only 16.67% per hour (15 MW per minute) [11], whereas VRE may ramp-up or down at 200 MW per minute [12].

Furthermore, the country does not have an available domestic gas supply for the OCGT and CCGT systems as the current Mozambique import supply to the industry is already fully constrained [13]. It is therefore assumed that the future supply of gas will be domestic UCG,

with imported LNG or unproven coal bed methane (CBM) and yet to be confirmed Karoo shale gas [14] mentioned as a long-term gas supply alternatives [15].

Simultaneously with the electricity crisis, the planned upgrading of SA oil refineries to produce European Standards Organisation (CEN) Directive 2009/30/EC or so-called "Euro-5"-specified fuels have been delayed until 2021, after the SA Department of Energy (DOE) initially set the deadline for the introduction of the Clean Fuels 2 (CF2) program for mid-2017. The government and petroleum industry reached a stalemate on how the refiners would be able to recoup the estimated US$ 4.6 billion facility upgrade cost [16]. CF2 regulations stipulate that sulphur levels in petrol and diesel must be kept below 10 parts per million (ppm) and for the old refineries it thus makes more economic sense to shut down than comply with CF2.

The DOE published concerns about increases in petroleum product imports due to the potential shut-down of the nation's existing refineries as the import capacity of the country is currently limited to 10 billion litres and any new import capacity may only be available from 2023, and will not provide sufficient future capacity as it will immediately be constrained. (See Figure 3).

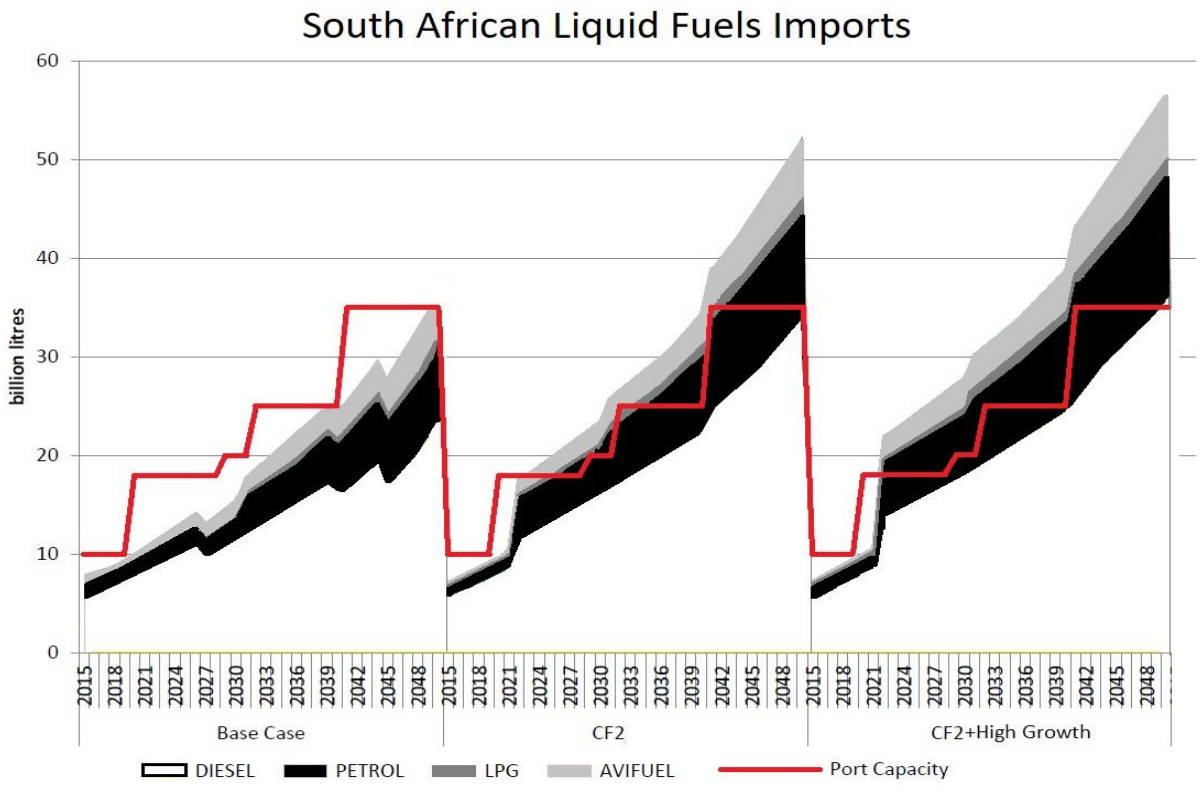

Figure 3 DOE forecast of impact on liquid fuel imports for implementing the CF2 program [17].

Increase in demand, combined with deteriorating coal quality and a looming shortage of imported natural gas and oil-derived fuels, have resulted in a critical energy crisis for SA. This is made manifest in large scale power black-outs due to rotational load-shedding by Eskom

[18] with devastating effects on the SA economy. The scale of infrastructure investments required to fill the demand shortfall is too large for Eskom and the refineries to carry alone. This is where Africary's UCG projects can be a breakthrough solution for independently produced electricity, liquid fuels, hydrogen, and natural gas in a poly-generation configuration. Industrial scale Fischer-Tropsch (FT) facilities (> 160 000 bbl/day) have been operating for decades in SA at both Sasol with coal-to-liquid (CTL) and at PetroSA for gas-to-liquid (GTL). Thus, the implementation of coal gasification in combination with FT technologies is not new to the country and its legislators.

The same goes for the petrochemical industries, as already in 1960, ammonia, styrene, and butadiene became the first chemical intermediates sold by Sasol, with the ammonia also used to make fertilisers [19]. From 1964 on Sasol became a major player in the nitrogenous fertiliser market. This product range was further extended in the 1980s to include both phosphate- and potassium-based fertilisers. Today Sasol sells an extensive range of fertilisers and explosives to local and international markets and is a world leader in its low-density ammonium nitrate technology [17].

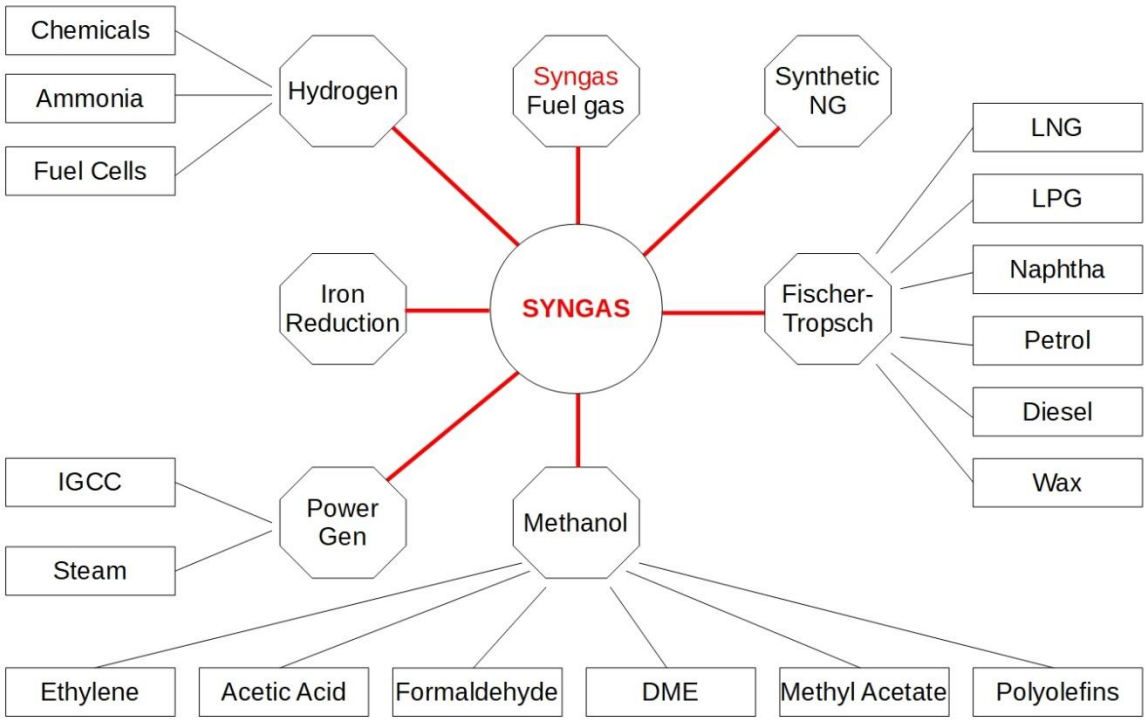

Figure 4 Syngas utilisation options [20].

Over the decades Sasol matured from being primarily a South African fuels provider into an integrated international energy and chemicals company with more than 200 products being sold worldwide. Syngas is the cornerstone from which many products can be derived (see Figure 4). Some of the main fuel products produced by Sasol today are diesel, petrol,

naphtha, illuminating paraffin, kerosene (jet fuel), liquid petroleum gas (LPG) and natural gas. Sasol also provides commodity sales of bulk chemicals such as olefins, alcohols, polymers, solvents, surfactants, co-monomers, ammonia, methanol, sulphur, bitumen, various phenolics and acrylates [17].

On 24 April 2013 Mining Weekly reported [21] that former Sasol executive, Johan Brand and his late partner Eliphus Monkoe had bought 1.4 billion tons of coal near Theunissen, in the Free State. They have teamed up as African Carbon Energy (Africary) to transform coal mining, electricity production and coal-to-liquids in South Africa. Africary immediately aligned itself to take advantage of the government's 2014 request for Independent Power Producers (IPP) to provide proposals for the baseload gas-IPP power supply.

The two entrepreneurs self-funded current activities and completed a bankable feasibility study. on 4 July 2014 Mining Weekly reported [22] that Africary had completed engineering work on its 50 MW Theunissen underground coal gasification (TUCG) project which would use only five-million tons of coal from the possible one-billion tons of coal at its disposal. The TUCG project is also ideally situated to stabilise the electricity grid and it also has the added advantage of being close to the major 400 kV transmission lines taking power to the Western, Eastern and Northern Cape.

The energy conversion process consists of mining and gasifying about 30 ton per hour of coal into syngas. The syngas is then scrubbed of unwanted contaminants during a gas-cleaning process and conditioned into a stable-quality clean fuel gas for consumption by gas engines designed specifically for syngas operation. The highly efficient engines are syngas rated and provide excellent emission levels that contain no particulate matter. The engines offer higher fuel efficiency than any boiler-to-steam system currently operated in South Africa and have an expected short construction timeline of only 12 months.

UCG is an alternative coal mining technology that can provide South Africa with the tremendous incentive of abundant clean energy sources. Africary also engages and works together with government, industry, and academia to grow and promote understanding and support for the technology.

Although the UCG industry has been around for more than 80 years, it was historically a less attractive alternative to low-cost oil and abundant natural gas and as such its development and commercialisation was severely hampered by the varying oil and gas prices. However, with the modern developments in directional drilling technology, UCG is now a cost-effective gas producing system and a real, viable alternative for South Africa with no oil and natural gas supplies. UCG renders previously un-exploitable resources economically feasible and ensures less reliance on old inefficient and polluting coal-fired boilers. UCG provides a domestic, stable and economical energy source for electricity generation.

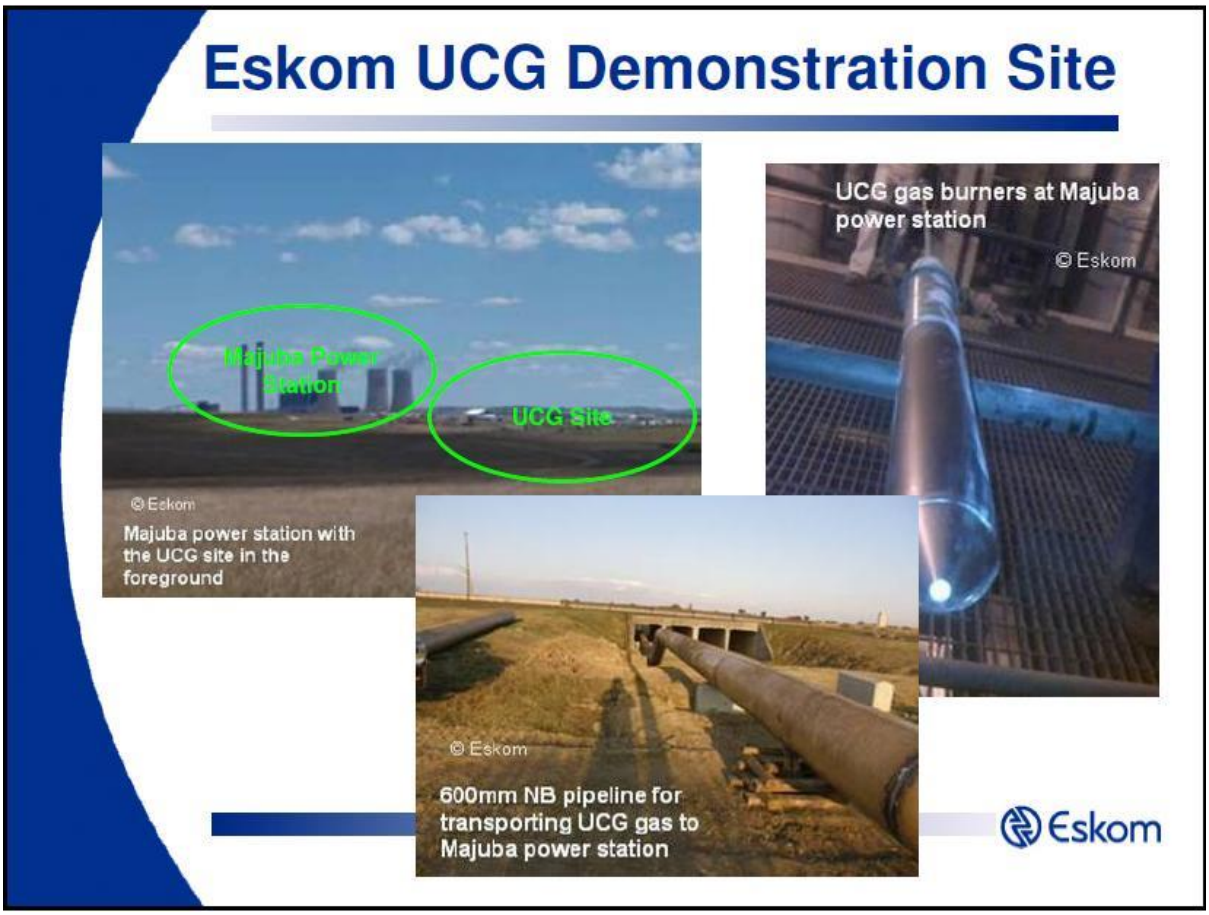

Figure 5 Pictures of Eskom Majuba site showing pipe connection feeding syngas to the boiler. (Source-Eskom 2010 presentation at ESI conference) [6].

1.3 Problem Statement and Research Objectives

The low efficiency of conventional coal mining and pulverised fuel combustion technologies provide a meagre 20% utilisation of the coal potential [5]. This low utilisation coupled with the intensive capital and operating costs of newly built super-critical power stations supports the implementation of producing UCG fuel gas for power generation.

The objectives of this body of work were to support the establishment of a UCG community, to address technology and regulatory shortcomings, and develop optimised processes and cost models whereby UCG could be commercialised in a country where there is no practical domestic alternative to coal.

Furthermore, UCG offers the opportunity to implement the petrochemical derivatives for future expansion and returns to investors. Therefore, the specific aims of the investigation were to support the industrialisation of UCG in South Africa by:

1. Creating a community to promote the production of UCG for the country – The SA UCG Association. (Paragraph 2.3);
2. Researching and developing UCG mining safety and legislative issues. (Chapters 3 to 6);

and by optimising of the Africary Theunissen UCG projects by:

1. Investigating and modelling cost-efficient processes of removing contaminants and sulphur from syngas for power and FT. (Chapter 7 and 8).
2. Researching and developing a process of removing and sequestering CO_2 by exploiting the heated CO_2 waste-gas as gasification agent (Chapter 6 to 8).
3. Adopting the cost-effective use of wastewater as a gasification agent. (Chapter 8).
4. Creating an energy and chemical mass balance model for a commercial modular FT system that allows production of many high-value products such as electricity, ultra-low sulphur diesel (ULSD), LNG and hydrogen (Chapter 8).

1.4 Thesis Outline

This thesis will be based on publications and will be presented in nine chapters including this introductory chapter. Chapter 1 will serve as the introduction to UCG technology implementation in South Africa, followed by background information and several chapters based on international presentations and full-length articles.

Chapter 1 - serves as the introduction to gasification and deliberates the existing South African energy predicaments and envisions the future energy landscape and provides the advantages of UCG technology;

Chapter 2 – serves as background and a literary review and presents the challenges posed when industrialising the technology and explains the potential advantages that Africary's TUCG project would bring to South Africa;

Chapter 3 – is an article that presents a paper on the experimental design of operating parameters to verify the gasification process model kinetics prior to progressing UCG to full-scale implementation [23];

Chapter 4 – provides an article published in the Journal of the Southern African Institute of Mining and Metallurgy [24]. Africary participated in the drafting and promoting of a National Standard Proposal [25] and this article examines well-established groundwater monitoring for conventional coal mining. It proposes the incorporation additional monitoring standards for a commercial UCG operation in order to support the industrialisation of the technology. The sole focus of this standard is towards UCG groundwater monitoring and applies to water sampled from dedicated monitoring wells around the UCG site, which will include the shallow aquifer (referred to as 'groundwater') and water at the level of the underground gasifier (referred to as 'coal water') [26];

Chapter 5 – provides a conference paper based on the research of operational criteria that are fundamental to the UCG system by scientifically testing and ranking the feasibility of metals and alloys for producing long-term safe and efficient UCG syngas [27];

Chapter 6 – is based on work presented at the 35th Annual International Pittsburgh Coal Conference, in Xuzhou China [28] in 2018. It was shown that the effectiveness and carbon efficiency of UCG can be improved by CO_2 gasification with the recycling of waste captured CO_2 to be used as the main gasification agent to drive the Boudouard Reaction, where $CO_2 + C \rightarrow 2\,CO$ above 850°C to carbon capture and sequester (CCS) the gas. The CCS potential of UCG was first presented in May 2017 [29], but the concept was originally contemplated to incorporate spontaneous combustion test procedures for designs of the UCG ignition process and presented in June 2015 [30] and may be summarised in future publications;

Chapter 7 – is based on an article published in the Journal of the Southern African Institute of Mining and Metallurgy and examines and discusses novel treatment options for trace coal components, especially condensable water, oils, tars, inorganic trace elements and particulate matter that make their way to the surface via the production well and can cause adverse impacts on downstream processes. In this chapter, the conceptual use of vortex technologies for syngas purification is discussed and a novel gradient gas separation for future cost-effective UCG applications is shown [31];

Chapter 8 – consists of a full-length article published in the Clean Energy Journal [32], and brings together several of the technologies and finding from the previous chapters to provide an economic overview of a two-agent UCG process with Fischer-Tropsch (FT) based poly-generation; and

Chapter 9 – provides an overall conclusion of the thesis based on the studies and research and development activities for UCG implementation and industrialisation in South Africa.

1.5 Key Highlights of the different Chapters

The following innovative processes and systems were created and developed or incorporated in commercial UCG plant models to enhance the environmental and economic feasibility of UCG and elaborated or applied in the different chapters:

1. Exploration drilling with substantive gasification coal and strata tests;
2. Testing and assessing different metals and materials for UCG construction;
3. Ignition of coal studies based on spontaneous combustion test work;
4. Water sampling and water management proposals;
5. Cleaning and reusing dirty water with the supercritical water oxidisation system;
6. Sulphur removal by means of a novel warm gas desulfurisation system;
7. Comparing capturing CO_2 with Amine or vortex separation systems;
8. Modelling of a typical process network of a mining operation;
9. Sour-Shift hydrogen production and blending for H_2:CO control;

10. UCG Poly-generation process;
    a. utilising mining, gasification and gas treatment effluents or waste streams such as grey water and CO_2 as gasification agents;
    b. FT 2-Stage processing with novel tail-gas management;
    c. Power generation from waste gasses.

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2 BACKGROUND

2.1 Overview

Underground coal gasification is a mining process that produces synthesis gas from in situ coal by replacing conventional mechanical mining with a chemical mining method. UCG is an age old technique which has been studied or trailed in almost every country that has coal and even commercialised in the former Soviet Union [33, 34]. UCG can be described as an advanced emerging clean coal technology that offers many solutions to South Africa's energy challenges. UCG is however not new to SA as the government-owned power monopoly Eskom initiated a technology scanning study as far back as April 2001 [6]. By November 2002 Eskom had highlighted the potential of the clean coal technology and completed a pre-feasibility study by December 2003. Simultaneously, Sasol initiated a UCG development study lead by Johan Brand. Sasol completed a Secunda pilot project to final execution stage in 2008 [23]. However, the global economic recession necessitated Sasol to place the UCG project on hold.

In the previous chapter the Africary project near Theunissen in the Free State was introduced in paragraph 1.2, stating that over the 20 year lifespan the first 50 MW power project will only require five million tons (from the possible one billion tons of coal) at its disposal. The project has huge potential to grow to gigawatt capacity and therefore stabilise the 400 kV electricity grid. Amid accusations of corruption and state capture at the monopoly, Eskom failed by mid-2016 to sign and confirm the DOE's IPP programme's power purchase agreements (PPAs) for renewables projects. This stalemate lead to a 3-year lapse in the assignment of already approved IPPs [35] and delayed the gas-IPP programme (for which Africary targeted its UCG power option) indefinitely. This necessitated a new corporate strategy for 2016 and after deliberation led Africary to consider investigating CTL as an alternative prospect for future projects.

In 2018 the new SA president, Cyril Ramaphosa, removed corrupt ministers and managers at Eskom and mandated the newly appointed Minister of Energy to complete and finalise the outstanding IPP agreements [36] reigniting economic growth. This has reopened the door for gas power options as well as poly-generation of both power and liquid fuels.

2.2 Fundamentals of UCG

UCG is a mining method that extracts previously stranded coal reserves in situ ('as they sit in the coal seam') through a gasification process that converts the coal into synthesis gas ('syngas'). UCG takes place in deep, undisturbed coal seams, connected to the surface only by cement-sealed boreholes, (specially designed according to international oil and gas field standards (to withstand both high temperature and pressure), for the injection of air or

oxygen and the removal of syngas, and constructed in such a manner as to provide a leak-proof access to the mine.

The process is also completely sealed from the surface by the geological strata (thick rock layers of more than 300 meter that are permeated with non-potable groundwater). This creates a deeply buried system and with the interruption of the air/oxygen supply the gasification process will stop completely. Therefore, there is no possibility of an uncontrolled fire.

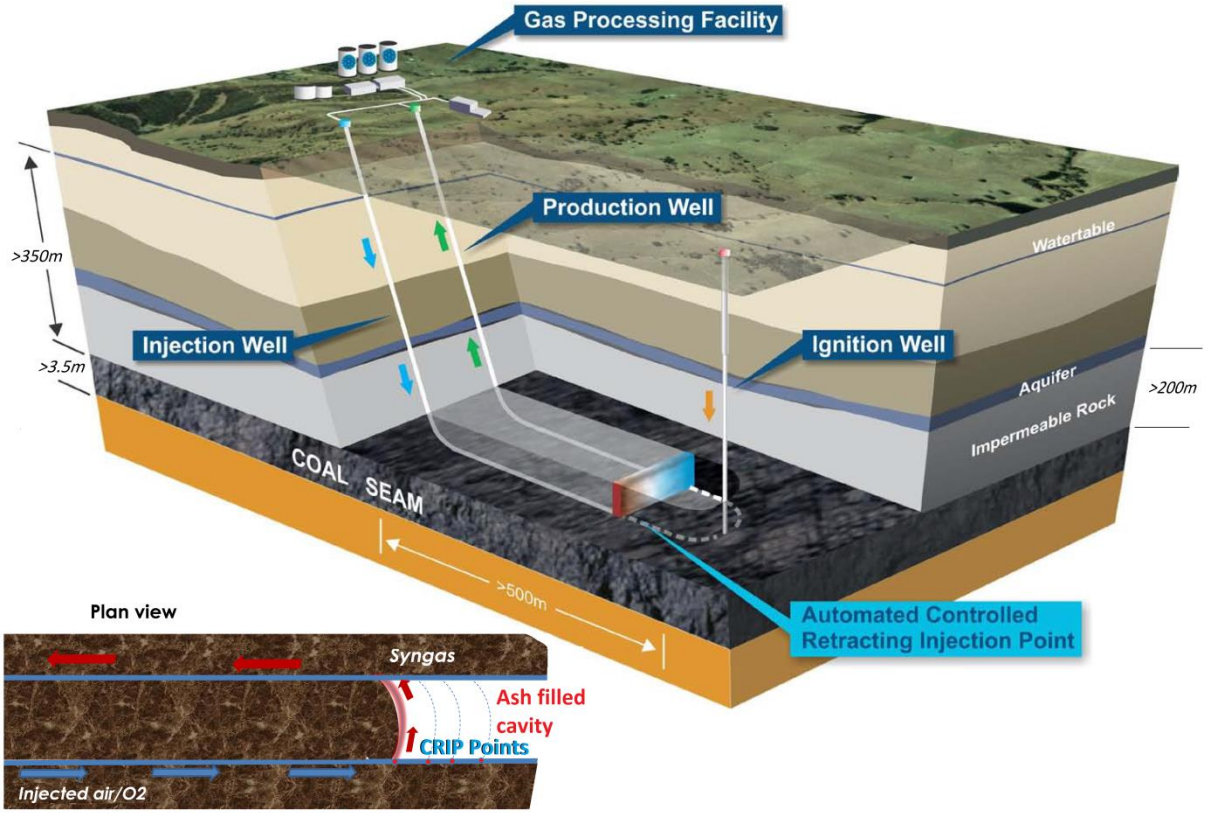

Figure 6 Graphic representation of CRIP based UCG (not to scale). Adapted with permission from [37].

Coal gasification is a process that converts the hydrocarbons contained in the coal into carbon monoxide, hydrogen and carbon dioxide by leaving an ash residue. This is achieved in a high temperature (> 800°C) environment by partial oxidisation of the coal with a controlled amount of air and/or oxygen and/or steam.

In a gasifier, the coal undergoes several different processes:

1. The dehydration or drying process occurs at above 100°C. The resulting steam diffuses into the syngas and mixes with any injected steam to participate in subsequent chemical reactions, like the water-gas reaction.
2. The pyrolysis (or devolatilisation) process occurs at around 200°C to 300°C. Volatile organics released from the coal produce a char, consisting mostly of pure carbon and ash, which will then undergo further gasification reactions.

3. The combustion process occurs as the volatile products and some of the char react endothermically with oxygen to primarily form carbon dioxide (and small amounts of carbon monoxide), which provides heat for the subsequent gasification reactions $C + O_2 \rightarrow CO_2$.
4. Gasification occurs when the char reacts with steam and carbon dioxide to produce carbon monoxide and hydrogen, via the two gasification reactions $C + H_2O \rightarrow H_2 + CO$ and $C + CO_2 \rightarrow 2\ CO$.
5. The reversible water-gas shift reaction may also reach equilibrium to balance the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen $CO + H_2O \leftrightarrow CO_2 + H_2$.
6. The methanation reaction occurs when carbon monoxide and steam or hydrogen react to form methane and water or carbon dioxide $CO + 3\ H_2 \rightarrow CH_4 + H_2O$ and $4\ CO + 2\ H_2O \rightarrow CH_4 + 3\ CO_2$. This reaction may be more prevalent in UCG reactors due to the longer gas residence time and the presence of ash (that may act as a catalyst) at high heat and pressure.

The reactions above provide a mixture of these reactants and are collectively called “syngas”. Table 1 provides a general composition of UCG syngas produced with either air or oxygen enriched air.

Table 1: Typical UCG syngas quality [31].

Component	**mol %**	**Air blown**	**O^2 Enriched Air**
H_2	%	12	12
CO	%	18	33
CO_2	%	14	13
CH_4	%	8	10
C_2H_{4-6}	%	0.5	0.5
N_2	%	46	30
O_2	%	0	0
H_2O	%	<0.5	<0.5
H_2S + COS	%	<0.2	<0.3

In essence, the UCG process injects a stoichiometric limited amount of oxygen into the coal seam where the surrounding rock becomes the gasification reactor. This allows some of the coal to be oxidised to produce steam, carbon dioxide and heat, which then drives the successive reactions that convert further coal to syngas. A critical aspect of UCG operations is the continual injection of oxygen in fresh coal due to the constant depletion of the coal by

the process. Historically this was accomplished by drilling copious numbers of closely spaced vertical boreholes into the coal and leaping from one well pair to the next as the coal gets consumed. This so-called "Vertically Linked Wells" resulted in a batch-approach with poor average quality gas and inconsistent volumes of gas production and was one of the key barriers to successful commercialisation.

Figure 7 Example of a CRIP operated UCG injection borehole.

Innovations in site selection with geological modelling and modern directional drilling allow for a Controlled Retraction Injecting Point (CRIP) method to be applied. (See Figure 6.) Carbon Energy demonstrated the commercial application of CRIP with parallel lateral boreholes [38]. The directionally drilled pattern (referenced as a production panel) allows for a consistent coal face partition and the progressive mining of the coal between the injection and production boreholes. This approach provides the greatest quantity of coal per well-pair and can extend for many kilometres. Modern CRIP design permits continued UCG operations which delivers greater consistency and a steady flow of high calorific quality gas.

Table 2 Modern UCG with CRIP mitigates operational risks [39].

Production Issue	**Modern parallel-CRIP UCG**	**Traditional vertical drilled UCG**
Consistent and continuous gas production	Directionally drilled (> 1 km) parallel boreholes can produce for more than 5 years.	Closely spaced (< 50 m) vertical boreholes continuously operate less than 3 months per reactor.
Consistent gas quality	A CRIP intervention can be performed as and when the gas quality deteriorates.	The gas quality decreases over the life of the fixed reactor and the only way to improve gas quality is to move to a new reactor.
Coal-to-gas	Unilateral gas flow over a long coal	The reactor has a fixed size but

conversion efficiency	face provides for a stable gasification front that offers a high mining and production efficiency.	constantly changes shape, which reduces mining and gasification efficiency.
Operability	CRIP provides fully automated production over the entire life of the production panel. Dedicated production and injection wells in fixed positions allows for long-term stable temperature application.	Requires often repeated drilling and manual movement of injection and production points on surface. Thermal shock may damage the casings and create leaks.
Subsidence	Directional drilling allows cost-effective access to very deep coal which eliminates risk of subsidence.	Vertical drilling is cost prohibitive for deep coal and in shallow coal the subsidence risk is increased.
Environmental Impact	Operating the gasifier at lower than hydrostatic pressure ensures gas and groundwater containment. The surface impact is minimised and farming activities continues unhindered.	Large amounts of boreholes and connecting surface pipe-work must constantly be moved and reconnected and may increase the risk of gas leaks.

It is important to understand that the coal is the only source for the energy and that extracting energy from the coal with UCG is equivalent to conventionally mining the coal and gasifying it on surface and then returning the ash underground. However, the extraction advantage for UCG is that the process requires only a small portion (about 12% of the syngas produced consist of CO_2) of the coal's hydrocarbons to be combusted underground, whilst the rest transforms into a valuable and clean syngas with many productive uses. The unwanted gasification ash stays behind and does not require any future environmental intervention.

2.3 Formation of the South African UCG Association (SAUCGA)

To promote and advanced UCG R&D in the country, Africary became a founding member and Johan Brand a Trustee of the South Africa UCG Association [40]. Recognising the potential of UCG for SA, companies like Exxaro, Eskom, Sasol, Africary and several universities have joined forces and created the South African UCG Association to champion the technology and create industry standards and training schemes for UCG. It is with these objectives that the association will propel our energy-starved country to the forefront of global industry based on unconventional technology. The organisation will promote the

implementation of UCG technology in South-African for harnessing the energy from previously uneconomically deep unminable coal.

Africary has and continues to promote the implementation of UCG in the country, firstly for electricity production and secondly for CTL. Several SA UCG projects have not yet reached financial closure, mostly because of mining policy uncertainty and the capture of Eskom as discussed in chapter one. However, the recent approval of 27 outstanding IPP contracts in 2018 [41], coupled with renewed load-shedding and blackouts, provided newfound proactive vigour from the central government in advancing the electricity market and encouraging all stakeholders to positively support UCG implementation.

The main objective of the SAUCGA for 2018 was to provide a UCG Roadmap [1] which seeks to consolidate and provide a consensus pathway for the development of UCG in SA (over the period 2016 to 2040). The Roadmap was also aligned with the South African Integrated Resource Development Plan of 2010 [42], the South African Coal Roadmap of 2013 [43], and the National Development Plan [44] published in 2012. Other key strategic documents (such as the South African Coal Sector Report [45], and the South African Gas Utilisation Master Plan [46], Integrated Energy Plan [47], and Integrated Resource Development Plan [48]) was considered in their draft format at the time.

The following key principals apply to the UCG Roadmap produced by the SAUCGA:

- UCG has a definite role to play in South Africa's future as assessed for the period 2016 to 2040.
- The roadmap focuses on UCG application within South Africa but may be expanded to include neighbouring countries in Southern Africa.
- The current economic, environmental and social paradigms are the basis for this roadmap.
- The country needs the energy to support the growth of 6% per annum and therefore no significant decline in the SA market demand for electricity, liquid fuels and chemicals are foreseen. The focus is rather shifted towards the potential of UCG to support higher growth.

The SAUCGA Roadmap contextualises UCG opportunities and challenges. It strives to address all stakeholders to provide a common and shared basis from which to advance industrialisation and support future plans for technology development.

2.4 Country Benefits and Opportunities

Local domestic coal is free from international currency fluctuations and commodity pricing and compared to LNG becomes the most competitive gas option for SA. Syngas, as opposed to other unconventional gas technologies, is not sensitive to foreign exchange rates or will not be reliant on imports. Since domestic coal and utilities are employed, UCG can be priced

in SA Rand and future price escalation can be in line with Consumer Price Inflation (CPI). Furthermore:

- Local high-value jobs can be created in directional drilling, gas processing, and CCGT maintenance industries.
- UCG can also promote the establishment of an entirely new energy industry that compares to that of Sasol (R 35 billion in 2015), subsequently providing a boost to the SA economy.
- Other products essential for agricultural and local manufacturing industries, such as diesel, methanol, ammonia, hydrogen, LNG and urea can be produced from UCG.
- A 500 MW UCG IGCC project can be brought into commercial operation faster than conventional coal mines and boilers of similar size.
- UCG uses 90% less water than conventional coal-based mining technologies and will promote national water security. Furthermore, the dry cooling of IGCC uses much less water per kW or about 10% of the water of a conventional coal power station.
- The Theunissen projects will be located in an economically depressed area of South Africa and provide a much-needed injection of capital and jobs.

South Africa is a developing country with an economy dominated by coal to which it has no other practical short to medium term alternative as a domestic baseload option. UCG is the only clean and efficient technology that will allow SA to continue its economic prosperity by utilising its own abundant domestic resources in an environmentally sound and efficient way.

2.5 Advantages of UCG over Conventional Coal or Natural Gas

South Africa has no gas resource worth mentioning available and has therefore relied on the gasification of coal to provide syngas to industry. Other than planning-stage LNG imports or the future expansion of the Sasol Gas import pipeline, Karoo shale gas is the most promising large gas prospect in SA. Shale gas is, however, speculative and associated with fracking, chemical injection, flaring and an adverse impact on the water table. Other advantages of UCG over the alternatives are:

1. UCG mines stranded coal by converting it into a gas, which can be used for industrial heating, power generation or the manufacture of fertiliser, synthetic natural gas or diesel fuel.
2. The UCG process avoids the requirement for traditional coal mining, coal handling and transportation, the surface gasifier equipment and then the transportation as well as disposal of ash with cost, labour and environmental benefits.
3. UCG projects have a quick construction time with a typical project turnaround of 24 months from financial close.

4. UCG has synergies with conventional mining as it can make use of stranded coal that would not otherwise be mined.
5. The strategic benefit of avoiding the dollar-linked cost of imported gas.
6. No fracking is required for UCG and no toxic chemicals are used for producing gas.
7. UCG has a minimal impact on the water table compared to CBM and shale gas where groundwater has to be abstracted for gas to be produced.
8. Agriculture: UCG has several advantages over other mining methods like open cast mining and shaft mining as this process can be performed with boreholes without disturbing the land above the mine. During operations the technology further improves land use by not requiring any surface ash dumps and using much less water.
9. It does not need heavy transport equipment, noisy conveyor systems or the trucking of coal loads on national roads. And unlike open cast coal mining there are no blasting operations, no dust, no stockpiling and it does not require the removal, pumping and storage of groundwater and therefore has far fewer rehabilitation requirements.

2.6 The role of African Carbon Energy

Africary was formed in 2009 as a junior coal mining company to produce syngas from a stranded deep coal deposit in the Free State to supply an independent power producer or CTL plant. During the 31st International Pittsburgh Coal Conference, October 2014 Johan Brand presented [49] to the audience the following graphic:

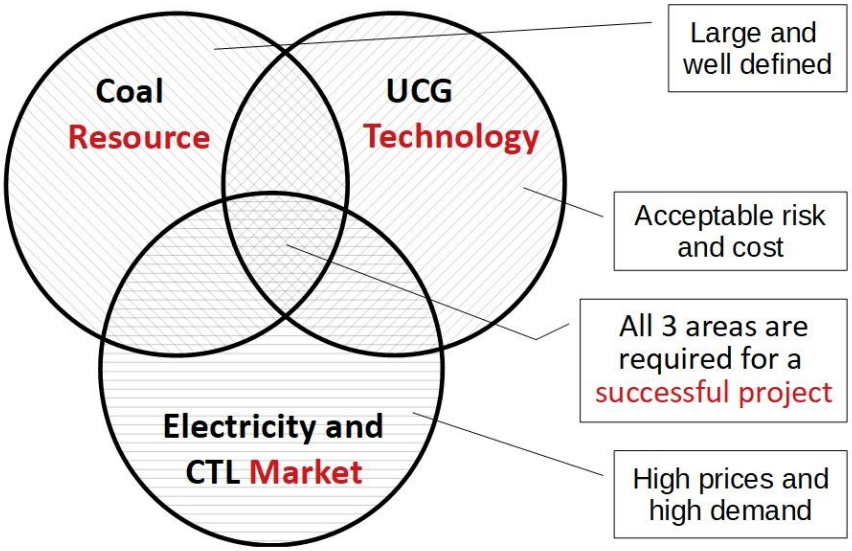

Figure 8 UCG – Bringing a Resource, Technology and Economics together for a 50 MW UCG power station in South Africa. [50].

It is clear in the graphic that Africary has a "project overlap" as the company has a proven resource that is well studied, in combination with suitably developed UCG technology that can supply cost-effective electricity and liquid fuels to the South African market. It was further stated during the conference that divestment from coal in SA does not recognise the reality of the growing energy demand of a fast-urbanising population. Coal is an easily accessible, reliable source and the most affordable baseload energy option for SA.

However, the role of environmentally friendly technology, and specifically the application of efficient and clean fossil fuel technologies, is a key requirement for future investment. Worldwide implementation of clean coal technology, like UCG in combination with highly efficient CCGTs, can save 2 billion tons of CO_2 annually by raising the global average efficiency of coal plants by a mere 6% from 34% to 40% [51].UCG is the obvious solution for clean coal implementation because:

- Due to efficiency increases it makes 25% less CO_2 per MWh and in large-scale combined-cycle mode can reach energy efficiencies of up to 60% versus the current average global efficiency rate of coal-fired power plants of 33% [52].
- There is 90% less water usage.
- It has no particulate emissions or ash handling and little or no leaching of trace elements from ash when operated correctly.
- Less sulphur and heavy metals are released or emitted.
- It can monetise economically un-minable coal (less than 26% of SA coal reserves are economically / technically recoverable with conventional mining).
- Deployment can create new high-value jobs.
- UCG projects can be located in economically depressed areas.
- No chemicals are used underground - only air and water are required.

The Africary UCG projects will support the implementation of community upliftment, with a social and labour plan combined with skills development through local economic development initiatives. The implementation of the first 50 MW electricity generation followed by IGCC of up to 2 000 MW is estimated to provide jobs for about 1 773 directly employed personnel during construction. The project area straddles three local municipalities and based on the 2011 census data estimate that 26% of people in the community have not received any formal schooling, with only 16.3% completing high school level Grade 12 and only 5.8% completing a higher education course.

Mining still dominates the local economic scene by contributing 58% of the GDP of the district and 19% of the province. Recently there has been an economic downturn within the mining sector, especially in the gold mining sector. Most of the retrenched labourers remain in the region, adding to the social problems associated with declining economic conditions.

The UCG projects may potentially utilise the services of hundreds of local service providers including the following:

- emergency services (ambulance and firefighting)
- clinics
- catering and food facilities
- accommodation
- transport, including taxis
- fuel supply
- water supply agreements
- engineering and maintenance support

Africary has negotiated agreements to increase the local manufacturing of many of the plants and their auxiliary units to employ locals for labour and maintenance. The power projects may also be integrated with a chemical stream, as the UCG syngas and the oxygen plant's (ASU) discard nitrogen could be appropriated as feedstock for ammonia and urea production. Methanol production is another opportunity for UCG as the process of synthesising methanol requires H_2 and CO_2 as feedstock and this may become a sink for a substantial volume of CO_2.

2.7 Africary UCG Coal Resource

Coal characteristics and geology are the given inputs for a UCG technical and economic evaluation, and thus the most important factors to consider when matching the gasification technology to the coal resource. More specifically, the coal geological conditions become the scientific building block for developing a UCG project.

The underground gasification process mines the coal chemically, by constructing at least two boreholes from the surface horizontally into the coal seam (where one borehole is used to inject air/oxygen to convert the coal into syngas and another to bring the syngas to surface). The Theunissen resource comprises of low-grade coal, with high ash content, as typically found in the Free State coalfields of South Africa [53].

The company's vision is to maintain and grow the Theunissen UCG mine on the Palmietkuil farm into an established producer of syngas for an increasing number of gas customers. The mission of Africary is to present itself as producer of a stable quantity and high-quality syngas, based on its propriety UCG technology and vast coal resource.

Seam 3 is the most widely distributed and economically significant developed at Theunissen, and also the most suitable for UCG, with an average thickness of 3.2 m (up to >5 m) and a depth ranging from 345 to 385 m below surface in the project area, where both the coal quality and geological conditions are excellent for UCG. The in-situ calorific value average is

20.3 MJ/kg, average volatile matter content is 19.2% and the average ash content is 30.8% (on an air-dried basis).

Successful UCG demands a thorough understanding of the resource and surrounding strata. To provide this understanding the following Theunissen studies have been implemented:

1. Exploration drilling for proven and measured coal reserves, thereby statistically quantifying the quality of the coal targeted for UCG.
2. 3D Electro-seismic study in support of geological results. The study could pinpoint the two shallow aquifer systems at 20 m and 40 m as well provide the permeability and hydraulic conductivity values of the strata.
3. A study to understand the impact of gasification operation parameters and CO_2 reactivity of the coal.
4. A study of the spontaneous combustion (SPONCOM™ test) characteristics of the coal and indication of the optimum ignition regime and relative ignition temperature.
5. Completion of the geophysical study provides support for the minimum and maximum width of a UCG cavity and management of the immediate roof collapse to prevent subsidence.
6. Inorganic mineral transformation and gasifier operation with a FACT™ Thermo-equilibrium simulation.
7. Detail coal characteristics to provide an in-depth scientific understanding of the project's gasification behaviour and curb the environmental footprint.

Theunissen is arguably one of the largest known coal resources in the Free State province and has been earmarked for development since 1971 [54]. It has SAMREC compliant inferred resources of 1.4 billion tons of coal and the project has completed further exploration drilling of 3.7 million tons in 2013 to a measured status. A measured coal resource is that part of a coal resource for which tonnage, densities, shape, physical characteristics, and coal quality can be estimated with a very high level of confidence. It is based on detailed and reliable exploration, sampling and testing information gathered through core drilled boreholes. The locations are spaced closely enough (at least one borehole per 300 m radius) to confirm both physical and quality continuity.

The Theunissen measured coal is enough to fuel a 200 MW power station for 5 years. Obviously, a vast amount of coal remains in the reserve and can be utilised for many other syngas-related projects. It is estimated that the project pipeline can quickly be extended to add 150 MW as 'carbon copies' of the first 50 MW.

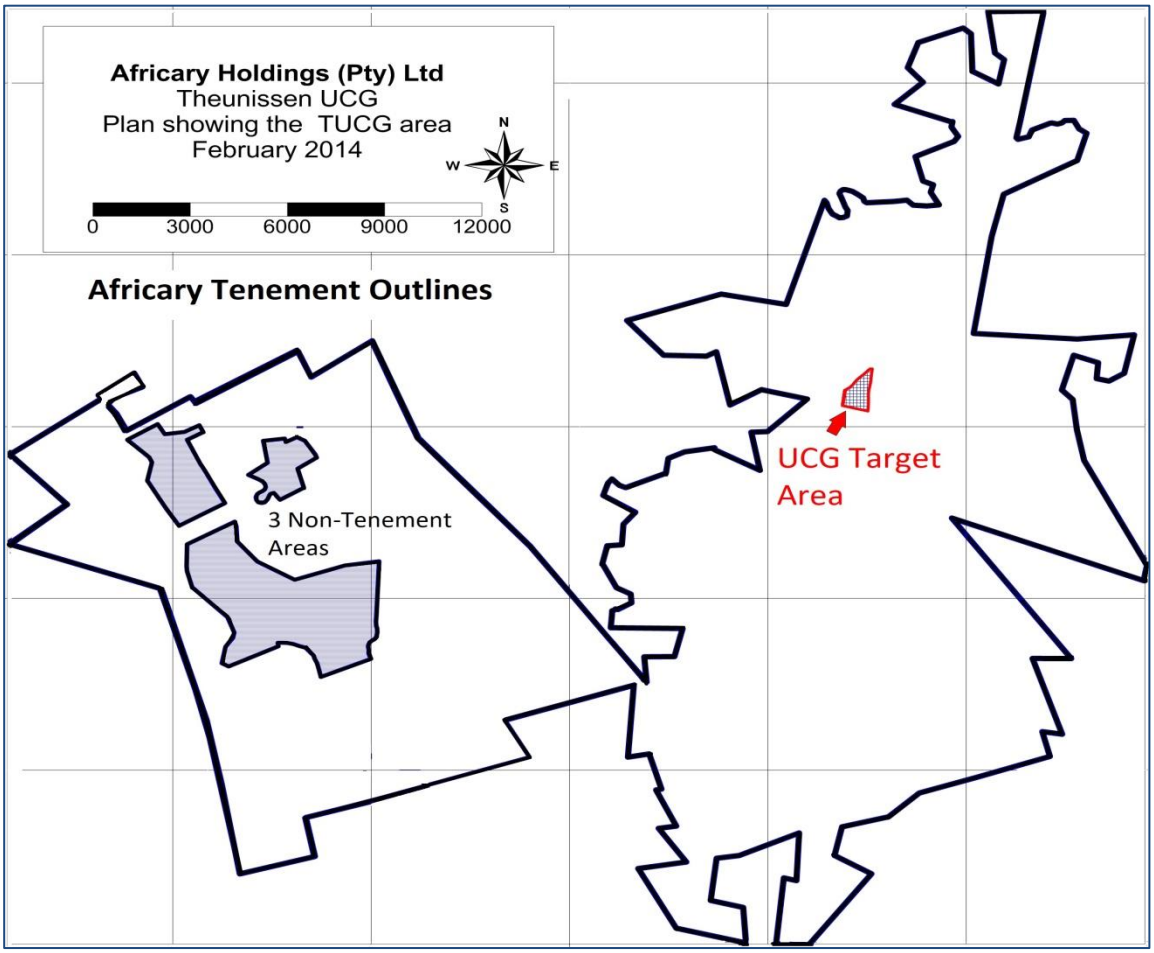

Figure 9: The TUCG project area (in red = 200 ha or 2 km^2) indicated on the farm Palmietkuil and shown relative to the full extent (330 km^2) of Africary's coal mining rights.

Africary will in the future be instituting a follow-up exploration programme with more infill drilling on the remaining 27.3 million tonnes (see Figure 9) to convert this to a measured resource.

Table 3: Resource Statement for Palmietkuil 584 [54].

Block	Area (ha)	Gross Tons In-Situ	SAMREC
South01	43.5	2 757 943	Measured
South01	12.8	317 934	Inferred
South02	3	221 606	Inferred
South03	2	355 282	Measured
South03	225.3	12 022 152	Inferred
North01	8.1	610 723	Measured
North01	57.2	2 785 106	Inferred
North02	105.9	5 207 513	Inferred
West01	223.4	6 793 173	Inferred
Total Measured	**53.6**	**3 723 948**	
Total Inferred		27 347 485	

2.8 UCG Concerns

The main concerns with UCG are the possibility of subsidence and groundwater pollution.

Often mentioned cases of failed UCG projects are the shallow attempts at Hoe Creek (1976 to 1979) in the USA [55], and Linc Energy in Australia. Hoe Creek operated at a meagre 39 meters below the surface and both subsidence and groundwater pollution occurred after an 11 meter cavity formed and collapsed forming a chimney to the surface. Fortunately, the trial was followed by DOE managed site remediation that led to a clean audit [56] proving that UCG damage can be corrected when it occurs.

Subsidence and overpressure are easily avoided by targeting deep-lying coal seams (> 200 m) as the risk of subsidence occurrence decreases exponentially with depth. The higher hydrostatic pressure also provides an effective water seal around the chamber and sufficient back pressure to avoid over-pressurising and possible deep groundwater pollution. It is important to note that the water found in and around a deep coal seam is not potable and is avoided for irrigation or human use as it most likely may contain organic and metal contaminants from the coal seam.

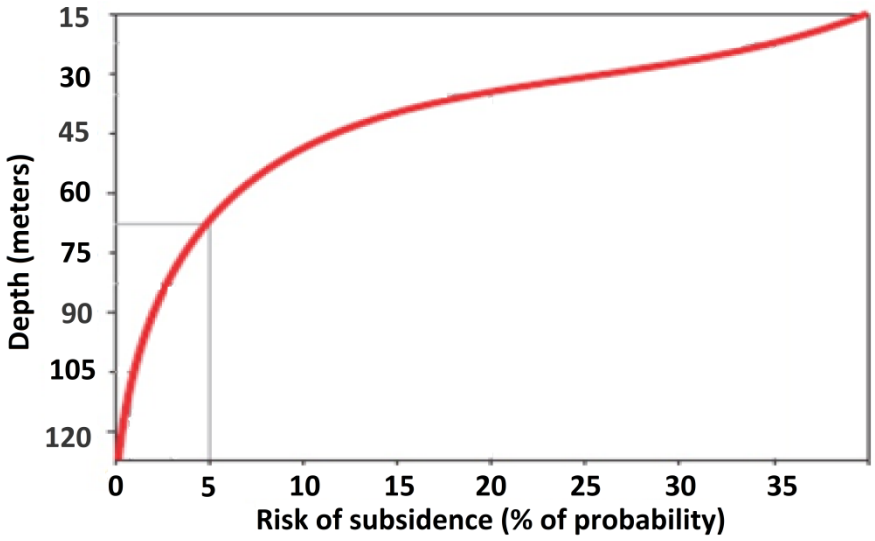

Figure 10: Risk of UCG subsidence becomes almost null at 120 m depth. Adapted from: Viability of UCG with CCS in Indiana. [57].

The other sites are in Queensland Australia where Linc Energy's fourth generation UCG panel, (at 120 meters below the surface [58]) may have been over-pressured and that may have resulted in groundwater pollution with trace amounts of phenolics. An Independent Scientific Panel (ISP) provided advice to the Queensland government on the UCG trials and has come to the following overall conclusions regarding subsidence and groundwater impacts [59]:

- UCG could and has been responsibly conducted and in a manner that is acceptable socially and environmentally safe and when compared to a wide range of other existing resource-using activities it is by far the safest mining method.

- The importance of water and the environmental impact that specific operations may have on groundwater necessitate that standardised monitoring and rehabilitation programmes be adopted and implemented.

2.9 UCG Opportunity for Africary as Project Developer

UCG can provide competitive electricity from coal, with limited environmental impact and reduced operational risk as modern power generation is specifically designed to run on syngas with diesel, LPG or LNG as back-up fuel. The SA Minister of Energy has indicated that the gas bid will be up to 3,126 MW capacity and Africary's project size and future growth opportunities will fit comfortably within these parameters.

Africary's immediate strategy is to establish itself as a UCG mining company which provides syngas as fuel to off-takers. The initial operation of a 50 MW commercial demonstration power plant by 2021 will give a decisive strategic advantage when growing to large-scale power generation. The company's medium-term strategy is to ramp-up production of syngas and to expand the power plant by bidding in subsequent rounds for new large-scale projects in multiples of 500 MW and up to 2,000 MW by 2028. However, there is also an opportunity to provide growth through CTL plants.

2.9.1 Overview of 50 MW commercial demonstration

This project has already drawn significant investment from Africary to obtain the coal resource, engineering designs, environmental applications and all required permits, including the land access and a commitment from local banks and construction companies to build and operate the power station. Africary's first project already has the following approvals and permits: environmental authorisation, air emissions licence, mining application, and waste management licence [60]. 132 kV grid connection capacities are available only 8 km (as the crow flies) from the site and the substation has available spare capacity up to 280 MW. Eskom's mandatory capacity study to connect to the 132 kV grid was completed in 2014 and includes quotes to implement the high voltage overhead line, substations and servitudes.

Reciprocating engines can be a substitute for gas turbines due to their higher efficiency, low water requirement, fuel flexibility and fuel variation tolerance. These engines offer operational flexibility and integration options and the ability to maintain a low heat rate at partial load and, most importantly for the Theunissen site, gas engines are unaffected by altitude. Africary plans to use 31 engines of at least 2 MW per engine for the first project. The total project cost for the 50 MW (nett) power station, including mining and gas management, will be about R 2.7 billion and can be operational within 12 months. The target electricity tariff will be between R 1.20/kWh and R 1.60/kWh.

2.9.2 Overview of 2 000 bbl/day concept study

Africary completed a concept study for integrating its UCG technology with a mini-GTL system. Syngas will be used for power production and synthesis of liquid fuels in a unique poly-generation configuration [32]. The process will consist of two parallel gasifiers, operated on different agents, making the Theunissen UCG, CTL and power generation tightly linked and interdependent, but reducing both cost and emissions.

UCG offers an alternative: a lower capital investment to conventional underground mining and surface gasification due to the removal of the surface gasifier and coal mine operations. The gas clean-up systems will remove undesirable components from each gasifier and blend the cleaned syngas for H_2:CO ratio control and provide the implementation of carbon capture and sequestration (CCS). The 2017 Africary Concept Study has minimised the complexity and optimised the process flow to provide own use electricity and about 4 000 bbl/day equivalent fuels (about 2 000 bbl/day diesel plus 200 ton/day LNG) at a capital cost estimate of about $ 350 million and operating cost of around 28 $/bbl.

2.9.3 Overview of 500 MW IGCC system

Africary has planned for a mining layout for the expansion of sufficient gas production for the operation of its first 500 MW (gross) Integrated Gasification Combined Cycle power plant. Future grid balancing and reduce transmission losses are foreseen when connecting to the Theseus substation that connects Mpumalanga with the Western Cape Province via several 400 kV and 700 kV transmission lines. The total project cost of 500 MW (nett) including mining, gas management and IGCC plant will be about R 15 billion and can be operational within 24 months. The target electricity tariff will be between R 1.10/kWh and R 1.20/kWh.

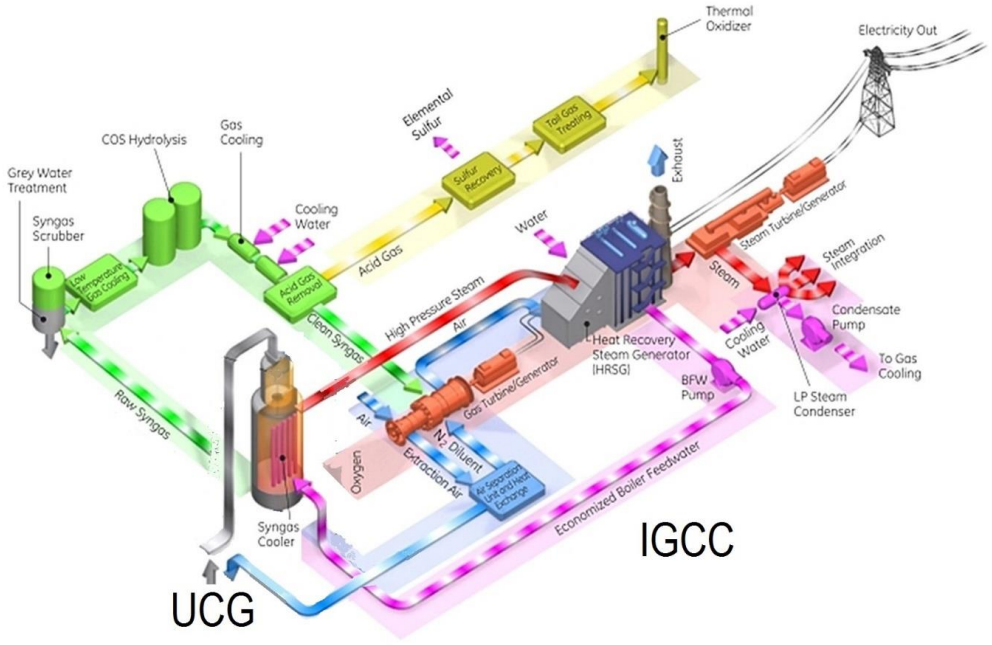

Figure 11 Graphic layout of the proposed Theunissen UCG - IGCC System.

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3 UCG PILOT STUDY IN SECUNDA SOUTH AFRICA - THE EXPERIMENTAL DESIGN AND OPERATING PARAMETERS FOR THE DEMONSTRATION OF THE UCG TECHNOLOGY AND VERIFICATION OF MODELS

Author: J.F. Brand

Conference paper presented at the 25th Annual International Pittsburgh Coal Conference in 2008.

Summary

Sasol Mining (Pty) Ltd, the mining division of Sasol Ltd, has been mining coal with conventional mining methods such as opencast and underground board-and-pillar, as well as longwalls; at its Secunda (South Africa) complex since 1976. To ensure the optimum consumption of the coal reserve, Sasol Synfuels and Sasol Mining are continuously investigating alternative options.

Sasol intended to test UCG as an alternative mining method to be applied in the mining of its stranded coal. It was estimated that about 66% of the Secunda coal resource will not be recoverable by conventional methods. The gas produced from UCG can be used as feedstock in chemical production or as fuel for power generation, thus exploiting coal reserves that cannot be mined economically or with conventional underground mining methods.

In a previously unpublished study by Sasol a UCG process model was completed by Sasol R&D and calibrated with the Rocky Mountain experimental results. A UCG business model was developed to understand the cost and interpret operational integration of the UCG technology into a CTL process indicating the value of implementing a UCG pilot operation at Secunda.

The value of this paper and the UCG demonstration proposed lies in the extraction of stranded coal with the cost savings of utilities supplied by the existing facilities and the future monetisation by different gas application options.

UCG PILOT STUDY IN SECUNDA SOUTH AFRICA - THE EXPERIMENTAL DESIGN AND OPERATING PARAMETERS FOR THE DEMONSTRATION OF THE UCG TECHNOLOGY AND VERIFICATION OF MODELS

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Abstract

Sasol Mining (Pty) Ltd has been mining coal with conventional mining methods at its Secunda complex since 1976. To ensure that all the coal in the relevant area is utilized optimally, Sasol Synfuels and Sasol Mining are continuously investigating alternative options to optimize the relevant coal reserve. Sasol intends to test Underground Coal Gasification (UCG) as alternative mining method to be applied in the mining of coal. UCG is a term applied to different techniques that produce in-situ, synthesis gas from coal seams. This gas can be used as feedstock in chemical production or as fuel for power generation, thus utilizing coal reserves that cannot be mined economically or with conventional underground mining methods.

In a previous study by Sasol and in conjunction with a UCG process model completed by Sasol R&D, a UCG business model was developed to understand the cost and interpret operational integration of the UCG technology into a CTL process. It was concluded that the UCG model developed, compared well with the Rocky Mountain experimental results and that the business model indicated the value of implementing a UCG pilot operation.

The value for Sasol of demonstrating the UCG technology in combination with its CTL operations in Secunda lies in the extraction of stranded coal with the cost savings of utilities supplied by the existing facilities and the future monetization by different gas utilization options.

Keywords: Underground Coal Gasification, UCG, pilot study, South Africa, Experimental design, Operating parameter, Modeling verification

1. BACKGROUND AND INTRODUCTION

Sasol recently decided to investigate UCG as another mining-gasification method (technique) to produce syngas for its processes. Experimental research on UCG started in the 1930's, in the former Soviet Union. Since 1955, six commercial UCG sites were operated, mining more than 15,000,000 tonnes of coal [Walker, 2001]; of which Angren, in Uzbekistan is arguably the best known. The Soviet research effort on UCG far exceeds that of any other country, but there have also been significant research programs on UCG in USA, Australia, UK, China, India, Pakistan, Belgium, European Community, New Zealand, Spain and recently Eskom's Majuba Pilot in South Africa.

For the Secunda UCG, a network of boreholes will be drilled into the coal seam and the coal ignited and operated by injecting oxygen underground. A fire-front is essentially used to "mine" the coal. Utilizing UCG, coal is turned into valuable gas, using oxygen (O_2) and steam (H_2O), as follows (Figure 1):

- Preheating and igniting the in-situ coal with steam and Air respectively
- Injecting O_2 and steam into the coal seam through injection wells.
- Collecting the resulted synthesis gas product through production wells.

The technology to be tested at the Sasol Mining Secunda Complex is the Linked Vertical Well method (LVW). Using the LVW method, the Secunda UCG technology is comparable to conventional Longwall underground mining in concept, but very different in execution. The UCG technology has been proven to provide very high coal extraction rates of more than 90% and the overall resource extraction rate shows potential to far exceed that of conventional underground mining.

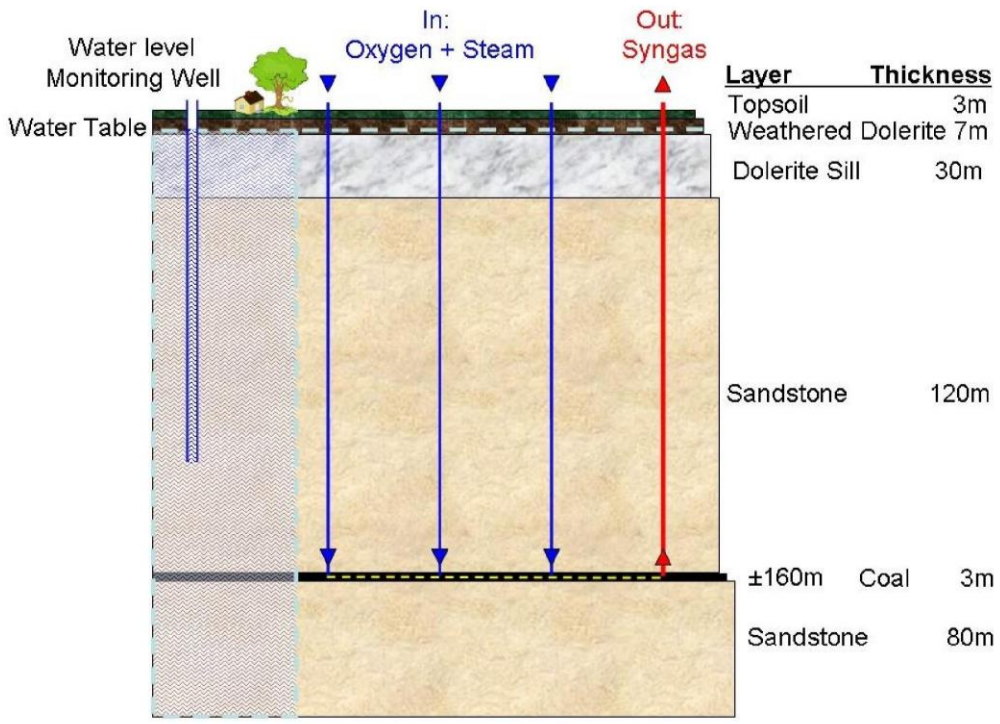


Figure 1: 2D Graphic of the Secunda UCG Process

2. OBJECTIVE OF THIS STUDY

The principle aim of this paper is to elaborate on, and present the approach proposed by Sasol for the Experimental design and operating parameters for the demonstration of UCG technology, and obtaining results in order to validate the models. The present study will describe the geological data gathered and the assumptions made to finalize the UCG design.

The UCG method appears to offer a considerable degree of flexibility in terms of different types of coal and depths, using various methods. By selecting gasifying media and operational conditions, it is possible to achieve the expected composition and the desired volume of gases. The existing technology enables the processing of by-products of underground gasification, resulting in marketable commodities and, by the same token, preventing environmental pollution. Storing areas for ash or discard, inevitable in the case of traditional coal processing units, are virtually non-existent with the use of UCG (Shackley, *et al.*, 2004).

The extent to which all the advantages can be claimed as real benefits depends firmly on the economics of a planned project. As in any other case, the final balance between profit and expenditure will have a conclusive impact. A logical conclusion therefore emerges from reflection upon the development of UCG and its potential on the one hand, and the South African resources and needs on the other. If any serious and longer-term attempts to utilize the UCG method are to be carried out in South Africa, such projects will call for a benefits evaluation method that is universal enough to be used in preliminary business cases.

It was decided to develop an UCG pilot and demonstration facility as close as possible to the Secunda main complex. By integrating with the existing feed and effluent handling

infrastructure the schedule and cost of the project will be reduced. The above ground facilities will be developed with the aim to pilot and demonstrate the technology as well as conversion to a production facility during subsequent commercial phases.

Specific questions to be answered during the piloting and demonstration phases:

- Is Secunda coal, geology and hydrology suitable for UCG commercialization?
- Will oxygen blown UCG technology produce a product gas suitable for the production of synthetic fuels?
- What are the long term effects of UCG on the environment?
- What is the optimal operational parameters and well layout?
- What skills, competencies and resources are required to commercialise UCG?
- What are the process conditions and product compositions expected from future UCG sites?
- What is the coal extraction ratio obtained during commercial scale demonstration?

By answering the above research questions, the objective of this study is to structure, propose and test a method suitable for the estimation of achievable benefits through the application of UCG on stranded coal resources at Sasol's Secunda operation.

3. UCG PILOT PROCESS

The UCG design process can best be described as an iterative process taking into account all the different mining and gasification data from a specific site. There is not such a thing as a generic UCG method and in each of the listed areas below the different parameters will have to be considered and engineered for effective UCG.

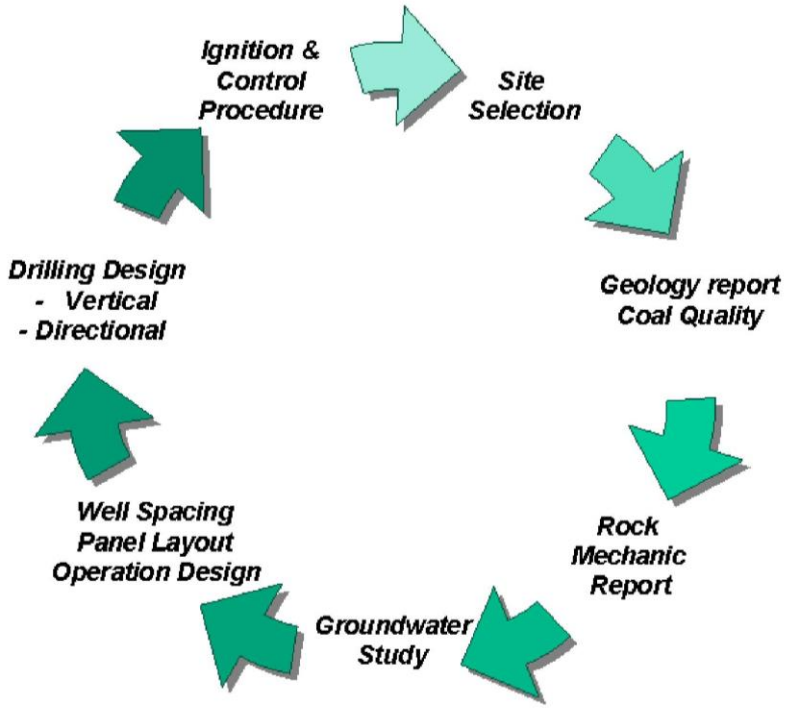


Figure 2: UCG Design Process

This process and the reasons for this design are explained in the paragraphs below.

PCC Paper for the Secunda UCG Pilot Project in Secunda, South Africa

3.1 Site Selection

Some 30 million tons of coal in 8 sites have been identified within the secondary area and other nearby areas of the Secunda complex. The close proximity of these sites to the complex would greatly assist the supply of utilities (mainly oxygen, steam and electricity), thereby lowering the piloting costs. Equally, the close proximity of the reserves will enable testing and the incorporation of the rawgas into Synfuels. The identification of potentially suitable UCG sites was done individually as the geology and environment of each site is unique. Poor site selection can be catastrophic if underground aquifers are breached or when hydrostatic pressure is lost.

Since piping is required directly above the coal seam being gasified, there may be restrictions on gasifying under property not belonging to Sasol. Therefore it became a requirement that both the mineral and surface rights should belong to Sasol. The opportunity should also allow connecting the pilot site to the Sasol Infrastructure and using the gas as feedstock for Fisher-Tropsch.

The site selected is 0,5 km east of the main Secunda factory within the Secondary area. It contains approximately 2Mt of low ash content coal. The reason it was not mined is because it is enclosed by dolerites, slips and the graben and it was therefore deemed uneconomical to mine. The UCG footprint was arranged so that the above ground area falls on the Sasol property currently used as a construction lay down area.

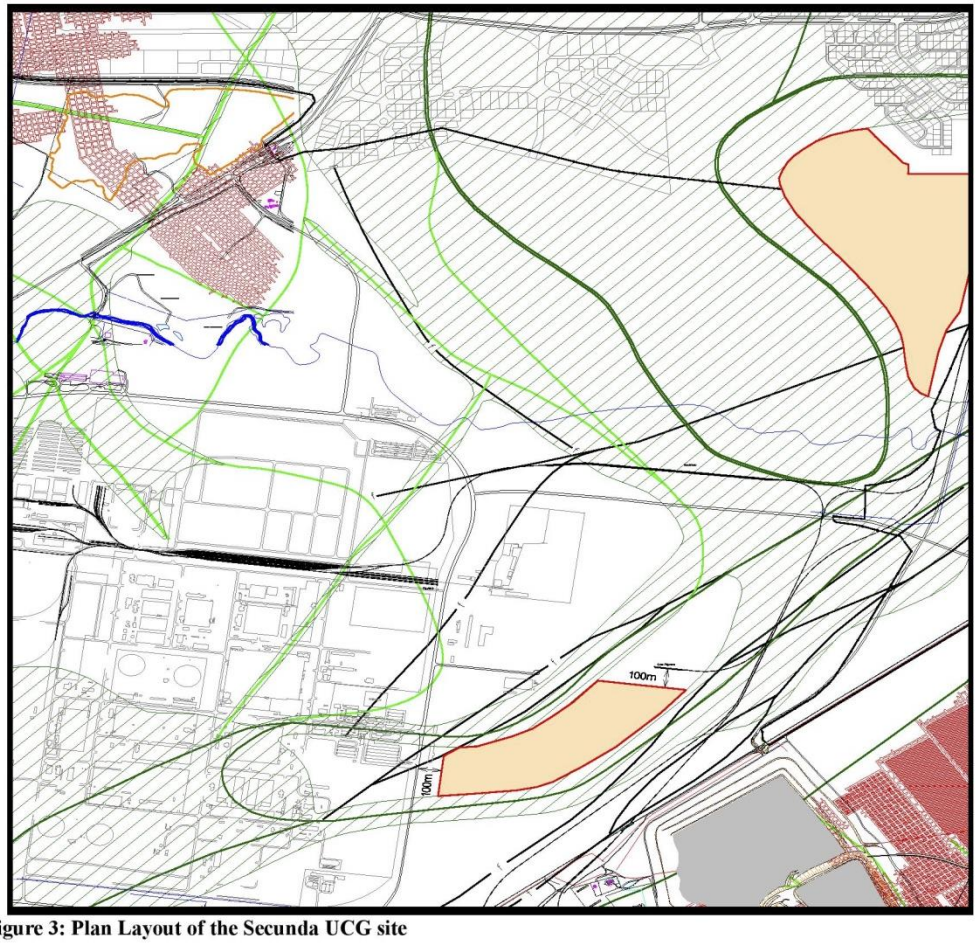
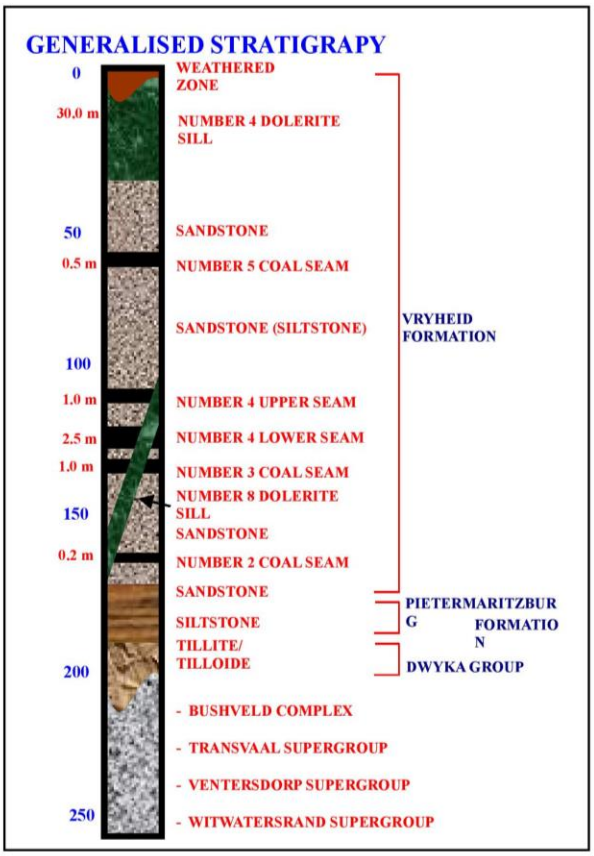


Figure 3: Plan Layout of the Secunda UCG site

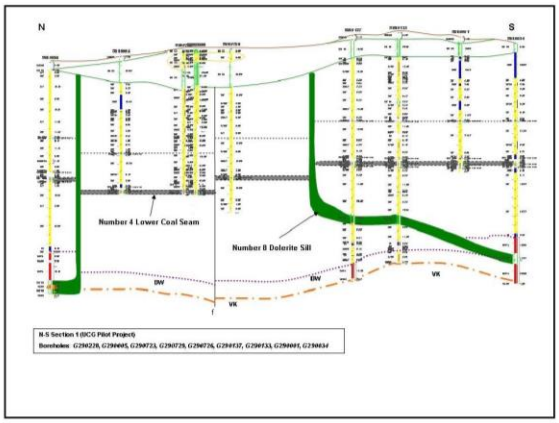
3.1 Geology

The site can be described as the orange block presented above. Phase one will be in the northern eastern corner and will be 150 m wide and 200 m long. A number of vertical boreholes (both core and percussion holes) were drilled in the area to gather geological information. The general stratigraphy of the pilot site area is indicated in Figure 1 and was confirmed by the exploration boreholes.

The Numbers 4 Lower, 4 Upper and 5 Seams are generally present and occur within the siltstone and sandstone succession of the Vryheid Formation of the Ecca Group. The Number 4 Dolerite Sill occurs at or close to the surface, is approximately 50 metres thick and highly weathered in places. The Number 8 Dolerite Sill mostly occurs towards the base of the Ecca Group, sometimes intruding into the Dwyka Group and Pre-Karoo strata. It generally occurs close to the pre-Karoo floor and occasionally intrudes towards the surface in a semi-vertical nature.



PCC Paper for the Secunda UCG Pilot Project in Secunda, South Africa



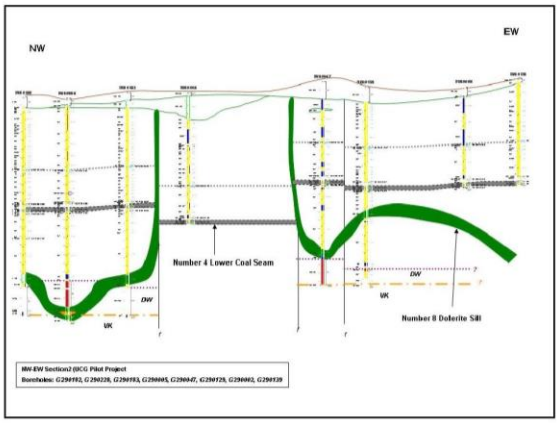


Figure 4: Generalized Stratigraphical Column in the Secunda Complex and site sections.

A combination of N-S and NW-SE borehole sections was drawn based on exploration information. Interpretation of the sections confirmed the presence of the Number 4 Dolerite Sill at the surface. The Number 8 Dolerite Sill occurs mostly below the Number 4 Lower Coal Seam, in some cases intruding towards the surface along fault planes associated with the well known Graben. The coal seams are displaced by intersecting dolerite sills and faults, the latter which occur parallel or sub-parallel to the NE-SW trend of the graben.

The C4L coal properties for this area are a follows. Proximate analysis (Air dried basis):

- Moisture 4.5%
- Ash 22.2%
- Volatiles 22.0%
- FC 50.8%

Ultimate analysis (Air dried basis) is taken as the averages for Secunda mining:

- C 54.2%
- H 33.1%

- O 8.7%
- N 1.4%
- S 1.16%

3.3 *Rock Mechanics and Rock Engineering of the UCG Pilot*

The term applied to that part of the mine from which the coal has been removed and the cavity more or less filled up with waste or overburden is called a goaf: Goafing is required to close up the excess cavity to reduce heat loss to the surrounding strata and channel the Agent close to the coalface. The goaf behavior is primarily determined by the roof span above the cavity and forms the single largest parameter in UCG cavity control. The caving of the immediate roof, an integral part of the process, is important for efficient reactor flow regime. The following critical Rock Engineering aspects have been identified:

- Regular goafing must occur to ensure that the agent injected into the chamber is forced to flow along the coal face.
- Goafing must be high enough to ensure that the broken rock (rubble) has bulked to the extent that it is in contact with the un-failed overburden and thus prevent gas flow and loss over the goaf (broken material).
- The goaf rubble must compress and flood with water to such extend that the permeability of the goaf is an order of magnitude lower than that of the cavity.
- Cavity pressure must be maintained. In shallow areas goafing to surface may cause undue pressure loss.

From calculations, modeling and practical Longwall mining and pillar extraction experience the Sasol Mining Rock Engineering department established the following:

- The initial goaf will occur within the creation of a ± 80 m unsupported roof span.
- The goafing behaviour is controlled by numerous other factors, such as local rock mass characteristics, stress and discontinuities. These macro factors can be strategically utilised in site selection so as to ensure controlled goaf behaviour.
- If the initial cavity is too small the goaf is not high enough to ensure adequate bulking to fill the void up to the intact overlying strata.

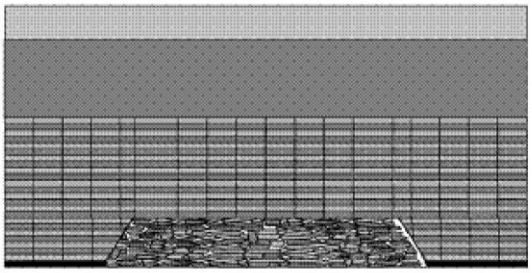
The Rock Engineering department therefore must ensure the following with regards to the design of the geometry of the gasification cavity:

- The initial goaf must occur as soon as possible.
- The initial goafing must be high enough to ensure that adequate bulking has occurred to prevent gas flow (loss) over the rubble.
- Prevent the entire overburden from failing in shallow areas.

Minimum required goaf heights:	
Seam height	Goafing height
2 m	± 20 m
3 m	±30 m
4 m	±40 m
5 m	±50 m

Table 1: Goaf heights

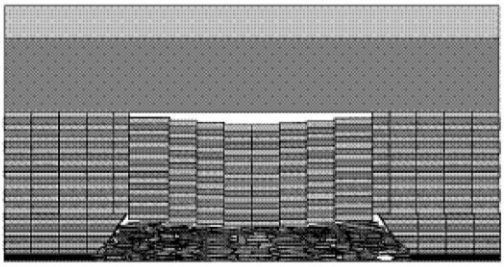
The above table shows the relationship between the seam height and the required height of the initial goaf to ensure complete filling of the void above the goaf. The implication of this table is that a wider span must be created in thicker seams to ensure failure to a higher horizon. This will ensure that sufficient bulking of the immediate overburden occurs to fill the void above the rubble completely.



2nd phase : cavity span is > 100 m and height of the goaf is approx. 40 m. Top of the goaf is in contact with the upper unfailed rock.

Figure 5: Goafing behavior for cavity larger than 100m

In Figure 5 it can be seen once the roof span exceeds 100m goafing has progressed high enough to ensure that the top of the goaf is in contact with the un-failed rock and no void is present. The geometry of the borehole layout must therefore ensure that the critical span of 100m is created. (The critical span is the minimum unsupported roof span). The wider the critical span is the less the risk of a goaf "hang-up".



3rd phase : cavity span 100 - 200 m and the height of the goaf now close to 40 m. Goaf recompressed by overlying large blocks. There is now a cavity at the base of the thick dolerite, approx. 90 m above the coal.

Figure 6: Goafing behavior for cavity small enough not to break the Dolerite Sill on surface

Figure 6 shows a simplified section of the overburden at the proposed site for Phase 1 of the Pilot Project. It has been agreed that for the first phase of the Pilot Project no subsidence will occur. This is possible due to the presence of a thick 30m dolerite sill in the overburden. To ensure that the dolerite sill remains intact the critical span must be limited below 133 m. This figure is obtained by the calculation of the critical span using site specific parameters.

Since Sasol Mining has been managing these issues for many years, ground stability issues and caving mechanisms are well understood and actual goafing can be managed and predicted within the parameters of the Secunda Coalfield. With the process of UCG we can expect changing geological and hydro-geological conditions responding to the growth of the cavity. In addition several management mechanisms can be utilised to control the goaf behaviour, such as leaving barrier pillars in-situ, pre-blasting or inducing goaf by hydrostatic pressure.

3.4 Hydrogeology

This study was commissioned to the Institute of Groundwater Studies (IGS). In April 2008, nine water monitoring wells were drilled at various depths and several test were performed in the ensuing months. The data obtained from these tests will provide the

background levels of water quality as well as serve for the inputs in to a Hydrogeology model for the site.

Preliminary feedback from the study indicates that the site is suitable for UCG.

3.5 Statistical Experimental Design

From a research point of view, one would like to determine the optimal or best feasible conditions at which to operate the reaction volume. The experimental design is for the case of a well pair system operated through a life cycle and in this case there are three input parameters that can be controlled:

- Feed rate
- Feed steam:oxygen ratio
- Cavity pressure

In this pilot the temperature of agent is considered constant or that the effect of variability can be factored in the results obtained rather than to incur the expense of maintaining temperature. An important parameter that cannot be controlled is water ingress, which is determined by a combination of cavity pressure, cavity size and overburden characteristics. In turn, the cavity pressure must be maintained below the hydraulic pressure, which is determined by the level of the water table.

In contrast to normal laboratory experiments, which are performed under controlled conditions, one experiment may last several days and up to a month. An experimental plan is suggested, whereby variable input parameters are varied in such a way so as to minimize the amount of experiments required. The results from the experiments will have to be analyzed statistically to try and determine the optimum set of conditions to perform UCG in Secunda.

Statistical experimental design is the methodology of specifying the least number of experiments for obtaining the maximum amount of information on the variables of interest. In this case, the effect of the variables feed rate, feed steam to oxygen ratio and cavity pressure on gasification performance will be investigated. Due to the high experimental costs and time constraint it is necessary to reduce the number of experiments required.

Therefore, it is proposed to deploy a 23-1 fractional factorial design for the three variables under study. The design is depicted in Table 1 below. Each variable is changed at two different values, i.e. a low value (-1) and a high value (+1). The design yields four experiments varying the values for the three variables simultaneously. Therefore, only four cavities are required for the experimental program. Because the design is orthogonal, i.e. orthogonal columns, the effect of each variable on gasification performance parameters can be isolated and statistically quantified. If however, one of the variables is not significant, then the interaction of the remaining two important variables may be estimated.

In order to eliminate the effect of cavity size, it is important that all experiments be performed from the same reference point. Hence, for every experiment a new cavity will have to be started and allowed to grow in a similar manner every time. Furthermore, the individual cavities will have to be separated by a significant barrier of coal between them, so that they do not affect each other. It is also assumed that the area of experimentation is homogeneous in terms of coal quality. In other words, the differences to be observed between the experiments in Table 1 in terms of the gasification performance parameters should be attributable to the differences in experimental conditions and not any other extraneous variables, such as coal quality.

Run	Feed rate	Feed steam:oxygen ratio	Cavity pressure
1	1	-1	-1

2	1	1	1
3	-1	-1	1
4	-1	1	-1

Table 2: Experimental design for the UCG experiments

Values will be allocated to the +1/-1 combinations as soon as Synfuels has committed to oxygen and steam supply. The upper values will be determined by the maximum possible supply whereas the lowest values will be decided from an operational feasibility view.

During the piloting an estimated 8–10 t/h oxygen will be required. During the commercial demonstration stage a maximum of 15 t/h oxygen will be consumed. The maximum feed rate is determined by utilizing the maximum oxygen flow at the lowest steam:oxygen ratio to be tested. Hence, assuming an availability of 9 t/h (281 kmol/h) of oxygen, at an steam:oxygen of 1 (molar), 5 t/h (281 kmol/h) of steam will be required. Thus 14 t/h should be the maximum feed flow that can be achieved in order to perform the tests.

Based on the combinations given in above, it is proposed that the following values be allocated to the maximum and minimum values. These design parameters may change in the lead-up to the UCG trial.

Table 3: Operational variables that will be piloted.

	Feed rate [t/h]	Steam:O_2 [molar ratio]	Pressure [kPa]
+1 value	14	2	800 (or max)
-1 value	1,4	0,5	400

Thus, in summary, four pilot cavities and one commercial demonstration cavity are required for the R&D phase of this project. The pilot cavities will consecutively be commissioned and operated separately under different operating conditions. After the cavity piloting phase a full extraction mining method is used to extract maximum coal from the area in a long wall mining technique. Dynamic parameters like pressure cycles, cross injection, goafing behavior and changes in cavity sizes are parameters that will be evaluated.

3.6 Site Layout

The layout is a matrix of wells spaced at 50 m by 25 m and connected on surface with header lines connected to the Utilities and Cooling and sampling Skid.

There are 5 Production Wells (red dots) on the left hand side and 27 Injection Wells (Blue dots) on the right hand side.

4. UCG Operations

Four pilot cavities will be commissioned at different process conditions during the Experimental Design operation to establish the optimum operating parameters for UCG in Secunda coal. A fifth cavity will then be commissioned for the commercial scale demonstration on the same site and used to consume all coal available to the pilot including coal left by the Experimental Design operation.

The process of UCG consists of a sequence of cycles taking place one after the other. Each gasifier lifecycle has a compression phase and an expansion phase leading to a decompression phase, but it is possible to maintain a steady state operation where the expansion phase covers several Injection Well (IW) movements and Production Well (PW) changeovers over many weeks.

During UCG, all the oxidant flow is directed down through the selected IW or combination of IW's, into the connected gasifiers. The gasifier is operated with the cavity pressure maintained below hydrostatic pressure, and the flow rate and composition ratio of agent are adjusted for optimal mineral extraction. During this process all the product gas flow is evacuated by a selected PW. Systems are in place in order to shut down or idle the process on low pressure air.

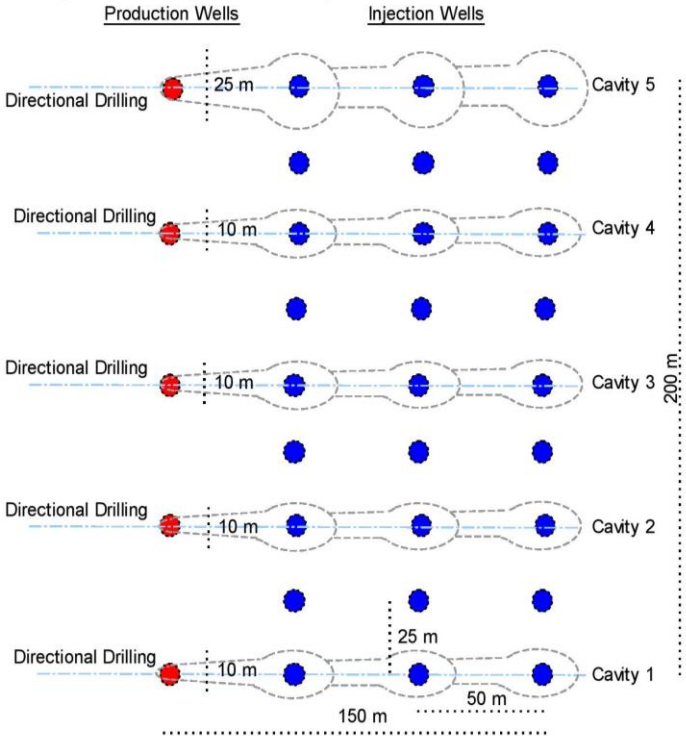


Figure 7: Well matrix for pilot plant.

The sequence of operation will be as the same for each of the four experiments namely to ignite the cavity and operate the cavity throughout an growth and stabilization phase until the cavity reaches the maximum diameter allowed for roof stability. Hereafter the cavity will be idled on low pressure air to keep it dry. The next phases will each follow the same operation until eventually the fifth phase.

In the fifth phase the cavity will be allowed to grow to its maximum size hereafter the intermediate injection well will be utilized to link the cavity to the next row. This system will be followed until the cavity is grown large enough to initiate the first goaf. Thereafter the regular movement of IW's will ensure that the flame front is controlled through the coal seam.

5. Impact on existing Mining operations

- This area is not currently assigned to any mine and is well secluded from other mining areas.
- This area and therefore it has a low risk of gas migrating to adjacent mines.
- No impact is foreseen on any current or future mining activities.

6. Impact on Existing Synfuels Operations

- Several tie-ins are required for: utilities, control systems, services, etc,
- If oxygen production is the bottleneck of the plant the supply to the site will be cut-back, but an advantage of UCG is that it has 100% turndown for a short period and it can be sustained using low pressure air
- Impact of dumping black water (gas liquor) to the existing liquid treating facility is small (±50 t/d) compared to the approximately 30 t/h of condensables is produced per gasifier.

7. Preliminary Schedule:

To fully exploit the relevant reserves will take approximately 3 to 4 years. However, the first phase of the test is planned for a period of 6 to 12 months after successful start-up and stabilization.

Establishment of the infrastructure required, including the drilling of the required boreholes will take approximately 6 months. A milestone schedule is provided below:

- Start of exploration and construction: January 2008
- Commissioning of test facility: September 2009
- Start of Operation: Late 2009
- End of Operation: Mid 2010
- Start of Decommissioning and Rehabilitation: December 2010

8. CONCLUSIONS

It can be shown from numerous studies all over the world that UCG is an environmentally safe, alternative mining method that will improve the economic viability of future CTL. Furthermore, as a focus on costs reduction is implemented, this novel gasification method will beat the limitations of conventional mining and surface-gasification and open doors to new opportunities.

UCG was proven in many pilot studies all over the world with manageable product properties and environmental performance. If the Secunda UCG Pilot is successful it will open the door to a new paradigm in coal mining. It is expected that crude oil prices and trends will support coal conversion technologies and UCG can be the foremost among these. UCG is the natural choice in technology that will see FT taking its place as a viable alternative to crude oil.

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4 GROUNDWATER MONITORING DURING UNDERGROUND COAL GASIFICATION

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Summary

Underground coal gasification (UCG) is a fast-emerging, in situ mining technology that provides access to low-cost energy through the utilisation of coal reserves that are currently not technically or economically exploitable by conventional mining methods. Groundwater monitoring for conventional coal mining in South Africa is well established, with SANS, ASTM, and ISO standards for the specific environment, location, and purposes. South Africa's groundwater is a critical resource that provides environmental benefits and contributes to the well-being of the citizens and economic growth. Groundwater supplies the drinking water needs of large portions of the population, and in some rural areas, it represents the only source of water for domestic use. Implementation of, and adherence to, groundwater monitoring standards are thus non-negotiable.

This paper proposes a fit-for-purpose groundwater monitoring standard for a commercial UCG operation. It is important to proactively prevent or minimise potential impacts on groundwater through long-term protection and monitoring plans.

Africary has participated in the drafting and promoting of a National Standard Proposal [25] to emphasise groundwater monitoring as one of the five strategies of the '*Policy and Strategy for Groundwater Quality Management in South Africa*' (Department of Water Affairs and Forestry, 2000) and to align it with the *National Water Act, Act no. 36 of 1998* (Republic of South Africa, 1998). The focus of this standard was directed solely towards groundwater monitoring during UCG. *Groundwater* in this context refers to water as sampled from dedicated monitoring wells around the targeted site, which will include the shallow aquifer referred to as groundwater, and water found at the level of the underground gasifier referred to as 'coal water' [26].

In summary, it is proposed that:

1. Baseline groundwater quality to be measured and monitored on a continuous basis.
2. SANS 241-1 to be used as a standard to compare to the baseline quantity.
3. Minimum limits to be determined between a combination of (1) and (2) above and the specification to be set at the determined quality values.

Groundwater monitoring during underground coal gasification

by J.C. van Dyk*‡, J. Brand*, C.A. Strydom†, and F.B. Waanders‡

Synopsis

Underground coal gasification (UCG) is a fast-emerging, *in situ* mining technology that provides access to low-cost energy through the utilization of coal reserves that are currently not technically or economically exploitable by conventional mining methods.

Groundwater monitoring for conventional coal mining in South Africa is well established, with SANS, ASTM, and ISO standards for the specific environment, location, and purposes. South Africa's groundwater is a critical resource that provides environmental benefits and contributes to the well-being of the citizens and economic growth. Groundwater supplies the drinking water needs of large portions of the population, and in some rural areas it represents the only source of water for domestic use. Implementation of, and adherence to, groundwater monitoring standards are thus non-negotiable.

The groundwater quality management mission, according to the Department of Water and Sanitation in South Africa, is set in the context of the water resources mission and reads as follows:

'*To manage groundwater quality in an integrated and sustainable manner within the context of the NationalWater Resource Strategy and thereby to provide anadequate level of protection to groundwater resources and secure the supply of water of acceptable quality.*' (SABS, 2016).

In this paper we propose fit-for-purpose groundwater monitoring standards for a commercial UCG operation. It is important to proactively prevent or minimize potential impacts on groundwater through long-term protection and monitoring plans.

Keywords
Groundwater monitoring, underground coal gasification, national standards.

Scope of study / standard proposal

The purpose of this paper is to set out a National Standard Proposal to emphasize groundwater monitoring as one of the five strategies of the '*Policy and Strategy for Groundwater Quality Management in South Africa*' (Department of Water Affairs and Forestry, 2000) and to align it with the National Water Act, Act no. 36 of 1998 (Republic of South Africa, 1998).

The focus of this standard is directed solely towards groundwater monitoring during underground coal gasification (UCG). Groundwater in this context refers to water as sampled from dedicated monitoring wells around the targeted site, which will include the shallow aquifer referred to as groundwater, and water flow at the level of the underground gasifier, referred to as 'coal water'.

The period of monitoring will include:

1. Baseline monitoring before commissioning and start-up
2. Start-up and commissioning
3. Normal operation
4. Decommissioning or site closure
5. Monitoring after closure.

The proposal includes and will be limited to the following aspects:

- Groundwater
- Underground coal gasification (*in situ* coal mining)
- Monitoring boreholes
- Quality control,
- National standards
- Frequency of monitoring.

The proposal does not include:

- Technical specification of monitoring well design
- Monitoring well design and location (only general comments)
- Sampling methodology
- Pollution remediation
- Analytical standard per specific quality parameter
- Borehole location.

Background information

Groundwater monitoring for conventional coal mining in South Africa is well established, with specific SANS, ASTM, and ISO standards dedicated for the specific environment, location, and purposes. Coal mining can have a major impact on groundwater quantity and quality. Groundwater monitoring programmes are thus non-negotiable. The important aspect is to implement a fit-for-purpose monitoring programme for the specific technology,

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Groundwater monitoring during underground coal gasification

process, or site location. It is thus important to proactively prevent or minimize the potential impacts on groundwater through long-term protection and monitoring plans.

A successful monitoring program is one that (Barnes and Vermeulen,2007)

(1) Consists of an adequate number of wells, located at planned and strategic points
(2) Yields sufficient groundwater samples
(3) Follows a dedicated monitoring programme and quality control standard.

In order to have an efficient monitoring programme and to avoid unnecessary analysis and costs, it is also critical to determine upfront which parameters have to be monitored for the specific process and site conditions.

An overview of the coal industry in South-Africa, the future energy requirements, and a brief technical discussion on UCG, is presented to sketch the context of the proposed groundwater monitoring standard.

Utilization of coal in South Africa

Coal is globally the most widely used primary fuel, accounting for approximately 36% of the total fuel consumption for electricity production. In South Africa, coal provides approximately 77% of the country's primary energy needs (Figure 1). This is unlikely to change significantly in the next two decades, due to the lack of suitable alternatives. Globally and in South Africa, coal will continue to be the most important fossil fuel for energy production, and with the growing energy demand the demand for coal will increase (Time for Change, n.d.).

Coal is mined in South Africa by both underground and opencast methods, with approximately 37% of production from underground and 63% from opencast mining (Time for Change, n.d.).

Many of the South-African deposits can be exploited at extremely favourable costs, and as a result, a large coal-mining industry has developed (Department of Energy, 2012). The operations range from collieries that are among the largest in the world to small-scale producers. A relatively small number of large-scale producers supply coal primarily for electricity generation and synthetic fuel production. In addition to the extensive use of coal in the domestic economy, approximately 28% of South Africa's coal production is exported, mainly through the Richards Bay Coal Terminal, making South Africa the fourth-largest coal exporting country in the world.

Technologies to improve coal mining and extraction techniques have reached their peak, and according to rough predictions, there is still enough coal for the next 200 years if extraction continues at today's rate. This implies that in the near future the security of coal supplies will not be a concern. However, recovery of currently unmineable coal resources may be problematic in the long term because of the economic and ecological aspects of using this energy resource (Department of Energy, 2012). Coal utilization has always increased and forecasts indicate that in the absence of a dramatic change in policy, this trend will continue in the future. The IEA thus believes that greater efforts are needed by governments and industry to embrace cleaner and more efficient technologies to ensure that coal becomes a much cleaner source of energy in the future (YEA, 2017).

UCG is playing an increasingly important role as a cleaner and more environmentally friendly 'chemical mining' technique. This technique enables highly efficient utilization of the energy and chemical value obtained from the coal without the need for conventional mining operations, stockpiling, reclaiming, and transportation. The generation of mining wastes from overburden, discards, and ash is also avoided. Furthermore, the much-reduced underground infrastructure and elimination of the need for personnel to go underground makes UCG applicable to many deposits that would otherwise be unsafe to mine, unmineable, or sub-economic (Department of Energy, 2012). The 'UCG coal miners' are essentially 'chemical' miners, who work from the surface using drilling technology to access the coal resource and transform it into a recoverable reserve. The work environment is therefore more controllable, and safer. The shorter coal value chain from the resource in the ground to end-product enables UCG to produce lower cost energy than conventional mining.

As a practical illustration, a resource in the Free State area was reclassified from and Inferred Resource to a Measured Resource for UCG applications by Africary. An amount of 3.7 Mt (GTIS) was additionally classified as Measured, according to SAMREC (2009) and SANS 103020:2004, the South African guides to the systematic evaluation of coal resources and coal reserves. This serves as an example of utilizing a reserve that would be unmineable using conventional techniques, through applying the UCG process.

Underground coal gasification (UCG)

UCG is a gasification process used to produce gas from coal *in situ* (underground in the coal seam) by injecting air or oxygen, with or without steam, into the seam and extracting the product gas via wells drilled from the surface. UCG is a high-extraction mining method utilizing at least two boreholes (wells) that are drilled horizontally into the coal seam parallel to one another. Ambient air or air that has been enriched with oxygen is delivered to the coal seam via one or more boreholes (the injection wells) and the coal is ignited in order to start the gasification process. This may be thought of as a thermo-chemical mining process. The burning front results in high temperatures (>1000°C) that cause the coal ahead of the front to effectively reform into gas. Groundwater, augmented by water added to the injection borehole if necessary, reacts with the carbon in the coal to form a combustible gas mixture consisting mainly of carbon

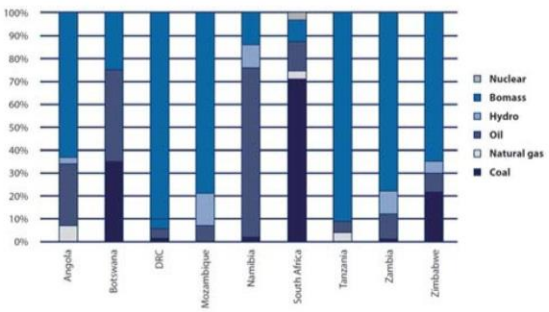

Figure 1—Coal utilization in Africa (Luckos, Shaik, and van Dyk, 2010)

monoxide (CO), hydrogen (H_2), and methane (CH_4). The resulting synthetic gas (syngas) can be used to produce electricity, as well as chemicals, liquid fuels, hydrogen, and synthetic natural gas (Sourcewatch, n.d.). These gases are then forced out through a second borehole (the production well). Ash and other remnants of the coal remain underground in the gasifier. The gasification of coal in this manner creates a reduced coal cavity below the surface, the size of which depends on the rate of water influx from the water table, the heat content of the coal, the location and specifications of the injection and production wells, and the thickness of the coal seam.

This coal reformation takes place at high temperatures, which are created by the gasification front, and high pressure, which is caused by the build-up of hot gases in the underground gasifier. It should be noted that the pressure in the gasifier will always be lower than the hydrostatic head of the groundwater at the depth of the coal seam, which will cause the groundwater to flow slowly towards the gasifier.

UCG has lower environmental and safety impacts than traditional coal mining and power generation. The technology eliminates mine safety issues, surface damage, stockpiles of overburden and discard coal, and solid waste discharge such as ash dumps, and has lower sulphur dioxide (SO_2), nitrogen oxide (NO_x), and particulate (PM_{10}) emissions.

The earliest recorded mention of the idea of underground coal gasification was in 1868. The first successful test was conducted by the Donetsk Institute of Coal Chemistry on 24 April 1934 at Lysychansk in the Soviet Union, where a local chemical plant began using the gas commercially in 1937. A number of UCG projects were established across the world after the Second World War, and UCG is now recognized globally as a technically and economically viable method of accessing deep, otherwise unrecoverable coal reserves, both on- and offshore. It has been estimated that UCG technology could effectively double the energy reserves obtained from the world's coal deposits (African Carbon Energy (Pty) Ltd , n.d.).

UCG presents certain environmental advantages over conventional coal mining. By not requiring mining, UCG can reduce the effects of issues such as acid mine runoff, mine safety, overuse of groundwater, and land reclamation. During gasification, approximately half of the sulphur, mercury, arsenic, tar, and particulates from the coal remain below surface. UGC syngas also has a higher hydrogen concentration than syngas produced on surface, giving it a potential cost advantage when used for electricity generation.

The basic UCG concept, together with the general gasification reactions (van Dyk, Keyser, and Coertzen2006; Luckos, Shaik, and van Dyk, 2010) is illustrated in Figure 2.

Groundwater monitoring at operating sites

Numerous articles on groundwater science, the impacts of industry on groundwater, and groundwater monitoring have been published and it is impossible to capture all information in this paper. However, the most critical and recent views in the literature related to groundwater and also to UCG are highlighted below.

According to Barnes and Vermeulen (2007), the coal industry impacts qualitatively and quantitatively on groundwater in two main areas:

1. Sulphur is one component in particular that contributes in a number of ways to changes in groundwater quality. When water and oxygen come into contact with a sulphide-bearing mineral such as pyrite, a reaction resulting in acid mine drainage occurs. Pyrite reacts with water and oxygen to form dissolved ferrous iron species, which with time increase the acidity of the water.
2. Deterioration of groundwater quantity is caused by the removal of water that has entered the mining operations. This result in a depression cone (decrease in hydraulic head) surrounding the gasification zone, causing dewatering of surrounding aquifers. The depression cone alters the natural flow of groundwater through the creation of paths of less resistance, which results in water entering the mining area.

In developing an analyses list, it is necessary to establish and define the objectives of the monitoring activity (*i.e.* baseline, construction, operational, closure, and post-closure monitoring). Conventional and UCG process-specific analyses techniques should be selected. The general chemistry of an aquifer may be used to monitor changes in the hydrogeological system surrounding a UCG plant. The monitoring of the mobility of chemical species, correlating recharge and flow zones with water quality, assessing the chemical equilibrium and kinetics of groundwater reactions, and developing contour maps and graphical plots are thus all needed to understand the flow and quality of the groundwater system. Monitoring programmes should include basic chemistry species analyses (especially important for ambient and compliance monitoring at larger sites that have the potential to be influenced by other contaminants), neighbouring facilities, and groundwater flow paths (Commonwealth of Pennsylvania, 2001).

Ahern and Frazier (1982) investigated changes in groundwater quality at various field test sites and in laboratory experiments. Their report summarizes more than 300 articles and 19 UCG field tests that were in operation or completed in the 1980s. The most significant findings and summaries related to UCG groundwater are highlighted.

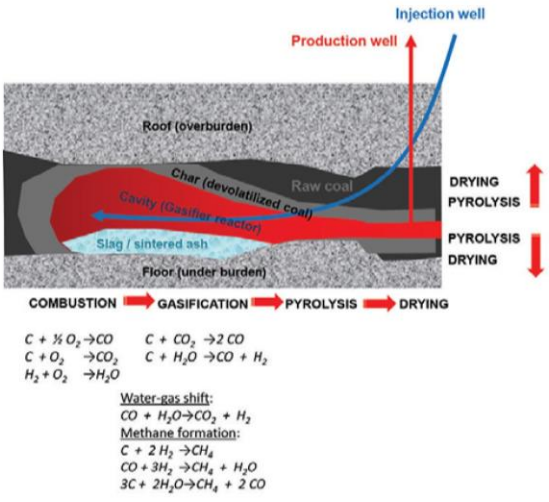

Figure 2—General concept of UCG

Groundwater monitoring during underground coal gasification

1. At the Hoe Creek I monitoring network, in the Powder River Basin, Wyoming, 11 wells were drilled into the coal aquifer. Water quality samples were taken during the burn, and 3 days, 83 days, 183 days and randomly over a 25-month period after the burn. Analyses for more than 70 inorganic and organic species were carried out. The following most significant changes were observed:
   a. Ammonium, boron, calcium, bromide, lithium, cyanide, magnesium, sulphate, potassium, and phenols showed at least a five-fold increase in the water in comparison to the baseline case, both within the burn zone and outside the zone.
   b. Other species reported to have increased in the water samples were barium, lead, organic carbon, and volatile organics.

   Most of the changes occurred within 10 ft (3 m) of the burn zone and independent of direction. Concentrations of several species increased over time at a monitoring well located 10 ft (3 m) from the burn zone, due to movement of contaminated groundwater out of the burn zone.
2. The Hoe Creek II monitoring network consisted of 14 wells drilled into the gasified coal cavity and overlying aquifer. Water quality samples were taken before the burn, during the burn, and at least five times up to 9 months after completion of the burn (Ahern and Frazier, 1982). The list of species at Hoe Creek II which increased in concentration in the groundwater closely parallels those measured at Hoe Creek I. The differences in concentration levels between the two sites can be attributed to differences in coal quality and rates of gasification.
3. Water quality data from the Hanna sites was obtained from the Hanna III test, which consisted of 12 wells drilled into the coal seam and overlying aquifer. Water quality was monitored before, during, and after operation (Ahern and Frazier,(982), and the main findings were summarized as follows:
   a. Conductivity and temperature increased over baseline values in both the coal aquifer and overlying water aquifer.
   b. Sodium and dissolved solids increased in all wells up to a period of 1 year after gasification.
   c. Sulphate and chloride ionic concentrations decreased in all wells.
   d. Aluminium concentrations increased to almost 100 times over the baseline values during the UCG operation, but rapidly decreased to the baseline values afterwards.
   e. Other elements and compounds that increased during gasification were boron, copper, iron, lead, zinc, calcium, ammonia, and sulphate compounds, in agreement with both Hoe Creek I and II findings.
4. Water quality tests were also reported for the UCG tests in Fairland, Tennessee Colony, and the Big Brown sites in Texas (Ahern and Frazier, 1982). At the Fairland monitoring network four wells were drilled into the coal seam, six close-in wells to the other aquifers and 40 wells at greater distances from the burn. The water quality was monitored before the experiment, at the end of gasification, and also one year after gasification. The main findings were:
   a. Concentrations of all monitored inorganic species increased during gasification, especially calcium, zinc, iron, hydrogen, magnesium, ammonium, manganese, sulphate, mercury, and boron.
   b. Phenols were the principal organic species produced, but high amounts of two- and three-ring polynuclear aromatic hydrocarbons were also observed, especially during gasification.
5. In the Huntley UCG pilot operations, New Zealand, the first and most important conclusion was that there were no detrimental effects on the groundwater in the Tauranga Group aquifer by either contamination or depletion. A spike in the dissolved organic carbon (DOC) was observed at the coal seam in one well during a period of high pressure, which reverted to background levels once the pressure was reduced. Monitoring wells further away showed no response. Although a wide range of chemical components were monitored, changes in DOC proved to be the most responsive indicator of the effects of gasification (Dobbs *et al.*, 2014).

Despite similar results from the different sites at which groundwater has been monitored and specific species showing general trends, it has to be stressed that a number of factors can influence these results. The following information on the specific site has to be taken into account regarding the effect of groundwater changes.

- Coal type—the coal rank may determine the type and relative amounts of chemical species produced during a UCG process; for example, liquid hydrocarbons, phenols, *etc.*
- Amount of coal gasified—this may be related to the amount of chemical species generated.
- Injection agent—the chemical composition of the atmosphere in which the coal is pyrolised may influence the types of chemical species formed.
- System pressure—this factor influences the distances which volatile species can move from the burn cavity during UCG operation.
- Burn cavity temperature—the temperature affects the mineralogy of the coal ash in the burn cavity and the leachability of constituents within the ash.
- Product gas composition—the composition, together with the cavity temperature, provides a measure of the ash leachability.
- Gas losses—gases produced by UCG cause changes in the chemical equilibrium and dissolution of certain species in the surrounding water.
- Roof collapse—a collapse of overburden into the cavity can introduce material of different chemical composition into the gasification hot zone and affect movement of chemical species.
- Interconnection of aquifers—interconnection through fracturing, roof collapse, ruptured borehole casing, or by other means can change groundwater movement and the movement of chemical species.

The water quality information gathered at UCG sites is not abundant, but appears to be adequate for developing a theory that explains similarities and differences in water

Groundwater monitoring during underground coal gasification

quality at various UCG sites. Some of the similarities and differences in water quality may be real, while others are only apparent. Real differences may result from different gasification techniques, different coal ranks, different hydrogeologies, or different baseline water quality.

Well location (not discussed in this paper) is site-specific and will differ for projects with different aims.

Proposed groundwater monitoring standard for UCG sites

Groundwater or borehole water is used without treatment for human and livestock consumption and other agricultural activities. Groundwater, as a natural source of water, cannot be directly required to adhere to the specifications of SANS 241-1, but it is recommended that any changes in water quality due to UCG activities must not decrease the quality to below the minimum standard stipulated in SANS 241-1 standard. The SANS standard is specifically cited to incorporate a standard with tighter restrictions. In summary, it is proposed that

- Baseline groundwater quality to be measured and monitored on a continuous basis
- SANS 241-1 to be used as standard to compare to the baseline quantity
- Minimum limits to be determined between a combination of (1) and (2) and the specification to be set at the determined quality values. Thus, if the baseline value for a specific property is higher compared to the baseline for drinking water as specified in SANS 241-1, then the baseline value will be set as standard; otherwise the standard stipulated in SANS 241-1 will be used.

The drinking water parameters according to SANS 241-1 shall comply with the physical, aesthetic, and chemical limits for lifetime consumption, as specified in Table I.

There are only a few chemical species in water that can lead to health problems as a result of a single exposure, except through massive accidental contamination of a drinking water supply. Moreover, experience shows that in many, but not all single exposures, the water becomes undrinkable due to unacceptable taste, odour, and appearance. Chemicals that cause adverse health effects include fluoride, arsenic, phenols, benzenes, and nitrate compounds. Human health effects have also been demonstrated in the case of lead (from domestic plumbing), while there is also concern regarding the potential extent of exposure to iron, manganese, selenium, and uranium. . These species should be taken into consideration as part of any risk assessment process (SABS, 2016).

The methods of analysis should be chosen to apply the necessary limit of quantification of SANS 241 and to be of the required accuracy and precision (SABS, 2016).

It is proposed that sampling of groundwater be conducted according to current SANS or ISO standards (Table II).

Laboratory quality control may be conducted according to the ISO 17025:2005 standard.

Table III summarizes the groundwater monitoring properties to be measured on each monitoring well (sentinel and compliance wells) on both the groundwater and coal water, as well as the measuring frequency.

The SANS, ASTM, or ISO standards listed in Table IV are recommended for the analyses as specified in Table III and serve as a guide, but overall laboratory quality control based on ISO 17025:2005 should be adhered to.

Conclusions

The importance of water and the environmental impact that specific operations may have on groundwater necessitate that standardized monitoring and rehabilitation programmes be adopted.

UCG is a fast-emerging *in situ* mining technology that can be used to exploit coal resources that are currently not technically or economically viable by conventional mining methods. As such it offers significant potential to increase the world's recoverable coal resources. The UCG plant operation, however, has to be performed in an environmentally responsible manner.

Table I

Physical, aesthetic, operational and chemical parameters of drinking water as specified in SANS 241-1

Water properties	Standard limit[a]	Water properties	Standard limit[a]	Water properties	Standard limit[a]
Free chlorine	≤5 mg/L	Nitrate as N	≤11 mg/L	Zinc as Zn	≤5 mg/L
Monochloramine	≤3 mg/L	Nitrite as N	<0.9 mg/L	Antimony as Sb	≤20 µg/L
Colour	≤15 mg/L Pt-Co	Sulphate as SO_4^{2-}	<500 mg/L	Arsenic as As	≤10 µg/L
Conductivity at 25°C	≤170 mS/m	Fluoride as F^-	≤1.5 mg/L	Cadmium as Cd	≤3 µg/L
Odour or taste	Inoffensive	Ammonia as N	≤1.5 mg/L	Chromium as Cr	≤50 µg/L
Total dissolved solids	≤1200 mg/L	Chloride as Cl^-	≤300 mg/L	Cobalt as Co	≤500 µg/L
pH at 25°C	≥5 to ≤9.7	Sodium as Na	≤200 mg/L	Copper as Cu	≤2000 µg/L
Cyanide as CN^-	≤70 µg/L	Manganese as Mn	≤500 µg/L	Selenium as Se	≤10 µg/L
Iron as Fe	≤2000 µg/L	Mercury as Hg	≤6 µg/L	Uranium as U	≤15 µg/L
Lead as Pb	≤10 µg/L	Nickel as Ni	≤70 µg/L	Vanadium as V	≤200 µg/L
Aluminium as Al	≤300 µg/L	Chloroform	≤0.3 mg/L	Bromodichloro-CH_4	≤0.1 mg/L
Total organic C	≤10 mg/L	Bromoform	≤0.1 mg/L	Dibromochloro-CH_4	≤0.06 mg/L
Phenols and benzenes	≤10 µg/L	Microcystin as LR[b]	≤1 µg/L		

a – The health-related standards are based on the consumption of 2 L of water per day by a person of a mass of 60 kg over a period of 70 years.
b – Microcystin needs to be measured only where an algal bloom (> 20 000 cyanobacteria cells per millilitre) is present in a raw water source. In the absence of algal monitoring, an algal bloom is deemed to occur where the surface water is visibly green in the vicinity of the abstraction, or samples taken have a strong musty odour.

Groundwater monitoring during underground coal gasification

Table II

SANS and ISO standards for sampling of mine and groundwater

Date : 2014-06-06 — *List of Standards and Abstracts* — Page No : 1 Of 2
Report Id : std_abs — TITLE : SANS Standards - Mine and Groundwater Testing — Requested By: EILEEN WEBB

SANS Number Int. Relatedness	SABS Number	Year	Edition	Status Code	Title	Abstract	Amend Code	Amend Number	Corr Number	Amend Ind	Amend Date
SANS 376 (ASTM D 2972:2003, IDT)		2005	1.00	ST	Standard test methods for arsenic in water	Specifies test methods that cover the photometric and atomic absorption determination of arsenic in most waters and wastewaters.					
SANS 5667-11 (ISO 5667-11:1993, IDT)	SABS ISO 5667-11	1993	1.00	ST	Water quality - Sampling Part 11: Guidance on sampling of groundwaters	Provides guidance on the design of sampling programmes, sampling techniques and the handling of water samples taken from groundwater for physical, chemical and microbiological assessment.	A	1		N	2006-02-16
SANS 5667-14 (ISO 5667-14:1998, IDT, Ed. 1)		2007	1.00	ST	Water quality - Sampling Part 14: Guidance on quality assurance of environmental water sampling and handling	Provides guidance on the selection and use of various quality assurance techniques relating to the manual sampling of surface, potable, waste, marine and ground waters.					
SANS 5667-18 (ISO 5667-18:2001, IDT, Ed. 1)		2007	1.00	ST	Water quality - Sampling Part 18: Guidance on sampling of groundwater at contaminated sites	Provides guidance on the sampling of groundwater at potentially contaminated sites. Is applicable to situations where contamination of the subsurface could exist as a result of downward migration of pollutants whose source is at the surface or just below it, and when the guidance in ISO 5667-11 (published in South Africa as an identical adoption under the designation SANS 5667-11) is inappropriate.					
SANS 6059	SABS SM 1059	2010	2.01	ST	Water - Mercury content	Specifies a method for the determination of the mercury content of water and wastewater by using atomic absorption spectrophotometry. The method is applicable to the determination of mercury in the concentration range 0,001 mg/L to 0,010 mg/L.	A	1		N	2010-04-23
SANS 10286	SABS 0286	1998	1.00	ST	Mine residue	Covers the disposal of mine residue in residue deposits. This residue includes all waste that is produced by a mine and that is defined as waste in terms of the Minerals Act, 1991 (Act 50 of 1991). Slimes dams, tailings dams, rock dumps, slurry ponds and discards and similar deposits all fall within the scope of this standard.					

Date : 2014-06-06 — *List of Standards and Abstracts* — Page No : 2 Of 2
Report Id : std_abs — TITLE : SANS Standards - Mine and Groundwater Testing — Requested By: EILEEN WEBB

SANS Number Int. Relatedness	SABS Number	Year	Edition	Status Code	Title	Abstract	Amend Code	Amend Number		Amend Ind	Amend Date
SANS 10299-1	SABS 0299-1	2003	1.01	ST	Development, maintenance and management of groundwater resources Part 1: The location and siting of water boreholes	Covers requirements for the location and siting of water boreholes. Whenever a borehole is considered for conversion to a water production borehole, the relevant clauses of this part of SANS 10299 shall apply.	A	1		N	2003-09-12
SANS 10523 (ISO 10523:2008, IDT, Ed. 2)		2012	1.00	ST	Water quality - Determination of pH	Specifies a method for determining the pH value in rain, drinking and mineral waters, bathing waters, surface and ground waters, as well as municipal and industrial waste waters, and liquid sludge, within the range pH 2 to pH 12 with an ionic strength below I = 0,3 mol/kg solvent and in the temperature range 0 °C to 50 °C.					
SANS 16590 (ISO 16590:2000, IDT, Ed. 1)	SABS ISO 16590	2000	1.00	ST	Water quality - Determination of mercury - Methods involving enrichment by amalgamation	Specifies two methods for the determination of mercury, one using tin(II) chloride and the other sodium tetrahydroborate as reducing agent. The methods are suitable for the determination of mercury in water, for example in ground, surface or waste water, in the concentration range 0,01 µg/L to 1 µg/L. Higher concentrations may be determined if the water sample is diluted.	A	1		N	2006-11-17

Table III

Frequency of measurement of important groundwater properties of importance

Property to monitor	Baseline period[a] (12 months)	Pre-gasification period[b]	Gasification[c]	Shut-down post-gasification[d]	After shut-down[e] (36 months)
Water level	Monthly	Daily#	Daily#	Daily#	3-monthly
pH value	Monthly	Daily#	Daily#	Daily#	3-monthly
Conductivity	Monthly	Weekly#	Weekly#	Weekly#	3-monthly
Total dissolved solids	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total solids and loss on ignition	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total alkalinity	Monthly	Monthly	3-monthly	Monthly	3-monthly
Calcium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Magnesium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Potassium	Monthly	Monthly	3-monthly	Monthly	3-monthly

Table III (Continued)

Frequency of measurement of important groundwater properties of importance

Property to monitor	Baseline period[a] (12 months)	Pre-gasification period[b]	Gasification[c]	Shut-down post-gasification[d]	After shut-down[e] (36 months)
Sodium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Colour hazen unit	Monthly	Monthly	3-monthly	Monthly	3-monthly
Turbidity N.T.U	Monthly	Monthly	3-monthly	Monthly	3-monthly
Odour	Monthly	Monthly	3-monthly	Monthly	3-monthly
Carbonate Hardness	Monthly	Monthly	3-monthly	Monthly	3-monthly
Chloride	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sulphate	Monthly	Monthly	3-monthly	Monthly	3-monthly
pH value	Monthly	Monthly	3-monthly	Monthly	3-monthly
Conductivity	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total dissolved solids	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total solids and loss on ignition	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total alkalinity	Monthly	Monthly	3-monthly	Monthly	3-monthly
Calcium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Magnesium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Potassium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sodium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Colour Hazen unit	Monthly	Monthly	3-monthly	Monthly	3-monthly
Turbidity N.T.U	Monthly	Monthly	3-monthly	Monthly	3-monthly
Odour	Monthly	Monthly	3-monthly	Monthly	3-monthly
Carbonate Hardness	Monthly	Monthly	3-monthly	Monthly	3-monthly
Chloride	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sulphate	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sulphite	Monthly	Monthly	3-monthly	Monthly	3-monthly
Settleable solids	Monthly	Monthly	3-monthly	Monthly	3-monthly
Nitrate	Monthly	Monthly	3-monthly	Monthly	3-monthly
Nitrite	Monthly	Monthly	3-monthly	Monthly	3-monthly
Fluoride	Monthly	Monthly	3-monthly	Monthly	3-monthly
Mercury	Monthly	Monthly	3-monthly	Monthly	3-monthly
Hexavalent chromium	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total cyanide	Monthly	Monthly	3-monthly	Monthly	3-monthly
Phenolic compounds as phenol and benzenes	Monthly	Monthly	3-monthly	Monthly	3-monthly
Biochemical oxygen demand	Monthly	Monthly	3-monthly	Monthly	3-monthly
Chemical oxygen demand	Monthly	Monthly	3-monthly	Monthly	3-monthly
Total soluble solids	Monthly	Monthly	3-monthly	Monthly	3-monthly
Soap, oil and grease	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sulphide sulphur	Monthly	Monthly	3-monthly	Monthly	3-monthly
Sulphide sulphur	Monthly	Monthly	3-monthly	Monthly	3-monthly
Free and saline ammonia	Monthly	Monthly	3-monthly	Monthly	3-monthly
Kjeldahl nitrogen	Monthly	Monthly	3-monthly	Monthly	3-monthly
Acidity/P-alkalinity	Monthly	Monthly	3-monthly	Monthly	3-monthly
Dissolved oxygen	Monthly	Monthly	3-monthly	Monthly	3-monthly
Oxygen absorbed (permanganate value)	Monthly	Monthly	3-monthly	Monthly	3-monthly
Residual/free chlorine	Monthly	Monthly	3-monthly	Monthly	3-monthly
Bromide	Monthly	Monthly	3-monthly	Monthly	3-monthly
Calcium carbonate saturated pH	Monthly	Monthly	3-monthly	Monthly	3-monthly
Free carbon dioxide	Monthly	Monthly	3-monthly	Monthly	3-monthly
Arsenic, selenium, titanium, aluminium, nickel, manganese, iron, vanadium, zinc, antimony, ead, cobalt, copper, total chromium, silicon, tin, zirconium, bismuth, thallium, beryllium, cadmium, boron, phosphorus as phosphate, uranium, molybdenum, barium, silver, thorium, lithium, (also Ca, Mg, K, Na)	Monthly	Monthly	3-monthly	Monthly	3-monthly

a – Period before commissioning, drilling or start-up. The current situation.
b – When drilling of wells will start and ignition of coal seam will take place.
c – Normal operating period of the UCG process and gasifier cavity.
d – Period of de-commissioning, cooling and shut-down of gasifier cavity.
e – The period after shut-down when the site is rehabilitated and gasifier cavity out of operation.
– Variation in pH and conductivity according to ISO 17025:2005 will enforce monitoring on a daily basis until the cause of variation has been resolved or quality is back to baseline values

Table IV

Available and recommended SANS, ASTM, and ISO standards to evaluate water quality

Property to monitor	Standard to be applied
pH value	SANS 5011
Conductivity	SANS 7888
Total dissolved solids	SANS 5213
Total solids and loss on ignition	SANS 5213 and
Total Alkalinity	ASTM D1067
Calcium	SANS 450, 6265 and 11885
Magnesium	SANS 6265 and 11885
Potassium	
Sodium	SANS 6050 and 11885
Colour Hazen unit	SANS 5198
Turbidity N.T.U	SANS 375 and 5197
Odour	No specific standard
Carbonate hardness	ISO 9963
Chloride	SANS 163-1 and 374
Sulphate / sulphite	SANS163-1 and 6310
Nitrate / nitrite	SANS 5210
Fluoride	SANS 163-1, 10359-1 and 10359-2
Mercury	SANS 6059
Hexavalent chromium	SANS 6054 and 11885
Total cyanide	SANS 4374, 6703-1
Phenolic compounds as phenol	SANS 6439
Biochemical oxygen demand	ISO 15705
Chemical oxygen demand	ISO 15705
Total soluble solids	ISO 21338:2010
Soap, oil and grease	ASTM D4281
Sulphide sulphur	ISO 6326
Free and saline ammonia	SANS 5217
Dissolved oxygen	SANS 6047
Residual/free chlorine	ISO 7393
Bromide	ISO 11206
Calcium carbonate saturated pH	SAN 50897
Free carbon dioxide	ISO 10523
Organic compounds, *i.e.* phenols and benzenes	ISO 16-128
Arsenic, selenium, titanium, Aluminium, nickel, manganese, Iron, vanadium, zinc, antimony, Lead, cobalt, copper, Total chromium, silicon, tin, Zirconium, bismuth, thallium, Beryllium, cadmium, boron, Phosphorus as phosphate, Uranium, molybdenum, barium, Silver, thorium, lithium, (also Ca, Mg, K, Na).	SANS 376, 11885, 379, 6054, 11885, 6170, 5203, 4374, 382, 5209, 6171, 377 and 383

Numerous studies have been published on groundwater science, the impact of industries on groundwater quality, and groundwater monitoring. Using some of these findings, it is important to develop a groundwater monitoring programme for UCG sites before the start-up of such an operation.

Groundwater monitoring in the South African mining industry for conventional coal mining is well established, with specific SANS, ASTM, and ISO standards dedicated for the specific environment, location, and purposes. The South African UCG and gas industries, however, are relatively unregulated at this stage. South Africa's groundwater is a critical resource. Utilization and implementation of groundwater monitoring standards are thus non-negotiable.

A National Standard has been proposed in this paper as a fit-for-purpose groundwater monitoring programme for commercial UCG operations.

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- Professor I. Dennis, North-West University

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5 CORROSION TESTING OF STEEL FOR PRODUCTION AND INJECTION WELL APPLICATIONS IN A UCG PROCESS

Authors: JC van Dyk, JF Brand, FB Waanders, AC van Wyk and CJ Kahts

33rd Annual International Pittsburgh Coal Conference: Coal - Energy, Environment and Sustainable Development, PCC-2016, Volume 2016. August 2016.

Summary

Various chemical reactions, temperatures, pressures and gas compositions exist at different locations within a UCG gasifier, and in the injection and production wells. The injection and production boreholes are exposed for their entire operational life to a mixture of gas atmospheres, in the presence of varying temperature gradients. This can create a highly corrosive environment that may erode the borehole lining (casing), resulting in cracks and forming metal oxide shavings. Selection of the correct material is central to overall process safety, economy and efficiency.

Table 4: Sample qualities.

SAMPLE	GRADE
1	13CR80
2	P-110
3	110-SS
4	K-55
5	N80Q
6	P-110
7	SS-316L

The overall objective in this study was to expose a number of steel and alloy types to experimentally simulated UCG environments and conditions in order to determine the most suitable metal type for the production equipment. A secondary goal was to fit the experimental data to a corrosion rate model to determine the corrosion and safety limits for the UCG plant. Data with significant correlation coefficients for predictable corrosion rate calculations were obtained and used for predicting the optimal metal thickness for components.

The gaseous and temperature specific environments for an TUCG injection borehole were selected and seven casing samples were exposed to general corrosion attack. The metal loss and corrosion rate were tested with weight loss analysis by periodically removing the samples from the corrosive environments, cleaning and weighing them before placing them back for the rest of the experiment's duration.

In general, all runs displayed comparatively steady corrosion rates. SEM imaging was used to confirm the type of corrosion observed and determine the oxidation products present on the surface of the corrosion coupons. The results obtained in this study provided the selection of the final steel/alloy types and indicated which steel types should be used in which part of the UCG process.

CORROSION TESTING OF STEEL FOR PRODUCTION AND INJECTION WELL APPLICATIONS IN A UCG PROCESS

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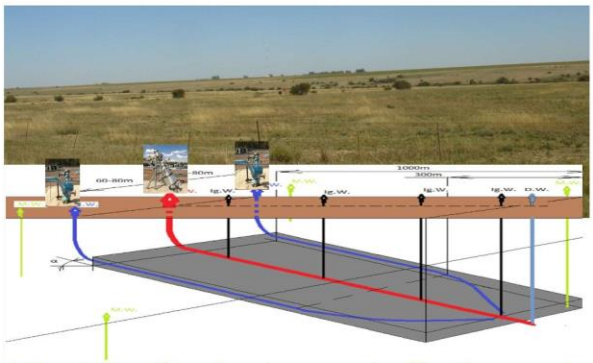
UNDERGROUND COAL GASIFICATION

UCG is an in-situ gasification process carried out in deep coal seams by injecting air (oxygen) into the coal and bringing the resulting fuel gas to the surface with a production well - drilled from the surface



Underground Coal Gasification is a cost-effective environmentally

the technical and economic confines of conventional mining with numerous environmental benefits over conventional coal mining

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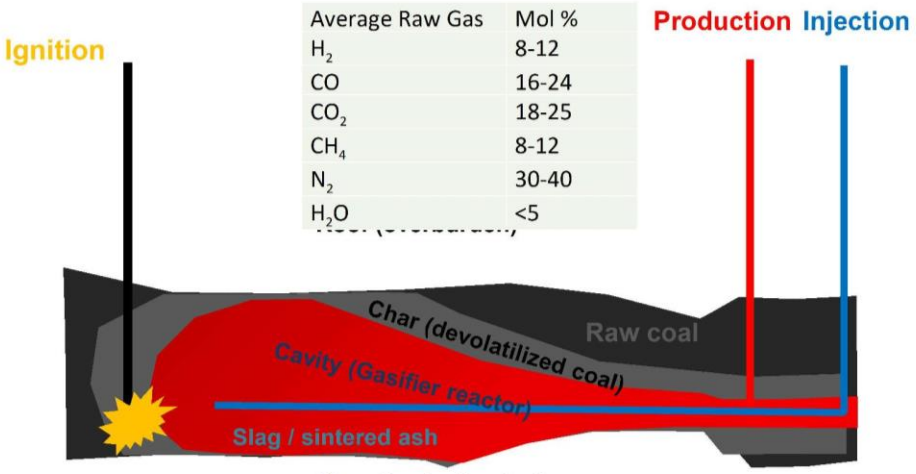
IGNITION, INJECTION AND PRODUCTION WELL

Average Raw Gas	Mol %
H_2	8-12
CO	16-24
CO_2	18-25
CH_4	8-12
N_2	30-40
H_2O	<5



COMBUSTION → **GASIFICATION** → **PYROLYSIS** → **DRYING**

$C + ½ O_2 \rightarrow CO$
$C + O_2 \rightarrow CO_2$
$H_2 + O_2 \rightarrow H_2O$

$C + CO_2 \rightarrow 2\,CO$
$C + H_2O \rightarrow CO + H_2$

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IMPORTANCE OF STUDY

- To **find the corrosion rates of various metals** in gaseous corrosive environments predicted for the Theunissen UCG process developed by Africary
- Obtain test data with significant correlation coefficients for **predictable corrosion rate** calculations
- **Identify suitable operating parameters** for production and injection applications
- **Determine optimal metal thickness** for components
- **Minimize maintenance,** plant shut-downs or failures due to well break-down caused by corrosion
- **Mitigate Environmental Risk** by minimising opportunity for possible gas leakages
- **Minimize Economic Losses** by using the best metals in each of the different UCG applications

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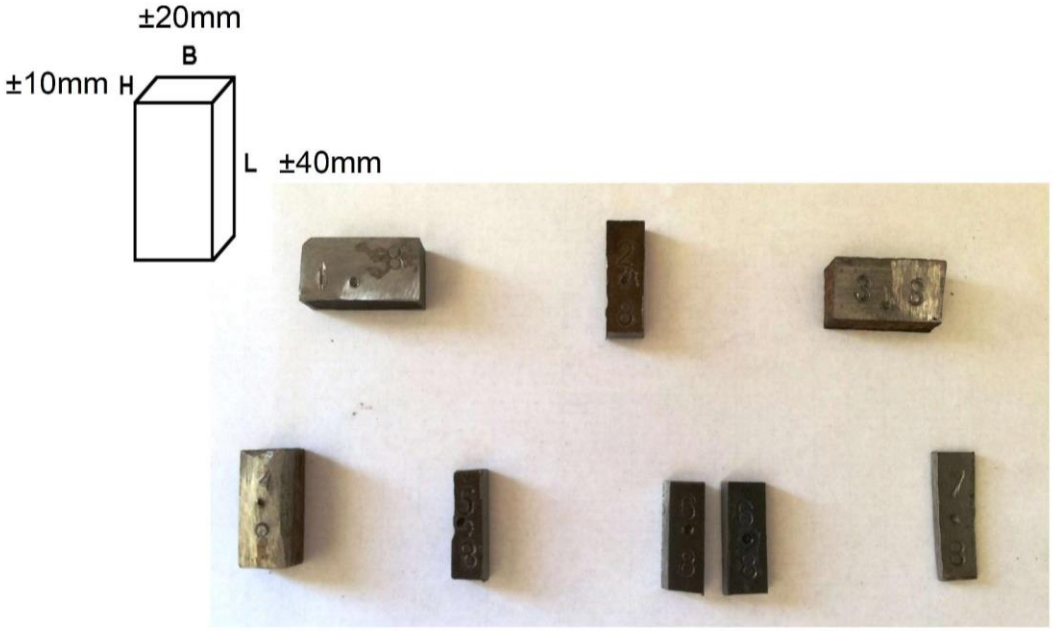
STEEL SAMPLES



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EXPERIMENTAL SETUP

1. Tests conducted at Chemical Engineering Department at NWU
2. 4 different students involved
3. Oven running time of 7 months over a period of 18 months
4. All gas mixtures prepared by Afrox
5. Simulated test conditions:
   - ❑ **350°C and Oxygen Enriched Air (Mixture-1)**
   - ❑ **350°C, 650°C and 850°C and Oxygen Enriched Air (Mixture-2)**
   - ❑ **350°C and Syngas**
   - ❑ **350°C and (Mixture-2):Steam (1:1)**

Mixture 1 = low oxygen %
Mixture 2 = high oxygen %

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EXPERIMENTAL SETUP

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CORROSION SIMULATION

Results fitted to theory from Frayne (1999) and Du Plessis (2014) – (CO on steel)

- *Frayne, C., 1999, Cooling water treatment: Principles and practice, 1st Edition, New York.*
- *Du Plessis, B.C., The corrosion effect in a continuous steel caster, subjected to solutions containing fluordie irons, M. Eng Thesis, North West University, March 2014.*

$$Corrosion\ rate\ (CR) = \frac{Weight\ loss\ (g) * K}{Alloy\ density\ (g.cm^3) * Exposed\ Area\ (A) * Exposure\ time\ (days)}$$

Corrosion rate per area unit = (area factor x weight loss) / E

E = exposure time (days, weeks, hours)

Area factor = 22.2 / (density of metal x area of exposure)

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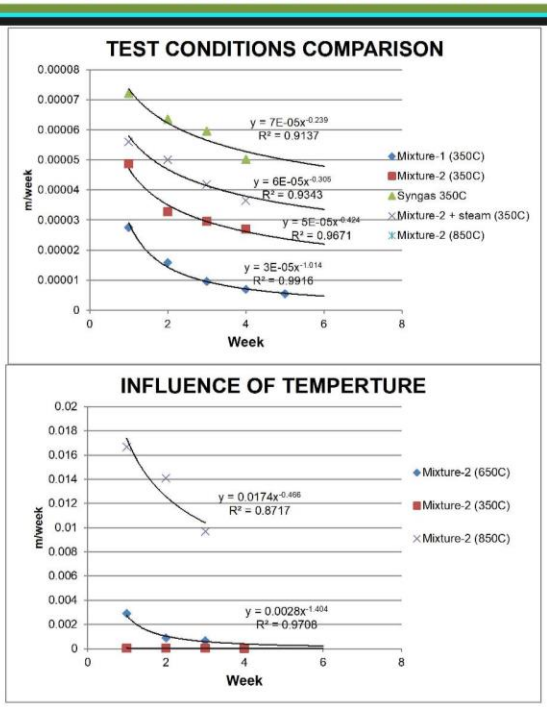
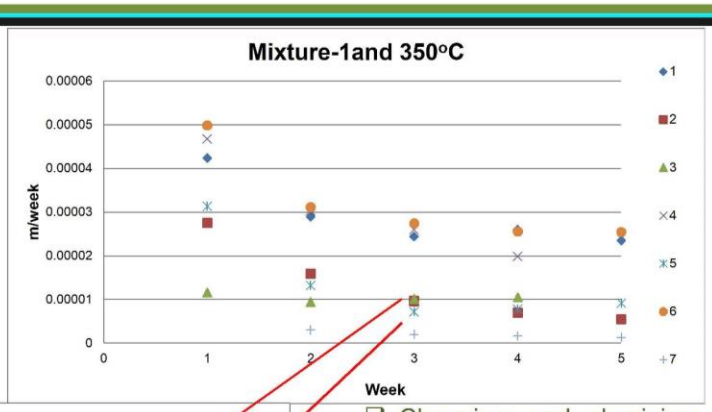
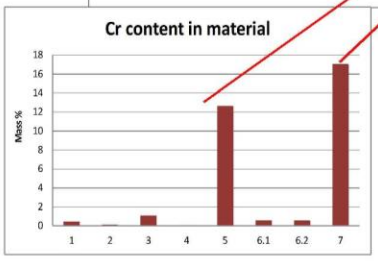
CORROSION RESULTS FOR DIFFERENT TEMPERATURES AND ATMOSPHERES



Illustrates the significant effect of high temperature on corrosion rate

COMPARISON OF SAMPLE CORROSION





- Chromium and aluminium in the sample form $(CrFe)Al_7$ and $(CrMn)Al_{12}$ intermetallic compounds, hindering recrystallization nucleation
- Strengthening effect, and also improve the alloy toughness and reduce susceptibility to stress corrosion cracking
- Chromium improves corrosion resistance
- The metal also improves hardenability, strength, response to heat treatment and wear resistance.

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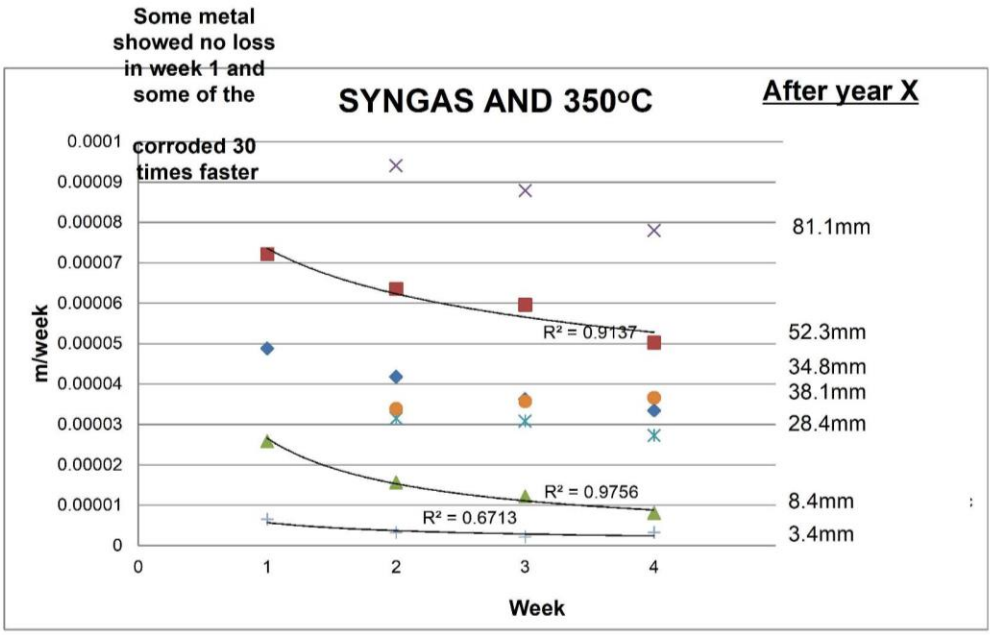
STEEL THICKNESS PREDICTIONS



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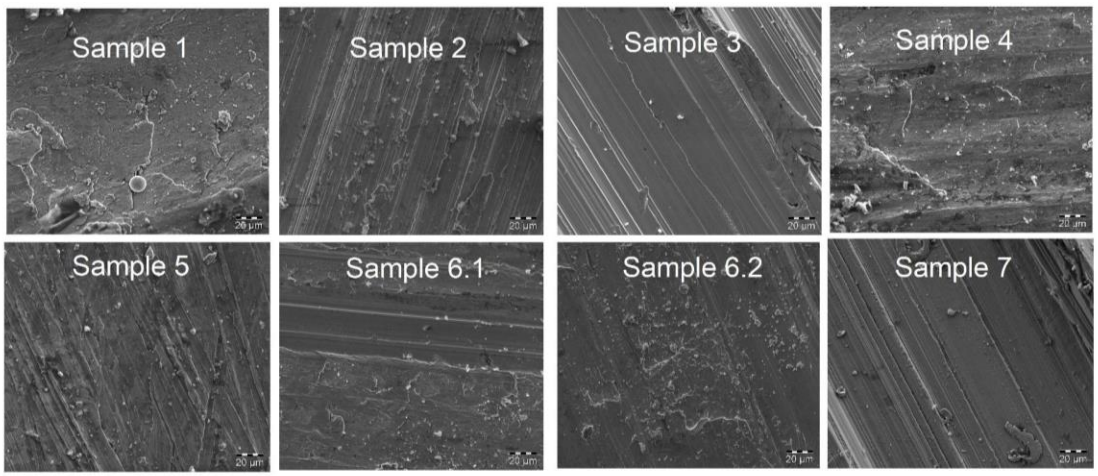
THERMAL SHOCK BEHAVIOUR OF MATERIAL

- Samples heated at 10°C/min under oxidizing conditions to 350°C.
- Holding time at 350°C was 60 minutes.
- Samples removed and then quenched in cold water



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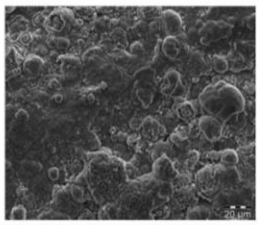
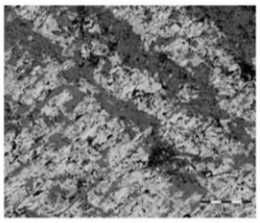
SEM AND CORROSION ANALYSES

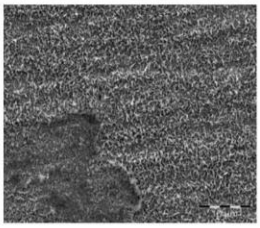
CO gas





O_2 gas

O_2 gas and steam



Mixture-2

- Homogeneous covering of corrosion products of corrosion products looking like small bubbles (possibly an iron oxide layer) which clearly indicates a uniform corrosion attack
- Darker spots on the surface are iron oxide that formed a protective layer and slowed down the corrosion rate
- The oxide layer covering the surface are iron oxides that formed (mostly Fe_2O_3 and Fe_3O_4)

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IN SUMMARY

- **Corrosion rates of various metals** successfully determined for the gaseous corrosion environments aimed for the Theunissen UCG process
- Data with significant correlation coefficients for **predictable corrosion rate** calculations obtained
- **Suitable operating parameters** for production and injection applications obtained
- **Optimal metal thickness** for components can be predicted

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6 APPLYING SPONTANEOUS ADIABATIC TEST PROCEDURE TO DETERMINE CO_2 GASIFICATION REACTIVITY AND KINETICS OF COAL UCG APPLICATIONS

Authors: JC van Dyk, JF Brand and FB Waanders

35th Annual International Pittsburgh Coal Conference, Xuzhou, China. 15-18 October 2018.

Summary

The CCS potential of UCG was presented an updated paper in May 2017 for the efficient in-situ CO_2 capture and conversion at the 8th International Conference on Clean Coal Technologies (IEA) [29], but the concept was originally presented at the 7th International Freiberg/Inner Mongolia Conference on IGCC & XtL Technologies, Coal Conversion and Syngas in June 2015 [30] with the focus on spontaneous combustion and its impact on the UCG ignition process. The R_{70} testing established the intrinsic spontaneous combustion reactivity and Relative Ignition Temperature (RIT) of the coal samples at 130-140°C, which give an indication of heat input required to start the UCG ignition. The tests showed that with ample continuous supply of oxygen (air), elevated temperature conditions (> 140°C) and minimal heat dissipation, coal from TUCG will reach thermal runaway within two days.

The presentations (added for background) and the test procedures applied became a segue into the adiabatic test work for CO_2 sequestration provided in the presentation. The effectiveness and carbon efficiency of UCG can be improved by applying CO_2 gasification/recycling waste captured CO_2 as gasification agent (replacing part of the oxygen and steam as gasification agent), resulting in an optimised operation. The most important reaction during the gasification process is the reduction process, (also known as the Boudouard Reaction, where CO_2 is converted to CO (above 850°C).

Advantages of CO_2 gasification at higher temperatures may include, but are not limited to:

- In situ CO_2 capture on active mineral components in the roof and floor rocks and the coal seam with Ca and Mg, to form carbonates.
- CO_2 reduction of 43% and 29% in the syngas equivalent ratio.
- A reduction of a minimum of 22% in situ coal to produce the same amount of syngas.
- Lowering the operating temperature of the syngas production and surface outlet temperature.
- A higher heating value gas, containing less nitrogen (9%) and inert substances.

The outcome of this study was to determine the minimum O_2 addition and minimum CO_2 temperature (350°C) for attaining effective Boudouard Reaction and should lead to future publications by the authors.

APPLYING SPONTANEOUS ADIABATIC TEST PROCEDURE TO DETERMINE CO_2 GASIFICATION REACTIVITY AND KINETICS OF COAL FOR UCG APPLICATIONS

應用自發絕熱試驗程序確定UCG應用中煤的CO_2氣化反應性和動力學

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African Carbon Energy

JC van Dyk, johan.vandyk@africary.com (see next slide)

International Pittsburgh Coal Conference, China, October 2018
2018年10月，中國國際匹茲堡煤炭會議

Collaboration partners
协作伙伴

AFRICARY

JC van Dyk[1,6], J Brand[2], F Waanders[6], BB Beamish[3], RS Whitney[4] and TP Levi[5], N Fasihiani[7]

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NWU

CB3

Simtars

Scope of study
研究的范围

1. The effectiveness and carbon efficiency of UCG can be improved by applying CO_2 gasification / recycling of waste captured CO_2 as gasification agent (replacing part of the oxygen and steam as gasification agent).
2. With CO_2 based gasification, the most important reaction is the reduction process, (also known as the Boudouard Reaction, where $CO_2+C=2CO$ above 850°C.

1. 通過應用二氧化碳氣化/回收廢物捕獲的二氧化碳作為氣化劑（替換部分氧氣和蒸汽作為氣化劑），可以提高UCG的有效性和碳效率。预测的加热温度和速率以有效的方式点燃煤层
2. 對於基於CO_2的氣化，最重要的反應是還原過程（也稱為Boudouard反應，其中$CO_2 + C = 2CO$高於850°C

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ORIGINAL PLANNED STUDY
原始計劃研究

1. The main aim of this study is to determine the minimum O_2 addition and minimum CO_2 temperature (350°C).
2. Understanding the properties of a coal is critical to effectively and efficiently operating an UCG process under CO_2 saturated environments.
3. Spontaneous Combustion and Reactivity behaviour may supply technical detail and scientific insight into gasification behaviour and carbon conversion of the coal.

1. 本研究的主要目的是確定最低O^2添加量和最低CO^2溫度（350°C）
2. 了解煤的特性對於在CO_2飽和環境下有效和高效地運行UCG過程至關重要
3. 自燃和反應性行為可以為煤的氣化行為和碳轉化提供技術細節和科學見解

OUTLINE OF PRESENTATION
演講概要

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Applying spontaneous adiabatic test procedure to determine CO_2 gasification reactivity and kinetics of coal for UCG applications

應用自發絕熱測試程序確定用於UCG應用的CO_2氣化反應性和煤的動力學

WORK NOT COMPLETED
工作沒有完成

1. UNDERSTANDING SPONTANEOUS GASIFICATION AND ITS APPLICATION WITH UCG
2. IN-SITU CO_2 CAPTURE AND RECYCLING DURING A UCG PROCESS

1. 了解自然氣化及其在UCG中的應用
2. 在UCG過程中的原位CO_2捕獲和再循環

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Innovation and novel approach
创新和新的办法

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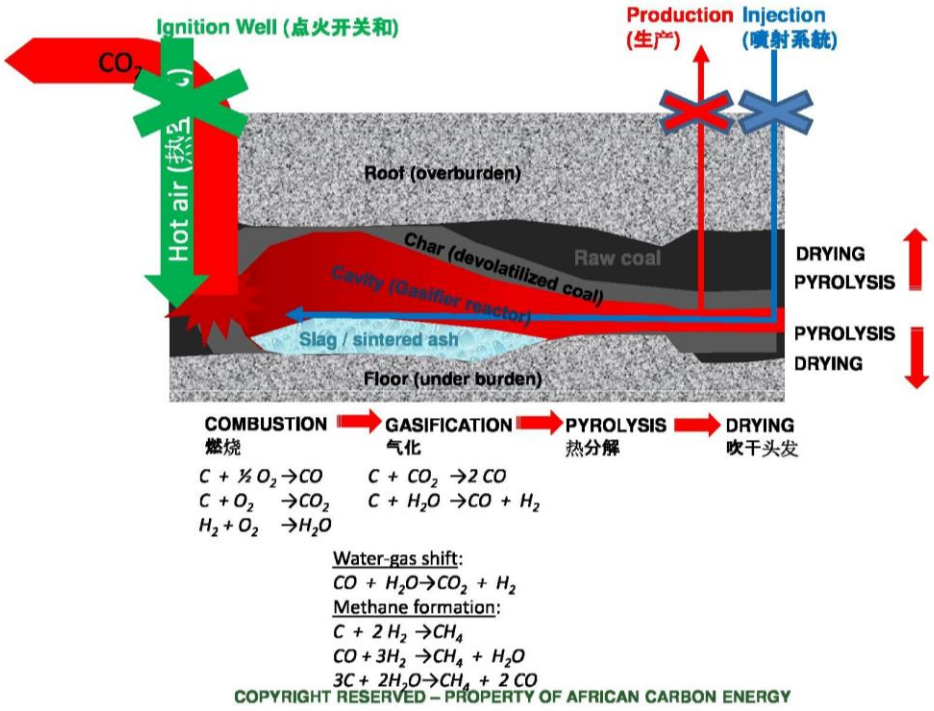
Adiabatic R70 and SponComSIM™ tests usually applied as a precautionary measurement of the self-heating properties of coal, e.g. to manage coal on stockpiles or during transport. The novel approach is applied in using R70 and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating) at which a coal reserve has to be ignited during the start-up phase of an UCG process.

绝热R70和SponSomSim™测试通常采用测量作为一种预防性的自我的物业供暖燃煤,例如管理煤炭储存或在运输过程中固定不动。 这种新颖的办法是应用在使用R70和SponComSim™测试,以量化的最佳条件(温度、持续时间、自加热),一个煤炭储备期间引发要的开始阶段UCG过程。

Background: UCG and ignition
背景:UCG和点火开关



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Background: Ignition methods
背景: 点火方法

- Coal ignition and acceleration can be accelerated through a number of processes:
  1. *electric coil to heat the coal seam,*
  2. *gas/oil firing near the face of the coal seam,*
  3. *thermite / explosives,*
  4. *chemical combustion via an agent such as air, oxygen and steam*

- This study is applying a novel approach of using R_{70} and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating) at which a coal reserve has to be ignited during the start-up phase of an UCG process

- 煤点火和加速可以加快的进程数的:
  1. *电磁线圈加热煤接缝,*
  2. *燃气/燃油喷射的面对附近的煤的接缝、*
  3. *thermite/爆炸物*
  4. *通过化学燃烧的代理,如空气、氧气和蒸汽*

- 这项研究采用的是一种新的方法使用R70和sponcomsim™测试,以量化的最佳条件(温度、持续时间、自加热),一个煤炭储备必须期间引发“Start(开始)”阶段的ucg的过程

Background: R70 Self-heating rate
背景: R70自加热速率

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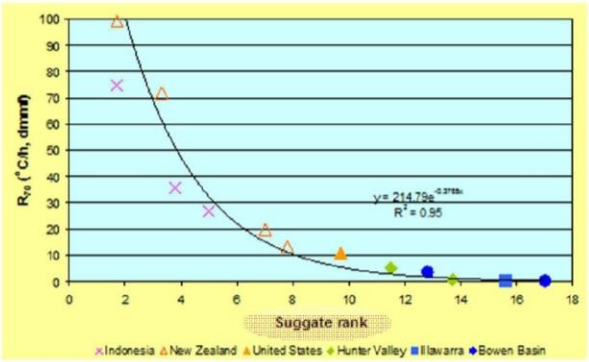
- R70 self-heating rate is the time taken for the coal temperature to reach 70ºC from a start temperature of 40ºC (average self-heating rate calculated due to adiabatic oxidations)
- R70自加热率所需的时间以达到煤温度70ºC,从一个开始温度为40oC(平均自助计算加热速率由于隔热oxidations)

Intrinsic spontaneous combustion propensity classification (ISCP)
内在自发燃烧倾向分类(ISCP)

		Queensland	New South Wales
ISCP Class	Propensity rating	R_{70} value (°C/h)	R_{70} value (°C/h)
I	low (L)	$R_{70} < 0.5$	$R_{70} < 1$
II	low-medium (LM)	$0.5 \le R_{70} < 1$	$1 \le R_{70} < 2$
III	medium (M)	$1 \le R_{70} < 2$	$2 \le R_{70} < 4$
IV	high (H)	$2 \le R_{70} < 4$	$4 \le R_{70} < 8$
V	very high (VH)	$4 \le R_{70} < 8$	$8 \le R_{70} < 16$
VI	ultra high (UH)	$8 \le R_{70} < 16$	$16 \le R_{70} < 32$
VII	extremely high (EH)	$R_{70} \ge 16$	$R_{70} \ge 32$

Relationship between R_{70} self-heating rate and Suggate rank
R70之间的关系自加热速率和suggate排



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Background: Relative ignition T
背景: 相对点火T

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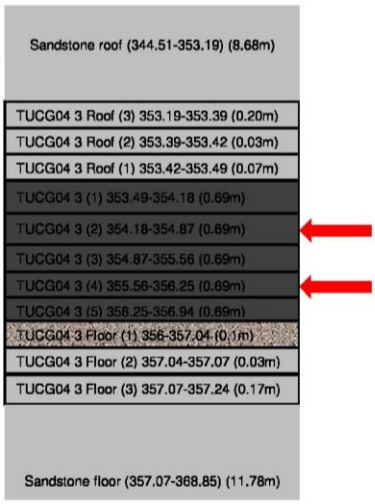
- RIT use an oven to drive the temperature of the coal, unlike the R70 test where the oven tracks the coal temperature as it reacts with oxygen
- RIT can be obtained from the R70 adiabatic oven test and defined as the point at which the oven can no longer keep up with the coal temperature rate rise, which equates to 2 ºC/min
- The higher the spontaneous combustion propensity, the lower the CPT or RIT value
  - CPT < 130ºC = high intrinsic spontaneous combustion propensity,
  - CPT 130ºC to 150ºC = medium intrinsic spontaneous combustion propensity and
  - CPT > 150ºC = low intrinsic spontaneous combustion propensity

- RIT使用一个烤箱,驱动器温度的煤炭,这不同于R70测试,其中跟踪炉煤温度与氧气反应
- RIT可以从R70隔热炉测试并定义为在该点烤箱再也不能跟上煤温度上升率,相当于2° °C/min
- 较高的储蓄倾向的自发燃烧,较低的RIT的CPt或值
  - CPT<130° C=高内在倾向自发燃烧,
  - CPT130° C至150° C=中等倾向内在自发燃烧,
  - CPT>150° C=低固有自燃倾向

Experimental: Coal source properties
实验：煤源属性

Proximate analysis (air-dried) 近似分析 (干)	TUCG04/3/2	TUCG04/3/4
Moisture (%) 水份(%)	5.4	4.4
Ash (%) 灰(%)	27.6	17.6
Volatile Matter (%) 挥发物(%)	17.7	25.9
Fixed Carbon (%) 固定二氧化碳(%)	49.3	52.1
Ultimate analysis (dry ash free) 最终分析 (干灰免费)		
Carbon (%) 二氧化碳(%)	81.0	80.3
Hydrogen (%) 氢气(%)	4.19	4.70
Nitrogen (%) 氮气(%)	1.90	2.34
Sulphur (%) 含硫量(%)	0.31	0.88
Oxygen (%) 氧(%)	12.6	11.8
Calorific Value (MJ/kg) 热能值(MJ/kg)	20.64	24.79
Suggate rank Suggate排	8.9	10.2



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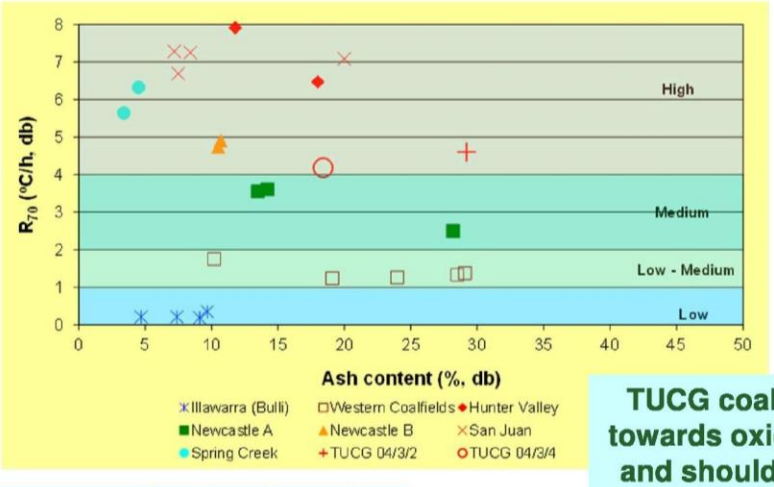
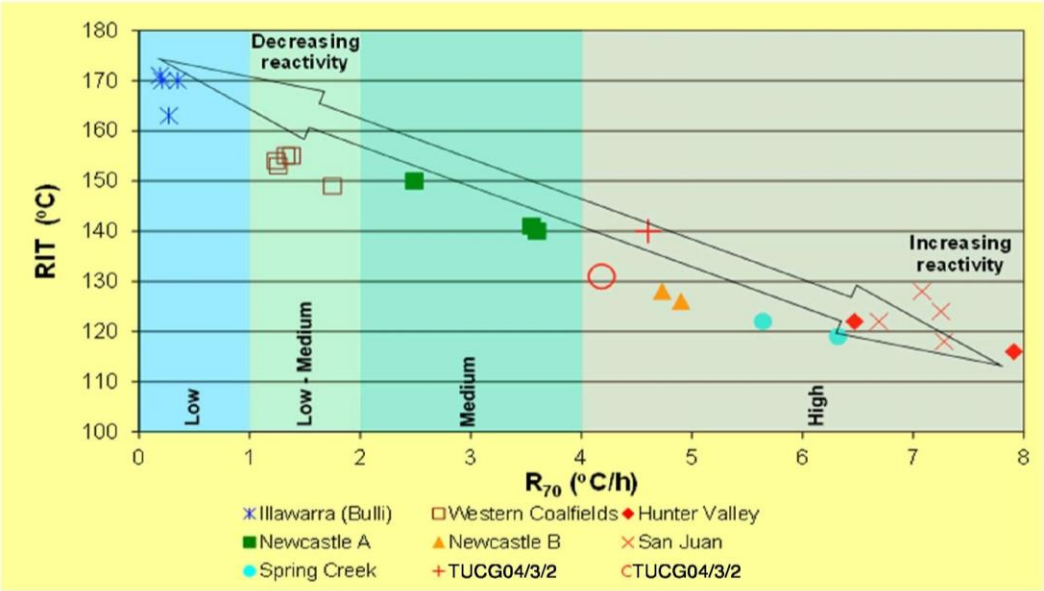
Results: Intrinsic spontaneous combustion reactivity analysis
结果:内在自发燃烧反应性分析



TUCG coal are highly reactive towards oxidation environments and should be easily ignited in the UGC process

Sample	Ash content (%, db)	R_{70} (°C/h)	RIT (°C)
TUCG04/3/2	29.2	4.60	140
TUCG04/3/4	18.4	4.18	131

Results: Relative Ignition Temperature Analysis
结果: 相对点火温度分析



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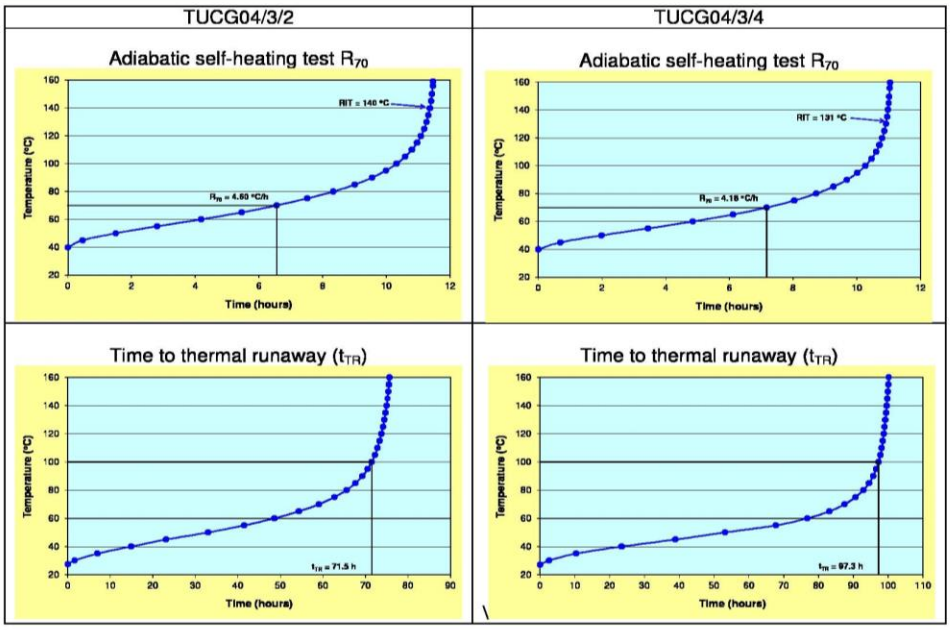
Results: R70 and thermal Runaway
结果: R70和散热条跑道



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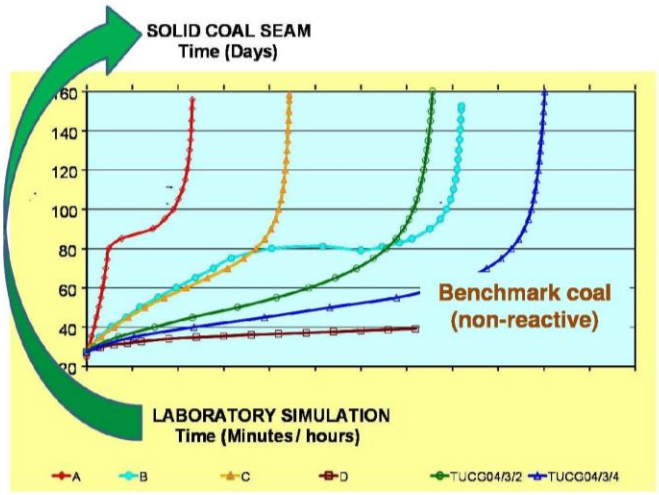
Results: Thermal Runaway Analysis
结果: 分析热耗散



- Based on the benchmark times for real site situations, TUCG04/3/2 and 4 would take a minimum of 36 74 days respectively to develop a spontaneous combustion event from a start temperature of 27.4°C with sufficient continuous air supply and minimal heat dissipation
- 根据基准时间的真实网站情况下, TUCG04/3/ 2和4,您就会采取一个最小的36 74天,分别制定一个自发燃烧事件从一个开始温度27°C的足够的持续的空气供应和散热最少

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INTERPRETATION OF TOWARDS IGNITION OF AN UNDERGROUND COAL GASIFICATION PROCESS
解释对点火的一个地下煤炭气化过程

- Experience from a commercial coal mine and thermal runaway lab scale results at ambient conditions and correlated, were applied
- Higher temperature region
  - Coal source X took 11 minutes to increase in temperature from 140 to 150°C.
  - Equates to approximately 6 days based on the pillar heating analogy.
- TUCG04/3/2 and TUCG04/3/4 showed that solid coal heating to ignition would take approximately double the time indicated by the reference coal due to the lower intrinsic reactivity, as it took over 20 minutes for the coal to increase in temperature from 140 to 150°C.
- This would equate to approximately 10-12 days.

- 从一个商业经验煤矿和散热失控实验结果规模在环境条件和互相关联的、已应用
- 更高的温度区域
  - 煤源的X11分钟了,温度升高时,从140到150°C
  - 约相当于6天的支柱基础上加热作类比。
- TUCG04/3/2和 TUCG04/3/ 4表明,固体煤加热到点火会花费约双所示的时间参考煤炭由于固有的低反应性,因为它接管了20分钟的煤炭增加温度从140至150°
- 这将等同于约10天。

INTERPRETATION OF TOWARDS IGNITION OF AN UNDERGROUND COAL GASIFICATION PROCESS
解释对点火的一个地下煤炭气化过程

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- Exposing the coal to higher initiating temperatures would speed up the time to self-ignition as there is a non-Arrhenius kinetics region that exists at low ambient temperatures during coal self-heating.
- At high initiation temperatures in excess of 150°C, the Arrhenius kinetics would promote a reaction rate doubling effect for every 10°C rise in temperature.
- Conversely, thermal runaway to ignition can also be delayed by the presence of moisture in the coal >10%).

- 暴露了煤炭在更高温度下开始将加快,自点火,有一种非阿累尼乌斯动力学区域存在的较低的环境温度下在煤自热。
- 开始在较高的温度会超过150oC,阿累尼乌斯动力学将促进一个反应率增加一倍的影响每一个10oC温度上升。
- 与此相反,散热失控,点火开关也可以推迟了存在的水分在煤炭>10%)。

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CONCLUSIONS
结论

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1. R70 self-heating rates from 4.2 to 4.6 °C/min and consistent with the coal rank and type
2. High intrinsic spontaneous combustion reactivity and propensity rating - self-heating can be an important factor in initiating UCG reactions in the Theunissen coals source
3. Measured RIT for the samples (130-140°C) give an indication of heat input required to start the UCG ignition
4. Test program confirmed that with carbon availability, ample continuous supply of oxygen (air), elevated temperature conditions (> 140°C) and minimal heat dissipation, coal from this reserve will reach thermal runaway within a couple of days

- R70自加热率从4.2到4.6°C(开心)/最小值和一致的煤与职级及
- 高内在自发燃烧反应性和偏好等级-自加热可以是一个重要的因素在UCG反应启动的煤源
- 测量负责人约瑟夫斯·托伊尼森的RIT的样本(130°C)会显示出所需的热输入的UCG,开始点火
- 测试程序,证实与碳可用性、连续供应充足的氧气(空气)、高温条件下(>140°C)和最小散热、煤从这一储备金将达到散热失控的几天内

UNDERGROUND COAL GASIFICATION – EFFICIENT IN-SITU CO_2 UTILIZATION AND CONVERSION

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8th International Congress on Clean Coal Technologies, 8-12 May, Cagliari, Sardinia

UNDERGROUND COAL GASIFICATION

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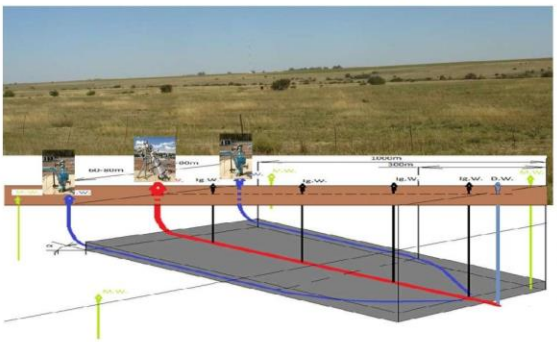
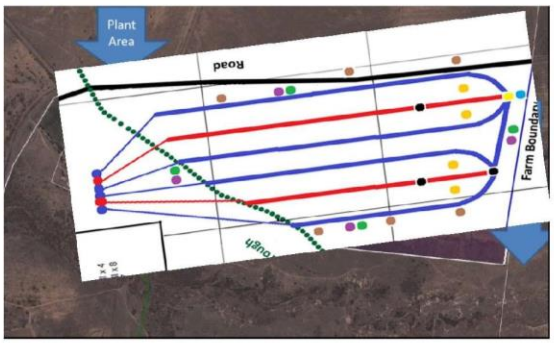
UCG is an in-situ gasification process carried out in deep coal seams by injecting AN AGENT (air, oxygen or steam) into the coal and bringing the resulting fuel gas to the surface with a production well - drilled from the surface





Underground Coal Gasification is a cost-effective environmentally friendly CLEAN COAL solution for resource recovery in areas beyond the technical and economic confines of conventional mining WITH SCOPE TO IMPROVE THE CARBON FOOTPRINT FURTHER

PURPOSE OF THIS STUDY

1. CO_2, **as gasification agent for UCG,** has received little attention and only studied by a few researchers to date - will be investigated on a thermo-equilibrium basis in this study.

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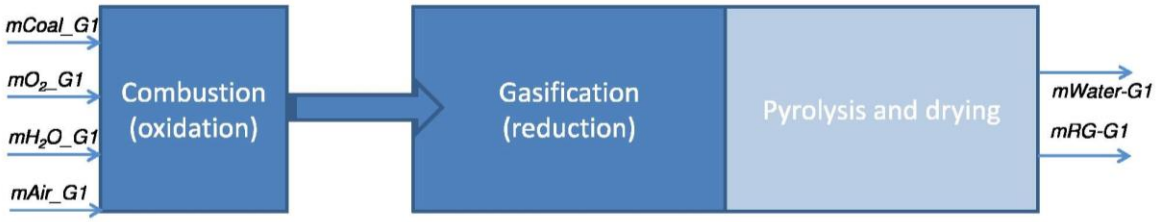
SIMULATION PROCESS (Gasifier 1)

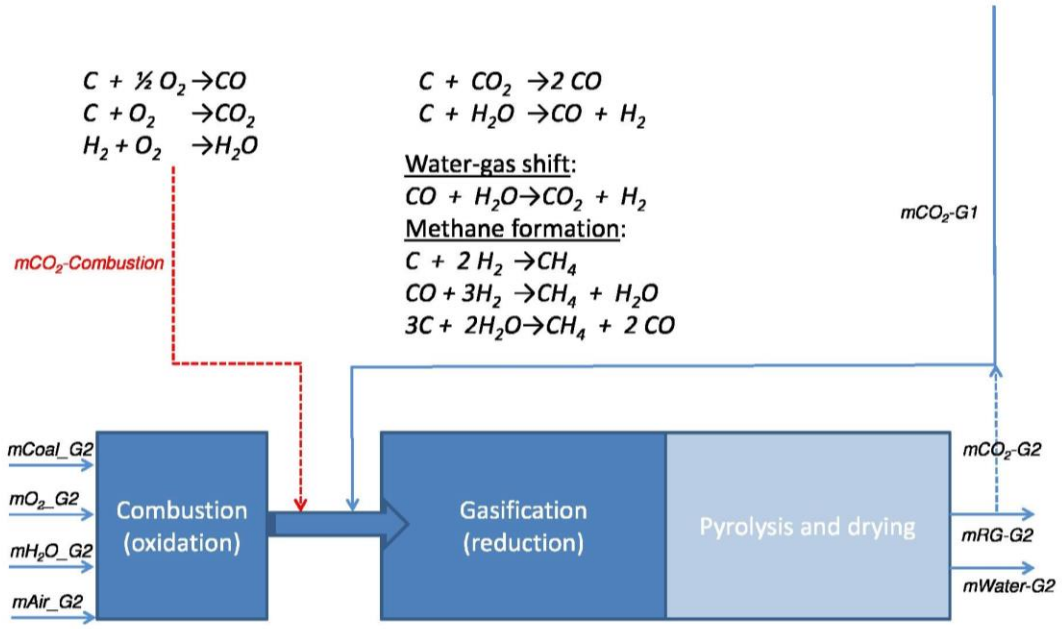


$C + ½\ O_2 \rightarrow CO$
$C + O_2 \rightarrow CO_2$
$H_2 + O_2 \rightarrow H_2O$

$C + CO_2 \rightarrow 2\ CO$
$C + H_2O \rightarrow CO + H_2$

Water-gas shift:
$CO + H_2O \rightarrow CO_2 + H_2$
Methane formation:
$C + 2\ H_2 \rightarrow CH_4$
$CO + 3H_2 \rightarrow CH_4 + H_2O$
$3C + 2H_2O \rightarrow CH_4 + 2\ CO$

SIMULATION PROCESS (Gasifier 2)



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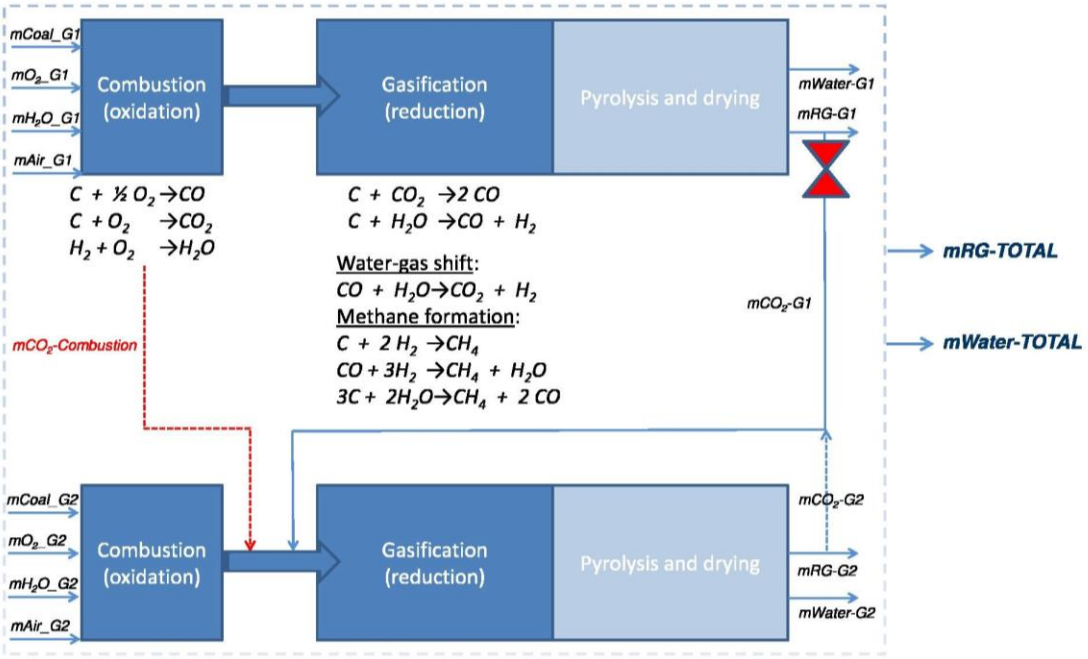
SIMULATION PROCESS (G1+G2)



RESULTS (COMBINED G1 + G2)

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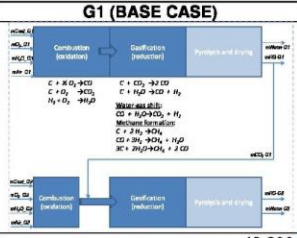
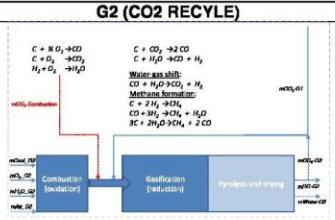
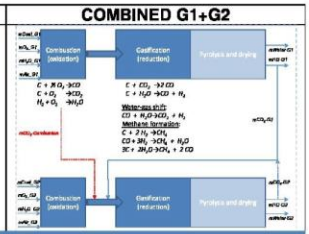
INDEX	G1 (BASE CASE)	G2 (CO2 RECYLE)	COMBINED G1+G2
Flow scheme			
Coal usage (kg/hr)*	49 800		
CO_2 produce (kg/hr)	10 556 (recyle)		
Oxygen (kg/hr)**	14 512		
Syngas (kg/hr)***	62 140		
CO_2:Syngas	0.17		
CO_2:Coal	0.21		
Nitrogen (kg/hr)	25 975		

* Total coal for equilibrium
** Total oxygen molecules air + pure oxygen
*** Syngas including CO_2
**** Excluding CO_2 from G1 recycled

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CONCLUSIONS

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- Effectiveness and carbon efficiency of UCG (OR GASIFICATION) can further be improved by applying CO_2 gasification / recycling waste captured CO_2 as gasification agent (replacing part of the oxygen and steam as gasification agent).

- Technical advantages may include, but are not limited to:
  - CO_2 reduction of 43% and 29% in the syngas equivalent ratio.
  - A reduction of a minimum of 22% in situ coal to produce the same amount of syngas.
  - Lowering the operating temperature of the syngas production and surface outlet temperature.
  - A higher heating value gas, containing less nitrogen (9%) and inerts.
  - In situ CO_2 capture on active mineral components in the roof and floor rocks and the coal seam with Ca and Mg, to form carbonates.

CO_2 gasification, and specifically applied to an Underground Coal Gasification process, is a practical solution to improve both carbon efficiency and lower the CO_2 footprint.

NEXT STEPS AND FUTURE WORK

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- Optimization of gasification operating conditions and agent ratio (oxygen, steam, CO_2).
- CO_2 capture on the mineral structure (i.e. Ca, Mg, etc.) within a UCG cavity or in roof / floor matrix.

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7th International Freiberg/Inner Mongolia Conference
on IGCC & XtL Technologies, Coal Conversion and Syngas,
8-12 June 2015, Inner Mongolia, China

SPONTANEOUS COMBUSTION ASSESMENT OF A COAL RESERVE PLANNED FOR UNDERGROUND COAL GASIFICATION UTILIZATION

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ABSTRACT

Underground Coal Gasification (UCG) is an emerging, in-situ mining technology to utilise a low cost energy source that is currently classified as not technically or economically accessible. It offers significant potential to dramatically increase the world's recoverable coal resource.

Understanding the properties of a coal field is critical to effectively and efficiently operating a UCG process. Important properties are the ***Spontaneous Combustion*** and ***Reactivity*** behaviour – which supply technical detail and scientific insight into the ignition and gasification behaviour of the coal during UCG.

Adiabatic oven testing using R_{70} and SponComSIM™ tests is usually applied as a precautionary measurement of the self-heating properties of coal, e.g. to manage coal on stockpiles or during transport. In this study, the novel approach of using R_{70} and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating) at which a coal reserve has to be ignited during the start-up phase of an UCG process is applied.

The purpose of this study was to establish the spontaneous combustion propensity of core samples from the Theunissen coal reserve in South-Africa aimed for UCG purposes. The scope was:

1. R_{70} testing to establish the Intrinsic Spontaneous Combustion Reactivity and Relative Ignition Temperature (RIT) of the coal.
2. SponComSIM™ to establish the time to thermal runaway for specific starting temperatures, moisture contents, and oxygen supply.
3. Coal quality analysis (proximate, ultimate and calorific value) of the samples to assist with interpretation of test results.

An important step in any UCG process, and related to the scope of this study, is where a borehole is drilled down to the coal seam, which is used to ignite the coal seam in a special manner to start the gasification process. The ignition process consists basically of a drying step and partial devolatilisation / degassing step, until thermal runaway occurs and spontaneous combustion starts. Coal ignition and acceleration of the UCG process are thus critical to understand and be able to controlled.

The results indicate R_{70} self-heating rates from 4.2 to 4.6 ^{o}C/h, consistent with the coal rank and type, and rate the coal as having a high intrinsic spontaneous combustion reactivity. Spontaneous combustion index parameters indicate the coal has a high spontaneous combustion propensity rating. Measured RIT for the samples (130-140^{o}C) are in agreement with the R_{70} results. SponComSIM™ tests of this coal, compared to a bench-mark pillar heating case from Australia, show that under ideal conditions of critical thickness (carbon availability), ample continuous supply of oxygen (air), elevated temperature conditions (>140^{o}C) and minimal heat dissipation, coal from this reserve will reach thermal runaway within two days.

Key words: Underground Coal Gasification, Spontaneous Combustion, Reactivity, Ignition

1. SCOPE OF STUDY

The purpose of this study was firstly to determine the spontaneous combustion propensity of the coal source from the Theunissen coal reserve in South-Africa aimed for **Underground coal gasification (UCG)** purposes and secondly to predict the heating temperature and rate in order to ignite a coal seam in an efficient manner. The detail scope included:

a) R_{70} testing to establish the Intrinsic Spontaneous Combustion Reactivity and Relative Ignition Temperature (RIT) of the coal.
b) SponComSIM™ to establish the time to thermal runaway for specific starting temperatures, moisture contents, and oxygen supply.
c) Coal quality analysis (proximate, ultimate and calorific value) of the samples to assist with interpretation of test results

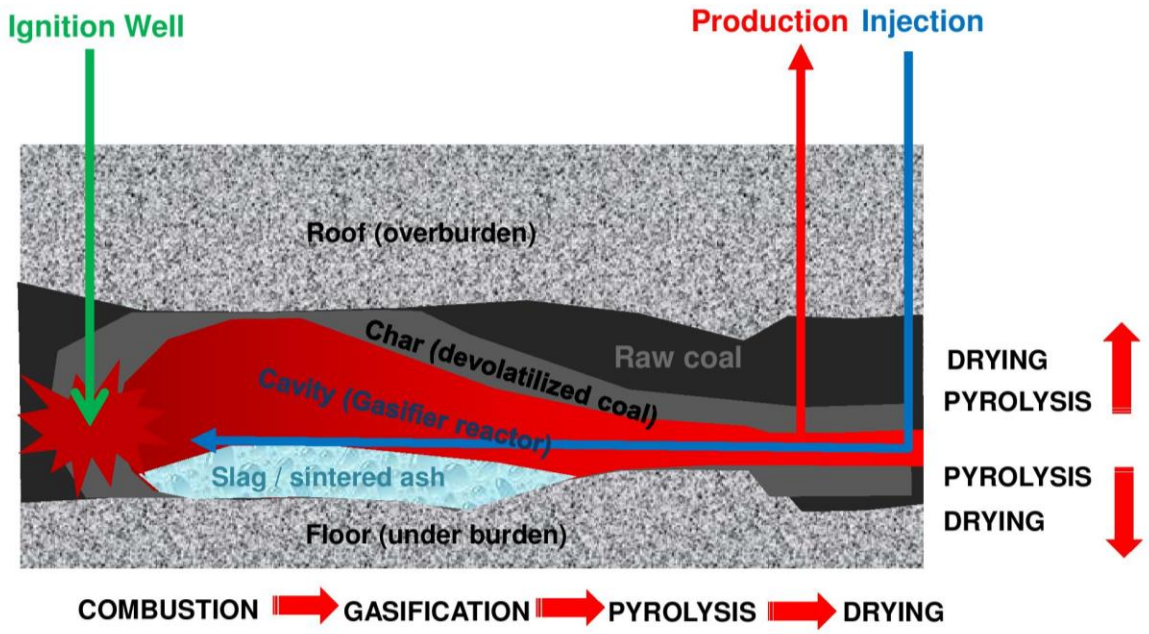
2. BACKGROUND

2.1 UNDERGROUND COAL GASIFICATION

The concept of coal gasification is nothing new and has been commercially applied for more than 200 years. It was first used during the late 1800's to produce town gas fuel for heating and lighting applications. Today, coal gasification is primarily used as energy source to provide fuel gas for power plants and chemical feedstocks for use in the chemical industry (e.g. Sasol and Siemens). Conventionally, coal is extracted from the ground through mining, processed, transported, and then gasified in a surface gasifier to produce syngas.

In addition to surface gasification technologies, **Underground coal gasification (UCG)** is receiving significantly more attention and priority, which is a combined extraction and conversion process. Experimentation on UCG was first performed in 1912 by Sir William Ramsay in England. Another source [1] stated that UGC was suggested by German brothers Werner and Wilhelm Siemens, as early as in 1868. Independently of that, the Russian scientist Dmitry I. Mendeleev had been developing a detailed design for, and operational concepts of UCG, he was published throughout the 1880s and '90s. An early UCG patent was granted in 1909 to the American inventor A.G. Betts. A plan for the first actual UCG experiment was announced by the English chemist Sir William Ramsey in 1912 [1].

UCG is a gasification process used to produce gas from coal *in situ (*underground in the coal seam) by injecting air or oxygen, with or without steam, into coal seams and extracting the product gas via surface wells. The resulting synthetic gas ("syngas") can be used to produce electricity, as well as chemicals, liquid fuels, hydrogen and synthetic natural gas [2]. Oxygen is injected to feed the combustion and drive the gasification reactions that produce a gas mixture made chiefly of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and some methane (CH_4). These gases are then forced out a second borehole to be harnessed at the surface. The gasification of coal in this manner creates an empty cavity below ground, the size of which depends on the rate of water influx from the water table, the heat content of the coal, the location and shape of the injection and production wells, and the thickness of the coal seam. A general UCG concept is given in Figure 1.



$C + ½\ O_2 \rightarrow CO$ $\quad C + CO_2 \rightarrow 2\ CO$

$C + O_2 \rightarrow CO_2$ $\quad C + H_2O \rightarrow CO + H_2$

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Methane formation:

$C + 2\ H_2 \rightarrow CH_4$

$CO + 3H_2 \rightarrow CH_4 + H_2O$

$3C + 2H_2O \rightarrow CH_4 + 2\ CO$

Figure 1: General UCG concept

An important step in any UCG process, and related to the scope of this study, is where a bore-hole is drilled down to the coal seam, which is used to ignite the coal seam in a special manner to start the gasification process. The ignition process consists basically of a drying step and partial devolatilisation / degassing step, until thermal runaway occurs and spontaneous combustion starts. In the case of low-moisture content coals (such as TUCG), the maximum temperature increases steadily with time. In the case of high-moisture coals, temperature increases rapidly initially before evaporation dominates and the temperature reaches a plateau value (generally around 80-90°C). Once the coal becomes dry locally the temperature will increase rapidly towards thermal runaway.

The coal ambient temperature also plays a major role in determining the initial coal self-heating rate. The R_{70} test is performed at 40°C to compare all coals on a standard basis. This temperature is more closely aligned with Queensland coals for which the test was originally developed and is indicative of underground or summer temperatures in the Bowen Basin [3]. For coal ambient temperatures at least 10°C lower than this, the initial self-heating rate of the coal will be greatly diminished (approximately halved). This increases the timeframe for any hot spot to develop assuming ideal conditions exist to allow heat to accumulate in broken coal.

Coal ignition and acceleration of the UCG process can be accelerated through a number of process, to list a few:

- the use of an electric coil to heat the coal seam,
- gas/oil firing near the face of the coal seam,
- thermite / explosives,

- chemical combustion via an agent such as air, oxygen and steam.

In this study, the novel approach is applied of using R_{70} and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating) at which a coal reserve has to be ignited during the start-up phase of an UCG process. The more spontaneous combustion prone the coal is the less drastic the acceleration process required.

When the coal seam has been ignited successfully, continuous oxidant flow through the injection well allows for gasification to be sustained. The temperature of the gasification process is maintained through varying the oxidant flow to the reactor. In UCG systems, the temperature of the coal face can reach temperatures in excess of 1100^{o}C.

There are mainly two, different commercially available UCG methods. One method uses vertical wells and reverse combustion to open up internal pathways in the coal. This process was used in the Soviet Union and later tested in Chinchilla, Australia. The second method was largely developed in the U.S. and creates dedicated in-seam boreholes, using directional drilling and completion technologies adapted from oil and gas production. It has a moveable injection point known as CRIP (controlled retraction injection point) and generally uses oxygen or enriched air for gasification.

Underground coal gasification presents certain environmental advantages over conventional coal mining. By not requiring mining, UCG avoids issues such as acid mine runoff, mine safety, overuse of groundwater, and land reclamation. During gasification, approximately half of the sulfur, mercury, arsenic, tar, and particulates from the used coal remain below ground. UGC syngas also has a higher hydrogen concentration than surface produced syngas, giving it a potential cost advantage when producing electricity.

In short, UCG is similar to surface gasification, with syngas produced through the same chemical reactions between carbon molecules and an agent (air, oxygen or steam). The main difference is that surface gasification occurs in a manufactured reactor, whereas the reactor for a UCG system is a cavity, a natural geological formation containing unmined coal

The agent is injected through a special designed and manufactured injection well into the coal seam. The product gas is again transported to surface via a special designed and manufactured production well. UCG involves an arrangement of injection and production wells drilled into coal seams. The coal is ignited and the gasification agent (air, oxygen or steam) are fed into the coal seam through injection wells which triggers and controls an in situ sub-stoichiometric combustion process, producing Syngas. Syngas is extracted using production wells. Various chemical reactions, temperatures, pressures, and gas compositions exist at different locations within a UCG gasifier. The gasification channel is normally divided into similar zones as a fixed bed gasifier: combustion, gasification, pyrolysis and drying, with an ash bed throughout the cavity. However, with a UCG reactor, the reaction zones are not directional in one specific way, but a multi-directional zone environment or 3D cavity growth and gasification are taking place.

3. SPONTANEOUS COMBUSTION

There are a number of spontaneous combustion tests documented in the literature that produce indices for rating the propensity of coal to spontaneously combust [4]. The more common ones that have gained wider use in the Australian and New Zealand coal industries are R_{70} self-heating rate, crossing point temperature (CPT), relative ignition temperature (RIT) and minimum self-heating temperature (SHT). The first three of these are available from laboratory testing that is offered in both Australia and New Zealand. SHT is a calculated value from coal quality data using the original equation developed by Smith and Lazzara (1987) [5] based on US coals, as this test is no longer offered by any laboratory.

All of the existing index parameters provide an indication of the intrinsic spontaneous combustion propensity of a particular coal using a classification scheme, but they do not provide any

indication of the timeframe taken for coal spontaneous combustion issues to occur. They also do not provide a proper risk evaluation of coal self-heating that takes into consideration the effects of extrinsic factors. The moderating influences of extrinsic factors such as in-mine ambient temperature and moisture (both in the coal and the surrounding environment) have been recognised and studied by Hodges and Hinsley (1964) [6], Guney (1971) [7] and Smith and Lazzara (1987) [5] using adiabatic oven testing. From these early studies it is clear that the entire coal self-heating behaviour from low ambient temperature to thermal runaway can only be fully assessed by simulating in-mine conditions. Recent investigations by Beamish and Beamish [8, 9] have shown how this can be achieved by benchmarking against known coal self-heating experience from operating mines and built stockpiles. Beamish *et al* [8, 9] provides a working example of the success of this new technique.

3.1 R_{70} Self-heating Rate

The basic test procedure to determine the R_{70} self-heating rate is the time taken for the coal temperature to reach 70°C from a start temperature of 40°C [10]. It is used to calculate the average self-heating rate due to adiabatic oxidation.

In the past generally coals with an $R_{70} < 0.5$ ºC/h was considered low propensity, 0.5-0.8 ºC/h medium propensity, and coals with an $R_{70} > 0.8$ ºC/h were considered highly prone to spontaneous combustion [11]. This ranking has been superseded with a more appropriate self-heating propensity classification that incorporates low rank coals, shown in Table 1, for both Queensland and New South Wales conditions. The two schemes are required to take into consideration the different start temperature conditions that exist in both settings.

Table 1: Intrinsic spontaneous combustion propensity classification (ISCP), based on Queensland and New South Wales coal conditions

		Queensland	New South Wales
ISCP Class	**Propensity rating**	**R_{70} value (°C/h)**	**R_{70} value (°C/h)**
I	low (L)	$R_{70} < 0.5$	$R_{70} < 1$
II	low-medium (LM)	$0.5 \leq R_{70} < 1$	$1 \leq R_{70} < 2$
III	medium (M)	$1 \leq R_{70} < 2$	$2 \leq R_{70} < 4$
IV	high (H)	$2 \leq R_{70} < 4$	$4 \leq R_{70} < 8$
V	very high (VH)	$4 \leq R_{70} < 8$	$8 \leq R_{70} < 16$
VI	ultra high (UH)	$8 \leq R_{70} < 16$	$16 \leq R_{70} < 32$
VII	extremely high (EH)	$R_{70} \geq 16$	$R_{70} \geq 32$

The non-linear boundary for each class takes into account the non-linear rank relationship with R_{70} values, as shown in the Suggate rank parameter, Figure 2. This is determined from the calorific value and volatile matter content of the coal expressed on a dry mineral matter and sulphur free (dmmsf) basis [12, 13]. The higher the Suggate rank value the higher the coal rank. A Suggate rank value of 2 equates to lignite and a Suggate rank value of 17 equates to low volatile bituminous.

It is important to realise an R_{70} value is not only rank dependent [10, 14], it is also affected by coal type [10, 15] and mineral matter constituents [1, 16, 17]. As such, a true comparison between samples can only be obtained by plotting R_{70} against the ash content of the coal on a dry basis.

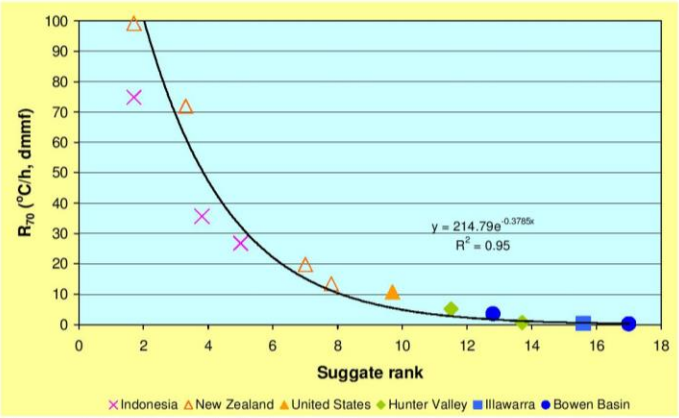

Figure 2: Relationship between R_{70} self-heating rate and Suggate rank for a range of Australian and overseas coals [18]

3.2 Relative Ignition Temperatures

Relative Ignition Temperatures (RIT) use an oven to drive the temperature of the coal, unlike the R_{70} test where the oven tracks the coal temperature as it reacts with oxygen. The RIT has seen some modifications, in particular the development of a wire basket test that uses an ignition/non-ignition criteria combined with a heat-release rate method [19].

A value for RIT can be obtained from the R_{70} adiabatic oven test. This is defined as the point at which the oven can no longer keep up with the coal temperature rate rise, which equates to 2 ºC/min.

The higher the spontaneous combustion propensity of the coal, the lower the CPT or RIT value. Banerjee *et al* [20] determined that coals with CPT values < 140ºC have a high intrinsic spontaneous combustion propensity, those within the range of 140ºC to 160ºC have a medium intrinsic spontaneous combustion propensity, and coals with CPT values > 160ºC have a low intrinsic spontaneous combustion propensity. More recent checks of the CPT equations for a range of Australian coals suggests that the boundaries should be set at 130ºC for high propensity and 150ºC for low propensity.

3.3 Minimum Self-heating Temperature

Smith and Lazzara [5] tested a range of US coals to determine the minimum self-heating temperature (SHT) that was required for coal self-heating to proceed to thermal runaway. They found that this parameter was closely correlated with the oxygen content (O) of the coal on a dry ash-free basis. It can be misleading especially if carbonate mineral matter is present in the coal producing an elevated oxygen content.

Coals that have SHT values < 70ºC are considered to have a high intrinsic spontaneous combustion propensity, those within the range of 70ºC to 100ºC have a medium intrinsic spontaneous combustion propensity, and coals with SHT values > 100ºC have a low intrinsic spontaneous combustion propensity [5, 21, 22]. More recent checks of the SHT values for a range of Australian coals suggests that the high intrinsic spontaneous combustion propensity boundary should be increased to 80ºC.

This index parameter was found to be related to the coal oxygen content (O, % dry, ash-free basis) according to the following equation [5]:

SHT (ºC) = 139.74 - 6.57 x O

To account for the increased (or decreased) reactivity of a coal due to ambient in-mine temperatures, the value for the minimum SHT determined from the equation can be adjusted based on

the ambient in-mine temperature of the coal. A value of 12.8ºC (55 ºF) is used as the baseline in-mine temperature [22]:

SHT_{adj} (ºC) = [SHT – ($T_{ambient}$ – 12.8)]

Beamish and Beamish [8] found that for a range of Australian coals the high intrinsic spontaneous combustion propensity boundary should be increased to 80ºC using the original Smith and Lazzara equation for SHT [5]. Therefore, the Smith and Lazzara [5] equation and the modified boundary are applied to the samples in this report.

Typical values for SHT are shown in Figure 3 where a strong linear relationship with coal rank is observed. Very low rank coals produce negative values as these coals have very high oxygen contents. As such, coals containing significant amounts of carbonate mineral matter will produce a high oxygen content value, which can give a misleading low SHT value, and consequently indicate a false high spontaneous combustion propensity for the coal. Results for lignite samples are often misleading - so it is generally assumed that these coals have a high spontaneous combustion propensity due to their low rank.

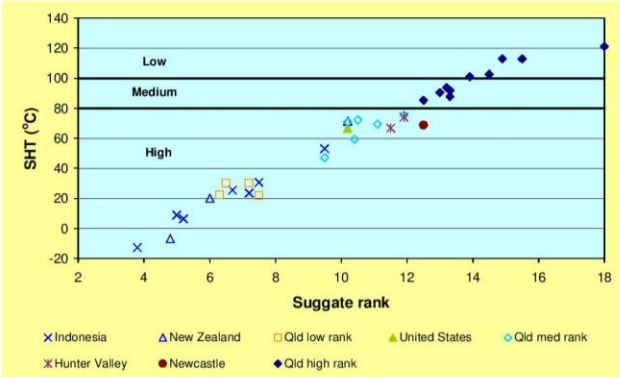

Figure 3: Relationship between SHT and Suggate rank for a range of coals.

3.4 Moist coal adiabatic benchmark testing and test differences

The influence of moisture on coal self-heating has been studied in detail [6, 7, 20, 23, 24]. The impacts result from both the moisture present in the coal and the moisture present in the surrounding environment. These effects are particularly influential on the initial self-heating rates of the coal at low ambient temperatures, and in certain situations may either impede the development of a heating (due to heat loss from evaporation) or act in a synergistic manner to promote a heating through additional heat gained from heat of wetting (such as occurs after a rain event or during a wet season with high humidity) or initiation of pyrite oxidation.

The high temperature index parameters CPT and RIT do not consider moisture moderation and therefore omit a crucial factor in assessing the risk of spontaneous combustion. The R_{70} self-heating rate is a dry basis parameter and only provides an indication of the intrinsic reactivity of the coal. To overcome these deficiencies a new moist coal adiabatic test method has been developed SponComSIM™ [25] and benchmarked against known coal self-heating performance in a loose pile situation. The test is conducted on the coal with its as-received moisture content, using a larger sample mass and a lower oxygen flow rate, thus more closely simulating site conditions, of high mass to flow rate ratio.

This adiabatic test method incorporates the complete spectrum of coal self-heating behaviour from low ambient temperature to thermal runaway [18]. The database of results using this test method, benchmarked against site experience, is rapidly growing and it is the most appropriate test method for spontaneous combustion assessment input to development of an SCMP. The test can be adjusted to suit any mine environment taking into account the initial boundary conditions of mine temperature and humid or dry air. It also quantifies any self-heating acceleration from the presence of reactive pyrite, natural inhibition from the presence of other mineral

matter or seamgas and artificial inhibition through the use of additives to the coal.

4. EXPERIMENTAL

Core samples (Figure 4) were collected in the Theunissen Coalfield in South-Africa, a middle Ecca coal deposit which is in a Karoo aged coal basin with a floor of volcanics (extrusives) of the Ventersdorp Supergroup in the north and in the south quartzites of the Witwatersrand Super Group. Seam 3 is the most widely distributed and economically significant developed coal seam and also the most suitable for UCG, with a thicknesses ranging from 0.83m to greater than 5m and a depth ranging from 245m to 385m below surface in the target area. The coal quality is suitable for UCG and the raw calorific value has an average of 20.3 MJ/kg. The raw volatile matter content has an average value of 19.2% and the raw ash has an average value of 30.8%, all on an air dried basis.

Figure 4: Core samples collected during exploration

The samples were supplied as fresh core samples from 2 boreholes. The samples were wrapped, and once received at the laboratory frozen to minimise oxidation and deterioration. As soon as possible after receiving the samples they were prepared for spontaneous combustion testing. The two samples, representing the Theunissen Underground Coal Gasification (TUCG) coal field, will further be referred to as **TUCGY04/3/2** and **TUCGY04/3/4**. The core samples are representing depths of 354.18m and 355.56m respectively.

4.1 Adiabatic oven R_{70} test procedure

Prior to each R_{70} test, the core sample is crushed and sieved as quickly as possible to minimise the effects of oxidation on fresh surfaces created by the grinding. A sample is placed in a volumetric flask under a flow of nitrogen in a drying oven. Precautions are taken to ensure the exclusion of oxygen from the vessel prior to heating the coal for drying. The air is flushed from the system at room temperature, the oven is ramped up to 110°C and the coal dried under nitrogen All R_{70} tests were performed on a dry basis to standardise the test results.

Once dry, the coal is transferred into the reaction vessel and left to stabilise at 40°C in the adiabatic oven with nitrogen passing through it. When the sample temperature is stabilised, the oven is switched to remote monitoring mode. This enables the oven to track and match the coal temperature rise due to oxidation. The gas selection switch is turned to constant oxygen. The temperature change of the coal with time is recorded by a datalogging system until sample reaches 160°C.

4.2 Adiabatic oven SponComSIM™ test procedure

This test is designed to provide a simulation of the true coal self-heating behaviour from low ambient temperature. The normal in-mine temperature is used as the starting point for the test. The nature of the test assumes that in the real operational situation there is a critical coal pile thickness present that minimises any heat dissipation (represented by the adiabatic oven testing environment) and there is a sufficient supply of oxygen present to maintain the oxidation reaction. A larger sample mass and lower oxygen flow rate is used, compared to the R_{70} test method, to produce conditions that more closely match reality.

The coal sample either reaches thermal runaway, or begins to lose heat due to insufficient coal intrinsic reactivity to overcome heat loss from moisture evaporation and/or heat sink effects from non-reactive mineral matter. As the coal is tested with its as-received moisture content, for some coals this may produce a prolonged temperature shoulder on the way to thermal runaway.

5. ANALYSIS OF RESULTS AND INTERPRETATION

5.1 Coal quality analysis and rank

Proximate analysis, ultimate analysis and calorific value determination were performed on duplicates of the R_{70} and SponComSIM™ test samples. A summary of the results obtained are contained in Table 2.

Table 2: Analytical, rank and calculated spontaneous combustion index data for coal samples from borehole TUCG

Proximate analysis (air-dried)	TUCG04/3/2	TUCG04/3/4
Moisture (%)	5.4	4.4
Ash (%)	27.6	17.6
Volatile Matter (%)	17.7	25.9
Fixed Carbon (%)	49.3	52.1
Ultimate analysis (dry ash free)		
Carbon (%)	81.0	80.3
Hydrogen (%)	4.19	4.70
Nitrogen (%)	1.90	2.34
Sulphur (%)	0.31	0.88
Oxygen (%)	12.6	11.8
Calorific Value (MJ/kg)	20.64	24.79
Suggate rank	8.9	10.2

The ASTM rank of the samples is high volatile B bituminous based on the volatile matter and calorific value of the coal. The upper sample has a much lower volatile matter and calorific value, possibly as an artefact of the mineral matter correction. As such, an ASTM rank determination for this sample is not valid. A Suggate rank plot (Figure 5) shows that these samples plot below the lower boundary of the New Zealand coal band indicating they are inertinite-rich. There is also a clear coal type difference between the two samples.

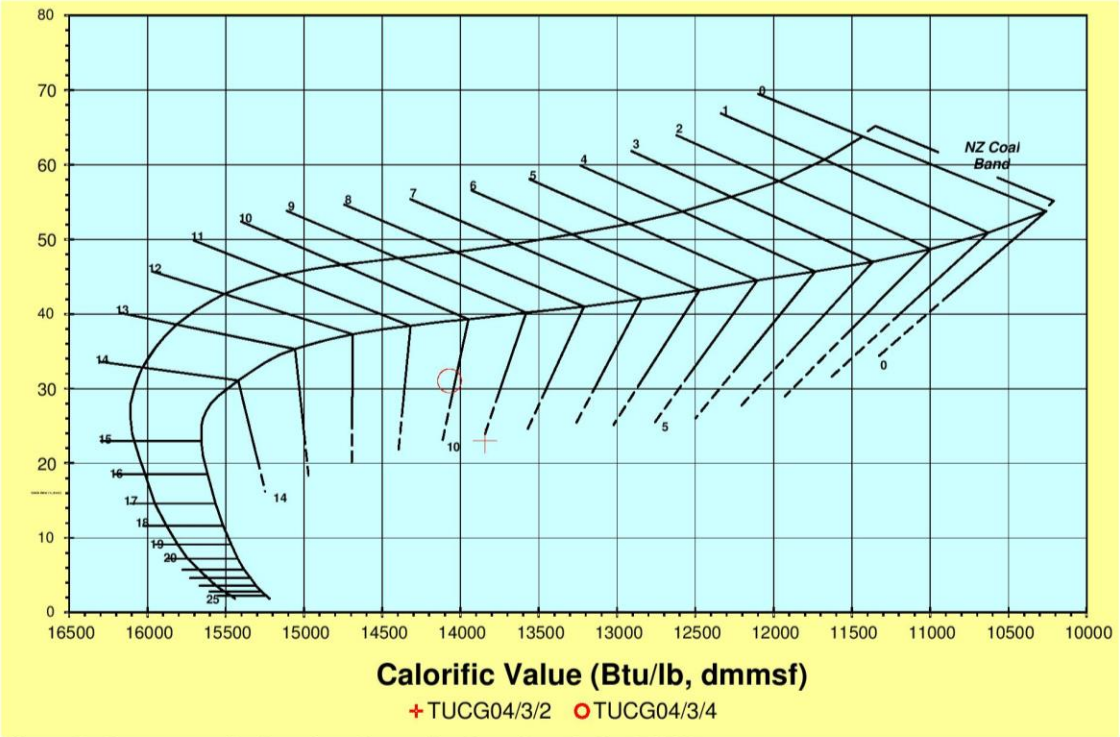

Figure 5: Suggate rank plot of coal samples from boreholes TUCG

5.2 Intrinsic spontaneous combustion reactivity analysis

An overview of the temperature data recorded for the R_{70} tests of the samples is contained in Appendix 1. The R_{70} values range from 4.18 °C/h to 4.60 °C/h (Table 3), which indicates that the samples are highly reactive towards oxidation environments, and should be easily ignited in the UGC process

Table 3: R_{70} and RIT values of coal samples from borehole TUCG

Sample	Ash content (%, db)	R_{70} (°C/h)	RIT (°C)
TUCG04/3/2	29.2	4.60	140
TUCG04/3/4	18.4	4.18	131

When interpreting R_{70} values it is important to realise that the value is not only rank dependent [10, 14], it is also affected by coal type [10, 15] and mineral matter constituents [10, 15, 17). As such, a true comparison between samples can be obtained by plotting R_{70} against the ash content (acting as an indicator parameter of mineral matter content) of the coal on a dry basis as shown in Figure 6.

The intrinsic spontaneous combustion reactivity rating based on New South Wales coal conditions for these samples is high, which is consistent with the rank and type of coal. There is a noticeable difference between the two samples, which can be attributed to the coal type difference noted in section 5.1 of this paper. These R_{70} values are lower than the results obtained for San Juan Mine in New Mexico, which uses a proactive goaf inertisation mitigation strategy for spontaneous combustion management [26] and are also lower than the results for Spring Creek Mine in New Zealand, which has recorded several underground heatings in recent years [27] The nearest coal with a similar intrinsic spontaneous combustion reactivity is Newcastle B (Figure 6), which experienced a pillar heating in 2011 [28].

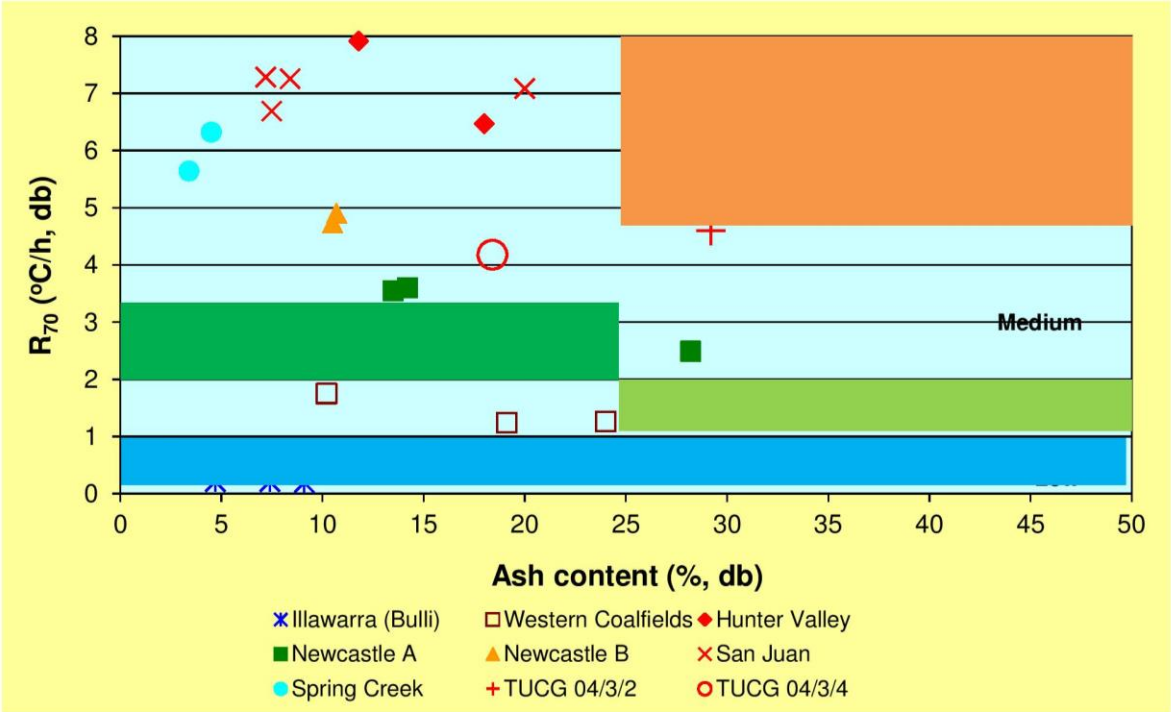

Figure 6: Self-heating relationship with ash content and coal rank for a range of mined coals and coal samples from borehole TUCG, showing intrinsic spontaneous combustion reactivity classes based on New South Wales conditions

5.3 Relative Ignition Temperature Analysis

The R_{70} self-heating rate is a low temperature oxidation spontaneous combustion index parameter. In contrast, the Relative Ignition Temperature (RIT) is a high temperature spontaneous combustion index parameter. It is important for application in UCG, as it will reflect the and determine the minimum temperature of the agent (which can be steam, air or oxygen) used to heat the coal and start the ignition The RIT is normally obtained by heating a coal sample at a fixed rate (usually 2 °C/min) from a start temperature of 70°C. The rate of self-heating in this region is controlled by Arrhenius kinetics and the RIT value is defined as the point at which the coal temperature overtakes the oven temperature using this particular test. This region of coal self-heating is also recorded in the R_{70} adiabatic oven test.

Figure 9 shows the RIT value with respect to the corresponding R_{70} value for each sample tested. Spring Creek Mine (Figure 5) in New Zealand is a benchmark example of a coal that has both a high self-heating rate and a low RIT. Site experience shows that this coal has an incubation period of between 6-8 weeks. The mine experienced an underground heating from a roof fall in July 2008 that was managed very successfully using data obtained from bulk coal spontaneous combustion testing [27]. The Illawarra coal (Figure 5) is a benchmark example at the opposite end of the spectrum, with both a low self-heating rate and a high RIT. This coal has never recorded a heating incident. The samples from borehole TUCG have a high self-heating rate and a medium RIT similar to the Newcastle B coal. The higher RIT value for TUCG04/3/2 is due to a higher mineral matter content.

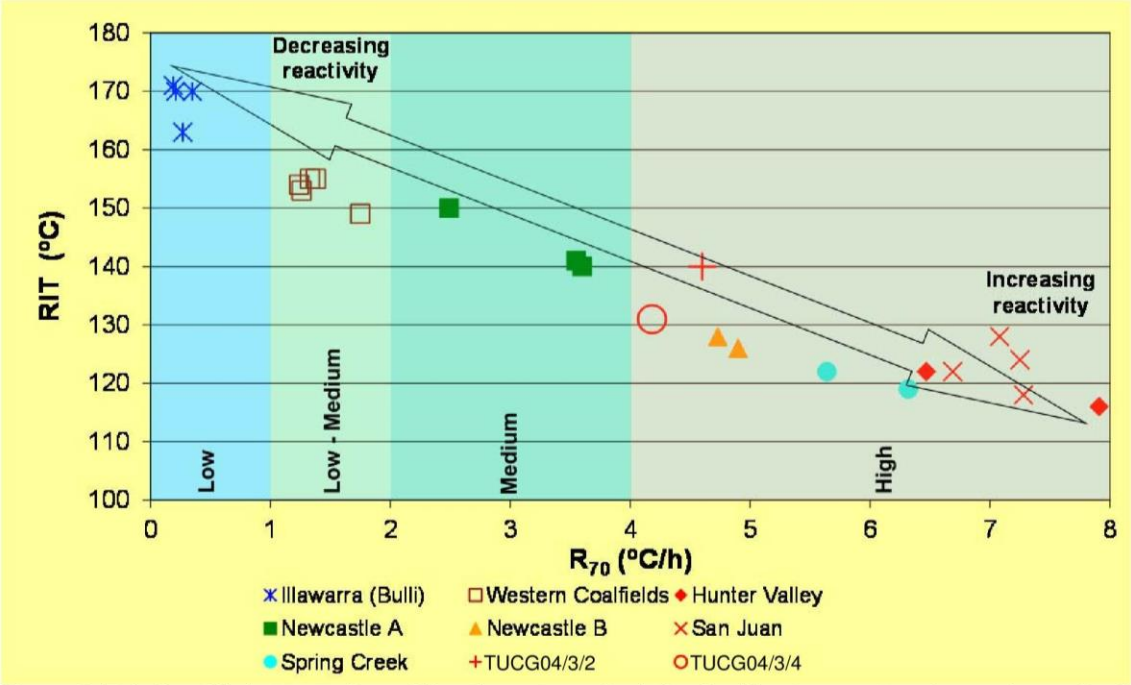

Figure 9: Relationship between R_{70} self-heating rate and relative ignition temperature for coal samples from borehole TUCG with selected coals of known self-heating behaviour included

5.4 Thermal runaway analysis

Beamish and Beamish [8, 9, 18, 26] showed that the time taken for coal to reach thermal runaway under **loosely piled conditions and ambient conditions** can be determined using a laboratory adiabatic testing technique that is benchmarked against known coal performance on site. The self-heating curves are shown in Figure 10.

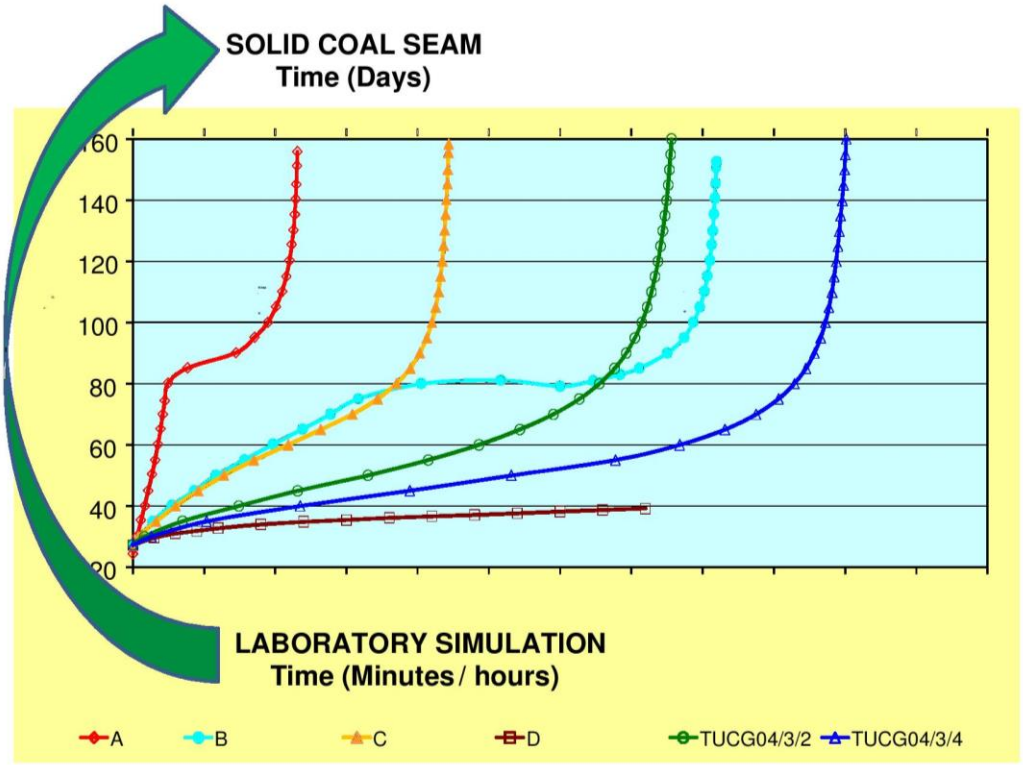

Figure 10: SPONCOMSIM™ test results for coal samples from borehole TUCG compared against coals with known self-heating behaviours

Coal D is a standard benchmark of a coal that has never created a mine self-heating incident. It is a high rank, bituminous coal and has a very low intrinsic reactivity. Also conditions in the mine where this seam is extracted are generally reasonably cool and thus heat dissipation is also a site-specific factor for this coal.

Both samples reached thermal runaway in the time allocated for the tests. Based on the benchmark times for real site situations, TUCG04/3/2 would take a minimum of 36 to 55 days to develop a spontaneous combustion event from a start temperature of 27.4°C, **if a loose pile of this coal is formed at critical thickness with sufficient continuous air supply and minimal heat dissipation**. Similarly, TUCG04/3/4 would take a minimum of 49 to 74 days to develop a spontaneous combustion event from a start temperature of 27.2°C.

5.5 INTERPRETATION OF SPONCOM AND SELF-HEATING RESULTS ON SOLID COAL DURING IGNITION OF AN UNDERGROUND COAL GASIFICATION PROCESS

An identified coal source X in Figure 9 experienced a pillar heating in solid coal [28] which took four years to develop from the starting in-mine temperature at ambient conditions. This was caused by a significant pressure differential being present across the pillar allowing air to penetrate into the solid coal through the fractures. In simple empirical terms and laboratory scale, this equates to 40 hours to reach thermal runaway, which equates to the four years in this situation.

In order to relate the above results to an ignition of coal for an UCG Process, at elevated temperatures and agent flow rates, the following thermal runaway and spontaneous combustions conditions are predicted.

At the higher temperature region of the test it took just 11 minutes for the Newcastle B coal to increase in temperature from 140 to 150°C. This would equate to approximately 6 days based on the pillar heating analogy. Bulk testing of coal using a 16 m^3 chamber showed that at these temperatures, high volatile bituminous coals can rapidly progress to ignition within a matter of days, if a sufficient supply of oxygen is available [28] TUCG04/3/2 and TUCG04/3/4 in Figure 9 showed that solid coal heating to ignition would take approximately double the time indicated by the Newcastle B coal due to the lower intrinsic reactivity, as it took over 20 minutes for the coal to increase in temperature from 140 to 150°C, and would equate to approximately 10-12 days. Exposing the coal to higher initiating temperatures would speed up the time to self-ignition as there is a non-Arrhenius kinetics region that exists at low ambient temperatures during coal self-heating. At high initiation temperatures in excess of 150°C, the Arrhenius kinetics would promote a reaction rate doubling effect for every 10°C rise in temperature. Again, this effect was observed in the bulk testing work by Clarkson [28].

Conversely, thermal runaway to ignition can be delayed by the presence of moisture in the coal, which normally shows as a plateau temperature region as seen in Figure 9 for the Kideco and Spring Creek coals. This normally occurs when the coal moisture content is in excess of 10%. Both TUCG04/3/2 and TUCG04/3/4 show no signs of a moisture plateau. However, one aspect that needs to be considered in terms of Underground Coal Gasification is whether any particular target seam is acting as an aquifer. Under these circumstances the water present would play a critical role in development of coal heating to ignition.

6. CONCLUSIONS AND RECOMMENDATION

Adiabatic oven testing using R_{70} and SponComSIM™ tests is usually applied as a precautionary measurement of the self-heating properties of coal, e.g. to manage coal on stockpiles or during transport. In this study, the novel approach is applied of using R_{70} and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating) at which a coal reserve has to be ignited during the start-up phase of an UCG process.

The purpose of this study was to establish the spontaneous combustion propensity of core samples from the Theunissen coal reserve in South-Africa aimed for UCG purposes. The scope was:

1. R_{70} testing to establish the Intrinsic Spontaneous Combustion Reactivity and Relative Ignition Temperature (RIT) of the coal.
2. SponComSIM™ to establish the time to thermal runaway for specific starting temperatures, moisture contents, and oxygen supply
3. Coal quality analysis (proximate, ultimate and calorific value) of the samples to assist with interpretation of test results.

The results indicate R_{70} self-heating rates from 4.2 to 4.6 ^{o}C/h, consistent with the coal rank and type, and rate the coal as having a high intrinsic spontaneous combustion reactivity. Spontaneous combustion index parameters indicate the coal has a high spontaneous combustion propensity rating. This high propensity means that SponCom or self-heating can be an important factor in initiating UCG reactions in the Theunissen coals.

Measured RIT for the samples (130-140^{o}C) which are in agreement with the R_{70} results give an indication of heat input required to start the UCG ignition.

SponComSIM™ tests of this coal, compared to a bench-mark pillar heating case from Australia show that with ideal conditions of critical thickness (carbon availability), ample continuous supply of oxygen (air), elevated temperature conditions (> 140^{o}C) and minimal heat dissipation, coal from this reserve will reach thermal runaway within two days.

The following recommendations for further R&D can be highlighted:

- Coarser coal particle testing with increased temperature and heating rate conditions.
- Effect of mineral composition on heating rate.
- Statistical approach in correlating bench-scale ignition characteristics with underground in-seam ignition comparison.
- Additional information on the coal heating performance from thermal runaway to ignition may be obtained from applying a modified wire basket test to the remaining lumps (not crushed) of coal supplied for this project. This would require setting up an elevated initiation temperature for the test (for example 200^{o}C) and recording whether the coal goes to ignition or not and in what timeframe. The rate of change in coal temperature may provide reaction rate data that could be used for future modelling.

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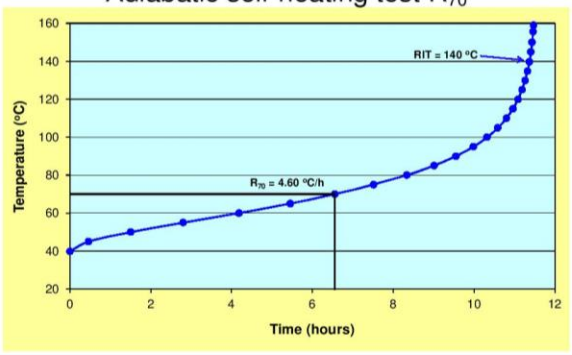
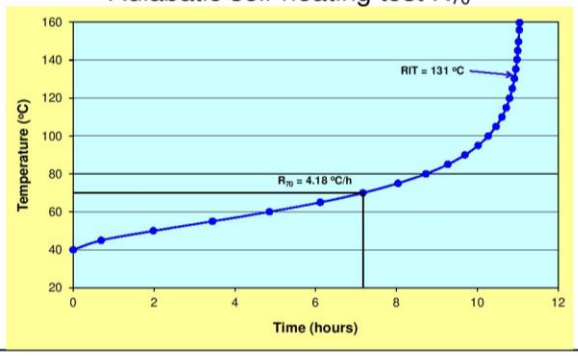
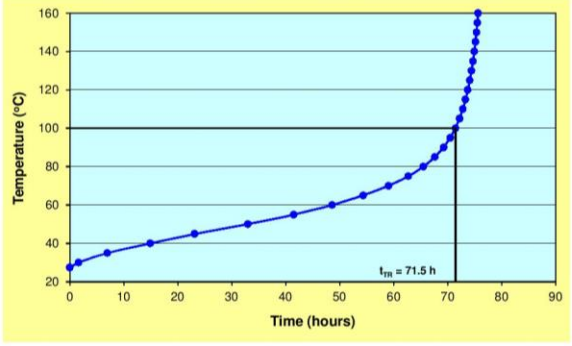
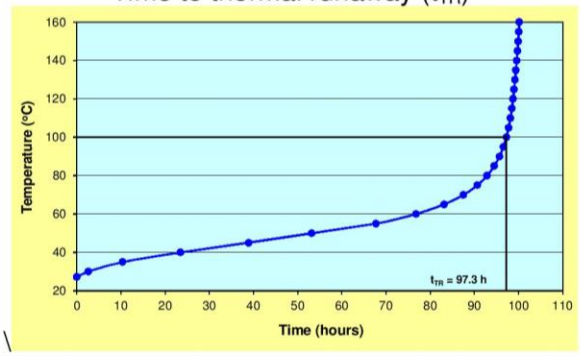
APPENDIX 1
ADIABATIC TESTING RESULTS OF COAL SAMPLES TUCG

	TUCG04/3/2	TUCG04/3/4
Adiabatic self-heating test R_{70}	4.60°C/h	4.18°C/h
Relative ignition temperature (RIT)	140°C	131°C
Moisture content (as-received)	6.2%	6.0%
Time to thermal runaway (t_{TR})	71.5h	97.3h

TUCG04/3/2	TUCG04/3/4
Adiabatic self-heating test R_{70}	Adiabatic self-heating test R_{70}
	
Time to thermal runaway (t_{TR})	Time to thermal runaway (t_{TR})
	

7 CONCEPTUAL USE OF VORTEX TECHNOLOGIES FOR SYNGAS PURIFICATION AND SEPARATION IN UCG APPLICATIONS

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Journal of the Southern African Institute of Mining and Metallurgy, October 2018, 118(10) p. 1029-1039.

Summary

Syngas from Africary's Theunissen underground coal gasification (UCG) project will be used for power production and synthesis of liquid fuels and commodity chemicals. However, some of the coal components, especially condensable water, oils, tars, inorganic trace elements, and a small fraction of fly ash and particulate matter, make their way to the surface via the production well and can cause adverse impacts on downstream processes. Other impurities in gasification feedstock, especially different kinds of sulphur species, nitrogen compounds, halogens like chlorine, and inorganic mineral matter like mercury entrained in the syngas may also have negative downstream implications. Africary's standard gas clean-up design incorporates relatively mature techniques and effective wet scrubbers and Acid Gas Removal (AGR) systems such as Rectisol®, Selexol® or aMDEA®, but with the downside of low energy efficiency and wastewater generation.

High-temperature syngas cleaning has been the focus of research decades, but a scientifically proven and tested technology has not been commercialised yet. Although noteworthy improvements were achieved with candle filters, these conventional warm gas cleaning technologies have fundamental limitations to improvement, due to the intrinsic material properties that lead to unacceptable availability.

UCG produce syngas that is both hot and at pressure, ideal for gas turbine power generation or FT. The preservation of both temperature and pressure during syngas clean-up can greatly enhance the efficiency of the overall system. Based on hydrostatic pressure modelling the syngas production pressure designed for Africary's Theunissen UCG (TUCG) project is 25 times atmospheric pressure and will reach the surface with a target temperature of between 250 to 350°C.

In this study, the aim is to address fundamental limitations and practical constraints of the existing hot particulate removal technologies for removing contaminants and species separation from the hot (T > 300°C) raw syngas. Comparisons are made between supersonic gas separation, Ranque–Hilsch vortex tube, vortex gradient separation, and inertia vacuum filtering, and a vortex-based gas separation concept is proposed for UCG applications.

Next-steps and future work includes the modelling, design and experimental testing of a vortex gradient separator for both particulate filtering and gas separation efficiency.

Conceptual use of vortex technologies for syngas purification and separation in UCG applications

by J.F. Brand*†, J.C. van Dyk*†, and F.B. Waanders†

Synopsis

Syngas from Africary's Theunissen underground coal gasification (UCG) project will be used for power production and synthesis of liquid fuels and commodity chemicals. However, some of the coal components, especially condensable water, oils, tars, inorganic trace elements, and a small fraction of fly ash and particulate matter, make their way to the surface via the production well and can cause adverse impacts on downstream processes. Africary's standard design incorporates a cold gas clean-up system that relies on relatively mature techniques based on highly effective wet scrubbers and acid gas removal (AGR) systems such as Rectisol®, but with the downside of low energy efficiency and waste water generation. In this paper, novel technologies for removing contaminants and species separation from the hot ($T > 300$°C) raw syngas are compared. Comparisons are made between supersonic gas separation (SGS), Ranque–Hilsch vortex tube (RHVT), vortex gradient separation (VGS), and inertia vacuum filtering (IVF), and a vortex-based gas separation concept is proposed for UCG applications.

Keywords

underground coal gasification, gas cleaning, supersonic gas separation, Ranque–Hilsch vortex tube, vortex gradient separation, inertia vacuum filter.

Introduction

Impurities in gasification feedstock (coal, biomass, waste, *etc.*), especially sulphur, nitrogen, chlorine, and inorganic mineral matter, often end up in the syngas and can cause adverse impacts on downstream processes. Africary's standard design incorporates a cold gas clean-up system that relies on relatively mature techniques based on highly effective wet scrubbers and acid gas removal (AGR) systems such as Rectisol®, Selexol® or aMDEA®; but with the downside of low energy efficiency and waste water generation.

Hot ($T > 300$°C) gas clean-up technologies are attractive because they avoid cooling and reheating of the syngas stream. Some available warm gas cleaning technologies include traditional particulate removal devices such as cyclones, candle filters, membranes, and molecular sieves. The warm gas desulphurization process technology developed by RTI LLC (2018) requires hot syngas to remove sulphur and has become commercially ready. Many other hot gas clean-up systems are still under development, given the technical difficulties caused by extreme environmental and operating conditions.

High-temperature syngas cleaning has been the focus of research for over three decades (Sharma *et al.*, 2008), but a scientifically proven and tested technology has not yet been commercialized. Significant improvements have been achieved with candle filters in the past few years (Prabhansu *et al.*, 2015); however, these conventional warm gas cleaning technologies have fundamental limitations due to the intrinsic material properties of candle filters that cause practical problems and lead to unacceptable availability.

Sharma *et al.* (2008) presented the status of syngas cleaning technologies for particulate removal systems and reviewed the practical problems and limitations faced by these gas cleaning systems. Recommendations were also made to overcome these fundamental limitations. Gas clean-up technologies can be classified according to the process temperature range: hot gas clean-up (HGC), cold gas clean-up (CGC), or warm gas clean-up (WGC) (Woolcock and Brown, 2013). There is considerable ambiguity in these definitions, and Woolcock and Brown (2013) propose a more rigorous classification based on condensation temperatures of various compounds. CGC generally describes wet scrubbing processes (Balas *et al.*, 2014) that operate at near-ambient conditions, utilizing water sprays, and which result in exit temperatures that allow water to condense and the contaminants either being absorbed into the water droplets or serving as nucleation sites for water condensation (Woolcock and Brown, 2013). WGC is often assumed to occur at temperatures higher than the boiling point of water but which still allow for ammonium

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chloride condensation. This typically implies a warm upper limit of temperatures of about 300°C. HGC typically occurs at temperatures higher than 300°C, at which it is still likely that several alkali compounds will condense (Hirohata *et al.*, 2008).

UCG has the potential to produce raw syngas at the production well on surface that is both hot and at pressure; ideal for the Fischer-Tropsch (FT) process, which preferably requires the clean syngas to be at temperatures of >250°C and pressures >25 atm. The preservation of both temperature and pressure during gas clean-up will greatly enhance the efficiency of the overall system. The syngas production pressure designed for Africary's Theunissen UCG project is 25 atm., based on hydrostatic pressure modelling, and the gas will reach the surface with a target temperature of 250–350°C.

In this study the aim is to address the fundamental limitations and practical constraints of existing hot particulate removal technologies. These systems generally suffer from poor availability caused by factors associated with tensile strength, the sealing system, thermal transient behaviour, corrosion, and residual ash accumulation (Hirohata *et al.*, 2008). These problems can be circumvented by introducing alternative hot gas separation and/or cleaning methods such as supersonic gas separation (SGS), Ranque–Hilsch vortex tube (RHVT), and vortex gradient separation (VGS) with inertia-vacuum filter (IVF). A vortex-based gas separation concept is proposed for UCG applications.

Description of Africary's UCG syngas content and contaminants

Contaminants generally include particulate matter (mineral particulates, trace elements, and char), water vapour, condensable hydrocarbons (oils and tars), sulphur compounds, nitrogen compounds, alkali metals (primarily potassium and sodium), and hydrogen chloride (HCl). The sulphur compounds and CO_2 are usually removed by various adsorption-based acid gas removal systems, but novel alternatives like the SST, RHVT, and VGS are proposed for the vortex tube concept for UCG applications.

The major syngas constituents and the predicted contaminants expected from the UCG production well are based on experimental work (van Dyk, Brand, and Waanders, 2014). The results are presented in Table I. Water, in the form of steam, is removed to dry the syngas by wash-cooling the gas to below its saturation temperature. This allows some condensable hydrocarbons like oils and tars to be removed with the water. Some of the water-soluble gases like ammonia are also removed during this process. The tars consist of condensable organic compounds and may vary from primary oxygenated products to heavier deoxygenated hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) (Africary, internal modelling work).

Thermochemical conversion processes generate numerous tar species depending on the operating parameters, especially temperature, pressure, heating rate, type and amount of agent/oxidant, and residence time (Africary, internal modelling work). A UCG gasifier may yield 1 to 3% (mass basis) tar; however, regardless of the amount or type, liquid hydrocarbons like tar and oil are a universal challenge because of their potential to foul filters, lines, and equipment, as well as deactivate catalysts in downstream processes (Torres, Pansare, and Goodwin, 2007). Although eliminating all tar and oil is desirable, a more practical strategy is to simply remove sufficient liquid hydrocarbons at a temperature lower than the minimum temperature that the gas is exposed to downstream.

Inorganic compounds and residual solid carbon from the UCG production well constitute the bulk of the particulate matter. The inorganic content includes alkali metals (potassium and sodium), alkaline earth metals (mostly calcium), silica (SiO_2) and alumina (Al_2O_3), and other metals such as iron and magnesium (Africary, internal modelling work). Minor constituents present in trace amounts include arsenic, selenium, antimony, zinc, and lead (van Dyk and Keyser, 2014). Most nitrogen contaminants in syngas occur as ammonia (NH_3) with smaller amounts of hydrogen cyanide (HCN).

Coal from the Northern Free State Basin, South Africa, which will be used for the Theunissen UCG project, contains alkali and alkaline earth metals. The alkali metals are primarily potassium and to a lesser extent sodium, and are more problematic in syngas applications than alkaline earth metals due to their higher reactivity and potential to form substrates with halides like Cl and F.

Table I

The two types of raw syngas that can be produced from Theunissen UCG project (Africary, internal modelling work)

Streams	Raw gas 1	Raw gas 2
Components	**mol%**	**mol%**
H_2	34.5%	43.1%
CO	46.0%	27.5%
CO_2	7.3%	9.6%
CH_4	7.0%	12.4%
$C2H_4$	0.0%	0.0%
N_2	0.6%	0.6%
O_2	0.0%	0.0%
H_2O	4.4%	6.6%
H_2S + COS	0.2%	0.2%
Trace	**mg/h**	
Ba	1.3E-19	1.2E-19
Sb	1.4E+04	1.3E+04
Cd	2.5E-02	2.3E-02
Cr	7.4E-20	6.8E-20
Be	3.1E-07	2.8E-07
Pb	2.2E-02	2.0E-02
Mo	2.8E-14	2.6E-14
Cu	1.6E-17	1.5E-17
Co	8.4E-27	7.8E-27
Mn	1.2E-26	1.1E-26
Hg	9.2E+02	8.5E+02
Sn	9.5E+02	8.8E+02
As	7.6E-01	7.1E-01
Ni	1.0E-13	9.6E-14
Zn	7.4E-04	6.8E-04
V	5.8E-14	5.4E-14
Cl	1.4E+06	1.3E+06
F	2.1E+05	1.9E+05
Liquids	**kg/h**	
Tar	310	290
Oil	305	280
Naphtha	160	145

Conceptual use of vortex technologies for syngas purification and separation

Common issues with particulate matter are fouling, corrosion, and erosion, which cause efficiency and safety concerns if not removed or addressed before syngas processing. For example, due to the inclusion of gas engines and compressors in the Africary Theunissen UCG plant, the particulate content must be reduced to below 1 mg/m^3. Particulate matter is classified according to aerodynamic diameter. For instance, PM10 denotes particles smaller than 10 µm, and PM1 particles smaller than 1 µm (Federal Remediation Technologies Roundtable, 2016). It is common practice to remove particulates of a certain size to below a given level, as indicated in Tables II and III.

Alkali compounds reaching the surface in the form of chlorides, hydroxides, and sulphates can cause substantial fouling and corrosion in downstream processes. Chlorides are the predominant halide in syngas, usually in the form of hydrochloric acid (HCl). Chlorine in coal occurs as alkali metal salts, which readily vaporize at the high gasification temperature and react with water vapour to form HCl. Substantial hot corrosion can occur, and reactions can also occur between HCl and other contaminant species in the gas phase, which can generate compounds such as ammonium chloride (NH_4Cl) and sodium chloride (NaCl) which cause fouling in downstream equipment upon cooling.

UCG syngas clean-up requirements for polygeneration

When a UCG plant is operated in a stable and correct manner, much less particulate and mineral matter is produced in the raw syngas compared to conventional gasification operations and only a small amount of particulate removal is required. However, the raw syngas may still contain a lot of moisture, tars, and oils, requiring removal. CGC relies on mature techniques, like wet scrubbers, that are decidedly effective but generate waste water and have poor energy efficiency and a large environmental footprint.

The level of cleaning that is required is based on the downstream consumer's technology requirements, fuel specification, and emission standards. For Africary's UCG polygeneration (power and diesel fuel) design, the cleaned syngas product specification is defined by the feed specification for the FT process vendor (Table II), and/or the gas engine vendor (Table III).

The liquid fuel products produced by the FT unit must follow the Euro-5 specification, as required by South African legislation, therefore removal of HCN, NH_3, Hg, Sb, Sn, sulphur compounds, metals, halogens (Cl and F), and several other trace components is required (Prabhansu *et al.*, 2015; correspondence with several FT process licensors). The syngas clean-up system must dry the raw syngas and effectively capture (> 99.9%) all the trace elements listed in Table I, as well as remove all particulate matter. It also needs to effectively separate (> 99.99%) acid gases like H_2S, COS, and CO_2 from the syngas, with an availability factor above 98%.

Separating at least 85% of all the H_2 and CH_4 from the raw gas 1 stream to augment the H_2:CO ratio of raw gas 2 stream is highly desired. As a second step, CO_2 separation from sulphur and capturing the sulphur either as organic or sulphuric acid will be desirable.

Cold gas clean-up – wet scrubbing

The cold gas clean-up (CGC) system is the predominant gas treatment technology chosen for UCG in combination with gas engines due to its proven reliability (Balas *et al.*, 2014). For the Africary Theunissen UCG process design, a cyclone in combination with a wet scrubber system can be implemented for power generation. The system will recirculate and cool water to remove the moisture, tar, oil, and particulates by wet scrubbing and may include lime dosing as sulphur adsorbent and pH control (National Lime Association, 2007; Wang, Pereira, and Hung, 2005).

Table II

Post clean-up syngas specifications for FT (Prabhansu *et al.*, 2015; correspondence with several gas engine vendors)

Components/ properties	Limit value
Heavy metals	< 1 ppm_w
Silica	< 0.1 ppm_w
O_2	< 1 ppm_w
Halogens as H-X (HCl *etc.*)	< 5 ppb_w
Alkali metals	< 10 ppb_w
Soot/dust/solids	< 1 ppm_w
Tars and aromatic components	< 1 ppm_w
Nitrogen compounds, including NH_3, HCN, and amines	< 10 pp_{bc}
Sulphur (including H_2S and organic sulphur)	< 5 ppb_w
CO	> 30%
H_2 +CO	> 60%
Wet gas dew point	H_2O: saturated at syngas temperatures up to 50°C

Table III

Gas engine fuel gas specifications (Prabhansu *et al.*, 2015; Balas *et al.*, 2014; Scheibner and Wolters, 2002; correspondence with several gas engine vendors)

Components/ properties	Limit value
Sulphur	< 1 200 ppmv
Hydrogen sulphide equivalent	< 1 500 ppmv
Total sulphur compounds	< 57 mg/MJ or 2000 mg/10kWh
O_2	< 2% v
C4 and higher	< 2% v
H_2	< 40% of total LHV
Gas humidity	< 60%
Wet gas dew point	> 15°C below gas temperature
Silicon and siloxanes	< 0.56 mg/MJ or 0.2 mg/10kWh
Chlorine equivalent	< 3.5 mg/MJ or 400 mg/10kWh
Ammonia	< 1.5 mg/MJ or 55 mg/10kWh
Oils and tar	< 1.19 mg/MJ or 5 mg/10kWh
Particulate matter (soot, dust, ash)	< 1–3 µm and < 0.8 mg/MJ or 50 mg/10kWh
Calorific value (CV)	4.7–7.6 MJ/ Nm^3
Temperature	< 40°C
Pressure	< 200 $mbar_g$

Conceptual use of vortex technologies for syngas purification and separation

To minimize the wet scrubbing thermal penalty for FT, Africary will utilize a dual-stage cooling process, whereby the syngas will be cooled to approximately 150°C in the first stage before being introduced to the warm gas desulphurization (WGD) system. A portion of this syngas will be used as the fuel gas stream and further wash-cooled in a second stage to 80°C. An additional trim water cooler will ensure that the fuel gas meets gas engine vendor requirements of < 40°C (Clarke Energy, 2016 personal communication). Wet scrubbing technology is considered the norm and state-of-the-art, as it deals with most of the condensable liquids and particulates. However, it only removes portions of the gaseous contaminants and does not perform any gas separation, and will therefore have to be used in conjunction with a separate acid gas removal (AGR) system. Further cooling of the syngas in the AGR system may reduce the temperature to as low as –62°C (the condensation point of chilled methanol) and the syngas must be heated afterwards.

Warm gas clean-up

Warm and hot gas cleaning technologies are attractive to avoid cooling and reheating of the gas stream as required for CGC. Existing technologies for gas cleaning at warm temperatures (< 300°C) include cyclones, candle filters (for removing solid contaminants), molecular sieve membranes (for gas separation), and sorbents (for removing sulphur-containing compounds (RTI LLC, 2018).

Molecular sieves

Carbon molecular sieve membranes are in development for the separation and purification of hydrogen from syngas. The potential benefits of high-temperature gas separation and membrane reactor processes are substantial; however, commercialization still remains elusive. A major technical barrier is the lack of robust inorganic membranes and full-scale modules that are suitable for use at the high-temperature and high-pressure conditions required (Parsley *et al.*, 2014). According to a supplier, hydrogen seems the most suited for gas separation with molecular sieves; however, the gas must be free from all sulphur-containing compounds, making it infeasible for raw syngas processing.

Candle filters

Despite decades of research with metallic filters (Sharma *et al.*, 2008), the materials have achieved only limited commercial success due to a natural correlation between porosity, mechanical strength, and thermal conductivity. Increasing the porosity of the material to increase the filtration area leads to a decrease in mechanical strength. This is a fundamental limitation for candle filters. An increase in the porosity increases both the filtering rate and surface area (m^2/g), but decreases the mechanical strength and thermal conductivity and accelerates the corrosion rate.

Significant improvements in candle filters have been achieved in the past few years (Prabhansu *et al.*, 2015); however, the reliability of these systems has never been successfully tested in a commercially integrated gasification-based system environment. From the literature (Swanson and Hajicek, 2002; Guan *et al.*, 2008), it is evident that most candle filters have operated for only a short period of a few thousand hours at 400°C, although they last much longer at lower temperatures of around 285°C (Scheibner and Wolters, 2002) in a coal gasification environment. Even the use of exotic state-of-the-art metals and ceramics has provided only limited success. The failure of candle filters after a short period of operation leads to an uneconomical plant availability factor and higher operating cost than for CGC and they are therefore not widely used.

Warm-temperature candle filter technology deals with most of the particulates; however, it removes only a portion of the contaminants and does not remove any condensable liquids or alkali metals, nor does it perform gas separation, and it will therefore have to be used in conjunction with a separate AGR and CGC wet scrubber system.

Hot gas clean-up

Supersonic gas separation

A theoretical approach by Sforza, Castrogiovanni, and Voland (2012) shows that supersonic gas separation (SGS) has promise as a robust method for hot separation of fuel species (CO, CH_4, and H_2) from H_2O, CO_2, and H_2S obtained from coal-derived syngas. They performed calculations based on general Lurgi-based gasification syngas input (31 atm., 450°C and 210 000 Nm^3/h) (Sforza, Castrogiovanni, and Voland, 2012) for a concept that performs segregation by condensation of some of the gases.

This process is illustrated in Figure 1. A particulate-free, hot, wet syngas enters a chamber with an arrangement of static blades or wings, which induce a fast swirl in the gas. Thereafter the gas stream flows through a Laval nozzle, where it accelerates to supersonic speeds and undergoes a pressure drop to about 30% of feed pressure. Supersonic isentropic expansion results in a rapid decrease of temperature (–80°C to –115°C) and pressure, leading to the sequential condensation (and/or solidification) of H_2O, CO_2, H_2S, NH_3, HCN, and COS, which form a fine mist including some liquid hydrocarbons (Secchi, Innocenti, and Fiaschi, 2016) like ethane, propane, and butane. The mist droplets agglomerate to larger drops, and the swirl of the gas causes cyclonic separation.

The dry gas, consisting of H_2, CO, N_2, CH_4, and Ar, continues through the separator, while the liquid phase, together with some slip gas (about 15% to 30% of the total stream), is separated by a concentric divider and exits the device as a separate stream. In the final section both streams are diffused back to subsonic conditions; the gas is slowed down and about 50% to 80% (Netušil and Ditl, 2012) of the feed pressure and temperature (depending on application) is recovered.

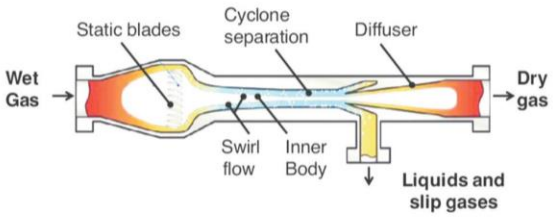

Figure 1—Schematic diagram of the supersonic gas separator for natural gas dehydration (Netušil and Ditl, 2012)

Conceptual use of vortex technologies for syngas purification and separation

Such mechanical separators have no moving parts and a very small environmental footprint. However, the commercial use in drying natural gas from wells that inherently provide gas at very high pressures and modest temperatures is far different from the hot syngas cleaning proposal of Sforza, Castrogiovanni, and Voland (2012). In practice, the presence of any particulate matter in syngas travelling at supersonic speeds will result in a high probability of erosion, and further problems like hydrate plugging, flow rate inflexibility, and narrow turndown ratio (Haghighi, Hawboldt, and Abdi, 2015) have been reported. Furthermore, Netušil and Ditl (2012) stated that a 27.6% pressure loss is required for a separation efficiency of 90% moisture and > 50% for > 95% separation, showing diminishing returns for deep cleaning and recompression of the syngas might be required.

Condensing diverse gas mixtures into sizeable drops for accumulation and separation remains commercially untested, but Theunissen *et al.* (2011) proposed a rotational particle separator device to assist nucleation to reach the required size for cyclonic separation (> 15 µm).

Ranque–Hilsch vortex tube

The RHVT is a mechanical device with no moving parts that separates ambient temperature compressed gas into hot and cold streams. The gas emerging from the 'hot' end can reach temperatures of 200°C, and the gas emerging from the 'cold' end can reach –50°C. Pressurized gas is injected tangentially into a swirl chamber and accelerated to a high rate of rotation. A conical nozzle at the end of the tube allows only the outer shell of the compressed gas to escape at the hot end, while the remainder of the gas returns in a smaller inner vortex within the outer vortex towards the cold end.

The working principle (see Figure 2) can be approximated as follows (Xue, Arjomandi, and Kelso, 2013).

(1) The adiabatic expansion of the incoming gas cools the gas and turns its heat content into kinetic energy of rotation while the total enthalpy is conserved.
(2) The outer rotating gas flow moves towards the hot end outlet. The kinetic energy of rotation allows for friction and turns into heat by the means of viscous dissipation, and the temperature of the gas rises to higher than that of the incoming gas.
(3) A portion of the gas exits at the cold outlet and obeys the traditional notion (the Joule-Thompson effect) in that temperature drops with a decrease in pressure.
(4) Heat is transferred between the quickly rotating outer flow and the opposite, slowly rotating, smaller internal axial flow, allowing for heat transfer from the cold to the hot vortex. A zone of no mixing exists between the two, allowing separation based on temperature.

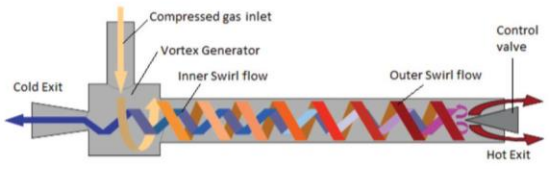

Figure 2—Flow structure inside a Ranque-Hilsch vortex tube (Netušil and Ditl, 2012)

The literature shows (Linderstrom-Lang, 1964, 1966) that partial separation of the components of a gas mixture occurs when it is passed through a RHVT. Marshall (1976) confirmed this effect using different gas mixtures and different sizes of tubes. He also studied the effect of reduced inlet and outlet pressures and found that if the outlet pressure is substantially below atmospheric, the separation factor is higher than the predicted correlation he derived (Marshall, 1976). This suggests that the performance can be improved by operating the vortex tube at vacuum pressure, which is also described further in the VGS technology description and indicates that the cut 'θ' at which the peak separation appears was generally at about 0.4, but varied for different settings between 0.2 and 0.6 (Wikipedia, 2018). This means that a RHVT can generally double the feed percentage of light species to the light side and double the heavy species to the heavy side. However, as a pure separation system the RHVT had poor performance and could only achieve an α value of approximately 1.025, indicating a very low separation efficiency. This led to more focused research on the heat separation capability of an RHVT than on the gas species separation capability.

In the late 1990s renewed interest in the technology was shown, with more focus on cryogenic air separation for space transportation and new work yielded a promising 80– 85% oxygen enrichment with a recovery in the 30–36% range (Binau, 1997), but also poor results using an oversized RHVT (Spracklen, 1998). Balepin, Rosshold, and Petley (1999) claimed that the best performance for air separation occurred with a 68% O_2 concentration, with a 38% recovery factor and highest concentration of 85–90% O_2 but with only a 7–10% recovery factor.

Kulkarni and Sardesai (2002) studied the application of a RHVT to enrich the methane concentration in gas from production wells. The experiments conducted on separating CH_4 from N_2 confirmed that gas separation does occur in a vortex tube. The inlet pressure was found to be the most dominant factor affecting separation, and the maximum separative power attained was $5.5 \times 10^{+7}$ kg.mol/min.

Farouk, Farouk, and Gutsol (2009) simulated temperature, pressure, mass density, and species concentration fields within the vortex tube and found that even though a large temperature difference was obtained, only minuscule gas separation occurred due to diffusion effects. An investigation of the correlations between velocity, temperature, and species mass fraction revealed that the inner core flow has a large Eddy heat flux and Reynolds stresses that adversely influence the gas separation efficiency. Dutta, Sinhamahapatra, and Bandyopadhyay (2011) supported this finding, and observed that although the separation of air into its main components (oxygen and nitrogen) occurred, the separation effect was very small and the process of species separation was driven mainly by Soret diffusion. It is, however, notoriously difficult to separate streams like air, where the components have very similar molar mass densities. The accurate measurement of O_2 and N_2 concentrations is also difficult to manage and may require specialized set-up and calibration conditions.

More recent research has indicated encouraging performance for a RHVT. Chatterjee, Mukhopadhyay, and Vijayan (2017) developed and published a one-dimensional

mathematical model that can compute mass transfer based on inlet pressure, temperature, inlet concentration and flow rate and outlet pressure, temperature, and flow rate. This model can be used for rapid design and simulation of species separation in an RHVT. The model considers simultaneous heat and mass transfer in a RHVT. A set of experiments was carried out with three vortex generators of different capacities to validate the mathematical model. Using the largest unit at a flow rate of 0.26 m^3/s the oxygen concentration was boosted from the normal 21% to almost 28% for an $\alpha > 1.45$ with recovery in the 10–15% range. If this performance can be repeated with a feed stream containing species with large variation in molar mass, then the level of separation may well be in the commercial application range for a UCG flow scheme; where the pressure has to be let down anyway and a slight increase in temperature could easily be accommodated by the trim cooler.

Brand and Esterhuyse (2018) conducted similar experiments with air using a commercial RHVT. Their results, as shown in Table IV, indicate that separation of air occurred, but the calculated error of ±3% limits the accuracy of the measurement. Each sample was run twice, and the averages are reported in Table IV. The control sample of atmospheric air was run eight times, while a 95% confidence interval was used to determine an error of ±3%. The gas chromatograph used could measure the N_2 content of a sample with an accuracy of ±0.1%; however, O_2 and Ar were combined in a single measurement.

The first samples taken (C1 and H1 at 25% cold side flow) provide the expected O_2 decrease at the cold side (±0.5%) and increase of O_2 at the hot side of about 1.6%. However, the best results of about 2% increase in O_2 at the cold side of the RHVT and about the same increase of ±2% N_2 at the hot side in the second samples, using a smaller 10% flow at the cold flow orifice, was unexpected. This runs counter to the initial assumption that the heavier O_2 molecules will concentrate at the hot end while the lighter N_2 molecules will concentrate at the cold end.

Vortex gradient separation

A vortex gradient separator (VGS) has no moving parts, and a series of guide vanes/static blades induces a fast swirling vortex in the outer gas, surrounding a central core that passes thorough nozzles and diffusers that separate dirty flue gas or raw syngas into three streams (Chentsov, Beloglazov, and Korsakov, 2009). Figure 3 shows a schematic drawing of a VGS.

A dirty gas stream, comprising a mixture of gases, is fed into the inlet parabolic nozzle (1), consisting of sections 'α' and 'β', where the flow is accelerated and the outer gas tangentially accelerated by internal guide vanes/static blades (2). The outer gas flow is accelerated and rotated, while preserving its laminar flow structure by implementing a constant area change (dA/dL), and by steadily increasing the tangential and axial acceleration. The constants for area change are determined experimentally, depending on the gas stream properties (temperature, viscosity, density), but should not exceed Re 100 000. The gas then enters section 'δ', for laminar acceleration in a parabolic nozzle (3), again under constant area change. The gas then enters the vortex diffuser (4), where the rotation is accelerated, while the axial speed is decreased to perform initial separation. This separated gas is then again axially and tangentially accelerated in a paraboloid nozzle (5) and finally fed to a separation diffuser (6), a concentric divider where the stream is cut into light (7), medium (9), and heavy fractions (8).

The laminar vortex induces a higher pressure at the periphery, which allows heavy gas components such as sulphur dioxide to accumulate and collect in layers and the solid particles to coagulate in the centre (Figure 4) (Korsakov, 2010). Thus, it becomes possible to remove heavy acidic and toxic gas components with the simultaneous withdrawal of any suspended particles and vapour from a dirty gas source.

Chentsov, Beloglazov, and Korsakov (2011) described the gas dynamic flow formed in the VGS as 'fast rotating' with 'negatively-strained intermolecular bonds' with the following qualities. (1) The available kinetic energy (the molecular-kinetic motion of the gas molecules) is constrained. (2) The suspended particles transported by the gas are concentrated in the central zone of the channel in the form of a dust 'core'.

Table IV

Results for the RHVT air separation test (Brand and Esterhuyse, unpublished work)

Sample number	O_2 (mol.%)	N_2 (mol.%)	Total (mol.%)
Control (air)	22.3	75.9	98
C1	21.8	76.0	98
H1	23.9	77.0	101
C2	24.1	75.9	100
H2	22.8	77.6	100

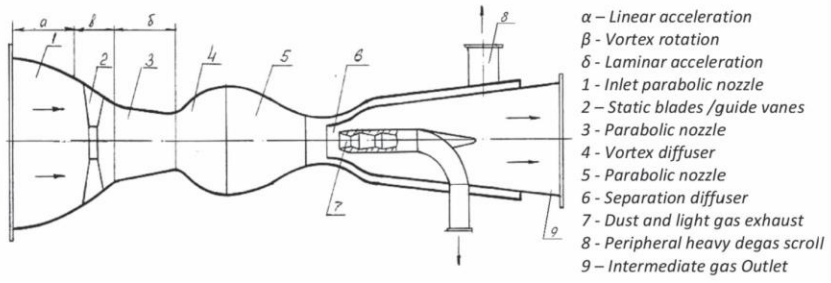

Figure 3—A typical vortex gradient separator (Chentsov, Beloglazov, and Korsakov, 2009)

Conceptual use of vortex technologies for syngas purification and separation

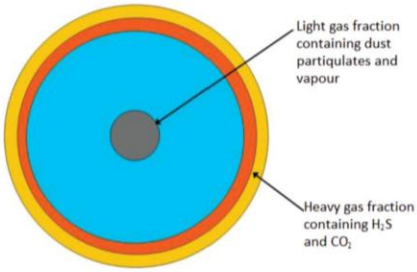

Figure 4—Cross-section of the gradient separator channel showing density variation (Korsakov, 2010)

Dust and aerosols are transported into the core from the rotating gas volume with the smaller size particles closer to the centre. (3) The VGS divides a gas mixture into its molecular components, based on their molecular weight and density, in the cross-section of the swirling channel, and the heavier gas components (like SO_2, CO_2, *etc.*) are distributed and collected in the peripheral zone.

In fluid dynamics, a negative pressure gradient, also called an *adverse pressure gradient* (APG), occurs when the static pressure increases in the direction of the flow. This is mathematically expressed as $dP/dx > 0$ for a flow in the positive x-direction. This is achieved by over-expanding a compressed gas into this 'negatively-strained' state. Gas in this state has many features that do not fit into the traditional molecular-kinetic theory, as the gas is basically flowing 'uphill' in the direction of the high pressure. This has an important impact on boundary layers, as increasing the fluid pressure is akin to increasing the potential energy of the fluid, leading to a reduced kinetic energy and deceleration of the gas while preventing laminar separation.

The principle observations associated with gas flow in an APG are (Korsakov, 2010):

1. In an APG, an axial gas flow accelerating in a converging nozzle *maintains its laminar structure* while transforming its potential energy into a laminar vortex.
2. If two streams containing dispersed dust particles in the 'over-expanded state' intersect, then the *particles transfer to the jet with the highest velocity*.
3. If a high-velocity gas stream travels over a large stationary gas volume separated by small slots, this *large stationary gas volume acts as a 'sump' for suspended particles*.
4. The *thermal conductivity of the gas rises sharply*. The thermal conductivity of air is usually 0.030–0.035 W/mK, but for air in a negative-stressed state it increases 10 000-fold to 340–420 W/mK. Rank's effect also becomes more pronounced, *i.e.* the effect of the temperature distribution over the channel cross-section, decreasing the temperature in the centre of the channel cooler while increasing it at the periphery.
5. The *heat transfer coefficient also increases* 100-fold (gas to the separator wall) from the usual range of 20–60 W/m²K, to 2500–3000 W/m²K.

The first two effects mentioned can be observed in nature where a 'dust devil' forms a funnel-like chimney that sucks dust particles into the centre of a vortex. A numerical simulation by Gu *et al.* (2006) based on an advanced dust-devil-scale, large-eddy simulation model verified that the horizontal inflow vortex could entrain solid particles and carry them into the vertical swirling wind field. Another trend identified was for the fine dust grains to rise along the inner helical tracks, while the larger dust grains were lifting along the outer helical tracks.

CFD modelling (Chentsov, Beloglazov, and Korsakov, 2011) shows the formation of a stable central vortex entering the separator nozzle. The peripheral rotation was estimated at around 3000 r/min, while the rotation around the core reaches 100 000 r/min.

The Russian student website Studopedia (n.d.) provides insights into the working principles of the VGS as follows. An APG provides an inertial seal by increasing the strain of the gas to provide a contracting laminar vortex. This allows the density of the stream to increase towards the centre axis and to exceed the relative particle density. This allows any particulates to float on the gradient flow surface, creating a constant dust layer in the centre of the VGS channel.

Arguably the most detailed description of the principles of the VGS was published by Moiseev *et al.* (2016a). The focus of this paper was on separating less than 0.5% methane from a mine ventilation gas flow by recovering the methane in concentrations of up to 80%. The authors further explain that the separation of the gas and dust flows within a VGS occurs towards the axial direction, due to the generation of several vortices including countercurrent flows, with sharp decreases in tangential velocity as can be seen in Figure 5. The CFD studies of a methane-dust-air mixture revealed the following features (see Figure 5) (Moiseev *et al.*, 2016a).

1. A near-axial flow is swirled around the central axis and moves along it in the shape of a twisting and narrowing core.
2. A peripheral flow is swirled around the central axis (in the shape of a spiral) and moves more slowly down the axis of the gradient separator, resulting in the presence of a counter-return flow.
3. Pulsation occurs due to the high tangential velocity and radial pressure drop, resulting in cooling of the central/axial gas flow and heating of the peripheral flow, thus providing for the simultaneous concentration of lighter components.
4. Thermal energy fluxes result due to micro-cooling cycles of radial turbulent flows.

Inertia vacuum filter

The same APG principles that are used to separate dust particles and light gases in the VGS can also be used as a filter mechanism to filter micrometre-sized particulates from a gas. Moiseev *et al.* (2016b) evaluated an inertia vacuum filter (IVF) for removing particles from coal mines ventilation air. The unit was designed to clean a volume of 200 000 Nm³/h, using 500–570 kW/h. The particle removal efficiency was about 99.8% with the minimum size of the collected particles being 1 µm. In this device, gas containing dust particles is sucked/vacuumed through an accelerating nozzle (stream A in Figure 6).

Conceptual use of vortex technologies for syngas purification and separation

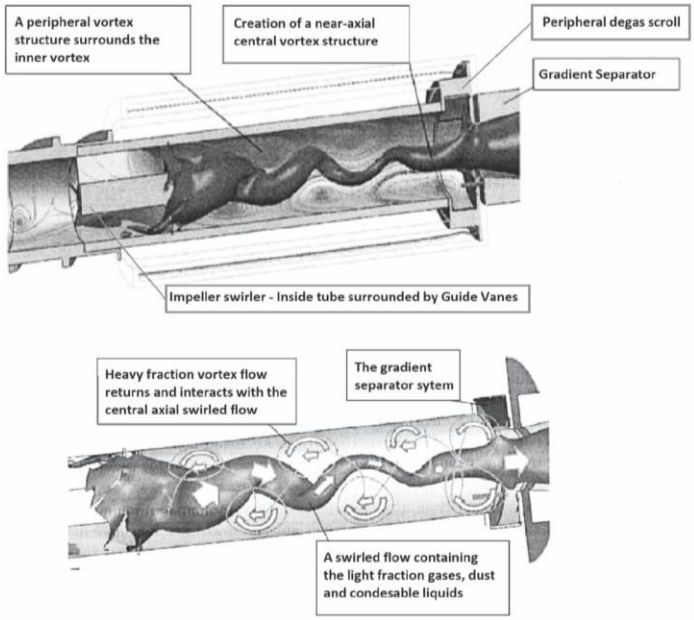

Figure 5—CFD model (Moiseev *et al.*, 2016a) showing the same countercurrent vortex formation as described for RHVT (Dutta, Sinhamahapatra, and Bandyopadhyay, 2011)

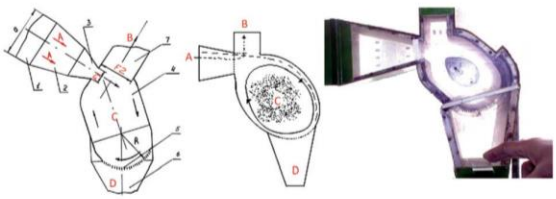

Figure 6—Schematic illustration of the principle of an inertia vacuum filter (Chenysov *et al.*, 2009; Korsakov, 2010)

The area 'F1' of the accelerating nozzle is smaller than the cross-section of the exit 'F2' and the velocity of the gas increases and expands in this section as the gas goes into an AGP state. The dusty input stream passing through the cross-section of F1 has a greater velocity than the stream in the cross-section of F2 and therefore the particles in this stream also have a higher velocity (greater kinetic energy), which allows them to overcome the drag force of slower exiting stream B (as the suspended matter from the two intersecting jets will be captured by the jet that moves fastest). This allows for two jets of APG gas to intersect and for the output stream to permeate the inlet stream with its particles and for the suspended particles to become trapped inside the circulating stream C.

While the two-phase gas circulates inside the rotary chamber (4), it passes over a precipitation grille (item 5 in Figure 6). This process creates an aerodynamic trap whereby particles can enter the rotary chamber of the device, but cannot exit and eventually settle in the collecting chamber (6). The gas circling the rotary chamber also becomes a highly efficient filter, consisting of layers of gas acting as layers of filtering material. About 2–3% ultra-fine particles may accumulate in the rotating C stream, but eventually they also coagulate and fall into the collecting chamber.

Chentsov, Beloglazov, and Korsakov (2009) successfully tested a VGS combined with an IVF at the Ekibastuz coal power plant that removed fly ash with a particle size of 5–100 µm. The installation had a capacity of 15 000 m³/h and was equipped with measuring equipment with a measurement accuracy of ±0.1 g. Forty-five tests were carried out with up to –35 mbar vacuum, which achieved filtering of up to 99.25% of all particles, and with the latest upgrades operating at 99.99%. Korsakov (2010) stated that the installation had been in operation for 4 years. Chentsov and Barsukov (2011) also tested an IVF device was at the Pavlodar power station boiler. Here, the device placed between the second stage economizer and the air pre-heater and achieved 65 to 70% dust removal down to 1 µm.

Characteristics of vortex separation for UCG

Several dusty and wet syngas clean-up technologies have been considered for raw (wet and dirty) UCG syngas at different implementation temperatures, and these are summarized in Table V.

The incorporation of HGC based on vortex gas separation with IVF may provide both particle separation and gas separation directly from a UCG production well. The advantages of such a hot, wet, and dirty gas clean-up system in combination with RTI's Warm Gas Desulfurization process can provide for efficient syngas clean-up for clean coal power generation. This process can further be combined with deeper acid gas removal, and control of the carbon to hydrogen ratio may allow the efficient blending of syngas produced by different UCG operating regimes to supply a cost-effective FT syngas for polygeneration operations.

Conceptual use of vortex technologies for syngas purification and separation

Table V

Comparison of raw syngas clean-up technologies proposed for UCG

Temp.	Type	Advantages	Disadvantages
Cold	Wet scrubbing	Mature. State-of-the-art and widely used. Removes all liquids, tars, solids. Adsorbents can remove all acid gases to ppb level. Low pressure drop.	Expensive, generates waste water, and has poor energy and thermal efficiency. Reheating of syngas required. Large environmental footprint.
Warm	Cyclone	Cheap. Modest pressure drop. Works well to remove large particles.	Cannot remove ultra-fine particles or liquids. Prone to fouling. No gas separation.
	Candle filter	Can remove very-fine particles from dry gas.	Poor reliability. Cannot remove or tolerate tars and liquids. No gas separation. Expensive and uses exotic materials. Moderate pressure drop.
	Molecular sieve	Can separate clean gases. Can commercially separate H_2 and CO_2.	Very low sulphur tolerance. Requires very clean and dry gas.
Hot	RTI's WGD	Removes sulphur compounds at high temperature. Can tolerate and remove minor trace metals and particulates. Low pressure drop.	All liquids must be removed below the operating dew point. Cannot remove CO_2 or condensable liquids.
	SGS	Commercialized for NG separation. Removes acid gases to % level. No moving parts. Possible removal of liquids, tars, solids.	May be damaged by particles. Can foul quickly. Not experimentally proven on syngas.
	RHVT	Cheap. No moving parts. Modest separation of light species from heavy species. May provide cooling/heating option.	May be damaged by particles or liquids. Can foul quickly. Moderate pressure drop. May create additional cooling or heating demand. Very low separation factor and gas must be cascaded and recompressed for high separation values. Not commercially tested as a separation device.
	VGS	Removes all liquids, tars, solids. Separates light species rom heavy species. Separates acid gases and light gases to % level. High separation factor. Commercially tested.	Modest vacuum compressor demand. Requires independent verification of published results.
	IVF	Can remove ultra-fine particles. Low pressure drop. Commercially tested.	May foul quickly from liquids. Modest vacuum compressor demand. No gas separation. Requires independent verification of published results.

Proposed UCG application

A conceptual novel UCG gas clean-up and separation unit design based on a VGS, cleaning raw syngas directly from the UCG production well is proposed. The concept will allow the hot and efficient separation of syngas into its useful components, together with partial cleaning for further gas utilization. As the UCG production well is pressurized the use of an axial flow pressure regulator will be required. This device must control the upstream flow in such a manner that the downstream compressors can vacuum the gas and allow the implementation of an APG of about 50 mm H_2O over the vortex separator and the filters. This modest vacuum requirement implies that the syngas well pressure is not reduced and that the power demand is kept relatively small compared to the total production plant requirements.

In a second step (see Figure 7) the incoming gas is separated and an initial vortex created by a stationary guide vane. The addition of a portion of recycled pure gas by a cyclone injector will impart significant tangential velocity to the outside of the incoming raw gas.

In a third step/chamber, the spinning gas will be allowed to intersect with the central dusty core (as described in the CFD studies), which will allow the transfer of dust to the central axial flow of light gases (mainly H_2 and CH_4), to be removed by the dust exhaust in the 'particle separation' step. This gas may be cooled with a steam-generating heat exchanger to protect the downstream vacuum compressors. Before the cooled gas is fed to the compressors it is passed through an IVF system or a CGC wet scrubbing system that will remove any condensable liquids and dust. This washed light fraction will be used for H_2:CO ratio control in the FT process.

In a fourth step the vortex speed is increased by internal guide vanes, which increases the pressure and density of the gases and allows the heavier molecular gases to move to the periphery, where they are removed by an inverted cyclone. The gas may be cooled to generate process steam and to protect the downstream vacuum compressors. Literature sources indicate that this heavy gas stream can be passed through a second-stage smaller VGS to separate the very heavy sulphur components from the CO_2. The sulphur components will be routed to a sulphur recovery plant and the CO_2 may be further processed on site.

The remaining cleaned gas (also called 'pure gas') is passed through the high-temperature booster-compressor, where a portion of the gas is recycled in the second step.

Although the proposed system may clean the syngas only partially it may still be reasonable to implement, as the removal of 99.9% of the particulates as well as acid gas will allow the use of smaller downstream equipment and guard beds instead of large process equipment.

Conclusions

The effectiveness and carbon efficiency of UCG can be improved by hot cleaning raw syngas directly from the UCG production well. The proposed vortex separation hot gas clean-up concept will allow for the removal of most of the particulates, together with the efficient separation of the syngas into its useful components, providing for acid gas removal and H_2:CO ratio control. The most important principle for vortex separation is the preservation of laminar flow allowed by the adverse pressure gradient. Other technical and economic advantages may include, but are not limited to:

Conceptual use of vortex technologies for syngas purification and separation

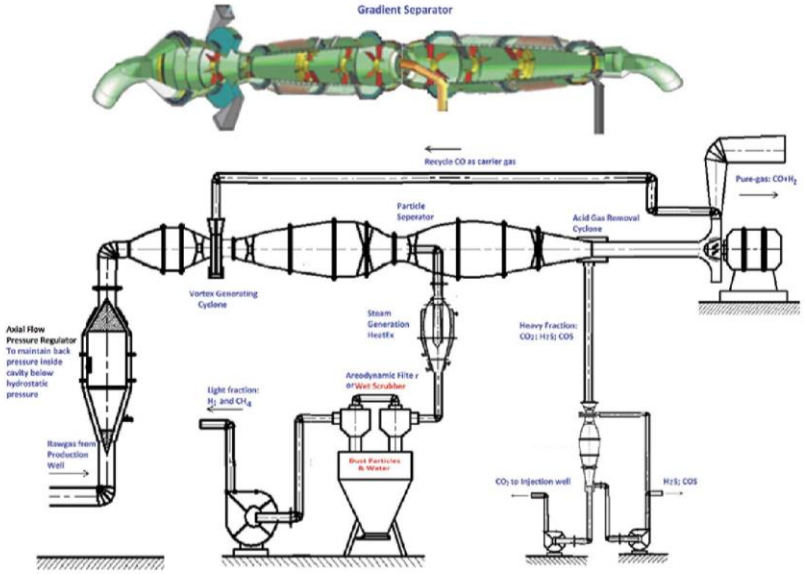

Figure 7—Diagram showing a proposal for hot gas clean-up of raw syngas from a UCG production well in several steps [adapted from Chenysov, Beloglazov, and Korsakov, 2009; Korsakov, 2010)

- Removal of most of the condensable water, oils, tars, fly ash, and particulate matter directly from the hot syngas, allowing hot gas processing and pressure boosting.
- Removal of most of the H_2S and CO_2, allowing for cheaper warm syngas desulphurization combined with guard beds, rather than low-temperature adsorption processes.
- Separation of H_2 from a second syngas stream for H_2:CO ratio adjustment before FT and negating the need for a CO-shift rector with a subsequent CO_2 avoidance.

The level of separation is in the commercial application range for the Theunissen UCG project as the syngas typically contains species with large variation in molar mass and the syngas pressure of the second stream used for power generation has to be let down anyway. Vortex separation specifically applied to a UCG process, is a practical solution to improve both energy efficiency and lower the CO_2 footprint.

The next steps and future work will include the modelling, design, and experimental testing of a VGS for both particulate filtering and gas separation efficiency.

Nomenclature

AGR	acid gas removal
APG	adverse pressure gradient
atm.	atmospheres / pressure ratio
CFD	computational fluid dynamics
CGC	cold gas clean-up
FT	Fischer-Tropsch
GC	gas chromatograph
HGC	hot gas clean-up
IVF	inertia vacuum filter
$N1$	mole fraction of heavier species at the inlet
$N2$	mole fraction of heavier species at hot outlet
$N3$	mole fraction of heavier species at cold outlet
PM2.5	< 2.5 µm particulates
PM5	< 5 µm particulates
PM10	< 10 µm particulates
Re	Reynolds number
RHVT	Ranque–Hilsch vortex tube
SGS	Supersonic gas separation
UCG	underground coal gasification
VGS	vortex gradient separation
WGC	warm gas clean-up
α	separation factor for light species between product and feed streams $= [(1 - N3) \div N3] \times [N2 \div (1 - N2)]$
θ	cut = molar flow in product stream (hot outlet) ÷ $N1$

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8 ECONOMIC OVERVIEW OF A TWO-AGENT PROCESS FOR UNDERGROUND COAL GASIFICATION WITH FISCHER–TROPSCH BASED POLY-GENERATION.

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Clean Energy Journal, Volume 3, Issue 1, March 2019, Pages 34–46.

Summary

Underground Coal Gasification (UCG) is a mining-gasification process that produces synthesis gas from in situ coal by injecting air (or oxygen and steam) and extracting the produced gas via boreholes. The resulting synthesis gas ('syngas') produced by UCG can be used directly as a fuel-gas or deep-cleaned to produce many other products like chemicals, liquid fuels, hydrogen and synthetic natural gas. UCG has significant environmental, safety and practical advantages over conventional coal mining and utilisation, foremost being cost and emissions reductions.

Facilities of an industrial-scale Fischer–Tropsch (FT) process have been operating in South Africa for decades on coal-to-liquid and gas-to-liquid conversion. Oxygen-blown UCG produces syngas, which contains a mixture of carbon monoxide (CO) and hydrogen, and these molecules can be conditioned to serve as feed for synthetic-crude-oil ('syncrude') conversion technologies based on the FT process.

African Carbon Energy (Pty) Ltd. (Africary) completed a study integrating its UCG technology with a mini gas-to-liquids plant. Syngas from Africary's Theunissen Underground Coal Gasification (TUCG) project will be used for power production and synthesis of liquid fuels in a unique poly-generation configuration. The TUCG process will consist of two parallel gasifiers, operated on different agents, making the component parts of UCG and CTL tightly linked and interdependent, but reducing both cost and emissions.

UCG offers a lower capital investment to conventional underground mining and surface gasification due to the removal of the surface gasifier and coal-mine operations. The gas clean-up systems will remove undesirable components from each gasifier and blend the cleaned syngas for H_2:CO ratio control and provide the implementation of carbon capture and sequestration. This study has minimised the complexity and optimised the process flow to provide own-use electricity and about 2 000 barrels/day fuels and 200 ton/day LNG at a capital cost estimate (2017) of about $ 350 million and operating cost of around 28 $/barrel.

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PERSPECTIVE

Economic overview of a two-agent process for underground coal gasification with Fischer–Tropsch-based poly-generation

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Abstract

Underground Coal Gasification (UCG) is a mining-gasification process that produces synthesis gas from *in situ* coal by injecting air (or oxygen and steam) and extracting the produced gas via boreholes. The resulting synthesis gas ('syngas') produced by UCG can be used directly as a fuel-gas or deep-cleaned to produce many other products like chemicals, liquid fuels, hydrogen and synthetic natural gas. UCG has significant environmental, safety and practical advantages over conventional coal mining and utilization, foremost being cost and emissions reductions. In South Africa, facilities of an industrial-scale Fischer–Tropsch (FT) have been operating for decades on coal-to-liquid and gas-to-liquid conversion. Oxygen-blown UCG produces syngas, which contains a mixture of carbon monoxide (CO) and hydrogen, and these molecules can be conditioned to serve as feed for synthetic-crude-oil ('syncrude') conversion technologies based on the FT process. African Carbon Energy (Pty) Ltd. (*Africary*) completed a study integrating its UCG technology with mini gas-to-liquids plant. Syngas from Africary's Theunissen Underground Coal Gasification (TUCG) project will be used for power production and synthesis of liquid fuels in a unique poly-generation configuration. The TUCG process will consist of two parallel gasifiers, operated on different agents, making the component parts of UCG and coal-to-(any product) (CtX) tightly linked and interdependent, but reducing both cost and emissions. UCG-CtX offers a lower capital investment to conventional underground mining and surface gasification due to the removal of the surface gasifier and coal-mine operations. The gas clean-up systems will remove undesirable components from each gasifier and blend the cleaned syngas for H_2:CO ratio control and provide implementation of carbon capture and sequestration. This study has minimized the complexity and optimized the process flow to provide own-use electricity and about 4000 barrels/day equivalent fuels at a capital cost estimate (2017) of about US$ 350 million and operating cost of around 28 US$/barrel.

Key words: underground coal gasification; Fischer–Tropsch; coal to liquids; gas to liquids; CCS; UCG; FT; LNG; CtX; economic study; South Africa

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Introduction

Underground Coal Gasification (UCG) is a mining method that utilizes gasification to produce gas from *in situ* coal (underground in the coal seam) by injecting combinations of air, oxygen, steam and carbon dioxide (CO_2) as gasification agent into coal seams and extracting the product gas to the surface via boreholes. UCG is a high-extraction mining method operating at least two boreholes (also referred to as wells) that are drilled horizontally into the coal seam parallel to one another. The agent is delivered into the coal seam via one borehole (the *injection well*) and the coal is ignited in order to start the gasification process of converting coal to gas.

UCG may also be thought of as a thermo-chemical mining process, as the gasification front results in high temperatures (>1000°C) that cause the hydrocarbons contained in the coal to effectively reform into a flammable gas. At these temperatures, the carbon (C) and moisture in the coal react with the oxygen to form a combustible hydrocarbon-rich syngas mixture of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4). The syngas flows towards the second borehole (the *production well*), whilst ash and other remnants from the mined coal source remain underground in the gasifier. The syngas can be used to produce heat, electricity, chemicals, liquid fuels, hydrogen and synthetic natural gas.

In a previous publication [1], the authors highlighted that South Africa is facing an energy crisis where its net maximum generating capacity of ±42 GW (85% coal-based) is characterized by an ageing fleet that underperforms environmentally against new legislation. About 75% of Eskom's (the principal national electricity provider) capacity is over 40 years old and set to be decommissioned, starting in 2019 (see Fig. 1). The average energy availability factor of the ageing Eskom fleet fell below 80% [2] in 2017, leaving a growing economy with almost zero operating margin and renewed load shedding and increased risk thereof.

The decommissioning of 28 GW of coal power capacity requires the integration of a 20% industrial-scale renewable energy penetration by 2040. South Africa thus requires a substantial increase in open-cycle gas turbine (OCGT) and combined-cycle gas turbine (CCGT) implementation at an estimated cost for incorporation of R 0.48/kWh [4] (±US$ 0.03/kWh), over and above the energy cost as conventional coal cannot attain the quick ramping rates required for such a system, and will increase carbon emissions. Furthermore, the country does not have an available domestic gas supply for the OCGT and CCGT systems, as the Mozambique import industry is fully constrained [5]. It is assumed that the future supply of gas will be imported as liquefied natural gas (LNG) or possibly produced from unproven shale gas [6] with UCG mentioned as a long-term domestic gas alternative [7].

Simultaneously, the planned upgrading of South African oil refineries to produce Euro-5-specified fuels has been delayed until 2021, after the Department of Energy (DOE) initially set the deadline for the introduction of the Clean Fuels 2 (CF2) program (initiated by the DOE) for mid-2017. The government and petroleum industry reached a stalemate on how refiners would be able to recoup the estimated US$ 4.6 billion facility upgrade cost [8]. CF2 regulations stipulate that sulphur levels in petrol and diesel must be kept below 10 parts per million (p.p.m.) and, for the old refineries, it makes more economical sense to shut them down than comply. The DOE published concerns about increases in petroleum-product imports due to the potential shutdown of the nation's existing refineries as the import capacity of the country is currently limited at 10 billion litres and the new capacity will only be available from 2023 (see Fig. 2).

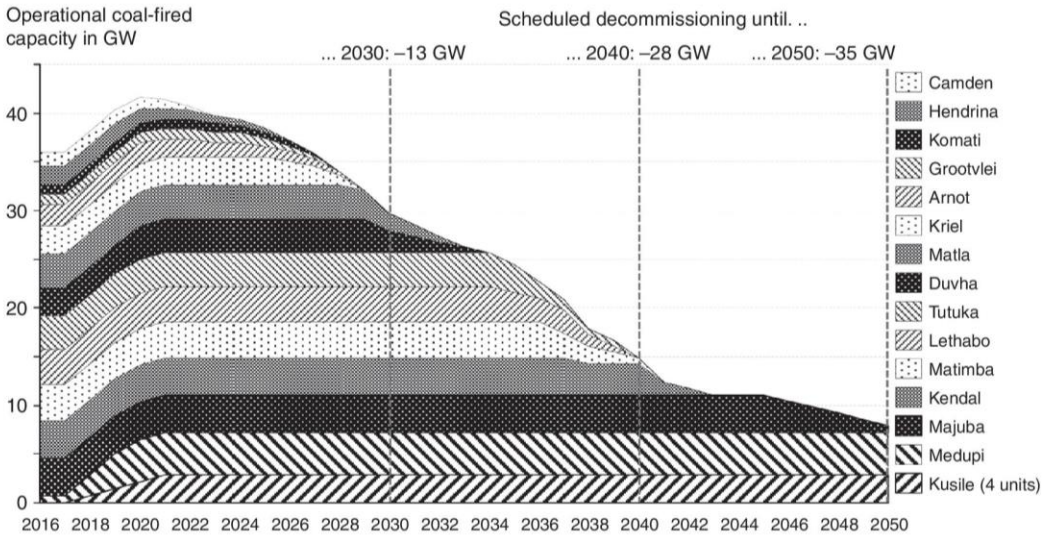

Fig. 1 South Africa is scheduled to decommission 28 GW of coal power plants by 2040 [3]

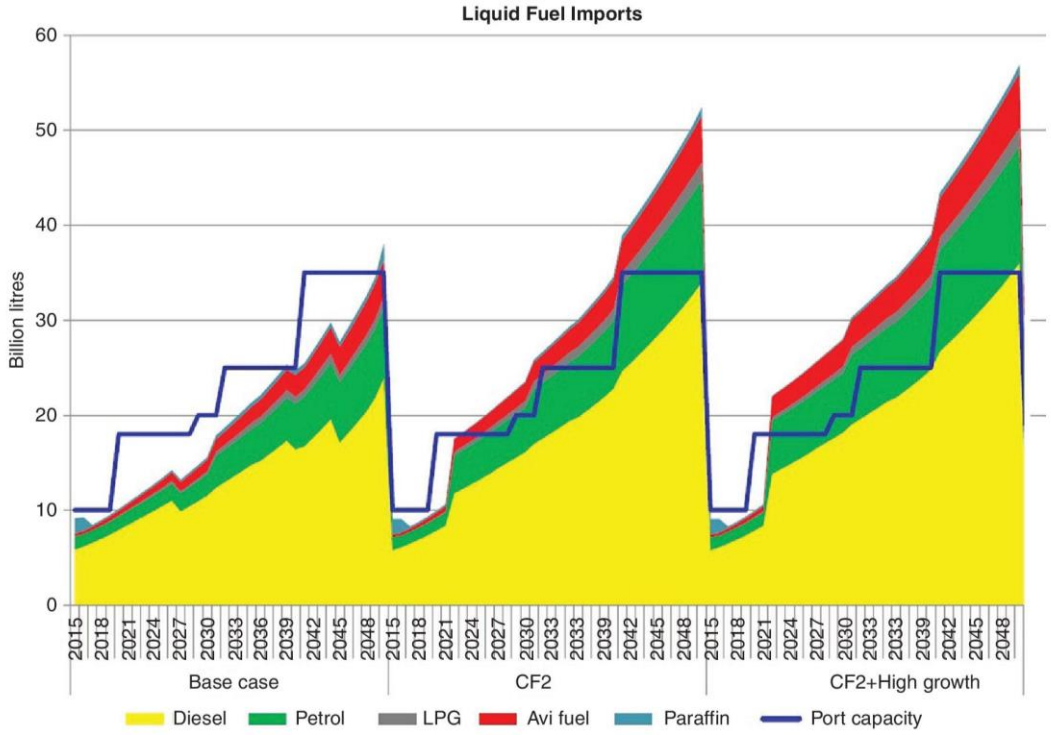

Fig. 2 DOE forecast of implementing the CF2 programme [9]

Growth in demand, combined with coal-quality deterioration and a looming shortage of oil-refined products, has resulted in a critical energy crisis for South Africa. The scale of infrastructure investments required to fill the demand is too large for Eskom and the refineries to carry alone. This is where South African private company Africary's Theunissen Underground Coal Gasification (TUCG) coal-to-(any product) (CtX (X = power, chemicals, liquids or gas)) project [1] could be a breakthrough solution for independently produced electricity, liquid fuels, hydrogen and natural gas in a poly-generation configuration. Industrial-scale Fischer–Tropsch (FT) facilities (>160 000 bbl/day (barrels of oil (or its equivalent) produced per day)) have been operating for decades in South Africa at both Sasol with coal-to-liquid (CtL) and at PetroSA for gas-to-liquid (GtL), whilst Eskom has operated a pilot UCG site since 2007 [10]. Thus, the implementation of coal gasification in combination with FT technologies is not new to the country and its legislators.

A common definition of the FT process is that of a set of catalytic reactions, which are used to convert syngas into predominantly straight-chain hydrocarbons [11]. Chemically, FT can be described as the associative adsorption of CO and splitting of the C-O bond, whilst the dissociative adsorption of two H_2 molecules will transfer hydrogen to the oxygen to yield water (H_2O). Desorption of H_2O will also transfer two H^+ to the C to yield CH_2 chemically described as: $CO + 2H_2 \rightarrow (CH_2) + H_2O$.

During FT, the length of the carbon chain can be controlled by using different catalysts at different temperatures, pressures and H_2:CO ratios. Alkane formation is favoured by a high H_2:CO ratio and a strong hydrogenating catalyst, and is chemically described as: $nCO + (2n+1)H_2 \rightarrow CnH_{2n+2} + nH_2O$.

Alkene formation occurs at a low H_2:CO ratio and in the presence of a weaker hydrogenating catalyst, chemically described as: $nCO + 2nH_2 \rightarrow CnH_{2n} + nH_2O$, whilst the water-gas-shift reaction occurs in the presence of a high quantity of iron (Fe) catalyst (and low cobalt (Co) or ruthenium catalyst); it is helpful to adjust the H_2:CO ratio and reduce the amount of water produced, but then produce more CO_2, chemically described as: $CO + H_2O \rightarrow CO_2 + H_2$.

It is important to note that a wide spectrum of liquids is produced containing carbon chains form C1 all the way up to C50. A standard FT product distribution is shown in Fig. 3.

The first commercial FT plant was piloted in 1936, with several commissioned soon thereafter to provide Germany and Japan with synthetic fuel during the Second World War followed by China piloting plants from the 1940s through to the 1960s. The US Bureau of Mines developed a two-stage high-temperature FT system, whilst Sasol piloted both high- and low-temperature processes for the production of petrol and waxes, respectively. The former was expanded on in the 1970s due to the increasing oil prices [13].

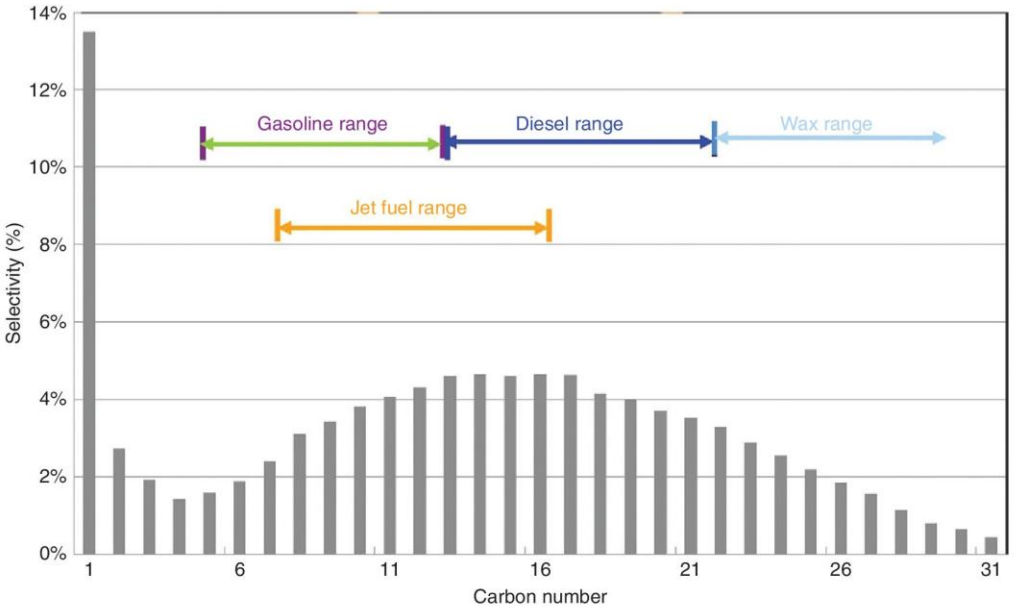

Fig. 3 Typical high-temperature FT product distribution [12]

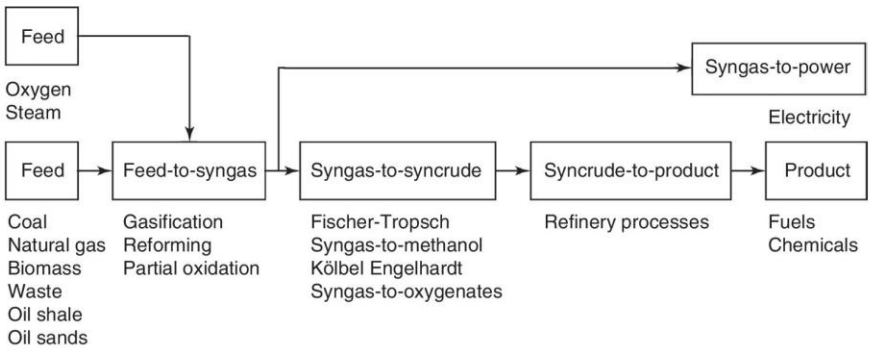

Fig. 4 Indirect (feed-to-syngas) liquefaction process for feed-to-liquids (XtL) and feed-to-power (XtX) conversion [15]

According to de Klerk (2011), the processes of CtL and GtL conversion can be divided into three steps: feed-to-syngas conversion, syngas-to-syncrude/wax conversion and syncrude/wax-to-product conversion. FT synthesis is not the only industrial technology available for syngas conversion but, together with syngas-to-methanol conversion [14], it remains the most relevant in the world today. Fig. 4 shows a simplified block flow for an indirect liquefaction process for feed-to-liquids (XtL) conversion and the production and refining of the syncrude into final marketable products.

UCG has been extensively studied and reported on [16, 17] and the combination of UCG with GtL for diesel and jet fuel production has been successfully trialled (from 2009 at Chinchilla by Australian Linc Energy), based on an FT demonstration plant designed by Hildebrandt and Glasser [18]. The combination of UCG and GtL by Linc Energy is said to be a world first and could have led to Australia becoming one of the world's major suppliers of liquid hydrocarbons, claiming UCG-GtL to be the cleanest, commercially viable implementation of CtL [19].

1 Product and market opportunities for CtX in South Africa

South Africa is facing a serious refinery quality problem, further exacerbated by poor reliability due to the age of the existing coastal import and refining infrastructure as well as the depletion of feedstocks of coal for CtL (Sasol) and natural gas reserves for GtL (PetroSA and Sasol Gas). Without domestic supply, South Africa will be import-dependent in an environment with volatile oil and currency markets. Therefore, the primary driver for CtX will be energy security rather than power generation and chemicals. In line with these drivers, the focus of Africary's CtX will be ultra-low-sulphur diesel (ULSD (with less than 10 p.p.m.

sulphur)), using technology provided by CompactGTL [20]. Since CH_4 and H_2 are available in the tail-gas, some of this will be converted to LNG with the option of producing Cryo-Compressed Hydrogen for the fuel-cell market.

UCG-derived ULSD with LNG and electricity production can partially alleviate some of the energy supply pressure by transporting it to different provincial hubs and even piping syngas directly to industrial end users. Additionally, the gasification and FT process itself requires large quantities of both electricity and steam that can be made from waste gases (vent, tail, purge and off-gas), further reducing demand. Some of the refinery low-grade/off-spec liquid fuel may also be considered as a peaking fuel, enabling a power plant to operate during peak hours.

UCG syngas derived from an air-blown gasifier is the lowest capital cost process for syngas production, but results in nitrogen (N_2) dilution and a low calorific gas of typically 5–7 MJ/m³. This low calorific value (CV) gas is difficult to transport or sell as a commodity, but is rather utilized locally as fuel-gas for heat or power generation. Therefore, the UCG syngas produced by Africary for FT will be based on producing high CV value gas based on two gasification agents consisting of $CO_2 + O_2$ and/or $H_2O + O_2$ [21].

UCG may yield pyrolysis products that contain valuable chemicals, for example light oil, tar, phenol, benzene and naphthalene [14]. The feed-to-syngas conversion step also creates the opportunity for chemical-co-production, the foremost being methanol. The advantage of methanol is that it can act as a single product for fuel, solvent, antifreeze and chemicals, and is well suited for ammonia (NH_3) and methyl tertiary-butyl ether (MTBE) production. However, methanol reaction is thermodynamically equilibrium-limited, requiring a high partial pressure of H_2 and CO, and it requires a very precise H_2:CO ratio to operate optimally. Wax/ULSD synthesis, on the other hand, is less sensitive to the H_2:CO ratio, is not equilibrium-limited and can operate with lower partial pressures of H_2 and CO [22].

It is important to note that the liquids and chemicals that can be produced in a CtX facility are not only limited to those from the FT synthesis. The separation and recovery of CO_2 during syngas cleaning and conditioning will be utilized in the UCG system, but pure CO_2 may also have value as a chemical. The cryogenic Air Separation Units (ASUs) can also produce N_2, argon (Ar), neon (Ne), krypton (Kr) and xenon (Xe) as by-products, with N_2 readily being converted by ammonia synthesis. Water, oil, tar, hydrogen sulphide (H_2S) and ammonia may also be recovered during syngas cleaning.

Chemicals may fetch higher prices than liquid fuels but may suffer from small local and even global market segments and can require complex plant integration. The scope for chemicals recovery from modular and relatively small-scale (± 2000 bbl/day) facilities is therefore rather limited and may not be cost-efficient for mini-GtL. Taking all the above into account and considering many alternative technologies, an Africary study [21] proposes the poly-generation of mainly ULSD, in combination with LNG and minimal grid-based electricity sales, provides the lowest complexity and integration. The ideal TUCG plant will consist of:

- oxygen-blown gasification;
- two parallel UCG reactors operating on two different agents, alternatively optimized for FT and power generation;
- modular two-stage FT with maximum CF2-compliant ULSD and least by-product production of naphtha and liquefied petroleum gas (LPG);
- CO_2 utilization/sequestration by using it as gasification agent;
- zero liquid effluent design, i.e. no waste water by using steam as gasification agent;
- minimized electricity production for own use with flexible grid sales provided by modular 2 MW gas engines;
- tail-gas converted to LNG sales with optional H_2 production.

2 Description of TUCG syngas

The representation in Fig. 4 does not do justice to the complexity of preparing feed for indirect liquefaction. All syngas-production technologies involve some form of partial oxidation but, irrespective of the feed, the syngas-production technology must meet the syngas requirements of the syngas-to-syncrude conversion technology. Syngas generally comprise the following gases: CO, H_2, CH_4, CO_2 and H_2O. For Africary's TUCG project [1], the syngas contaminants generally include particulate matter, water vapour, condensable hydrocarbons (i.e. oils and tars), sulphur compounds, nitrogen compounds, alkali metals (primarily potassium and sodium) and hydrogen chloride (HCl). The sulphur compounds and CO_2 are usually removed by various adsorption-based Acid Gas Removal (AGR) systems, whilst separating the H_2 and CH_4 from the fuel-gas stream to augment the H_2:CO ratio of the syngas to FT stream is highly desired. A deep scrub to remove most of the CO_2 and all sulphur components to parts per billion (p.p.b.) allows the so-called 'pure-gas' to be efficiently transformed in an FT reactor to liquid fuels. These syngas clean-up systems have been discussed and even new novel alternatives were proposed by the authors in a separate publication [23].

As a rule of thumb, one aims for a H_2:CO ratio of around 2 in the 'pure' syngas [14]. The exact H_2:CO ratio that is required depends on the FT technology catalyst, pressure and temperature, and the tail-gas management philosophy. The H_2:CO ratio can also be adjusted during syngas conditioning but this requires complicated additional equipment and utilities. The advantage of UCG is that it can extract the maximum energy from the *in situ* coal and bring it to the surface, but with the flexibility to operate on different gasification agents. Therefore, the TUCG project will operate two gasifiers in parallel (see Fig. 5). The first 'gasifier'

will have O_2 and steam as gasification agent to produce a high H_2-ratio syngas that is ideal for FT. The second 'gasifier' will have O_2 and CO_2 as gasification agent to produce a low H_2-ratio syngas suitable as fuel-gas. About a quarter of this stream will be used as fuel for power generation, whilst the remaining will be compressed to be utilized in a sour Shift-Reactor to generate H_2 to be mixed/blended with 'unshifted' gas and the FT syngas from the first gasifier.

In a previous publication [24], the authors concluded that both the effectiveness and the carbon efficiency of UCG can be improved when applying CO_2 gasification by recycling waste-captured CO_2 as gasification agent. The most important reaction during such a gasification method is the reduction process, also known as the Boudouard Reaction, where $CO_2 + C \rightarrow 2CO$ above 850°C. CO_2 gasification as applied to UCG becomes a practical solution to both improve carbon efficiency and lower the CO_2 footprint. The technical advantages of the CO_2 agent are:

- a 43% CO_2 reduction by converting CO_2 to CO;
- the *in situ* CO_2 capture (carbonate formation) on active mineral components like Ca and Mg contained in the mine's roof, floor and coal strata;
- a 22% reduction in coal mined to produce the same amount of syngas energy.

This blended, compressed and shifted gas is further processed in an AGR unit to remove all sulphur, CO_2 and trace components. After gas clean-up, the 'pure-gas' with an H_2:CO ratio of 2.0 will be transformed by the FT process to produce about (± 2000 bbl/day) of syncrude, reaction water and tail-gas. The tail-gas will be further processed for methane separation to produce (about ± 2000 bbl/day equivalent of) LNG and a hydrogen pressure swing absorption (PSA), to produce 99.95% pure H_2 for direct feed to the refinery, recirculation to the FT block and/or retail sales. To minimize utilities and effectively manage effluent streams, the integration of the two gasifiers and the power station becomes essential, as all waste water is made into steam agent for one gasifier, whilst CO_2 is utilized as agent for the other gasifier. The remaining tail-gas and many other collected off-gas and purge-gas streams will be used for power generation in modular gas engines.

The liquid-fuel products produced by the refinery must follow both the CF2 specification and the FT technology vendor requirements; therefore, removal of HCN, NH_3, Hg, Sb, Sn, sulphur compounds, metals, halogens (Cl and F) and several other trace components is required [21, 23]. For Africary's TUCG-CtX design, the pure-gas product specification to feed FT is defined in Table 1.

3 Pure-gas-to-syncrude conversion

There are basically three FT types that produce syncrude commercially. They are iron-based high-temperature FT (Fe-HTFT), iron-based low-temperature FT (Fe-LTFT) and cobalt-based low-temperature FT (Co-LTFT) (see Fig. 6). Syncrude compositions that are representative of each type are given in Table 2. Within each type, there is variation caused by reactor technology, operation, catalyst, catalyst deactivation and tail-gas management systems. Consequently, the selection of a catalyst and reactor technology combination is not straightforward, with each providing different advantages. Ultimately, the aim is to produce a specific syncrude yield that provides the most efficient conversion to the desired product slate and the lowest number of unwanted by-products.

Depending on the products desired and the type of catalyst used, FT can be classified as either high- or

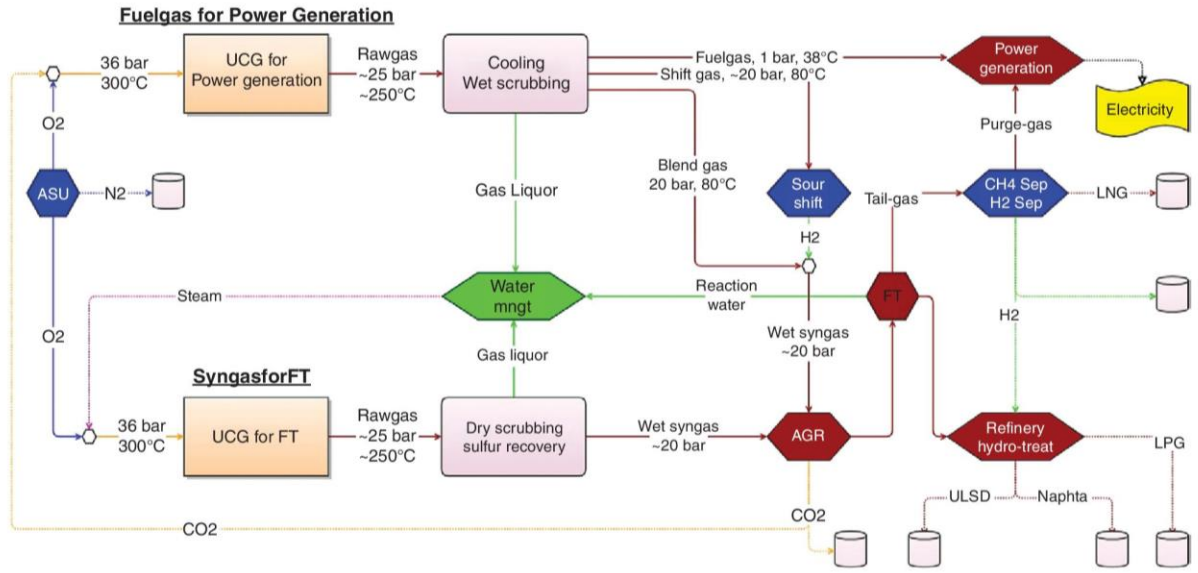

Fig. 5 Two UCG reactors to produce two feed streams optimized for CtX [21]

low-temperature [14]. High-temperature FT (HTFT) typically occurs between 300 and 350°C, where the cobalt catalyst produces mainly C1, i.e. methane (refer to Fig. 3), whilst an iron-based catalyst with alkali promoters mainly produces petroleum-spectrum hydrocarbons, with light olefin and oxygenates as by-products. Low-temperature FT (LTFT) typically occurs between 200 and 250°C, and mainly produces heavier hydrocarbons and waxes, which are further upgraded to produce the final products such as naphtha and diesel. Recently, the wax itself has also become a commercially sought-after product.

Table 1 Post clean-up syngas specifications for FT [21, 23]

Components/properties	Limit value
Heavy Metals	< 1 p.p.m.$_w$
Silica	< 0.1 p.p.m.$_w$
O_2	< 1 p.p.m.$_w$
Halogens as H-X (HCl, etc.)	< 5 p.p.b.$_w$
Alkali metals	< 10 p.p.b.$_w$
Soot/dust/solids	< 1 p.p.m.$_w$
Tars and aromatic components	< 1 p.p.m.$_w$
Nitrogen Compounds including NH_3, HCN and amines	< 10 p.p.b.$_v$
Sulphur (including H_2S and organic sulphur)	< 5 p.p.b.$_w$
CO	> 30%
H_2 + CO	> 60%
Wet-gas dew point	H_2O: saturated at syngas temperatures up to 50°C

The Africary flowsheet optimization strives for minimum capital cost and therefore the FT system will be optimized to produce maximum ULSD, whilst minimizing naphtha formation and making no or little LPG. A refinery will further hydro-crack/hydro-treat the waxy syncrude and produce CF2-specification diesel and naphtha. Each product will be stored in separate containers in a bulk loading facility to fill road tankers for transport of final products to customers.

Africary's CtX design reflects the anticipated South African market for 2019, but some flexibility was incorporated into the design to allow small future deviations. The modularity of the UCG and the FT units and refinery design may also be exploited during future implementations in order to respond to changes in product pricing and to continue optimizing the product slate for maximum income. The UCG syngas has several benefits over other sources of CtX, as the syngas is utilized at the point of production (the coal mine) without the need for complex storage, coal transportation, bulk handling, blending, ash handling, etc. If required, the UCG reactor can be operated to maximize methane production and the implementation of CO_2 sequestration by using it as agent is well understood.

Another key unlocking factor for UCG is its ideal size-fit with modular, small-scale FT. Mini-GtL was enabled by advancements made in catalysis and micro channel reactors. Some of the key design considerations by Africary for deciding on a Mini-GtL FT vendor are:

- the need to have an ASU prior to gasification;
- the pressures and temperatures of the UCG raw syngas and the possible requirement of additional compressors or heat exchangers before downstream conversions;
- sensitivity of the downstream conversion processes to variation in syngas composition, specifically the H_2:CO ratio;
- range and quality of products and the capital cost to make 'on-spec' products for the South African market, including the storage and transportation of the products;
- the level of complexity in plant configuration and operations of rural UCG sites far from service providers and markets as well as handling of waste effluent.

Taking into account the identified product and market opportunities and differences between low- and high-temperature FT, the Africary TUCG project decided to incorporate the FT technology provided by CompactGTL (CGTL).

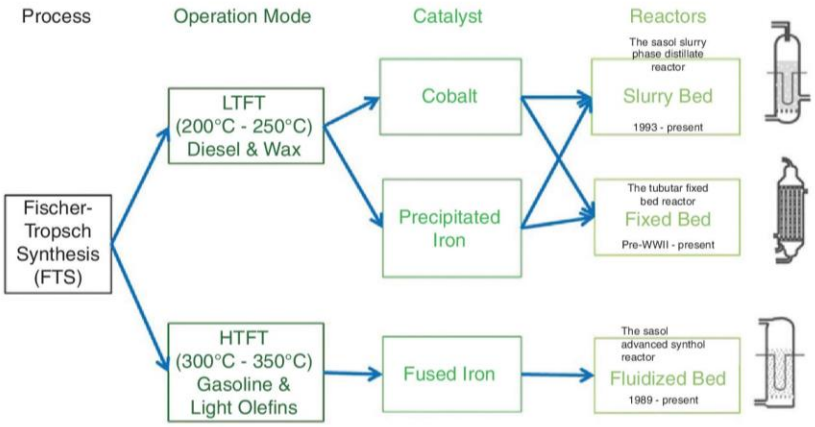

Fig. 6 FT-synthesis technologies utilized commercially [12]

Table 2 Comparing the different FT technology product composition slate [14, 21]

		Different FT compositions (mass%)			
Product slate	Carbon range	Fe-HTFT	Fe-LTFT	Co-LTFT	Africary Co-LTFT + LNG + H_2
H_2	C0				2
LNG	C1				33
Ethane	C2				23
Tail gas	C0–C2	23	6[a]	7[a]	Sum above = 58
LPG	C3–C4	24	8	5	4
Naphtha	C5–C10	33	12	20	4
Distillate	C11–C22	7	20	22	31
Residue/wax	C22+	3	50	45	Included as Distillate
Aqueous product	C1–C5	10	4	2	3

[a]Tail-gas reformed and recycled to FT feed for increased liquid production.

The nature of the CGTL Co-LTFT syncrude product (with its predominance of straight long-chain paraffin) renders it as an ideal feedstock for upgrading to a high-quality diesel. This diesel has a high Cetane value and effectively has no aromatics or sulphur and can be derived from a relatively conventional mild hydro-cracking process [21].

CGTL employs a proprietary compact modular FT system, which comprises two stages of reaction in series, for longer catalyst life and higher plant availability. CGTL's technology incorporates plate–fin heat exchangers as the structure for its FT reactors. This allows the precise control of heat and gas flow over the process catalysts, located in a regular array of thousands of closely spaced 'mini-channels'. CGTL inserts its catalysts directly into these plate–fin heat exchanger channels (3–10 mm across) to support very high specific heat transfer coefficients between the process streams and provide high 'voidage'. This enables thermally stable catalytic reactions to be achieved at production rates not attainable in conventional larger reactor designs, hence reducing the size of the reactors substantially, whilst maintaining high productivity levels [20].

This reduction in size allows high volumetric production rates for C5+ components with relatively low methane make and high levels of thermal control, operability and reliability. The reduced size of the reactors allows modularization to enable fitting within road/rail transportable containers. The cooling system employed by CGTL employs pressurized water and each reactor module has independent temperature control so that production can be optimized on a reactor skid basis. This allows the operation of individual reactor skids to be optimized to reflect different activities and prevents the situation in which the production of the entire facility is governed by the limits of the most aged catalyst. CGTL also facilitates module replacement for catalyst change-out on a rolling programme, which lowers the operating cost for the facility.

The FT tail-gas consists of the unreacted syngas plus the majority of the lighter (C1–C4) hydrocarbon components generated in the FT reactors. One of the optimizations incorporated in the UCG-CtX design was for the removal of the conventional tail-gas recompression and steam-reforming unit. The tail-gas is rather separated into its component streams of LNG and fuel-gas (see Fig. 7). Although this decision drastically reduces the usual ±90% syngas-to-liquids transformation to about 40%, South Africa has a scarcity of natural gas and a high demand for LNG, which is only available at a premium compared to the oil price. The FT tail-gas stream will be cooled for H_2 recovery as Cryo-Compressed Hydrogen, LNG recovery and the possible recovery of additional C3–C4 (LPG) components. This implementation allows the direct sales of LNG, whilst high-purity H_2 is required to meet the continuous demand for the Syncrude Upgrading Unit/Refinery and the intermittent demand to the FT activation skid [19]. The generation of electricity from the lower-valued scrubbed tail-gas will be utilized for own consumption and possible sale to the grid.

4 Synthetic crude upgrading/refining

The Africary design consists of the modular first- and second-stage FT reactor skids (see Fig. 7) and the product cooling and separation system (including the final separator for the tail-gas, syncrude and reaction water). The liquid hydrocarbon from the CGTL FT system is 'waxy' in nature and sent to the upgrading reactor. This reactor consumes H_2 in a fixed trickle-bed (containing multiple beds of different catalysts) to crack the syncrude. The selection of the different catalysts will depend on the desired product properties and is influenced by the relative selectivity between hydro-cracking and hydro-isomerization. In Africary's case, the focus is to maximize the conversion yield into CF2-specification diesel and associated stabilized synthetic naphtha. The cracked syncrude is fed to a steam stripper column where wild naphtha and light-end components are removed as off-gas. Naphtha is drawn off from the column overheads, whilst diesel is drawn off part way down the column, cooled and transferred to storage. LPG contained in a 'wild light naphtha' will be available as liquid fuels.

The functional specification must comply with the South African Bureau of Standards for petroleum, SANS 342 Automotive diesel fuel [25] compatible and with the proposed CF2 equivalent to Euro-5 emissions standard

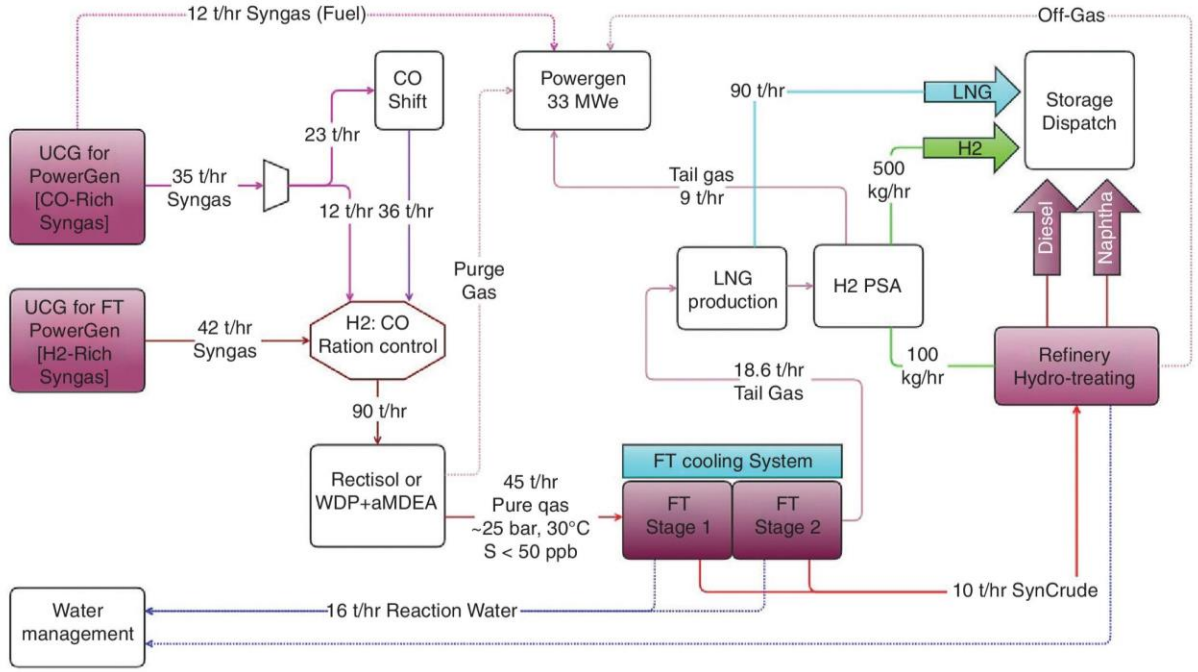

Fig. 7 TUCG syngas-to-liquids process layout [21]

Table 3 CompactGTL estimated synthetic hydrocarbon product properties [21]

Parameter	Units	Diesel	Naphtha
Standard density @20°C	kg/m^3	764	678
Sulphur	p.p.m.$_w$	Nil	Nil
Nitrogen	p.p.m.$_w$	Nil	Nil
Reid vapour pressure	kPa (abs)	<10	<50
Cloud point	°C	–5 (max)	–
Flash point	°C	55	–24
Lower heating value	MJ/kg	43.6	44.3
Cetane number	–	75	–

with cold flow properties as per Class C. However, because of its chemical composition, the density specification of GtL-derived synthetic diesel (see Table 3) is lower than the minimum density requirement of the European diesel specification (EN 590) and the current SANS 342 specification. The slightly lower density value of synthetic diesel does not change the operating efficiency of a diesel engine and may be used 'as-is'; however, it may also be used as a high-quality blend stock for a crude-oil-derived diesel. This long-standing South African practice of blending the two diesel stocks will benefit both blend stocks (by improving the sulphur content and CV value of the one and increasing the density of the other) and allows the blended diesel product to be sold at a slight premium.

Several studies have linked fuel density to particulate emissions [26, 27]. It has been shown that reducing fuel density can lead to a significant reduction in particulate emissions and that less dense fuels tend to reduce NOx emissions as well. Aside from emissions, density also directly affects an engine's power output [28], with less dense fuels usually leading to a reduced power output. However, Africary's ULSD has a higher CV value/Cetane value and therefore compensates amply for the 4.5% reduction in density.

Since the operation of the Upgrading Unit is set to maximize the diesel yield, there are limited degrees of freedom to control the naphtha quality. The naphtha co-product from the upgrader is characterized as light naphtha. The Reid Vapour Pressure <50 kPa specification will allow for safe storage and transport; therefore, this will be marketed as a low-sulphur heating fuel in the lamp oil/illuminating paraffin market. Several other by-products are also produced, as highlighted in Table 4.

5 UCG-CtX financial analysis

For UCG-CtX, the main economic drivers are capital and licencing cost, land access, feed cost (coal, electricity and water) and the logistics cost of transporting the product to the market. Some products also have a negative price associated with a disposal cost or tax (like brine, sulphur, CO_2 and grey water) and this becomes an important factor in determining the CtX economics. To minimize its impact, the Africary design actively pursues using by-products like CO_2, off-gases and grey water as UCG and power feedstock.

Table 4 Secondary products from FT and upgrading/refining [21]

Product	Description
Wild naphtha	Produced as distillate product in the stripper column. Contains light naphtha (C5 and C6) components and some LPG components and will require pressurized LPG storage. Utilized as a liquid fuel on site
Syncrude flash gas	Includes the non-condensable gases and light hydrocarbon vapours recovered during the flash stabilization of the high-pressure syncrude
Purge and vent gas	Consists of the H_2-rich high pressure purge-gas stream for the Hydrocracker reactor circuit
Stripper off-gas	This gaseous fuel stream will contain H_2 and some C3–C4 components
Reaction water	A big penalty of the FT process is the production of reaction water. About 35% of the syngas mass flow ends up as reaction water containing less than 1% hydrocarbons. This water will be mixed with the gasification gas liquor for oxidative destruction
Oily water	The refinery removes moisture from the syncrude. This water will be mixed with the gasification gas liquor for oxidative destruction
FT-derived fuel-gas	The FT tail-gas and C3–C4 (LPG) components are left over after downstream processing of extracted H_2 and methane. This is mixed with the purge, vent and off-gas from the whole plant to become the fuel-gas for the power-generation unit

For any investment to be profitable, it will require reasonable profit margins on its products. However, product pricing is never constant and, more importantly, relative product pricing also changes over time. These changes cannot be controlled, but designing the facility for flexibility in response to fluctuations can be incorporated to provide some level of assistance.

Another important consideration is to choose an FT provider that provides a large portion of main product (ULSD) and minimal by-products. On small-scale FT, this becomes crucial, as the small quantities of by-products produced may have a bigger nuisance value compared to its commercial value. During the CtX design, the emphasis is also placed on balancing the carbon efficiency with thermal efficiency, by giving the FT process the first opportunity to transform the hydrocarbons to liquids and thereafter making power or heat from 'difficult to treat' side streams.

The product-price difference between chemicals and fuels can quickly be eroded if the CtX facility is located far from chemical markets. ULSD has a local demand, whereas the LNG and any chemicals must be transported about 200 km to reach the Johannesburg market in South Africa. Furthermore, some chemicals are hazardous and difficult to store and transport, and it may be impractical to sell small batches to remote markets. Therefore, the decision was made to minimize the number of products to be sold by design and utilizing as much as possible internally.

Exporting power is highly regulated and dependent on the local-distribution infrastructure and, therefore, Africary decided that the initial amount of electricity produced should be just enough to cover own use with less than 1 MW for export. For Africary's UCG design, the primary feed for the power station is CO_2-blown syngas mixed with purge, flash, strip and tail-gas, thereby reducing the flare load and boosting the cost-effectiveness of the CtX facility. The main aim of the TUCG-CtX is not power generation but, as an inevitable by-product offsetting demand, it becomes a valuable contributor to the overall cost-efficiency, as a CtX plant has a substantial power demand.

5.1 Capital cost

There is a large capital cost associated with indirect coal liquefaction based on FT synthesis [14, 21, 29] (see Table 5). Although the size of investment is a serious obstacle to widespread commercial interest, CtX can become economical if the capital cost can be lowered and the price difference between all the products and feedstock cost is large enough. From Table 5, it is clear that conventional coal preparation and gasification contribute more than 30% to the capital cost, even before taking into account the cost of utilities, gas cleaning and air separation, which brings the total for non-UCG-based CtL syngas preparation to more than 70% of the capital cost [14].

The capital cost associated with GtL facilities is lower than for CtL, since the conversion of natural gas into synthesis gas is usually less complex. There can be a significant difference in the estimates and cost data on recent and current XtX (feed-to-X (X = power, chemicals, liquids or gas)) or CtX construction projects based on an extreme sensitivity to the complexity, economic climate, products and location [14]. Highlights from the table show that the capital cost associated with the refining of the FT syncrude is small (around 10%) compared to the total capital cost of the indirect liquefaction facility.

The high capital cost has some important implications for a system design. Whilst balancing the carbon and energy efficiency in the rest of the facility, the design must maximize the carbon efficiency in the refinery. Any carbon contained in the FT syncrude has already required 90% of the total capital cost to produce and designing a refinery that leaves syncrude unrefined in order to save on the refinery capital cost makes little sense. Some wax products may indeed be of higher value if not refined, but the market for these are not nearly as accessible as for liquid fuels.

Table 5 Comparing different feed to FT and product technologies [14, 21, 29, 30]

Capital estimates for various technologies				Capital cost distribution (%)						Total ($)
X-to-X technology	Capacity	Capital/unit	Unit	Syngas generation	Gas clean-up CO-shift	ASU	FT synthesis	Upgrading and refining	Off-sites, utilities, etc.	CAPEX (USD)
CtL 1 (2010) [14]	50 000	81 000	$/bbl	30%	11%	21%	23%		15%	4 050 000 000
CtL 2 (2010) [14]	50 000	78 000	$/bbl	42%	15%	17%	26%		NA	3 900 000 000
CtL 3 (2010) [14]	50 000	97 000	$/bbl	30%	17%	17%	18%		18%	4 850 000 000
CtL 4 (2010) [14]	50 000	85 000	$/bbl	37%	20%	10%	17%		16%	4 250 000 000
Oil shale recovery (2010) [14]	50 000	78 000	$/bbl							3 900 000 000
Oil sands recovery (2010) [14]	50 000	66 000	$/bbl							3 300 000 000
SNG (2010) [14]	10 250	230 000	$/bbl							2 357 500 000
UCG horizontal coal (2010) [14]	10 250	58 000	$/bbl							594 500 000
UCG Steeply dipping coal (2010) [14]	10 250	44 000	$/bbl							451 000 000
GtL 1 (2010) [14]	43 000	62 000	$/bbl	47%			15%	9%	29%	2 666 000 000
GtL 2 (2010) [14]	34 000	33 000	$/bbl	30%			15%	10%	45%	1 122 000 000
GtL 3 (2017) [29]	450	122 222	$/bbl							55 000 000
LNG (2017) [29]	82	548 780	$/tpd							45 000 000
Methanol (2017) [29]	124	443 548	$/tpd							55 000 000
CNG (2017) [29]	50.8	314 961	$/MW							16 000 000
Power generation (2017) [29]	19.4	1 288 660	$/MW							25 000 000
UCG to H_2, power and CCS [30]	204 765	5940	$/tpa	4%	40%	11%	0%	3%	43%	1 216 000 000
Africary—UCG-GtX (2017) [21]										**353 850 000**
Africary—UCG to FT (2017)	2000	105 000	$/bbl	4%	12%	4%	19%	10%	10%	210 000 000
Africary—UCG to LNG (2017)	78 000	800	$/tpa					14%	5%	62 400 000
Africary—UCG to H_2 (2017)	3700	1500	$/tpa					2%	2%	5 550 000
Total CtL (bbl equivalent)	4000	69 488	$/bbl							277 950 000
Africary—UCG to power (2017)	33	2 300 000	$/MW	4%	3%	4%			7%	75 900 000

Table 6 Operating-cost estimate for Africary TUCG (2017) [21]

Africary OPEX estimate	Quantity (or oil equivalent to) bbl/day	Cost	Cost (equivalent/bbl)	Unit
Syngas production and processing	5000		2	$/bbl
FT processing	2000		15	$/bbl
LNG +H_2 processing	2000		1	$/bbl
Power generation and its utilities	33 MW	40 $/MW	4	$/bbl
All other utilities/Balance of Plant	5000		3	$/bbl
Overheads	5000		3	$/bbl
Total for Africary CtX			28	$/bbl

For non-UCG XtL, there is a trap in performing incremental economics on an FT refinery, since it ignores the significant capital and operating costs associated with the production of the syngas and syncrude. De Klerk (2011) provides an example of a project not being able to justify spending 10% more to refine naphtha to a motor-gasoline spec, but defends the nine-times spending justification on making the naphtha in the first place. This guideline is, however, somewhat broken by the application of UCG, as it significantly lowers the upfront cost of producing syngas from the 70% claimed by de Klerk (2011) to about 32% and therefore requires careful consideration on which products will be upgraded and to what standard.

The de Klerk (2011) prediction that UCG-based FT would cost around 58 000 US$/bbl in 2010 is comparative with Africary's 2017 total cost of liquid fuels (ULSD + Naphtha + LNG + H_2) for US$ 278 million, producing the equivalent of 4000 bbl/day of product at about 69 000 US$/bbl. At first glance, the cost of 2300 US$/kW for Africary power generation seems high, compared to the values provided in reference [29] for a single large CCGT system. Considering that the Africary greenfield project is remotely situated, with high grid connection costs and the use of lower-efficiency modular 2-MW gas engines operating on what is essentially flare gases, this seems more reasonable.

5.2 Operating cost

The break-even crude oil price for a 50 000 bbl/day CtL facility in 2007 was reportedly around 50–70 US$/bbl [17]. Linc Energy's pilot scale UCG-GtL plant (±2 bbl/day) operated from 2008 to 2013 and its 'reformulated syncrude products' was used to drive a diesel car and fly a corporate jet across Australia. According to analysis released in 2013, a combined UCG-GtL plant could produce ultra-clean fuel for 30 AU$/bbl [31].

Table 6 provides the calculated operating expenditure for Africary and is inclusive of reactor refurbishment, gas-engine refurbishment, labour, routine plant maintenance, and catalysts and chemicals replacements. A strategy for FT reactor change-out is included and provides for spare reactor skids to replace skids removed for refurbishment under a cycle that replaces all reactors over a 4-year period [21].

The total plant operating expenditure of 28 $/bbl also allows for all catalyst replacement for the Synthetic Crude Upgrading Unit with a 3-year catalyst life assumption period and includes an FT royalty payment on a per-barrel basis. The Balance of Plant catalysts and chemicals and power-station maintenance are also included for each unit, as well as the organizational cost for operating personnel and plant maintenance.

6 Conclusions

South Africa is facing an energy crisis where its net maximum generating capacity of ±42 GW (85% coal-based) is characterized by an ageing fleet that underperforms environmentally against new legislation and thus requires a substantial increase in gas-turbine implementation. Furthermore, the country does not have a mentionable domestic gas supply, as the Mozambique import industry is fully constrained and the assumed future supply of shale gas is still unproven whilst the import harbour capacity for LNG has not been approved for construction. Africary's UCG-CtX project could be a breakthrough solution for independently produced electricity, liquid fuels, hydrogen and natural gas. Implementation of both UCG and FT technologies is not new to the country and its legislators as industrial-scale coal-based FT facilities have been operating for decades in South Africa, whilst Eskom has operated a pilot UCG site since 2007.

Integrating two parallel UCG gasifiers (operated on different agents) with mini-GtL to produce mainly Diesel and LNG provides a unique interdependent poly-generation configuration that reduces both cost and emissions. The use of CO_2 as feed for UCG-CtX provides for the implementation of carbon capture and sequestration, thus lowering overall carbon dioxide (CO_2) emissions, whilst the oxidative destruction of reaction water provides steam for the gasification process.

The TUCG process can cost-effectively be combined with a deep acid gas scrubbing to remove undesirable components (especially condensable water, oils, tars, sulphur and inorganic trace elements) from each gasifier and blend the cleaned syngas for H_2:CO ratio control. The scrubbed syngas will supply CompactGTL's FT-synthesis plant, which is at the heart of the conversion process for

liquids from syngas and forms a critical part of the overall design of a cost-effective poly-generation operation.

UCG-CtX offers a lower capital investment to conventional underground mining and surface gasification (due to the removal of the surface gasifier and coal-mine operations). This study has minimized the complexity and optimized the process flow to provide electricity and 4000 bbl/day equivalent fuels at a capital cost estimate (2017) of about US$ 350 million and operating cost of around 28 US$/bbl.

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9 CONCLUSION

South Africa is in the midst of an electricity crisis. A few years ago, Eskom was faced with the choice between spending money on maintenance of old power plants or to divert maintenance funds to the new build Medupi and Kusile projects to bringing them online sooner. Eskom decided on the latter, because if all the new units were operating optimally they would add 9 600 MW of electricity to the grid and relieve supply pressure that will allow it to decommission dirty and old power stations which are expensive to run and maintain.

But widespread corruption, theft, and mismanagement have seen the cost to build Medupi and Kusile increase by more than R 300 billion, and a decade after project kicked-off in 2009 only three units at Medupi and one unit at Kusile are in commercial service [61] and each producing only 600 rather than 800 MW each, with an energy availability factor of around 50%. This places Eskom is in a tough spot as the older plants now need to run optimally, but they have not been maintained properly for years because funds were focused on Medupi and Kusile.

Other long-term energy security challenges for South Africa include:

- Age of Sasol and PetroSA's CTL facilities and high cost of imported liquid fuels based on fluctuating exchange rates and high energy commodity prices;
- Dwindling local gas and coal supply;
- Energy access and affordability for the growing population;
- Mounting environmental concerns (especially with coal and nuclear energy generation);
- Balancing the electricity grid whilst incorporating an increasing proportion of variable renewable energy sources;
- Mounting environmental liabilities caused by defunct mining operations.

9.1 Commercialisation of UCG

UCG as an opportunity arose during a period of energy transition in South Africa, where consumers of fossil fuels are under pressure to reduce emissions significantly and at the same time the country has a commitment to increasing the population's access to affordable energy. Correctly managed, underground coal gasification is an advanced clean coal technology that offers huge potential solutions for the country's challenges, as it has the capacity to cost-effectively and cleanly liberate vast coal resources in the country that currently cannot be economically exploited using traditional mining technologies. UCG offers a considerable degree of flexibility making it the ideal gas load-following method to complement variable renewable energy.

For more than a decade, the promotion of UCG research and implementation of projects helped to establish several fundamental foundations for future industrialisation in SA.

Starting at Sasol Mining in 2006, several studies were initiated to describe and design the possible implementation of projects and to progress UCG to a full-scale implementation. An experimental UCG design with various operating parameters verified the gasification model kinetics.

Numerous studies praise UCG as an environmentally safe mining method. Furthermore, the 2008 Sasol presentation showed that UCG will improve the economic viability of future CTL as this novel gasification method will beat the limitations of conventional mining and surface gasification, and open doors to new opportunities. UCG is a proven technology with manageable product properties and environmental performance. UCG is a natural technology choice for incorporation into FT to provide a viable alternative to crude oil.

This thesis presented the challenges faced to industrialise the technology in general and explain the history of UCG development in SA and potential advantages that Africary's Theunissen underground coal gasification project. From a national view, the formation of the SAUCGA was critical. This non-profit organisation has played a vital role in bringing the major industry players together in combining efforts to promote the technology and to jointly address legalities, policy requirements and any government involvement to grow the industry. The association also provides a service to the public by supporting university research and development activities and engaging the public and any interested or affected parties in annual conferences.

Another aspect that was addressed for local implementation was the management of groundwater during UCG and to support the industrialisation of the technology and the incorporation of internationally and peer-reviewed fit-for-purpose groundwater monitoring standards for a commercial UCG operation was documented.

The importance of water and the environmental impact that specific operations may have on groundwater necessitate that standardised monitoring and rehabilitation programmes be adopted. The UCG plant operation, however, has to be performed in an environmentally responsible manner. In SA, shallow groundwater (borehole-water) is potable and can be consumed by humans and livestock without treatment. Thus, as it is from a natural source, groundwater cannot adhere directly to the specifications of SANS 241-1, and therefore the study recommends that any changes in water quality due to UCG activities must not lower the quality to below the minimum standard stipulated in SANS 241-1 standard. The SANS standard is specifically cited to incorporate a standard with tighter restrictions.

There are only a few chemical species in water that can lead to health problems as a result of a single exposure. Moreover, experience shows that in many, but not all single exposures, the water becomes undrinkable due to unacceptable taste, odour, and appearance. Some chemicals that cause adverse health effects include fluoride, arsenic, phenols, benzenes, and nitrate compounds. These chemical substances should be taken into consideration as part of

any risk assessment process and the methods of analysis should apply the limit of quantification and to the required accuracy and precision set by SANS 241 (SABS, 2016).

The body of work proposes that:

- UCG groundwater sampling is conducted according to current SANS or ISO standards and laboratory quality control be conducted according to the ISO 17025:2005 standard.
- Groundwater monitoring properties must be measured at each monitoring well (sentinel and compliance wells) in the surface aquifer and the coal water, with laboratory quality control adhered to ISO 17025:2005.
- UCG baseline groundwater quality must be monitored on a continuous basis.
- SANS 241-1 was provided as standard for baseline quantity comparison.
- Minimum limits should be determined before UCG initiation and baseline values will be set as the site water standard.
- The drinking water parameters shall comply with the physical, aesthetic and chemical limits, as specified according to SANS 241-1.

Another fundamental challenge faced by UCG designers was the correct choice of operational criteria of materials for producing long-term safe and efficient UCG syngas. Syngas can be highly acidic and could quickly erode poorly designed infrastructure. Corrosion rates were successfully determined for various metals earmarked for different UCG applications applicable to the gaseous corrosion environments provided for at the Theunissen UCG site.

Data with significant correlation coefficients for predictable corrosion rate calculations was determined and as applied to obtain suitable operating parameters for production and injection applications. The optimal metal thickness for components can be predicted and therefore this work will minimise maintenance time and reduce plant shut-downs or failures due to borehole failures caused by corrosion.

The study will mitigate environmental risks by using the best metals in each of the different UCG applications thereby minimising the possibility of gas leakages and this should negate any economic loss due to casing failures.

Coal ignition can be achieved through a number of processes of which an electric heating coil/element or gas burner is most commonly used. Understanding the thermochemical properties of the coal is critical to effectively and efficiently operate a UCG process. In previous work, Adiabatic R70 and SponComSIM™ tests were newly applied (usually these tests are applied as a precautionary measure to prevent coal fires on stockpiles or during transport) to find the optimal ignition conditions (temperature, duration, self-heating) at which the coal has to be operated during UCG start-up.

The R70 self-heating rate is the time taken for the coal temperature to reach 70°C from an initial temperature of 40°C (average self-heating rate calculated due to adiabatic oxidations). The intrinsic spontaneous combustion reactivity analysis showed that TUCG coal is highly reactive towards an oxidation environment and could be easily ignited.

Exposing the coal to higher initiating temperatures would speed up the time to self-ignition as there is a non-Arrhenius kinetics region that exists at low ambient temperatures during coal self-heating. At initiation temperatures above 150°C, the Arrhenius kinetics would promote a reaction rate doubling effect for every 10°C rise in temperature. Conversely, thermal runaway to ignition can also be delayed by the presence of >10% moisture in the coal.

The following results have been scientifically obtained:

- R70 self-heating rates from 4.2 to 4.6 °C/minute and consistent with the coal rank and type.
- High intrinsic spontaneous combustion reactivity and propensity rating. The self-heating is an important factor for initiating UCG reactions in the Theunissen coal source.
- Measured RIT for the samples between 130 to 140°C and this gives an indication of heat input required to start the UCG ignition.
- The test programme confirmed that with ample continuous supply of hot air (> 140°C) and minimal heat dissipation, Theunissen coal will reach thermal runaway within 48 hours.

It is recommended that this body of work be published in future and also verified at the TUCG commercial plant inception.

The Spontaneous Combustion and Reactivity behaviour in CO_2 saturated environments did supply technical detail and scientific insight into gasification behaviour and carbon conversion of the coal. In this study, we aim to show how the novel approach of using R70 and SponComSIM™ tests to quantify the optimal conditions (temperature, duration, self-heating, and carbon conversion) at which Theunissen coal can be successfully gasified with CO_2 as the agent. It was shown that the effectiveness and carbon efficiency of UCG can be improved by CO_2 gasification with the recycling of waste-captured CO_2 to be used as the main gasification agent to drive the Boudouard Reaction, where $CO_2 + C \rightarrow 2\ CO$ above 850°C to carbon capture and sequester (CCS) the gas. CO_2 gasification is a practical solution to improve both carbon efficiency and lower the CO_2 footprint.

Technical advantages may include, but are not limited to:

- In situ CO_2 capture, on active mineral components (Ca and Mg) in the roof and floor rocks and within the coal seam, to form carbonates.
- An overall process reduction of 43% CO_2.

- A minimum 22% reduction of in-situ coal to produce the same amount of syngas.
- Lowering the operating temperature of the syngas production and surface outlet temperature.
- Generating a higher heating value gas, containing less nitrogen (9%) and inert gases.

As a follow-up action, it is recommended that the detail of laboratory analysis procedures and results of TUCG coal in CO_2 atmosphere be published.

Chapter 7 examined and discussed novel treatment options for trace coal components; especially condensable water, oils, tars, inorganic trace elements, and particulate matter that make their way to the surface via the production well and can have adverse impacts on downstream processes. The effectiveness and carbon efficiency of UCG can be improved by hot cleaning raw syngas directly from the UCG production well. The proposed vortex separation hot gas clean-up concept will allow for the removal of most of the particulates, together with the efficient separation of the syngas into its useful components, providing for acid gas removal and H_2:CO ratio control.

A conceptual gas clean-up and separation design based on a vortex separator (VGS) are proposed. The concept will allow the hot and efficient separation of syngas into its useful components, together with partial cleaning for further gas utilisation. The most important principle of vortex separation is the preservation of laminar flow allowed by the adverse pressure gradient. Other technical and economic advantages may include, but are not limited to:

- Removal of most of the condensable and particulate matter from the hot syngas.
- Bulk removal of H_2S and CO_2, allowing for cheaper warm syngas desulphurisation combined with guard beds.
- Separation of H_2 from a second syngas stream for H_2:CO ratio adjustment.

The level of separation highlighted in the reference materials are in the commercial application range for the Theunissen UCG project as the syngas typically contains chemical compounds and substances with large variation in molar mass and the syngas pressure of the second stream used for power generation has to be let down anyway.

9.2 Investigation highlights

By managing the gasifying agent and operational conditions, it is possible to achieve a wide range of desired compositions and to control the quantity of gas produced. Commercially available gas clean-up and chemical process systems will enable the processing of any by-products, resulting in marketable commodities and, by the same token, preventing environmental pollution. Storing areas for ash or discard (inevitable in the case of traditional coal processing units) are virtually non-existent with the use of UCG.

The following conclusions and achievements arose from the modelling and investigations described in this thesis:

- Spontaneous combustion assessment of a coal reserve planned for UCG.
- Limited in-situ CO_2 capture during a UCG process by simulating possible CO_2 adsorption on roof and coal mineral structures.
- Corrosion testing of steel for production and injection well applications in a UCG process.
- The proposed use of vortex gas separation in UCG and other syngas systems.
- Investigation of a two-agent process for underground coal gasification with Fischer-Tropsch based poly-generation.
- A novel process to clean syngas by vortex before sulphur scrubbing by ZnO absorbent.
- A novel process of integration of two agents into a UCG-CTL facility.
- A novel process of managing CTL tail-gas for LNG, hydrogen and electricity production.

9.3 UCG Financial Analysis

Africary financial calculations included electricity pricing based on UCG and IGCC technology implementation at a potential tariff of 1.19 R/kWh (before the effect of any carbon tax on the project) can be implemented (on a 2019 cost basis). The technology has been operationally proven by Eskom at Majuba since 2007, and Africary's 50 MW TUCG Project is ready for commercialisation. Africary is ready to make UCG a cost competitive cleaner, more efficient and much safer power generation option. The project has the support of the local community and obtained its environmental authorisation to build the mine and power station as early as 3 September 2015.

Some CTL by-products have a negative price associated with a disposal cost or tax (like brine, sulphur, off-gas, CO_2 and grey water) and become important factors in determining the economics. To minimise their impact, the Africary design actively pursues using by-products like CO_2, off-gasses and grey water as process feedstock. Another important consideration is to choose a FT provider that provides a large main product ratio to by-products. On small-scale FT the small quantities of by-products produced have a big nuisance value as some chemicals are hazardous and difficult to store and transport and it may be impractical to sell small batches to remote markets.

The work discussed in Chapter 7 and 8 offered novel designs where the primary feed for the power station changes away from air-blown UCG syngas to a higher value CO_2-blown syngas. This CO-rich gas is then mixed with purge, flash, strip, and tail-gas before consumption by gas engines, thereby reducing the flare load and boosting the cost-effectiveness of the overall CTL facility.

9.3.1 Capital Cost

The high capital cost of CTL facilities has some important design implications. Whilst balancing the carbon and energy efficiency in the rest of the facility the design must maximise the carbon efficiency in the refinery. This guideline is however not strictly followed by the application of UCG, as it significantly lowers the upfront cost of producing syngas by a third. Africary's 2017 total CTL capital cost (ULSD + Naphtha + LNG + H_2) is about $ 278 million and reaches $ 350 million when the power generation system is included for a 2 000 bbl/day diesel with a 200 ton/day LNG facility.

9.3.2 Operating Cost

The calculated operating expenditure for Africary, inclusive of reactor refurbishment, gas engine refurbishment, labour, routine plant maintenance and catalysts and chemicals replacement has the total plant operating expenditure of 28 $/bbl. This also allows for all catalyst replacements for the Synthetic Crude Upgrading Unit with a 3-year catalyst life assumption period and includes the FT royalty payment on a per barrel basis. The balance of plant (BOP) catalysts and chemicals and the power station maintenance is also included for each unit as well as the organisational cost for operating personnel and plant maintenance.

9.4 Benefits for South Africa

When comparing UCG with other electricity generating technologies and their environmental impacts, we can summarise the major benefits provided by UCG as follows:

- It would form a centralised gas hub for South Africa that is immediately implementable.
- UCG is a massive environmental improvement over conventional coal technology.
- The use of CO_2 as feed for UCG lowers overall carbon dioxide emissions and provides the implementation of carbon capture and sequestration.
- UCG offers energy efficiency improvements and has a low-impact on the environment.
- It would ensure continued agriculture with professional management, clean water, infrastructure, electricity and possibly fertiliser from future poly-generation production, including clean fuels.
- It could be a new potential tax source and source of employment in an economically depressed part of the country.
- It could reduce the trade deficit and reduce dependence on oil and import gas.
- It would be clean, green, water efficient and safe.

In both the business-as-usual and green electricity development scenarios there is a clear opportunity for UCG to help South Africa meet its future electricity demand. Africary and its partners and the greater UCG community can implement large-scale power projects in line with the most demanding industry expectations and will simultaneously decrease the exchange rate and commodity price risks associated with gas-power generation.

UCG will help to reduce SA's electricity production land use impacts, greenhouse gas emissions and other unwanted air emissions. UCG is also preferable to imported natural gas for electricity generation because of worsening import deficits.

UCG has the potential to access the vast energy reserves locked in coal deposits that are uneconomic to mine using current technology. The technology will develop these resources with lower environmental impact than conventional coal mining and coal-boiler generation.

South Africa does not have a mentionable domestic gas supply as the Mozambique import industry is fully constrained and the assumed future supply of shale gas is still unproven whilst the import harbour capacity for LNG has not been approved for construction. Africary's UCG-CTL projects can be a breakthrough solution for independently produced electricity, liquid fuels, hydrogen and natural gas. Integrating two parallel UCG gasifiers (operated on different agents) with mini-GTL to produce diesel and LNG provides a unique interdependent poly-generation configuration that reduces both cost and emissions.

The TUCG process can cost-effectively be combined with a deep acid gas scrubbing to remove undesirable components (especially condensable water, oils, tars, sulphur and inorganic trace elements) from each gasifier and blend the cleaned syngas for H_2:CO ratio control. The scrubbed syngas will supply CompactGTL's FT synthesis plant, which is at the heart of the conversion process for liquids from syngas and forms a critical part of the overall design of cost-effective poly-generation operation.

Multi-product UCG (CTX) offers a lower capital investment to conventional underground mining and surface gasification (due to the removal of the surface gasifier and coal mine operations This study has minimised the complexity and optimised the process flow to provide electricity plus 2 000 bbl/day fuels and 200 ton/day LNG; at a capital cost estimate (2017) of about US$ 350 million and operating cost of around 28 $/bbl.

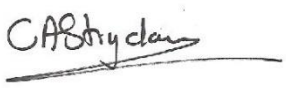
9.5 References

61 www.ee.co.za/article/eskoms-big-blunder-how-poor-decisions-and-corruption-caused-load-shedding.html. (Accessed 10 April 2019).

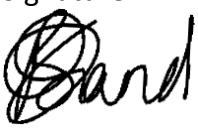
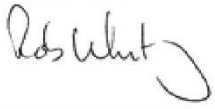
10 APPENDICES

10.1 Statements of Consent from Co-authors

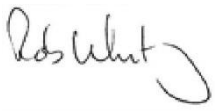
Paper Title	**UCG Pilot Study in Secunda South Africa - The Experimental Design and Operating Parameters for the Demonstration of the UCG Technology and Verification of Models.**
Authors	J.F. Brand.
Document type	Conference Paper
Journal	Proceedings of the 25th Annual International Pittsburgh Coal Conference, PCC - Proceedings. p. 17.
Year	2008
Author: Mr. J.F. Brand. Signature: 	I, as author, give my consent to include the use of this publication for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Groundwater Monitoring During Underground Coal Gasification.**
Authors	J.C. van Dyk, J.F. Brand, C.A. Strydom and F.B. Waanders.
Document type	Academic Journal
Journal	Journal of the Southern African Institute of Mining and Metallurgy, Volume 118 (10), p. 1021-1028.
Year	2018
Co-Author and Director: Mr. J.F. Brand. Signature: 	I, as author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this publication for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof. C.A. Strydom Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof. F.B. Waanders Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Corrosion testing of steel for production and injection well applications in a UCG process.**
Authors	J.C. van Dyk, J.F. Brand, F.B. Waanders, A.C. van Wyk and C.J. Kahts.
Document type	Conference Presentation and Poster.
Conference	33rd Annual International Pittsburgh Coal Conference: Coal - Energy, Environment and Sustainable Development, PCC-2016.
Year	2016
Co-Author & Director: Mr. J.F. Brand. Signature:	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this presentation for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof J.C. van Dyk Signature:	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof. F.B. Waanders Signature:	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Mr. A.C. van Wyk Signature:	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Mr. C.J. Kahts Signature:	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Applying Spontaneous Adiabatic Test Procedure to Determine CO_2 Gasification Reactivity and Kinetics of Coal UCG Applications.**
Authors	J.C. van Dyk, J.F. Brand, Beamish B.B., R.S.Whitney, T.P. Levi and N. Fasihiani.
Document type	Conference Presentation
Conference	35th Annual International Pittsburgh Coal Conference, Xuzhou, China, 15-18 October 2018.
Year	2018
Co-Author & Director: Mr. J.F. Brand Signature: 	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this presentation for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Dr B.B. Beamish Signature: p.p.	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Mr. R.S. Whitney Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Me. T.P. Levi Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Mr. N. Fasihiani Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Underground Coal Gasification – Efficient In-Situ CO_2 Capture and Conversion.**
Authors	J.F. Brand, J.C. van Dyk and F.B. Waanders.
Document type	Conference Presentation
Conference	8th International Conference on Clean Coal Technologies (IEA). 8-12 May 2017, Italy.
Year	2017
Co-Author & Director: Mr. J.F. Brand Signature: 	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this presentation for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof. F.B. Waanders Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Spontaneous Combustion Assessment of a Coal Reserve Planned for Underground Coal Gasification Utilization.**
Authors	J.C. van Dyk, J.F. Brand, B.B. Beamish, R.S. Whitney and T.P. Levi.
Document type	Conference Presentation
Conference	7th International Freiberg/Inner Mongolia Conference on IGCC & XtL Technologies, Coal Conversion and Syngas. Inner Mongolia, China. 8 – 12 June 2015.
Year	2015
Co-Author & Director: Mr. J.F. Brand Signature: 	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this presentation for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Dr B.B. Beamish Signature: p.p.	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Mr. R.S. Whitney Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".
Co-Author: Me. T.P. Levi Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: "Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project".

Paper Title	**Conceptual Use of Vortex Technologies for Syngas Purification and Separation in UCG Applications.**
Authors	J.F. Brand, J.C. van Dyk and F.B. Waanders.
Document type	Academic Journal
Journal	Journal of the Southern African Institute of Mining and Metallurgy, Volume 118 (10); p. 1029 - 1039.
Year	2018
Co-Author & Director: Mr. J.F. Brand. Signature: 	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this publication for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.
Co-Author: Prof. F.B. Waanders Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.

Paper Title	**Economic overview of a two-agent process for underground coal gasification with Fischer–Tropsch based poly-generation.**
Authors	J.F. Brand, J.C. van Dyk and F.B. Waanders.
Document type	Academic Journal
Journal	Clean Energy, Volume 3, Issue 1, March 2019, Pages 34–46.
Year	2019
Co-Author & Director: Mr. J.F. Brand. Signature: 	I, as co-author and as director of African Carbon Energy (Pty) Ltd, give my consent to include the use of this publication for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, in the thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.
Co-Author: Prof J.C. van Dyk Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.
Co-Author: Prof. F.B. Waanders Signature: 	I, as co-author, give my consent to Johan Francois Brand, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: “Industrialization of South African underground coal gasification (UCG) and optimization of the Theunissen UCG project”.

10.2 Accolades and industry references

Sasol Mining is responsible for producing and supplying about 50 million tons of coal a year and in 2002 received the prestigious International Coal Company of the Year Award in the 2002 Platts/Business Week - Global Energy Awards presented in New York City. The award is in recognition of Sasol Mining's team that have unlocked a substantial amount of new value in the often-difficult geological conditions and shows an ability to sustain business and human growth and prosperity through a process of focused business renewal.

This award was fitting tribute to the vision, diligence and passion of Sasol Mining's people implementing their comprehensive business renewal process and the continued aspiration to achieve and maintain world-best practices. In addition, the company has implemented several major technological advances in key areas such as virtual mining, directional drilling, mine planning, coal cutting, coal handling and ventilation [1].

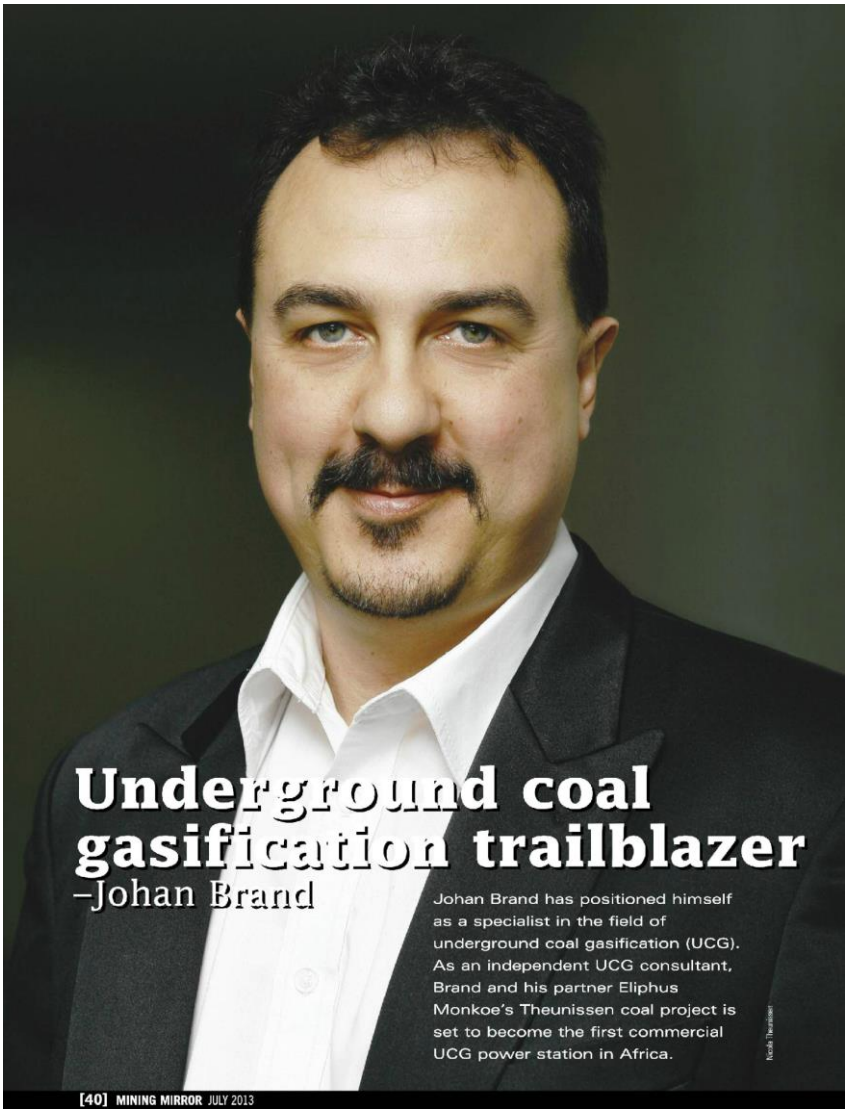


Figure 11: The Author has a long career in promoting and developing UCG technology commercialisation.

1 World acclaim for Sasol's high-achiever mines. The Journal of the South African Institute of Mining and Metallurgy. Jan/Feb, 2003. p. 33.

10.3 Other Publications on UCG by the Author or in Collaboration with the author (not mentioned directly in this thesis)

1. Brand JF, van Vuuren P and du Plooy, D. *Underground Coal Gasification (UCG): A viable coal mining option.* 2nd Annual Global Mining Technology Forum. Stockholm, Sweden. 25 May 2011.
2. Brand JF, van Vuuren P and du Plooy D. *Wildhorse Energy's UCG Technology Provide Clean Independent Energy for Hungary.* The Twenty-Eighth Annual International Pittsburgh Coal Conference. Pittsburgh, USA. 15 September 2011.
3. Brand JF, van Vuuren P, du Plooy D, Rugova Q., Bakalli D and Solovey A. *UCG PFS: 383mt Coal JORC Inferred Resource and Completion of Preliminary Feasibility Study Confirming Technical & Economic Viability of Flagship Mecsek Hills UCG Project.* UCG Association - 7th International Workshop. London, UK. 28 March 2012.
4. Brand JF, Dinsdale C and Solovey A. *Progress feedback on Wildhorse's Hungarian UCG Project and Economic Attractiveness of UCG in Central and Eastern Europe.* UCG Association - 7th International Conference and Workshop. London, UK. 3 May 2012.
5. Van Dyk JC and Brand JF. *Africary Underground Gasification Project: An in-depth coal characterization study of the Theunissen Coal Reserve in South-Africa.* 31st Annual International Pittsburgh Coal Conference. Pittsburgh, USA. 6-9 October 2014.
6. Brand JF and van Dyk JC. *UCG – Bringing a Resource, Technology and Economics Together for a 50MW Power Station in South-Africa*. (Plenary presentation). 31st Annual International Pittsburgh Coal Conference. Pittsburgh, USA. 6-9 October 2014.
7. Van Dyk JC and Brand JF. *Gasification Technologies, Science and Site Characterization.* UCGA Workshop at 31st Annual International Pittsburgh Coal Conference. Pittsburgh, USA. 5 October 2014.
8. Van Dyk JC and Brand, JF. *Determining the Commercial Viability of UCG with Focus on the Energy Challenges in South-Africa*. (UCGA Workshop.) 31st Annual Pittsburgh Coal Conference. Pittsburgh, USA. 6 October 2014.
9. Van Dyk JC, Waanders F and Brand JF. *Applying Thermo 350m underground: A Factsage™ equilibrium study for underground coal gasification.* Proceedings of the GTT Workshop. Aachen, Germany. July 2014.
10. Van Dyk JC and Brand JF. *When and Why an UCG Project can be Successfully Implemented – A Fly-over of the 50 MWe Theunissen UCG Project in South Africa.* Gasification India 2015. New Delhi, India. 13-14 February 2015.
11. Van Dyk JC, Brand JF, Waanders FB and Strydom C. *Update on the 50-MWe Theunissen Underground Coal Gasification Project*. CornerStone - The Official Journal of the World Coal Industry, Spring Issue 2015. 20 March 2015
12. Van Dyk JC, Brand JF and Waanders FB. *Equilibrium Coal Mineral Matter Simulation and Slag Formation during an Underground Coal Gasification Process*. 6th International Freiberg Conference. Germany. 19-22 May 2014.

13. Van Dyk JC and Brand JF. *Underground Coal Gasification: South Africa's electricity-generating breakthrough,* Mining Review Africa. (Article) November 2015 Edition.
14. Van Dyk JC, Brand JF, Waanders FB and Strydom C. *Groundwater Monitoring During Mining of Coal In-Situ By Means of an Underground Coal Gasification Process.* 14th Groundwater Division of the Geological Society of South Africa Conference and Exhibition. Ekudeni, Muldersdrift, South Africa. 21 - 23 September 2015.
15. Van Dyk JC, Brand JF, Waanders FB and Strydom C. *Groundwater Monitoring during Mining of Coal In-Situ By Means Of an Underground Coal Gasification Process*. IEA Workshop and Conference. Poland. April 2015.
16. Van Dyk JC, Brand JF and Hattingh C. *Coal Geology – A Scientific Building Block for Underground Coal Gasification.* 35th International Geological Congress. Cape Town, South Africa. 27 August 2016.
17. Brand JF and van Dyk JC. *UCG – Unlocking Southern-Africa's Coal Potential: Update on the Africary's Theunissen Underground Coal Gasification (TUCG) Project in South-Africa*. 33rd International Pittsburgh Coal Conference. Cape Town, South Africa. 12 August 2016.
18. Van Dyk JC, Brand JF and Roberg E. *Energy and CCS Potential In South Africa – A Review.* 8th International Freiberg Gasification Conference on IGCC and XtL. Cologne, Germany. 12-16 June 2016.
19. Brand JF and van Dyk JC. *UCG Application Opportunities for the Poly-generation of Power and Fuels*. Syngas Technologies Conference. Colorado Springs, USA. October 2017.
20. Van Dyk JC, Brand JF, Waanders FB and Collins AC. *Thermo-Chemical Simulation of a Coal Gasification Process (Applying Waste Captured CO_2 either from Combustion or Gasification),* 19th GTT Workshop. Aachen, Germany. June 2017.
21. Van Dyk JC, Brand JF, Waanders FB, Nguyen M, Scheithauer D and Meyer B. *Experimental Study On Liquid Hydrocarbon Formation During Pressurized Underground Coal Gasification Conditions*. 35th Annual International Pittsburgh Coal Conference, Xuzhou, China. 15-18 October 2018.