3. CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

Conceptual plant designs and economics have been developed for Fischer-Tropsch liquefaction plants producing high quality, liquid transportation fuels from synthesis gas produced either from coal or natural gas. Using these designs as the bases, various ASPEN Plus process flowsheet simulation models also were developed, along with a LOTUS spreadsheet economics model. These models provide DOE/FETC with a tool to explore, evaluate and identify additional promising areas for future research in the production of liquid transportation fuels via Fischer-Tropsch synthesis.

A 45,000 bbl/day indirect liquefaction plant at a mine-mouth location processing 20,320 TPD of Illinois No. 6 coal can produce liquid transportation fuels that will be competitive with those made from crude oil priced at 32.4 to 35.4 $/bbl. The Crude Oil Equivalent (COE) price range depends upon the product upgrading option selected. The products from a similar plant located near Gillette, Wyoming processing Powder River Basin coal can be competitive with those from crude oil priced a 29.1 to 31.9 $/bbl depending upon the product upgrading option selected. The cost of these plants were estimated to be in the vicinity of 3.0 billion mid-1993 dollars with some variation due to the upgrading option and plant location.

A similar sized indirect natural gas liquefaction plant located at southern Illinois processing about 410 MMSCF/day of natural gas can produce high quality liquid transportation fuels at a COE price of 32.8 $/bbl from gas costing 2.0 $/MMBTU. With 0.50 $/MMBTU gas, the COE price drops to 19.7 $/bbl. The cost of this plant was estimated to be about 1.8 billion mid-1993 dollars. The Illinois site was chosen for the natural gas design for the purpose of expediting the work and making comparison. It is not a good location for natural gas liquefaction, but it shows that the economics can be favorable with low cost gas. At remote sites with low cost gas, construction costs generally are higher because of a lack of infrastructure, an inadequate labor force, and/or a harsh climate. However, there are opportunities to reduce the plant cost by applying developing technologies, design changes, and producing only a pumpable liquid (syncrude) for upgrading with crude oil at a conventional petroleum refinery. These options should be explored.

The naphtha and distillate products from the above plants are sulfur, nitrogen and oxygen free. The distillate is a superior diesel fuel blending component with a cetane number above 70. When upgraded by the processes used in this study, the naphtha is a good gasoline blending component.

A design for a smaller once-through, natural gas Fischer-Tropsch liquefaction plant was developed employing the F-T synthesis technology of Syncrude Technology Incorporated. This plant processed 100 MMscf/day of natural gas and produced about 8815 bbls/day of a sulfur, nitrogen and oxygen free syncrude. It also produced about 84 MW of surplus electric power for sale. With low cost natural gas, a reasonable power selling price, and construction costs similar to those on the U. S. Gulf Coast, this syncrude can be competitive with conventional crude oil assuming a reasonable premium because of its superior property.

3.2 Recommendations for Future Work

During the course of this study, several areas for future investigation became apparent which could reduce the cost of preparing high quality liquid transportation fuels from carbon sources other than crude oil.

3.2.1 General Indirect Liquefaction Processes

The following recommendations apply equally well to a F-T indirect liquefaction plant processing syngas produced either from coal or natural gas.

- Investigate and incorporate advanced processes for oxygen production and syngas generation. Currently, the syngas generation area accounts for a major portion of the total plant cost. Promising technologies are on the horizon such as combined autothermal reforming, fluid-bed autothermal reforming, and ceramic membranes oxidation (e.g., DOE Contract No. DE-AC22-92PC92113), which can significantly improve the overall economics.

- Develop an effective design and up-to-date cost for larger diameter F-T slurry reactors. Advanced slurry F-T reactor design is the core of the overall process design, and the F-T synthesis plant represents 15% of the total plant cost. The original design was based on the premise that the reactor diameter must not exceeded 16 feet for transportation reasons. The current designs have 24 slurry F-T reactors, each about 16 feet in diameter. Development of larger slurry F-T reactors should be possible, and this will significantly reduce the cost of the F-T synthesis plant where water transportation to the site is available.

- Develop a cost effective scheme for minimal upgrading of the F-T wax into a shippable product which can be upgraded elsewhere into liquid transportation fuels.

- Obtain better experimental data on the coprocessing of F-T liquefaction products in a conventional refinery and on the quality of the products that

are produced.

- Perform additional linear programming (LP) studies to better define the F-T product values, as a part of the current Coal Liquids End Use Study (DOE Contract No. DE-AC22-93PC91029), using experimentally determined F-T liquid properties as input parameters to the model. Fischer-Tropsch synthesis produces a very high quality diesel (high cetane; no sulfur, nitrogen and aromatics; low smoke point, etc.) It is likely that the quality of this diesel is not adequately represented by the 7.19 $/bbl margin above the crude oil price used in this study. Furthermore, elimination of upgrading at the remote site and processing the F-T syncrude in the refinery along with crude oil may be a more economical overall operation.

- Develop a design for a once-through F-T liquefaction plant in conjunction with an IGCC plant. This plant can use either coal, natural gas, biomass, land-fill gases, waste material or a mixture thereof as the primary carbon source. In this design, the F-T recycle loop is eliminated and the large cost of the gasifier is distributed between the two products, power and the F-T liquids. The liquids only will be upgraded to produce a shippable material which will be converted to finished liquid transportation fuels elsewhere.

3.2.2 Coal Based Indirect Liquefaction Processes

The following recommendation principally applies to a coal based Fischer-Tropsch indirect liquefaction plant.

- Develop a improved iron based F-T liquefaction catalyst. Iron based catalysts are preferred for coal based designs because their high water-gas shift activity is required to produce sufficient hydrogen for the F-T synthesis reaction. The current design uses a ROSE supercritical solvent extraction unit to separate the catalyst from the wax product because the current iron catalyst particles quickly disintegrate to very fine material. This is expensive both in cost and utilities consumption. A more durable, longer lasting catalyst would allow the use of low cost filters, and furthermore, could reduce cost.

3.2.3 Natural Gas Based Liquefaction Processes

The following recommendations principally apply to a natural gas based Fischer-Tropsch indirect liquefaction plant.

- Design a natural gas F-T liquefaction plant to be located at a remote site of interest (e.g., Prudhoe Bay, Alaska) where low cost gas is available and incorporate into the design:

  a) Site-specific construction and operating costs
  b) Site-specific utility requirements and overall plant balance
  c) Minimal product upgrading
  d) Site and product specific transportation and storage requirements, and
  e) If applicable, a once-through power coproduction scheme to take advantage of the synergistic economic benefits of coproduction.

- Design a smaller, potentially barge-mounted, natural gas F-T plant of about 10,000 BPD capacity using a simplified, but possibly less efficient, design with minimal product upgrading. This plant will be different from the current design not only in terms of size, but also in construction. It will be designed specifically for gas reserves in remote areas of the U. S., including offshore discoveries along the U. S. Gulf Coast.

- Obtain additional and more detailed cobalt based catalyst data. The yield and kinetic data which were used to design the F-T slurry reactors are based on a single source (i.e., Satterfield et. al.) and are somewhat limited in scope. Additional, larger scale data are needed to confirm the kinetics and better define the F-T synthesis yields. Catalyst life is another variable which needs to be examined in a pilot plant scale facility.

APPENDIX A

MAJOR PROJECT REPORTS

APPENDIX A

MAJOR PROJECT REPORTS

This appendix contains a listing of the major project reports containing significant technical information that were prepared during the course of this DOE contract, Contract No. DE-AC22-91PC90027, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology." Monthly status reports are not included in the listing because, in general, they did not contain any significant technical information, and if they did, it was only of a preliminary nature, and it was repeated in more detail in the quarterly report covering that period.

This appendix is divided into four sections:

- A1 Topical Reports
- A2 Quarterly Reports
- A3 Technical Progress Meeting Conference Notes
- A4 Letter Reports

Topical reports were issued to document the final results from a portion or task of this study.

Quarterly reports were issued every three months. They contain technical data, and document the progress of the study to that point.

Technical progress meetings with DOE/FETC personnel were held periodically as needed. Following the meeting, conference notes were issued documenting the discussion and the action items.

Letter reports were issued sporadically, as needed, containing some technical information which were best transmitted by letter. Selected letters of transmittal for the project management plan, conference notes, etc. are included in this section to provide a reference to the transmitted items. Letters of transmittal for publications are not included because the publications are reprinted in Appendix B. For completeness, letters from either the DOE or Burns and Roe which fit in this category and are related to this contract are included in the listing. Again, letters not containing any significant technical information are not included in the listing.

All reports are listed chronologically in each of the four sections.

A1 Topical Reports

1. Topical Report, Volume I, *Process Design - Illinois No. 6 Coal Case with Conventional Refining,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, October, 1994.

2. Topical Report, Volume II, *Process Design - Illinois No. 6 Coal Case with ZSM-5 Upgrading,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, October, 1994.

3. Topical Report, Volume III, *Process Design - Western Coal Case with Conventional Refining,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, October, 1994.

4. Topical Report, Volume IV, *Process Flowsheet (PFS) Models,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA.,
   Part 1, October, 1994
   Part 2, Appendices - Part I (1 of 2), October, 1994.
   Part 3, Appendices - Part I (2 of 2), October, 1994.
   Part 3, Appendices - Part I (2 of 2), October, 1994.
   Part 4, Appendices - Part II (1 of 2), October, 1994.
   Part 5, Appendices - Part II (2 of 2), October, 1994.
   Part 6, LOTUS Spreadsheet Economics Model (Restricted Addendum), March, 1996.

5. Training Session Report, *ASPEN Process Flowsheet Simulation Model - Training Session Report,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, October, 1994.

6. Topical Report, Volume V (1 of 2), *ASPEN PLUS Process Simulation Models for Fischer-Tropsch Indirect Coal Liquefaction,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, November, 1994.

7. Topical Report, Volume V (2 of 2), *ASPEN PLUS Process Simulation Models for Direct Coal Liquefaction,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, November, 1994.

8. Topical Report VI, *Natural Gas Fischer-Tropsch Case, Volume I, Summary Report,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, August, 1996.

9. Topical Report VI, *Natural Gas Fischer-Tropsch Case, Volume II, Plant Design and Aspen Process Simulation Model,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, August, 1996.

10. Topical Report VII, *Natural Gas Based Once-Through Fischer-Tropsch Design with Power Coproduction,* "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, March, 1998.

A2 Quarterly Reports

1. Quarterly Report, October - December 1991, Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, April, 1992.

2. Quarterly Report, January - March 1992, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, June, 1992.

3. Quarterly Report, April - June 1992, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, August, 1992.

4. Quarterly Report, July - September 1992, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, January, 1993.

5. Quarterly Report, October - December 1992, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, March, 1993.

6. Quarterly Report, January - March 1993, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, June, 1994.

7. Quarterly Report, April - June 1993, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, June, 1994.

8. Quarterly Report, July - September 1993, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, June, 1994.

9. Quarterly Report, October - December 1993, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, August, 1994.

10. Quarterly Report, January - March 1994, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, August, 1994.

11. Quarterly Report, April - June 1994, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, October, 1994.

12. Quarterly Report, July - September 1994, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, December, 1994.

13. Quarterly Report, October - December 1994, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, February, 1995.

14. Quarterly Report, January - March 1995, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, November 1995.

15. Quarterly Report, April - June 1995, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, March, 1996.

16. Quarterly Report, July - September 1995, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, March, 1996.

17. Quarterly Report, October - December 1995, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology, Contract No. DE-AC22-91PC90027, Pittsburgh, PA, April, 1996.

A3 Technical Progress Meeting Conference Notes

1. October 21, 1991 Kickoff Meeting - conference note issued November 4, 1991.
2. February 26, 1992 Progress Meeting - conference note issued March 16, 1992.
3. August 5, 1992 Progress Meeting - conference note issued August 14, 1992.
4. March 4, 1993 Progress Meeting - conference note issued March 10, 1993.
5. June 17, 1993 Progress Meeting - conference note issued August 24, 1993.
6. February 2, 1994 Progress Meeting - conference note issued March 16, 1994.
7. July 1, 1994 Progress Meeting - conference notes issued July 12, 1994.
8. November 9, 1994 Project Meeting on 'Crude Oil Equivalent (COE)' Coal Liquefaction Economics - conference note issued February 22, 1995.
9. February 14, 1995 Progress Meeting on Coal Liquefaction Economics - conference note issued February 28, 1995.
10. February 16, 1995 Progress Meeting - conference note issued March 13, 1995.
11. November 16, 1995 Progress Meeting - conference note issued November 29, 1995.
12. February 20, 1996 Progress Meeting - conference note issued February 28, 1996.
13. December 4, 1996 Progress Meeting - conference note issued December 14, 1996.
14. June 12, 1997 Progress Meeting - conference note issued June 19, 1997.

A4 Letter Reports

1. Letter from Samuel S. Tam to Shelby Rogers, subject "Final Project Management Plan," March 6, 1992.

2. Letter from Gerald N. Choi to Gary Stiegel, subject "Syncrude Technology F-T Design Based on Natural Gas," September 8, 1995.

3. Letter from Gerald N. Choi to Shelby Rogers, subject "Revised Fischer-Tropsch Slurry Reactor Kinetic Model," March 25, 1996.

4. Letter from Donald P. Daley (Burns and Roe Services Corporation) to R. Huco, subject "Delivery of a Paper and Presentation Material for the Society of Petroleum Engineers Meeting," May 21, 1996.

5. Letter from Gerald N. Choi to Dr. Normal L. Carr, subject "Once-Through Fischer-Tropsch Design with Power Coproduction: Flow Drawings, H&M Balances and Preliminary Cost Estimate," March 3, 1997.

6. Fax from Gerald N. Choi to Dr. Ram Srivastava, [subject "Preliminary STI Study Results"], May 1, 1997.

APPENDIX B

PUBLICATIONS AND PRESENTATIONS

APPENDIX B

PUBLICATIONS AND PRESENTATIONS

This appendix reprints of all the publications and presentations that were prepared during the course of this DOE contract, Contract No. DE-AC22-91PC90027, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology." Following is a chronological list of these presentations.

1. Tam, S. S., Cheng, Y. L, Degen, B. D., Fox, J. M. III, Schachtschneider, A. B., and S. J. Kramer, "Indirect Liquefaction Baseline Design," DOE Liquefaction Contractors' Review Conference, Pittsburgh, PA, September 22-24, 1992.

2. Choi, G. N., Tam, S. S., Fox, J. M. III, Kramer, S. J. and J. J. Marano, "Baseline Design/Economics for Advanced Fischer-Tropsch Technology," DOE Coal Liquefaction and Gas Conversion Contractors' Review Conference, Pittsburgh, PA, September 27-29, 1993.

3. Choi, G. N., Tam, S. S., Fox, J. M. III, Kramer, S. J. and S. Rogers "Process Simulation Model for Indirect Coal Liquefaction Using Slurry Reactor Fischer-Tropsch Technology," Symposium on "Alternative Routes for the Production of Fuels," A. C. S. National Meeting, Washington, D. C., August 21-26, 1994.

4. Marano, J. J., Rogers, S., Choi, G. N. and S. J. Kramer, "Product Valuation of Fischer-Tropsch Derived Fuels," Symposium on "Alternative Routes for the Production of Fuels," A. C. S. National Meeting, Washington, D. C., August 21-26, 1994.

5. Choi, G. N., Tam, S. S., Fox, J. M. III, Kramer, S. J. and J. J. Marano, "Process Design/Simulation Models for Advanced Fischer-Tropsch Technology," DOE Coal Liquefaction and Gas Conversion Contractors' Review Conference, Pittsburgh, PA, September 7-8, 1994.

6. Choi, G. N., Kramer, S. J., Tam, S. S. and J. M. Fox. III, "Simulation Models and Designs for Advanced Fischer-Tropsch Technology," Proceedings of the DOE Coal Liquefaction and Gas Conversion Contractors Review Conference, Pittsburgh, PA, August 29-31, 1995.

7. Choi, G. N., Kramer, S. J. and S. S. Tam, "Effect of Product Upgrading on F-T Indirect Coal Liquefaction Economics," 12th Annual International Pittsburgh Coal Conference, Pittsburgh, PA,. September 11-15, 1995.

8. Choi, G. N., Kramer, S. J., Tam, S. S., Srivastava, R. D. and G. J. Stiegel, "Natural-Gas Based Fischer-Tropsch to Liquid Fuels: Economics," Society of Petroleum Engineers 66th Western Regional Meeting, Anchorage, AK, May 22-24, 1966.

9. Choi, G. N., Kramer, S. J., Tam, S. S. and J. M. Fox. III, "Economics of a Natural Gas Based Fischer-Tropsch Plant," First Joint Power and Fuel Systems Contractors Conference, Pittsburgh, PA, July 9-11, 1996.

10. Choi, G. N., Kramer, S. J., Tam, S. S., Fox, J. M. III and W. J. Reagan, "Fischer-Tropsch Indirect Coal Liquefaction Economics - Mild Hydrocracking vs. Fluid Catalytic Cracking," Symposium on "Coal Liquefaction/Coprocessing," A. C. S. National Meeting, Orlando, FL, August 25-29, 1996.

11. Choi, G. N., Kramer, S. J., Tam, S. S. and J. M. Fox III, "Design/Economics of a Natural Gas Based Fischer-Tropsch Plant," American Institute of Chemical Engineers Spring National Meeting, Houston, TX, paper 28d, March 10-13, 1997.

12. Choi, G. N., Kramer, S. J., Tam, S. S. and J. M. Fox III, "Design and Economics of a Fischer-Tropsch Plant for Converting Natural Gas to Liquid Transportation Fuels," Symposium on Clean Fuels, A. C. S. National Meeting, San Francisco, CA, April 13-17, 1997.

13. Choi, G. N., Kramer, S. J., Tam, S. S., Fox III, J. M., Carr, N. L. and Wilson, G. R., "Design/Economics of a Once-Through Natural Gas Fischer-Tropsch Plant with Power Co-Production," Coal Liquefaction and Solid Fuel Contractors Review Meeting, Pittsburgh, PA, Sept. 3-4, 1997.