Chapter 5

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In this chapter, a sammury of the findings as well as general conclusions based on the hypothesis and objectives of this study are discussed. Opportunities for future research are identified and discussed and so are the recommendations for plant operational and design improvements and/or optimization.

5.1 Summary of the Findings

The following is a summary of all the discussions and findings from Chapter 4 of this study. Although the findings apply only to the coals studied, they may at least be qualitatively applicable to gasification, in the S-L FBDB process, of many other coals similar to the ones tested.

<u>Chemical Properties and Identification of Reaction Zones</u>

- Volatile matter (as determined in the proximate analyses) as well as the Fischer tar was used to determine the drying and the pyrolysis zones in both the "Bernice" and "Albert" gasifiers. Tar recycling in the "Bernice" gasifier was clearly shown by an increase in Fischer tar content in the drying zone. This was not observed in the "Albert" gasifier.
- The beginning of carbon conversion as shown by an increase in ash content was used to determine the beginning of the gasification/ reduction zone.
- The beginning of the oxidation zone was determined using the oxygen profile in the gasifier fuel bed.
- The position of the fire bed was determined using information from the literature where it was determined at 70% of the fixed carbon conversion.

- The separation of the gasification, combustion and ash bed zones is always a challenge using the Turn-Out sampling methodology. In this study, the combustion and ash bed zones were clustered as one zone and determined using the ash content profile.
- Carbon in the DGC gasifiers was consumed within a third of the gasifier bed height.
- Due to the high moisture content in the lignite, the pyrolysis zone in both "Albert" and "Bernice" gasifiers occurred lower/deeper in the bed as compared to the Secunda GG41 which gasifies bituminous coal. All the other reaction zones in GG41 were also higher in the bed compared to "Albert" and "Bernice" gasifiers and this can explain the higher gas outlet temperature in GG41 (i.e. 550 °C as compared to in 222 °C in "Albert" and 232 °C in "Bernice").
- As expected, most of the H, N and S were released in the pyrolysis zone of both "Albert" and "Bernice" gasifiers.
- A significant increase in the reactivity of the chars from both the "Bernice" and "Albert" gasifiers was observed in the gasification zones of the gasifiers. It is due to this increased reactivity that the char/carbon in these gasifiers were consumed within only a third of the gasifier volume. The increased reactivity is most probably due to the catalytic reactions effected by the organically bound alkali and alkaline earth metals, particularly Ca as the coal was found to be Ca rich.

Physical properties

- Thermal fragmentation was found to be severe with the lignite tested. The lignite was found to decrease in size from 3% in the feed coal to 90% of <6.3 mm particles in the drying and pyrolysis zones of both the "Albert" and "Bernice" gasifiers. This is a new significant finding in the history of the FBDB gasification process which is traditionally known to operate on coarse coal.
- The feed coal to the DGC gasifiers did not show any caking propensity.

- The particle as well as the bulk density residual profiles of the fuel bed samples in both the "Bernice" and "Albert" gasifiers was found to be in line with the residual ash content profile.
- The ash fusion temperatures (oxidising atmosphere) determined in the feed coal for both "Bernice" and "Albert" gasifiers were higher when compared to those determined in the combustion/ash bed zone. This is a significant finding as it may have implications on the design and operating philosophy since the gasifiers are normally designed to operate between the initial deformation and flow temperatures of the ASTM ash, which is not the same as the ash formed in the gasifier.

Petrographic Properties

- The feed coal to DGC "Bernice" and "Albert" gasifiers had the mean random vitrinite reflectance (Rr%) of 0.25 and 0.23 respectively. It is therefore classified, as per the ISO 11760 - 2005 standard, as Low Rank B (Lignite B), high huminite, and low ash coal. The Secunda coal had the mean random vitrinite reflectance (Rr%) of 0.61 and hence classified as Medium Rank C (bituminous C) coal.
- The char particles formed in both the "Bernice" and "Albert" gasifiers were, as determined petrographically, mainly dominated by the dense chars which were nonetheless highly reactive.
- In the pyrolysis zones of both the "Bernice" and "Albert" gasifiers, the char particles increased very rapidly, in line with an increase in fixed carbon.
- In the gasification and combustion zones, the heated minerals increased rapidly in line with the ash content, whilst the char particles decreased rapidly, in line with the fixed carbon content.
- In the gasifier bed, some particles essentially changed rank from huminite to vitrinite typical of bituminous coals (i.e. an artificial coalification process)
- The solids temperature profile in the "Bernice" gasifier was determined using reflectance measurements on the chars. The temperatures

obtained, particularly the average temperature, were not that far out when compared to the figures obtained using the SLTC proprietary thermodynamic model.

Mineralogical Properties

- The major minerals in the feed coal to the "Bernice" gasifier were kaolinite, quartz, pyrite, illite and calcite. The bassanite detected by XRD was found to be resulting from the artefacts of low temperature ashing.
- The crystalline phases in the gasification and combustion zones were dominated by bredigite and gehlenite which may have formed from the transformation, at higher temperatures, of the organically bound Ca and Mg to CaO and MgO and subsequent interaction with the reactive silica and transformation products of the clays. Other crystalline phases formed in the gasifier were magnetite, anhydrite, calcite, gypsum, glauberite, nepheline, akermanite and pyrrhotite.
- A significant amount of calcite was found to be forming in the beginning of gasification zone, towards the end of pyrolysis, and decomposing slightly in the hotter combustion zone. It is suggested that the calcite was formed from the reaction of CaO (formed from the transformation of the organically bound Ca) with the CO_2 from the raw gas in the gasifier.
- The glass phase dominated the ash in the gasification and combustion zones and was found to be composed mainly of alkali and alkaline earth alluminosilicates, with some iron. This composition is common to the slag formed from the Fort Union lignite. There was therefore a significant amount of melting in the hotter zones (gasification and combustion zones) of these gasifiers. The fluxing elements (i.e. Na, Ca, Mg and Fe) in the dominating glass phase seem to be the reason behind low AFT in the bottom of the gasifier.
- The inorganic elements determined in the organic matrix were mainly Si, Ca, Mg, Na and Fe and were dominated by Ca and Si. It is these

inorganic elements that had a significant contribution to the formation of ash and most importantly the low melting point glass phase in the bottom of the gasifier.

- The included and excluded minerals probed in the feed coal consisted mainly of Si and Al and this indicates the presence of clays.
- The ash particles/minerals started forming in the beginning of the gasification zone and, as expected, increased towards the bottom of the gasifier. This is in line with the coal particle transformation profile as determined petrographically as well as the ash content and the density of the fuel bed samples.
- The volatile matter of about 10% (dry basis) in the ash bed of the "Bernice" gasifier was found to be inorganic and emanated from the decomposition of minerals like calcite and gypsum. Using only the volatile matter, as determined by proximate analyses, to determine the pyrolysis zone will in the case of DGC gasifiers therefore be delusive.
- Oxygen scavenging by ash minerals was found to be significant in the DGC gasifiers. About 16% of the oxygen fed as gasification agent to the gasifier was found to be captured by the ash minerals. From an economic viewpoint, this is significant given the cost of producing the 99% pure oxygen for gasification.

5.2 General Conclusions

The main objective of this study was to investigate the fuel bed behaviour as well as coal properties transformational behaviour in a S-L FBDB gasifier that gasifies ND lignite. It was hypothesized that using the FBDB gasifier sampling methodologies available in the literature, with some modifications to suit the context of this study, can help to explain the fuel bed behaviour as well as the coal properties transformation behaviour during gasification of lignite in the S-L FBDB process. The following general conclusions are drawn based on the results obtained in this study.

The different reaction zones in the "Bernice" and "Albert" gasifiers were successfully identified using the gasifier Turn-Out sampling method and chemical analyses (i.e. proximate and ultimate analyses as well as Fischer tar yields). Identification of reaction zones in the S-L FBDB gasifiers operating on lignite is a first in the history of the process.

In comparing Secunda GG41 gasifier with the DGC "Bernice" and "Albert" gasifiers, the reaction zones were found to be very different due to, amongst other things, the different operating philosophy, stability and coal rank. About two thirds of the reactor volume in the case of "Bernice" and "Albert" was found to be drying and devolatilizing the coal, leaving only about a third of the reactor volume for gasification and combustion. Nonetheless, due to the high reactivity of the lignite, the char was consumed within a third of the remaining gasifier volume. This is a significant new finding. The fact that the entire reactor volume was utilized for drying, devolatilization, gasification and combustion with carbon conversion of >98%, makes the S-L FBDB gasifier very suitable for lignite gasification.

In line with the Secunda GG41 gasifier, clear overlaps between the reaction zones were observed in the "Bernice" and "Albert" gasifiers. This therefore confirms the gradual transition from one reaction zone to another as reported in the literature.

There was an excellent match in the trends of the chemical, physical, petrographic and mineralogical properties of the samples obtained at different levels of the "Albert" and "Bernice" gasifiers. This may therefore confirm plug flow during the Turn-Out sampling methodology, and hence, is supportive of the hypothesis of this study.

5.3 Recommendations and Future Work/Research

- The dusty tar injection on top of the gasifier bed (i.e. in the drying zone of the gasifier) may, from a tar re-combustion perspective, not be optimal as the tar will be released again in the pyrolysis zone. A deeper injection into the gasifier bed, preferably in the fire bed, will ensure utilization of the carbon in the tar. Increased cracking of the tar may also be achieved with deeper injection. An investigation into the deeper injection of tar is therefore recommended.
- Some sulphur was found to be captured or retained in the ash from both the "Albert" and "Bernice" gasifiers. Mineralogy of the gasifier bed samples showed the presence of free lime that may be available to capture excess sulphur. This may therefore be an opportunity for H_2S recycling into the bottom part of the gasifier. Similarly, it may be an opportunity for *in situ* CO_2 capture. Further studies, both laboratory and full scale, are therefore recommended to confirm the technical feasibility of this idea.
- Given the fact that the DGC gasifiers are already gasifying fine coal, it may be possible to inject more fines (<6 mm) into the fire bed of the gasifier, the position of which was successfully identified in this study. Although it can be an engineering challenge, fines injection into the fire bed should require some consideration and investigation.
- For lignite gasification, the method used at Sasol to determine the thermal fragmentation of coal does not really represent the conditions in the gasifier. A modification of the method is therefore recommended to be able to improve the laboratory coal gasifiability tests.
- A detailed study on the reactivity of the chars from the ND gasifier fuel bed samples is recommended to further understand the phenomenon of increased reactivity in the gasification zone.
- Although the solids temperature measurements in the gasifier are closer to the expected figures as determined using the SLTC proprietary confidential model, verification using other methods like diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy is recommended.

- The organically bound inorganic elements seem to be playing a very significant role in the ND lignite gasification using the S-L FBDB process and should therefore be studied in detail to enhance the understanding of the process. A further dedicated mineralogical study on the gasifier fuel bed samples tested in this study, including trace elements analyses, and high temperature XRD, is therefore recommended. Prediction tools for the lignite ash behaviour in the S-L FBDB gasifiers may also be developed in this type of a study.
- The mode of occurrence of the inorganic species in the gasifier bed samples may require some further studies to confirm the quantity of the organically bound inorganic elements. The studies could include chemical fractionation of the gasifier bed samples.
- Oxygen scavenging by the ash minerals during gasification should also be further investigated to be able to accurately quantify the losses. Development of accurate prediction tools would definitely add more value in modelling and design of the S-L FBDB gasification process. The studies could include a comparison of mass balances from the models with operational data from the plants (including pilot plant data available in the databases). Fact Sage thermo-equilibrium modelling in combination with detailed and advanced mineralogical characterisation can also be used as supporting tools.
- It is a known fact that a Turn-Out sampling method only provides details pertaining to the axial behaviour of the gasifier bed. A Dig-Out sampling program, which will provide both axial and radial details of the fuel bed thus confirming the findings from this study, is highly recommended for future studies.
- The use of different thermodynamic models, Aspen based models for example, is recommended to compare with the results from *Drugas* as well as the experimental data.

<u>NB:</u> The joint venture between Sasol and Lurgi (SLTC) was dissolved on 31 December 2008. As from 01 January 2009, the S-L FBDB gasifier will be called the Sasol Fixed Bed Dry Bottom (SASOL® FBDB™) gasifier.