APPENDIX F

PEER REVIEWERS' COMMENTS

A draft final version of this report was sent to ten outside reviewers. The reviewers were chosen for their experience and background in coal liquefaction research and development. The following people served as peer reviewers of this report:

1. Mr. Seymour Alpert, Electric Power Research Institute
2. Dr. Raymond Anderson, National Institute for Petroleum and Energy Research
3. Dr. David Gray, MITRE Corporation
4. Dr. Gerald Huffman, University of Kentucky
5. Dr. Alex Mills, University of Delaware
6. Mr. Eric Reichl, Consultant
7. Dr. George Roberts, Air Products and Chemicals
8. Dr. David Schmalzer, Argonne National Laboratory
9. Dr. Howard Stephens, Sandia National Laboratory
10. Dr. Duayne Whitehurst, Mobil Oil

In most instances peer reviewers' comments were incorporated within this report, particularly those which dealt with corrections or specific changes. Policy recommendations, opposing viewpoints, and comments which may be of general interest are reproduced in this appendix.

F.1 COMMENTS FROM SEYMOUR ALPERT (FEBRUARY 2, 1989)

I have completed the review of the report on "Assessment of Coal Liquefaction Research Needs" that was sent to me on January 6, 1989. I find the report authoritative and thorough. The detailed Chapters 4 to 9 are well prepared and show an important recent body of work. The report competently summarizes the research work performed over the last decade or so. When the report is completed, I would like a copy for my files.

Enclosed are detailed comments on Chapter 3 which draws on the detailed treatment in the next Chapters 4 to 9. I agree with the panel's recommendations and priorities and the broad conclusions of the panel.

I have read each of the detailed chapters, which are well done. The subject of bioconversion is a difficult one. It is a research topic and will require a long duration program with uncertain outcome. I found that section of the report realistic in its appraisal and not too optimistic. The rest of the sections also seem to present a balanced perspective.

F.2 COMMENTS FROM ERIC REICHL (JANUARY 19, 1989)

I appreciate the opportunity to review this exceptionally fine report and hope you will find my comments helpful.

I. General Comment

This is an outstanding report. The high quality of the report is, of course, a reflection of the excellent choice of panel members; their wide experience and competence assured that the total status of the synfuel enterprise was exhaustively reviewed and the major advances of recent years were described in a clear manner; this includes particularly the reasoning underlying individual developments. This is true of all sections of the report, especially Chapters 4 through 8.

II. Comments on Direct Liquefaction

When IG-Farben decided in 1923 to proceed with the commercial development of the Bergius process, the ratio of gasoline to coal price, in terms of \$/BTU, was 8:1. Today, 65 years and billions of \$'s later, the ratio still is 6:1 (see Table 4-21); all this in spite of the great improvements which have been achieved, such as:

- reduction of pressure from 10,000 PSI to 2500 PSI;
- cutting H_2 - requirement in half (6 vs. 12%)
- improving the yield pattern (selectivity)
- lowering cost of hydrogen by pressure gasification

Evidently the processing of solids is inherently a forbidding, expensive task, and there is doubt whether the pace of improvement we have seen in the last 8 years, from EDS to H-Coal to ITSL to CTSL, can be maintained by further pursuit of the current path; specifically the 2-stage, thermal/catalytic process using the Co/Ni/Mo catalysts which dominate petroleum processing.

The cost of direct liquefaction, as currently perceived, is embedded in the basic need for processing coal at 2500 PSI with about 6% H_2 addition. Even if the catalytic reactors were completely eliminated, the cost of product would not drop very much. To make further advances implies the discovery of some new approach which might allow operation in the 250-500 PSI range. This would require new insights in coal chemistry, possibly a slight retreat from depth of conversion, and probably some new type of catalysis. In this context it remains unexplained why the unique results obtained 10 years ago with molten $ZnCl_2$ have not aroused more interest in the R&D community. There was a totally different homogenous catalyst with great activity and specificity; it certainly deserves another look with the benefit of the greatly improved diagnostic systems which have since come on line (see also Chapter 6; Reference 70 & 71 and Chapter 4; Reference 97). Quite generally, R&D needs to be more "exploratory" and less "programmatic", and particularly the university laboratories should be encouraged in this direction.

The key conclusion re direct liquefaction, as of 1989, is the remarkable advance made since EDS/H-Coal. Given the actual operating experiences from these earlier 200-T/D plants and the extensive use of catalytic hydrocracking in the oil industry, the current state of the art as described in the report makes the $35/bbl present cost very credible. The same range, incidentally, is evident from the latest operation of F-T indirect conversation at SASOL and Great Plains.

A firm and credible CAP is thus set on the price of petroleum, which is, of course, well below the $35/bbl figure since the world oil price must be kept well below the synfuel cost, lest it trigger the production of this alternate in quantity. In fact, the nation has been well rewarded for its synfuel efforts during the last 2 decades, all comments by the many detractors notwithstanding.

III. Comments on Indirect Liquefaction

Here again the report is an excellent comprehensive review of the present state of the art. However, the subject covered has relatively little to do with coal liquefaction. It is narrowly limited to the conversion of CO/H_2 mixtures to marketable liquid fuels. As is well known, this part of the total path from coal to liquids is very highly developed and well covered by R&D in the private sector. As matters stand, further efforts along the suggested lines of R&D will do little to improve the economics of indirect coal liquefaction.

The two major reasons for this are: first, the fact that in indirect liquefaction the cost of preparing clean synthesis gas from coal under pressure represents probably 4/5 of the total cost, and second, the fact that CO/H_2 conversion is already so efficient and specific that further improvements are destined to be irrelevant.

Finally, one may add, that CO/H_2 mixtures are much more economically produced from natural gas; the large and often remote resources of gas have led the oil and chemical industry towards a concentrated R&D effort in the catalytic CO/H_2 conversion area. There is no need for DOE to interfere with these private-sector efforts.

I realize that DOE has established a sharp programmatic distinction between "gasification" and "liquefaction" of coal; hence the MAIN issue of R&D in indirect liquefaction, i.e., the gasification/gas clean-up segment, was arbitrarily left out of the COLIRN report. This is most unfortunate, because the reader is misled about the subjects which are important in indirect liquefaction; they are gasification and gas clean-up.

Actually the field of gasification is very adequately covered in the U.S. and abroad, by government and by private-industry R&D. It is thus not likely that increased gasification R&D will lead to significant improvements unless here, too, the program is directed towards more exploratory, non-orthodox concepts. An example (listed unfortunately under pyrolysis) is the catalytic gasification of char at relative low temperatures, admittedly a long shot.

Next to gasification proper, the extensive clean-up of syngas, particularly desulfurizing to <1 ppm H_2S, is one of the large cost items in indirect liquefaction. Virtually all classic CO/H_2 conversion catalysts are exquisitely sulfur sensitive. Any advance which would allow a less costly desulfurizing step is thus an exciting breakthrough. Apparently this has occurred; see Chapter 7, p. 76: DOW-HAS Process.

A more extensive evaluation of indirect liquefaction based on sulfur-resistant catalysts in the CO/H_2 conversion step should be recommended.

A somewhat more uncertain reduction in the cost of synthesis gas might be found in the use of air in lieu of oxygen. Here the potential advantage will be strongly affected by the required level of desulfurization. To permit liquid synthesis from air-blown synthesis gas (approx. 40-50% N2) would call for extremely active catalysts, of the type claimed, for example, by Brookhaven N.L. (Chapter 5, References 64, 65, 66).

To sum up: the hope of significant reductions in the cost of indirect coal liquefaction would most likely be found in CO/H_2 conversion systems which will allow use of lower-cost synthesis gas; this means higher sulfur content and, possibly, air-blown gas. This point needs to be highlighted in the COLIRN R&D Recommendations; it is not mentioned there.

IV. Comments on Pyrolysis

Here again the draft report constitutes an exhaustive review of the subject with emphasis on the last 2 decades. Of course pyrolysis has a much longer history, and it should be remembered that at the high point of synthetic fuel production, during the 1940's in Germany, the largest block of coal-based gasoline was produced by pyrolysis (of low-rank coal) followed by high-pressure catalytic hydrogenation of the resulting tar. A major reason for this preference of tar over coal as hydrofeedstock was the much higher synfuel capacity resulting from a given volume of high-pressure hydrogenation reactors if tar is fed in lieu of coal. It was thus possible to rapidly increase output, because pyrolysis units could be built more rapidly than high-pressure hydro stalls.

The panel recommends no "push" toward pyrolysis because it correctly notes that no significant improvements are to be expected from R&D in this most exhaustively tested of all coal processing schemes. I will therefore simply express complete agreement with this conclusion. No attempt to unravel the chemistry of this complex thermal degradation of coal will open the door to any more economic pyrolysis. This is so even if there may be a few selected instances where it can succeed.

The report did not draw particular attention to one very important issue, usually the major operating problem which arises when coal is pyrolyzed at optimum tar-forming temperature (800-1000° F). A very large part of U.S. coals exhibit this "caking" property, which has dominated process technology. Various means to live with this property have been developed, but all ultimately result in higher cost plant per ton of throughput.

The swelling or "caking" tendency is enormously increased by any hydrogen treatment, however applied. Coal simply fuses as hydrogen begins to react with coal; as expected, this tendency is less with lower-rank coal. The obvious answer to this problem, first recognized by Bergius, is of course operation in liquid phase; this breakthrough remains as valid today as it was in 1912.

I am therefore not optimistic about the potential of hydropyrolysis, which is recommended by the COLIRN Panel. This is particularly so, if the "pyrolysis" is to be carried out under > 2000 PSI of hydrogen. If coal is to be processed with high-pressure hydrogen, it should be done in liquid phase along the line of direct liquefaction, say CTSL. A "dry" coal reactor with 2000 PSI hydrogen would be inoperable due to swelling of the coal. Besides, in the absence of catalysts, the use of hydrogen would be very inefficient, much of it going to CH4; it would be a major step backward.

This leaves the potential of "catalytic hydropyrolysis"; this is of course just another word for "direct hydrogenation in dry phase" as I understand the proposed thrust. In chemical terms there is little difference between testing coal with 2000 PSI hydrogen in a "dry" system or a liquid system; if it works, it will not stay "dry" very long.

This comment is not intended to deny the interest in the low-pressure hydrogenation of Utah and Montana coals with $ZnCl_2$ catalyst (see Fig. 6-3). This work was probably done on a small laboratory scale, and the correct technology for carrying out this reaction on large scale may very well be liquid (slurry) phase, just to keep control of runaway temperatures, which are the key concern with large-scale hydrogenation systems treating coal.

In other words: catalytic hydropyrolysis may simply be a new buzzword and should really be treated as part of the wider subject of "innovative catalysts for hydrogenation at lower pressures." This is certainly a proper target for R&D.

F.3 COMMENTS FROM DAVID SCHMALZER (JANUARY 30, 1989)

The subject draft report is generally well written by knowledgeable individuals, and I would concur in most of the recommendations. I believe, however, that process development and large pilot-plant activities must receive substantially greater resources than DOE has provided in recent years if there is to be any substantial likelihood of commercially deployable, U.S.-based technology available in the foreseeable future.

There are fundamental problems in the current DOE programs that virtually assure the failure of advances from basic research finding their way into process development, and also of processes being developed to the point that technical and economic risks become consistent with commercial deployment. Absent adequate resources at the process development and demonstration level, basic work will tend to dead end. In this environment, fundamental findings are likely to provide interesting and valuable scientific literature; however, their economic value is much more likely to be exploited in Japan or Germany than in the United States. I believe, therefore, that the panel's recommendations over-emphasize the need for and value of basic research on liquefaction given the inadequate resources provided for meaningful utilization of the products of basic research.

Some other advisory groups, notably the Energy Research Advisory Board (ERAB), have placed much greater emphasis on the need for pilot- and demonstration-scale activities if synfuel technologies are truly expected to be commercialized.

Direct liquefaction well illustrates two concerns expressed by the panel: the seeming inability to transfer basic research findings into the process development sphere and the seeming inability to move liquefaction technology from the process development phase to demonstration-scale or commercial-scale plants. The termination of DOE funding of bench-scale continuous flow process exploration and initial process development units has created a major barrier to the transfer of chemistry findings to the process development sphere, as process development work has virtually stopped in the United States. In a similar vein, the termination of the large pilot-plant and demonstration-plant programs leaves U.S. process developers with no vehicle for moving partially developed processes to the point of readiness for commercial deployment.

The recent Union Oil shale retorting plant has graphically illustrated that technological risk cannot be ignored in pioneer plants employing new technology at substantial scale. Similarly, the Great Plains Gasification Plant has shown that even for a facility where the technology of the major process elements is relatively mature, environmental issues and product price shifts can make a multi-billion dollar plant uneconomic.

In indirect liquefaction, the report devoted great attention to the potential for improvement in well-developed catalyst systems and chemistry for the production of methanol and higher alcohols from synthesis gas, but said little regarding the technology or economics of the production, purification, and shifting of synthesis gas derived from coal. As production, purification, and shifting represent a substantial, possibly dominant, fraction of the costs in a coal-based facility, greater research attention to those aspects of the process could have greater economic impact than minor improvements in well-developed catalyst systems.

The usability and value of char produced in coal pyrolysis is critical to process economics, and I feel the panel is accurate in indicating that conventional pyrolysis approaches are unlikely to produce major improvements in yields or economics.

Coal-petroleum coprocessing can be viewed as a special case of direct liquefaction, and any substantial scale coprocessing or other special applications of direct liquefaction should be encouraged as their experience will be valuable in reducing the technical risk of subsequent direct liquefaction facilities.

I appreciate the opportunity to comment on this draft report and hope that you and the panel will find the comments constructive. I would like to receive a copy of the final report when it issues.

The following are specific comments on the subject report keyed to the page numbering on the draft.

Page 3-14 - Paragraph 1
An additional need for the operation of an integrated pilot plant is a development of meaningful environmental, safety, and health information. Worker health and safety and the potential environmental impact of such facilities on local areas are highly sensitive issues are potentially critical to the permitting, construction, and operation of demonstration or commercial scale liquefaction facilities. These issues will exist notwithstanding any election to limit net plant product to 650° F minus streams which appear to have toxicological properties similar to their petroleum counterparts.

Page 3-49 - Figure 3-2
Under coprocessing it indicates DOE seeks transitional technology having potential for near-term production of coal liquids using, to a large extent, existing petroleum refining facilities and technology. If one assumes that existing ebullated-bed hydrocracking units could coprocess petroleum and meaningful quantities of coal without major rework, an assumption that is likely unwarranted, the number and capacity of ebullated-bed units in the United States is very small. It is exceedingly difficult to envision the utilization of fixed-bed hydrocracking/hydrotreating units for coal oil processing without major rework of such units.

Page 4-50 - Paragraph 3

The paragraph asserts that U.S. industries and processes have usually employed high-area supported catalysts operating at lower pressures and accepted higher catalysts costs than European (e.g., German) developers. This is inconsistent with the facts. Of the processes reaching large pilot plant-scale of development, EDS, SRC I, and SRC II employed native coal minerals or throw-away materials as liquefaction catalysts, and only H-Coal used a supported catalyst. EDS employed catalytic hydrotreating of coal derived distillates in its pilot plant, and SRC II had developed and patented a variant of the SRC II process that employed catalytic hydrotreatment of reactor effluent high-pressure separator overhead (distillate) materials.

Page 4-73 - Paragraph 4

As discussed earlier, environmental, safety, and health issues have the potential for being major impediments to commercialization. Any DOE program that envisions ultimate commercial deployment of the technology would be well advised to implement supporting activity that will provide a firm basis for "regulatory agency and public perception concerns."

Page 4-164 - Paragraph 2

While Wilsonville has been and remains a useful facility it is more a large PDU or small pilot plant than a large pilot plant, and has neither the scale of equipment nor level of process integration necessary for commercial process confirmation. Should DOE have the resources, some combination of a few bench-scale continuous recycle units for process screening and process parameter studies and at least one integrated pilot plant of 100 to 200 tons per day capacity would be desirable. A PDU-scale unit, perhaps with 0.5 to 2.0 tons per day of capacity, and the design and instrumentation capable of highly accurate material balances and yield determinations would also be desirable.

Page 5-41 - Bullets 1 through 6

Given that the heterogeneous methanol catalysts have high activity, excellent selectivity, relatively low cost, and three-four year lifespans there seems to be little economic incentive in those areas for developing homogeneous liquid-phase catalysts. If a homogeneously catalyzed system has economic merit over existing systems it will likely be from improved heat transfer, allowing higher per-pass conversation. That reaction kinetics are simpler and intermediates more easily characterized in a homogeneous system seems unlikely to motivate a change in industrial practice. Methanol synthesis reactor design is generally limited by heat transfer from the highly exothermic reaction, not by catalyst activity or selectivity.

Page 8-10 - Paragraph 2

If the mature cheese industry typically loses 3% of its batches due to biological contamination, similar problems could exist in a much less mature coal conversion process, though the scale of the batches would tend to be much larger. The environmental consequences of contaminated bioprocess batches should be explored.

Page A-3 - Paragraph 6

The FERWG-II recommendation regarding measurement and control instrumentation and devices was well taken and deserves consideration in the present assessment.

F.4 COMMENTS FROM G. ALEX MILLS (JANUARY 28, 1989)

The draft report "COAL LIQUEFACTION: A RESEARCH AND DEVELOPMENT NEEDS ASSESSMENT" has been reviewed as requested. My comments are presented below.

This report provides a comprehensive and authoritative review of the status of coal liquefaction science and technology. In general I am in agreement with the recommendations. Many of the sections are excellent.

This report does not bring out the surge in technology and commercialization for oxygenate fuels made from syngas. Fundamental to their success is the new evaluation of fuels based on their high performance as octane enhancers, made critically significant with phase-out of lead. Pertinent information is the phenomenal success of MTBE (synthetic methanol makes up 36% of MTBE), the scale of M-85 (85% methanol) in California and of premium gasoline containing mixed alcohols in Italy, new capabilities for use of methanol in flexicars and diesel engines, and the recent requirements for use of fuels containing oxygenates in Colorado to assist in protecting the environment. I think that DOE is not giving sufficient support to indirect liquefaction and particularly for research on synthesis of the oxygenates.

I believe that there should be more importance given to innovative research. Emphasis is given to fundamental research. This can be fruitful in a practical sense if it leads to inventive ideas. Thus the encouragement of fundamental research should be matched by support of inventive research. The Japanese program stresses exploratory innovative research.

I would like to add emphasis to the recommendation for coal gasification research, a subject not discussed at length in this report. It did receive a fairly high rating as Item D 4.

Chapter 4. Review of Direct Liquefaction.

This chapter is particularly useful in that it is so comprehensive, including as it does research, development, and economics. The interrelationships of the various processes and their evolution is very helpful, as well as a clear account of the advances achieved by utilizing the close-coupled two-stage concept, configurations which include new solvent separation techniques, and the production of a liquid of < 650° F boiling point. I have two particular concerns and some comments.

1. Liquid Yields. The yield of liquids, either in terms of % or Bpt, is presented in a manner which is incomplete or indeed misleading. Table 4-11 makes it appear that the distillate yield has increased from 41 to 78 wt% in the period 1982 to 1987. (2.4 to 5.0 Bpt). Likewise Table 4-9 gives the impression that 5.0 Bpt of coal are obtained, although careful reading does show that there is the requirement for chemical hydrogen. I believe that the amount of coal needed to produce the hydrogen should be shown and the net Bpt of liquid produced.

2. This chapter calls repeatedly for innovation but does little to point the way. Certainly in the right direction is the statement on page 4-26 that "research is needed to develop catalysts which will positively affect the initial coal conversion". But there is little presentation of innovative ideas.

3. In regard to reference to foreign technology, it seems to me an overstatement that they have adopted the two-stage concept. The Japanese have just made a commitment to build a large pilot plant based primarily on the U.S. EDS process. The Germans' process is a continuation of their WWI Bergius process using red mud. Incidentally, it might be worth noting as a footnote to Table 4-42 that the German process can operate successfully on U.S. coals at 200 atm pressure although German coals require 300 atm.

4. There is an environmental issue of importance which is not addressed. This is the restrictions of the aromatic contents of

gasoline. California is proposing 0.8% benzene, and Europe has a benzene limit of 5% effective in 1989.

5. Boiler Fuel. As a somewhat historical note, it can recalled in connection with p. 4-81, -85, that coal liquefaction received its major push in the 1970's to produce a clean boiler fuel. This need has been met by effective stack - gas scrubbers using technology which was not available then nor was it obvious that economical processes could be developed.

Chapter 5. Review of Indirect Liquefaction.
This chapter presents both an excellent overview and a critical summary of the catalytic chemistry involved. There are several comments and a few minor suggestions.

1. MTBE. The report could bring out more strongly that there has emerged a new criterion for determining the value of synthetic oxygenate fuels. This is based on their high performance in use, particularly their ability for octane-enhancement, made more significant with phase-out of lead in gasoline. This comment is particularly true for the ethers but also applies for the alcohols.

The statement that the volume of MTBE is limited by the availability of isobutylene, page 5-115, is misleading. Butanes are available in large supply and can be converted by isomerization and dehydrogenation to isobutylene. This is being done commercially in a Texas plant and in the largest MTBE plant in Saudi Arabia mentioned on page 5-116.

Page 5-115 states that MTBE relies on petroleum at least to 80-83%. However, methanol, mw 32, provides 36.4% of the weight of MTBE, mw 88.

The pioneering commercialization of MTBE and its phenomenal growth in Europe is particularly well described in "European Oxygenates Experience," F. Morandi, R. Trotto, G. Pecci and M. Sposini, Energy Progress, 8, no. 1, p. 1-15 (1988).

2. Methanol. Many are convinced that neat or near-neat methanol will be a major fuel of the future. While the technology for methanol manufacture is old, there have been recent technical advances, for example - Macnaughron, Pinto and Rogerson, Energy Progress, 4, no. 4, p. 232 (1984) and Dybyjaer and Hansen, Chem. Ec. and Eng. Rev., 17, no. 5 (1985).

3. Dual-Site Catalysis and Catalyst Design. The establishment and delineation of the essential dual-site mechanism of syngas hydrogenation seems to me to be a major breakthrough. This appears in various places in the report, p. 5-54 and 55, 5-105 and 5-107. It could be emphasized more, particularly in the sense that this provides the opportunity to design superior catalysts in which each site is optimized and including the knowledge that the site for hydrogen activation should be one which is not poisoned by CO.

4. Mobil Slurry FT. Reference is made to the processing of FT products using catalysts containing ZSM-5 molecular sieve. However, the research conducted at Mobil goes beyond that. By use of a slurry FT synthesis technique and followed by processing with ZSM-5, it was possible to obtain high yields of wax and of 92-octane gasoline. (Ref. 1 of Chapter 5).

5. It may be pointed out that the information given relating to group VIII metal catalysts is very abbreviated relative to the major research activity in this field. Table 5-16 is particularly abbreviated.

Chapter 9. Liquefaction Development Outside the U.S.

This chapter provides a concise and comprehensive account of foreign developments in direct coal liquefaction. However, a similar account would be desirable for indirect liquefaction. The following or similar information is suggested.

Federal Republic of Germany.

The Winkler process has been improved by developing technology for operation at high temperature, 950° C, and elevated pressure, 1 MPa. Rheinische Braunkohle constructed and operated a large demonstration plant, which converts 30 t/h German brown coal to syngas which is used to produce about 14 t/h of methanol. Some of the methanol is used to operate demonstration VW autos fueled by a mixture of 85% methanol-15% hydrocarbons.

Japan.

An intensive R&D effort is underway to convert syngas to mixed alcohols for motor fuel use. This is sponsored (1) in universities by the Ministry of Education, Science and Culture, (2) in industry by the RAPAD program -- Research Association for Petroleum Alternative Development -- and (3) in extensive research in the National Institute for Chemical Research for Industry. There is emphasis on innovation, with the particular objective to produce alcohol mixtures with relatively large amounts of ethanol.

Using technology developed by the French Institut du Petrol and in Japan, a 7,000-BPY plant producing mixed alcohols has been constructed and operated by Idemitsu Kosan.

Italy.

Italy has been a pioneer in the establishment of technology and commercial manufacture of MTBE and also of mixed alcohols from syngas for transportation fuels. The SEHT process, described in Chapter 5 of this report, was operated at a 15,000-TPY plant for the production of higher alcohols during the period 1982-87. The alcohols were blended at the 4.3% level in gasoline and marketed as SUPER E.

Italy was also the pioneer in the commercialization of MTBE, building a 100,000-TPY plant in 1973. Production of MTBE was expanded greatly and reached 1,150,000 TPY in western Europe by 1988.

The above information and relevant references are provided in the report G.A. Mills, "Catalysis for Fuels from Syngas, New Directions for Research", IEACR/09, 1988, [NTIS # IEACR 8901].

F.5 COMMENTS FROM G.P. HUFFMAN (FEBRUARY 1, 1989)

I have completed my review of the COLIRN report, "Coal Liquefaction -- A Research and Development Needs Assessment." I found it to be well-written and informative and I congratulate the panel on a thorough, well-done job. Specific comments are given below.

Chapter 3.

Section 3.2.1, p. 3-12. Priority 1, Retrograde Reactions.

It would be of interest to investigate the coke/char formed by various coals under identical liquefaction conditions by petrographic, chemical and physical techniques. The recommendation does not specifically call for such research, although it is implied.

Generally speaking, I agree with the rankings in Section 3.2, but would have rated Coal Structure-Reactivity and Homogeneous Catalysts higher.

Section 3.4.2--Pyrolysis

Since the large amount of char produced seems to be the major problem, I would have thought studies of char gasification, perhaps coupled with indirect liquefaction of the syngas, might have been a high-priority topic.

Section 3.9, p. 3-56

I agree that many DOE RFP's are unnecessarily constrictive. This causes fewer responses because potential proposal writers feel that the RFP is directed towards a particular group, laboratory or process. RFPs should be more generic.

Chapter 4

Section 4.2.1.3 p. 4-10

The need for adsorptivity measurements using appropriate solvents should be noted.

p. 4-15--New methods ought to be tried for determining M i.e. M_C, e.g., small angle synchrotron radiation scattering and atomic force microscopy (AFM) are possibilities.

p. 4-18--An additional reference to XAFS studies or organic sulfur in coal should be added: G.. Huffman, F.E. Huggins, S. Mitra, N. Shah, R.J. Pugmire, B. Davis, F.W. Lytle and R.B. Greegor, "Investigation of the Molecular Structure of Organic Sulfur in Coal by XAFS Spectroscopy," Energy & Fuels, in press.

p. 4-21--The paragraph on magnetic resonance should contain references to some excellent recent work by Pugmire et al. using the techniques of variable angle sample spinning (VASS) and depolar dephasing. Some excellent recent in situ ESR work by Seehra which determined the free radical concentration as a function of temperature during pyrolysis should also be mentioned. The references are:

> Sethi, N.K.; Pugmire, R.J.; Facellie, J.C.; and Grant, D.M., Anal. Chem., 60, 1574 (1988).
>
> Pugmire, R.J.; Sethi, N.K.; Solum, M.S.; Facelli, J.C.; and Grant, D. M., "The Use of Variable Angle Sample Spinning 13C-NMR Spectroscopy to Assess the Aromatic Cluster Size in Coals, Coal Chars, and Carbonaceous Materials," Carbon '88 Proc., University of Newcastle Upon Tyne, U.K. 18-23 September 1988, p. 349.
>
> M.S. Seehra, B. Ghosh and S.E. Mullins, Fuel, 65, 1315 (1986).41.5

p. 4-22--Low-temperature ashing followed by X-ray diffraction or FTIR is not a good way to study mineral matter. Computer-controlled scanning electron microscopy (CCSEM), coupled with element-specific spectroscopic methods like Mossbauer and XAFS spectroscopy, is preferable. These methods all investigate the whole coal directly. Typical references are:

> F.E. Huggins, G.P. Huffman, and R.J. Lee, in: Coal and Coal Products: Analytical Characterization Techniques, ACS Symposium Series, 205, ed. E.L. Fuller, Jr., pp. 239-258, Amer. Chem. Society, 1982.
>
> G.P. Huffman, F.E. Huggins, N. Shah, D. Bhattacharyya, R.J. Pugmire, B. Davis, F.W. Lytle, and R.B. Greegor, in: "Processing and

Utilization of High Sulfur Coals II," eds. Y.P. Chough and R.D. Caudle, pp. 3-12, Elsevier, 1987.

Sections 4.2.2 and 4.2.3 were both well written and informative. However, there was little discussion of catalyst structure versus catalyst performance. This would seem to be an area where more work is needed.

Section 4.3--Direct Liquefaction Process Development. An excellent review of pilot plant activities in this country. Sections 4.3.4 and 4.3.5 are good, brief summaries of the economic and environmental aspects of coal liquefaction.

Chapter 5

Section 5.3--A very thorough, informative review. The discussion of the various types of catalysts used in oxygenate technology was excellent. The models of alkali promotion mechanisms were summarized particularly well.

Chapter 6.

Sections 6.2.1 and 6.2.2 would have been clearer and easier to read with the additions of a few figures displaying pyrolysis behavior as a function of time, temperature, coal rank, etc.

The outstanding pyrolysis/mass spectrometry work by Meuzelaar et. al. should be referenced. Two recent papers are:

T. Chakravarty, H.L.C. Meuzelaar, P.R. Jones, and R. Khan, ACS Div. of Fuel Chem. Preprints, 33(2), 235-41 (1988).

B.L. Hoesterey, W. Windig, H.L.C. Meuzelaar, ACS Div. of Fuel Chem. Preprints, 32(2), 195-203 (1987).

p. 6-25--Catalytic hydropyrolysis sounds promising relative to other pyrolysis techniques, but isn't it essentially a low-pressure direct liquefaction process?

Chapter 7

The review of coprocessing was well done and identified most of the major research needs in that area. I would suggest two small additions, however. On p. 7-19, where demetallation of the oil is discussed, the following could be added: Recent work by Wender's group indicates that vanadium is present as a porphyrin in the crude oil and retains that same basic structure during incorporation into mesophase preceding coke formation (48).

48. T.J. Miller, S.V. Panvelker, I. Wender, J.W. Tierney, Y.T. Shah, and G.P. Huffman, ACS Division of Fuel Chem. Preprints, 33(3), 202-210 (1988).

In the discussion of small pilot scale coprocessing operations, recent work on tar sand coprocessing and isotope abundance studies at the Kentucky Center for Applied Energy Research should be mentioned.

Chapters 8 and 9 presented good summaries of bioconversion research and developments in other countries.

F.6 COMMENTS FROM R. P. ANDERSON (FEBRUARY 10, 1989)

Overall, I believe you have assembled an excellent panel and the study was well done. In general, I found the reviews of each of the five research areas well done. These reviews perhaps point out another research need; i.e., the need for a systematic complete review of everything we know about the liquefaction process to date. It is obvious that some of the work being performed has been done previously but may be published in obscure government reports, or obscure journals or in a foreign language.

Although it may have been difficult to reach a consensus, I believe that some relative weighting should have been assigned to each of the five research areas. There is perhaps an implicit ranking by the order in which the five areas are presented. I would agree with this ranking but would include coprocessing as a subtopic of coal liquefaction. For my own ranking of the level of effort for each area (based on my personal bias of where the most progress toward an economic process will be made), I would give very unequal ratings; e.g., direct liquefaction including coprocessing, 100; indirect liquefaction, 10; pyrolysis, 1; bioconversion, 0.1. I won't attempt a justification for this rating beyond the following. Significant improvements are being made in direct liquefaction. As for indirect liquefaction, we know that it works but the cost will surely be higher than for direct liquefaction. Attempts to beat the Anderson-Schultz-Flory distribution continue to fall short. It is doubtful that pyrolysis should be considered a liquefaction process, and char doesn't appear to be a very attractive primary product. Some effort on bioconversion may be justified, but for meeting any real energy needs I can't help believing bioconversion will remain pie in the sky.

I would have found references useful in the Executive Summary and/or Section 3. There are a number of assertions made which might be questioned. References to support such assertions would be useful. As an example, it is stated that coal liquids are suitable for processing in a refinery. I presume this is based on the Chevron work. I personally have no quarrel with the Chevron hydrotreating studies, but that work notwithstanding, I doubt that many refiners are going to welcome coal liquids into their refineries. Similarly, there are comments regarding retrogressive reactions without reference. Some leading references to this area would be useful. This is not a significant drawback to the report as copious references are provided in the following sections.

According to the report, a stated major objective of the DOE coal liquefaction program is to develop a data base that industry can use to commercialize coal liquefaction technology when needed. One area where data is needed which is recognized in the research reviews but is not addressed in the research needs is data required for engineering design and process scale-up. The absence and need for such data was recognized in the design efforts for the SRC-I and SRC-II demonstration plants, which led to overdesign and higher projected costs to compensate for the deficiencies.

In a recent engineering evaluation of the nonintegrated two-stage liquefaction (NITSL) process for coal prepared by Sterns Catalytic Corporation for the Electric Power Research Institute, the lack of thermodynamic data was highlighted in the section on critical areas of design and reliability.

There is no mention anywhere in the research needs report of the need for or use of thermodynamics. Physical chemistry is made up of two branches: thermodynamics and kinetics. The former tells you what can be done and the latter how fast you can accomplish it if it can be done. In the absence of thermodynamic data in the development of all stages of a process, the research is working in the dark. He/she is not able to know if the process is operating near equilibrium conditions, what effect changes in the conditions of operation will have, or if a change in catalyst will effect increased reaction. In the absence of accurate thermodynamic data, what could be done by calculation usually requires expensive and time-consuming experimentation.

F.7 COMMENTS FROM DAVID GRAY (FEBRUARY 21, 1989)

The size of the report is indicative of the enormous amount of effort that has been devoted to its preparation. The real meat of the matter is contained in the executive summary and the first three chapters. It is here that the research needs are identified and prioritized. The remainder of the report contains sometimes extensive overviews of the various technologies. My main criticism is that the research needs are not well justified by sound supporting material. For example, it should be possible for the reader to concur with the major recommendation in the direct liquefaction section that retrograde reactions should be minimized. However, there is no evidence provided that supports the supposition that these retrograde reactions are actually occurring or on how important they may be to the performance of the system. I suggest that a synopsis of the evidence supporting the R and D recommendations be included in Chapter 3. I think it should be specifically stated that the high capital costs of these plants is in large part due to the high severity of the current process conditions required to produce liquids. Thus the goal should be to reduce this severity without compromising the excellent yields that have been demonstrated at Wilsonville. Possible ways of accomplishing this may be through coal pretreatment, preconversion techniques or by more optimal temperature/time processing.

The same lack of scientific rationale exists in the recommendations for indirect liquefaction where the major recommendation is for improvements in catalysts. Current F-T catalysts at Sasol could be improved with respect to selectivity, but the major problem is heat removal from the highly exothermic F-T reaction. This is a problem of reactor design, not improved catalyst activity. It is well known that the greatest cost item in indirect liquefaction is the cost of preparing the clean synthesis gas; the effect of improved catalysts on the overall economics is not likely to be great. Catalyst R and D should be conducted for specific reactor systems since the requirements for fixed-bed and slurry systems will be different. As far as the DOE program is concerned, apart from a few precipitated iron catalysts that have been made in bench-scale amounts, there is no standard F-T catalyst on which to conduct reproducible R and D. Thus, a more down-to-earth goal of developing a working F-T catalyst that could be produced in a reproducible manner in sufficient quantities to be used by several contractors and in a larger PDU may be more appropriate. I do not understand the recommendation to develop sulfur-resistant water gas shift catalysts; these are already available commercially. A far better R and D goal would be to try and develop sulfur-resistant F-T or alcohol catalysts to minimize the complex and extensive gas clean-up currently required to protect catalysts.

There is no mention in the report of environmental aspects of these technologies that seek to use coal (a dirty word these days) to replace conventional petroleum. I think it would be wise to at least try and preempt criticism by emphasizing the positive aspects of these potential technologies with respect to their ability to produce clean products that are essentially sulfur free. Also, since the implicit goal of all this R and D is to improve overall efficiency, adverse environmental effects will be minimized.

With pyrolysis, the key question is always what is the point of pyrolysing coal when all I get are dirty gas, dirty liquids, and tar and a char that has considerably less value than the coal. Even if the liquids can be refined, at some considerable expense, there aren't enough of them to offset the large char yield. The major recommendation is for R and D on catalytic hydropyrolysis, which implies the panel does not think that thermal pyrolysis alone has any potential. In Chapter 6 there is some evidence to support the contention that catalyzed hydropyrolysis increases the liquid yield, as well it should considering the additional severity and expense this approach involves. A major problem not addressed in this area is that of reactor design. It is notoriously difficult to feed dry coal, especially high-volatile bituminous, under pressure into hot hydropyrolysis reactors. That is one reason slurry oils are used as in direct liquefaction. The other problem is removal of particulates in any pyrolysis process. When all these problems are taken into account and combined with the lower yields, it is difficult to imagine catalytic hydropyrolysis being economically competitive with direct coal liquefaction.

One aspect that could be mentioned is the complementary nature of the two processes of direct and indirect liquefaction. They are complementary in both the nature of the products that are produced (good gasoline from direct and good diesel from F-T) and also in many of their common process steps (gasification, product refining). There is thus the potential for hybrid plants in the future. I suggest a recommendation to study conceptual hybrid plants that utilize the best of both technologies as a potential way of reducing the costs of these technologies.

F.8 COMMENTS BY HOWARD STEPHENS, FRANCES STOHL, AND ARTHUR LYNCH (FEBRUARY 16, 1989)

We recognize that a review of the status of research and development efforts for coal liquefaction since the last similar report of the FERWG committee in 1980 was an immense task and that the COLIRN committee has made a commendable effort toward providing recommendations to effectively guide future research. From our perspective, we agree, in general, with the high-priority recommendations made for future R&D in coal liquefaction. Although we would add a few recommendations, reorganize them, and ladder rank the importance of the recommendations somewhat differently, we emphasize that, for the most part, they are sound recommendations made by persons with extensive experience in various aspects of research and development for coal liquefaction. We hope the following comments will make the report an even more effective document for planning future coal liquefaction research and development.

1. The body of the report is divided into two basic sections: coal liquefaction R&D Recommendations (Chapter 3) and a review of the status of the various liquefaction R&D technologies (Chapters 4 through 8). The bridge connecting the recommendations to the review of the status of R&D is the rationale or basis for formulating the recommendations. We found this rationale, as given in Chapter 3, to be weak, nonspecific and, in some instances, contradictory to other portions of the report. The rationale should directly link the specific needs identified in the review chapters to the recommendations given in Chapter 3 in order to demonstrate the need for the recommended research. The following are examples of weak or contradictory rationale.

   Pg. 3-17. Recommendation (Section) 3.2.2.8. "Develop new chemical techniques to solubilize coal." Again, the rationale needs to be clearly defined. It is stated that "nearly complete conversion of coal is achieved by alkylation with methanol." Conversion to products soluble in solvents such as THF or toluene (but not liquid themselves) does not necessarily lead to higher yields of liquid products.

Pg. 3-18. Recommendation (Section) 3.2.2.10. "Develop intrinsic rate expressions for initial coal dissolution reactions." Not only is this recommendation a subelement of Recommendation (Section) 3.2.2.7 -- develop kinetic models of direct liquefaction and 3.2.2.5 -- develop a coal structure-reactivity model, but there is no clear rationale given. One would assume that kinetic models of direct liquefaction would include the kinetics of the dissolution step, and that coal structure-reactivity models for coal liquefaction would include the kinetics of the reactions involved.

Pg. 3-24. Recommendation (Section) 3.3.2.1. "Apply new advances in materials science to catalyst preparation for F-T and alcohol synthesis." We agree with this recommendation, but the need for this approach needs to be clearly stated.

2. We note some inconsistencies between Section 4.2.3 "Catalysis of Direct Liquefaction" and the recommendations for direct liquefaction, specifically D6, D11 and D12. These recommendations address use of homogeneous catalysts, development of new catalysts, and studies of catalytic hydrogenation and cracking mechanisms. Although D6 recommends the evaluation of metal carbonyls for coal liquefaction, the basis for this is not mentioned in Section 4.2.3. In addition, the descriptions of promising new catalyst systems need to be augmented, and a discussion of the functions of catalysts in direct coal liquefaction needs to be included.

   In our judgement, <u>recommendations for augmenting catalyst R&D in support of direct liquefaction processes should rank as one of the highest-priority items</u>. This judgement is supported by the IEA Coal Research Report, "Catalysis in Direct Liquefaction: New Directions for Research," by Dr. Frank Derbyshire (COLIRN report, Chapter 4, reference 225). It is stated in this IEA report that "The supported catalysts now applied to liquefaction are plainly unsuitable for hydroprocessing high-boiling liquids due to their rapid deactivation."

We therefore recommend addition of the following as a high-priority need for coal liquefaction R&D:
Identify the mechanisms of catalyst deactivation in direct liquefaction processes and develop techniques to prevent or mitigate the effects of catalyst deactivation. The basis for this recommendation is clearly identified in Section 4.2.3, pages 4-57 through 4-63. Catalyst deactivation is an enormous problem for direct liquefaction. Catalysts used in Wilsonville runs lose up to 90% of their activity within the first few days of processing. To make up for this activity loss, Wilsonville is currently adding about 5 pounds of catalyst per ton of coal. For a full-scale commercial plant this would amount to approximately 200,000 pounds of catalyst per day, creating substantial additional expense due to the cost of the fresh catalyst addition and disposal of the spent catalyst. Approaches must be developed to prevent or mitigate deactivation, prepare catalysts resistant to deactivation, or alternatively, to regenerate spent catalysts.

3. For indirect liquefaction R&D we offer the following as another high-priority R&D need:
Investigate the fluid dynamics and reaction kinetics of slurry-phase catalystic reactors for indirect liquefaction and develop computational models to allow scale-up of these reactors.
Experience with bench and pilot-scale slurry-phase reactors for Fischer-Tropsch and methanol synthesis has demonstrated several advantages: 1) isothermal operation, 2) excellent heat exchange, and 3) use of small catalyst particles. However, the rates of reaction in certain slurry reactors appear to be limited by mass transport in the fluid phase. Additional studies of the fluid dynamics are required in order to develop models to predict requirements for scale-up to commercially-sized plants.

4. Division of the report into sections for review of the various technologies separately has artificially eliminated consideration of potential benefits derived from combining two or more processing technologies into one processing complex. For example, could combination of direct and indirect technologies into a single process lead to a more cost-effective approach? Perhaps an additional chapter on integrated technologies is warranted. Only one recommendation, (Section) 3.4.2.4 for pyrolysis, considers a systems analysis approach.

5. On page 4-3 it is noted that "There seems to be a gap between fundamental research and process development contractors, which must be bridged if we are to test and apply the fundamental work in the context of a liquefaction process." This COLIRN report should provide a bridge for that gap. Promising approaches for liquefying coal which have emerged from basic and applied research programs should be clearly identified, and recommendations for development of processes based on these advanced approaches should be made.

6. In our opinion the COLIRN report should not contain numerical ratings for the high-priority recommendations listed in the report. Such ratings are based on subjective judgements and the makeup or the committee with respect to fields of expertise, and may not be representative of the coal liquefaction research community as a whole. Furthermore, the method used to rate the recommendations does not allow comparison between categories of recommendations, for example, direct liquefaction with 12 high-priority recommendations and bioliquefaction with only one.

F.9 COMMENTS FROM D.D. WHITEHURST (FEBRUARY 17, 1989)

In general, the report is very well written, and I agree with most of the recommendations proposed by the panel. There are a few comments I would like to make regarding the report, however. I will address general features first, then go on to specific areas.

I object to the inference that the commonly accepted mechanisms for the conversion of coal are being "challenged" by new thinking. The proposed new mechanisms are like many in past proposals for additional chemistry that could help answer some questions on observed phenomena. Generally, such proposals have been made by researchers deeply involved in academic exercises using exclusively model compounds. It would be wise to recommend that new theory be tested with real coals and solvents under actual coal liquefaction conditions. If the new mechanism can predict a new approach to that derived empirically, it is extremely useful. If, however, it provides no means for process improvement, it should not be overly emphasized.

Let's put the chemistry involved in perspective. First, there should be a clear definition of what is meant by "coal conversion". It is commonly accepted that conversion means a change in form or composition of a starting material. It was clearly established by many groups over 10 years ago that under typical liquefaction conditions the reactive macerals of coal are converted completely to freely soluble products in 1 to 5 minutes, depending on the rank of the coal. During this conversion about 0.3 to 1% hydrogen is consumed by the conversion of the coal independent of the source of that hydrogen.

Consider what this means on a molecular level, using a typical bituminous coal. The coal will contain 77% C dmmf, and about 70% of that carbon is found in aromatic rings predominantly no larger than 3 condensed rings. Simple stoichiometry predicts that a pound of raw coal contains 116 moles of carbon bonds. About 12% of those are associated with heteroatoms. In converting that coal to soluble species, only about

2.5% of those bonds have to be broken. The products are still far from the compositions desired for conventional fuels; they have an average molecular weight of about 1000 and thus cannot be distilled even with high vacuum. At this size, even though they are soluble species, they have little access to the interior of conventional heterogeneous catalysts. In addition, they contain about 8 heteroatoms per molecule, 4 of which are phenolic. In upgrading these materials farther another 1% of the original carbon bonds in the original structure must be broken to produce distillable material (450 molecular weight), and the phenolic functionality must also be removed.

At this stage, all of the easy conversions are over. Fortunately, at this molecular size, catalysts with pore sizes of around 100 A can begin to alter the structures as access is less diffusionally restricted.

If there is a need for new chemistry, it is after this point, and here some of the arguments of thermal cleavage limitations are valid. Thermal reactions are very slow, and acceleration is needed for improved processes. Of the hydrogen consumed about 5% is needed to lower the molecular weight to 450, 30% to remove heteroatoms, and the other 65% is needed to convert the products to gasoline and diesel fuel. The predominant hydrogen consumption is for ring-opening reactions, and it is at this point where gas formation becomes problematic. There is essentially no difference between breaking an aliphatic ring fused to an aromatic and dealkylation of a short chain on an aromatic ring.

As far as the "theoretical" prediction that regression does not occur through benzylic radical coupling, there is ample evidence that even methyl naphthalene condenses and dehydrogenates to form 5-membered polycyclic ring systems when adequate H-donors are not available during coal liquefaction. Pyrene when present in liquefaction solvents can be substituted with as much as 1 out of 80 carbons from the original coal (found as methyl substituents on pyrene). This observation is strongly suggestive of benzylic coal radical addition and further cleavage of the coal fragment. It should also be recalled that any attempt to follow where H adds to coal with deuterated reagents is completely confused by very rapid scrambling of D throughout the product spectrum, which implies that radical addition and elimination is a rapid dynamic process.

As far as the "need" for a great deal of solid state characterization of catalysts with new sophisticated techniques, I have reservations. I am not aware of any new catalyst development that has come from such studies. Results so far have only confirmed what we already know from well-conducted reactions.

I wholeheartedly agree that a very important recommendation for the future use of coal in the U.S. is to maintain operation of Wilsonville. If funding limitations require restrictions of other recommendations, so be it!

Recommendations for increased understanding of structure and reactivity are also very worthwhile.

Recommendations to study pretreatment of coal could be quite important in view of recent Wilsonville results. However, such pretreatments are best directed to ash etc. removal, not to coal structure modification. Coal liquefaction reagents such as hydrogen are expensive enough. Why make things more expensive.

INDIRECT LIQUEFACTION

In general, the recommendations appear sound, but there is an overemphasis in expectation from surface science studies. More will be learned by actual experiments.

The need to improve MeOH synthesis is questionable. The process is already 75% thermally efficient. How much can this be improved, and how much will this improvement cost?

Conversion of syngas to oxygenates probably makes more sense than liquid hydrocarbon fuels, as the panel concluded.

PYROLYSIS

The main concern with this area will be char disposal. This will be increasingly of more concern in the future as environmental issues will limit direct combustion.

Reference to pyrolysis as a second-order process has no meaning. Getting two solid species together to form products as if they are freely diffusing soluble species makes no sense.

There was a whole body of information completely ignored in this section. It is contained in a book "Coal" by Wilfred Francis. This reference should be included in fairness to the readers.

I agree in general with the recommendations for more fundamental studies in this area and the need for higher yields of liquid before getting too excited.

COPROCESSING

In my view this will be the evolutionary entry of coal liquefaction into the commercial market. Product specifications will have to be met before coal liquids can be consumed in large quantity, and to produce them in an integrated facility where environmental issues can be addressed will be more efficient than separate plants.

The review was well done and though slightly biased was generally fair to all researchers in the field. One deficiency in this section is the lack of consideration of disposal of unconverted coal and resid. Gasification of such liquid slurries via Texaco type processes should be encouraged, e.g., proposed for funding. It is highly likely that even more synergisms will be found in partial oxidations than in liquefaction.

BIOPROCESSING

In my opinion this area has little hope for fuel production applications. Nature is inherently inefficient, and if researchers were to make a balance of Btu of nutrients consumed/Btu of fuel produced, it would clearly show a net consumption of energy. This is because organisms must perform a lot of very specialized tasks to metabolize their food. Thus most of the metabolism is concerned with CO_2 generation to provide the energy needed to perform the other transformations they wish to do. I would not encourage research in this area.

There is a need for biological processes in environmental control. Wilsonville is even now using special phenol-consuming bacteria for water cleanup. It would be well worth investigating the use of the newly discovered deep-sea microorganisms, which thrive at high pressure and temperature and which can tolerate and perhaps even consume H_2S. Perhaps new routes to H_2S scrubbing could be discovered.

CLOSING COMMENT

I enjoyed reading this report and feel it will be a valuable contribution to the literature as well as an aid to DOE personnel.