1. EXECUTIVE SUMMARY

This STAF reviews the broad problem of the impact on the U.S. Army of the use of synthetic fuels (defined as a non-petroleum derived fuel) over the time period of 1975 to 2000. The STAF is divided into three basic parts. The first part involves a forecast of which synthetic fuels will have a major impact in the time period under study. This analysis drew heavily on a companion program carried out concurrently by Exxon Research and Engineering Company for the Environmental Protection Agency entitled "Feasibility Study of Alternate Fuels for Automotive Transportation." In the second part of the STAF, those alternate fuels identified as the most feasible synthetic fuels in the future were subjected to detailed analyses. The third part of the STAF consists of the identification of a number of areas which appear to offer promise for fruitful R&D in the synthetic fuel area. This section of the report highlights both the salient features of the complex synthetic fuel question itself and the conclusions relative to it reached in this study.

Present Status

- Both the U.S. and world petroleum reserves at present and projected consumption rates face depletion at a time in the future which can no longer be ignored.

- Current petroleum fuel demand, particularly in the U.S. is so large that finding a substitute for this volume of fuel is an immense task regardless of the alternate fuel chosen.

- The majority of present day mobile power plants have been developed to run on petroleum derived liquids. Thus, a change to a fuel radically different from present petroleum derived liquids would correspondingly require a massive change in power plants.

- Small commercial sized synthetic fuel activities currently are scattered throughout the world (i.e. in the U.S.S.R., China, Canada and South Africa but not in the U.S.). Synthetic liquids are not new materials (some predate the discovery of petroleum). Many synthetic fuel activities have been abandoned in the face of open economic competition with inexpensive and readily available petroleum, and current commercial production appears to exist as a result of government policies rather than economic factors. However, even major past synthetic fuel efforts such as took place in Germany during World War II would be considered small today (when compared to present rather than past consumption levels).

The Change From Petroleum Derived to Synthetic Fuels

- Driving Force

The ultimate driving force for a change from petroleum to other sources for liquid fuels will be the exhaustion of the world's recoverable reserve of petroleum. Thus, the question is not if a change will take place but when the change will take place and what form will the change take.

- Nature of the Change

The change of commercial industry from producing petroleum fuels to synthetic fuels will be evolutionary i.e. synthetic fuels will begin to be used in conjunction with petroleum and that usage will expand as availability increases. The sheer magnitude of the task of substantial replacement of present U.S. liquid petroleum derived fuel production with synthetics, appears to dictate a time frame in the order of magnitude of two decades to accomplish the change, even assuming a strong national commitment.

- Timing

- At present many predict that the U.S. production of petroleum as influenced by recoverable reserves will begin to decline by the turn of the century, and world production slightly thereafter.

- It would appear logical that individual countries for political and/or economic reasons will begin the change prior to being forced into it by a genuine shortage of petroleum.

- Predicting a time-table for the buildup of synthetic crude capacity is difficult at this time. In early 1974 following the shock of the oil embargo, it appeared that the major effort to build a synthetic fuel industry (i.e. to construct commercial sized synthetic plants) would begin within the next few years. At present (Fall-1975), although synthetic fuel R&D activity in the U.S. is intense, the start of the actual construction of a synthetic fuel industry in the U.S. appears to await the establishment and implementation of a national policy to carry out the enormous effort which will be involved.

General Synthetic Fuel Consideration

- Which Ones Are Most Likely

The synthetics most likely to have a major world role in the time frame of 1975 to 2000 in terms of gasoline and distillate (i.e.: diesel and aircraft turbine) type fuels are judged to be:

- Shale rock derived liquids.
- Coal derived liquids.
- Tar Sand derived liquids.
- Methanol as a product from gasified coal.

- Resource Availability

The world's resources of coal, shale rock and tar sands are quite large. The U.S.'s coal and shale rock reserves are also large. However, tar sand reserves are located principally outside the U.S.

- Processes for the Production of Synthetic Crude Oil

- The process technology (without considering economics as a factor) for the production of synthetic liquids from coal, shale rock and tar sands is currently available throughout the world. The existance per se of process technology thus is not a limiting step to the creation of a synthetic fuel industry.

- The investment costs for synthetic crude producing processes are quite large; thus, much effort will be expended to develop more cost effective processes. Because of this process improvement effort it is difficult to predict what specific processes will be used in the future.

- As a result of a major solids handling problem (particularly with shale rock and tar sands) the processing plants when built will probably be located near the resource site. Thus synthetic fuel production is potentially geographically diffuse rather than concentrated because of the world wide distribution of coal, shale rock and tar sands.

- Relative Economics

- At present the cost of building and operating plants to produce synthetic crude oil is much higher than the cost of producing petroleum crude oil, particularly from sources such as located in the Persian Gulf area. Developments will be made to improve the cost effectiveness of processes to produce synthetic crudes, and the cost of finding and producing petroleum will increase as the more assessable petroleum sources are exhausted. Ultimately as the world's supply of petroleum begins to be exhausted the cost of petroleum must reach a level where synthetics will become cheaper. Thus, sometime in the future the relative cost advantage of petroleum versus synthetics will reach a cross-over point.

- However, before this cross-over point is reached, in the absence of some type of government incentives, it is difficult to see how a commercial scale synthetic fuel industry will be built.

Power Plant Considerations

- The nature of mobile power plants used by the Army (which have a 5 year development and 20 year life cycle) is essentially being fixed for the time period 1975 to 2000 by decisions which have been made or are being made in our current time frame.

- In the commercial sector, in order to readily accommodate the long, gradual change from petroleum derived fuels to synthetic derived fuels it is anticipated for the year 1975 to 2000 that highway vehicles will be powered by engines that will <u>not</u> be radically different in terms of compatability with existing petroleum derived fuels.

The Nature of Synthetic Fuels

- The exact composition of synthetic fuels is a function of (1) basic type of resource used i.e. coal, shale rock or tar sands, (2) the type of process used to convert the resource material to a synthetic crude oil (3) the type of secondary processing (i.e. refining) employed to make the finished fuel from the synthetic crude:

    - The chemical composition of synthetic crudes particularly those derived from shale rock and coal is different from that of petroleum crudes.

    - For a given resource type, particularly in the case of coal, the composition of the synthetic crude will vary depending on the process and process conditions used to produce it.

- Although some technology presently exists which may be applicable to the secondary processing (refining) of synthetic crudes to fuels similar to present day petroleum derived fuels, it is not at all clear at this time as to exactly what processing will be employed when a commercial sized synthetic fuel industry is actually created. Although small plants dedicated solely to processing synthetic fuels may be built for special purposes, it is more likely that large quantities of synthetic crudes will be processed in refineries initially handling both petroleum and synthetic crude. In this latter case, the large capital investment requirements will probably dictate a complex optimization of the processing scheme, making it difficult at this time to make predictions. Cost/availability tradeoffs versus fuel specifications will also undoubtedly occur, also adding uncertainty to any prediction of future detailed processing schemes.

- It would appear at this time that <u>although future synthetic fuels will be liquid products grossly similar to present petroleum fuels there will be significant differences between the detailed chemical composition of synthetic fuel and present petroleum fuels.</u> In addition, the differences cannot be predicted with any certitude at this time.

<u>Areas for Fruitful R&D Effort</u>

An examination of the anticipated trend regarding synthetic fuels indicates a number of areas where R&D work would appear potentially fruitful:

- The very uncertainty itself regarding future synthetic fuels suggests a strong need for extensive forecasts, analytical studies and information exchanges relative to synthetic fuels with emphasis on the Army's needs and point of view.

  - Forecasts of the composition of synthetic fuel by analyzing the nature of the processes used to both produce the synthetic crude oil and to refine this crude to a finished fuel.

  - Cost and availability versus specifications tradeoff studies with emphasis on middle distillate fuels.

  - Impact of changes in processing technology on the nature and supply of middle distillate fuels derived from synthetics.

- Analyses of the foreign synthetic fuel operations. Much of the current emphasis is on U.S. synthetic fuel developments when in reality the only present commercial sized synthetic fuel operations exists outside the U.S. Also, consideration should be given to factors such as the compatability of foreign synthetic fuels with domestic developed engines.

- Encouragement of maximum interaction between experts in the areas of fuel properties and product quality, power plant design and synthetic fuels process development. This interaction could be effected via joint study efforts or DOD funded workshops.

- Generation of background and expertise to provide a sound technical basis for an Army input to a national energy policy and to insure maximum integration of the Army's effort with that of other government agencies and private industry.

- Product quality studies carried out to characterize in detail the chemical and physical properties of both pure (i.e. unblended) synthetic fuels and fuels obtained from blends of synthetic and petroleum derived components.

- Storage stability studies should be carried out since the use of even small fractions of synthetic derived materials blended into a stable petroleum derived fuel could result in major stability problems which are not now encountered with pure petroleum derived middle distillate fuels, particularly in view of the Army's long term storage stability needs.

- Studies should be undertaken to assess possible problems in the deterioration, corrosion and materials compatability area.

- The combustion properties of synthetic containing fuels should be studied.

- Toxicity, emission and other problems should be considered from the point of view of the Army's mission.

- Studies to assess potential water reactivity problems should be carried out.

- Middle distillate fuels might be influenced by the introduction of organic oxygen compounds present in some synthetic fuel materials.
- Phase separation after contact with water is expected to be a major problem associated with the use of methanol in gasoline blends as motor gasoline fuel.

• A number of other areas for study have potential merit such as the use of synthetic fuel components to produce a high density fuel for volumetrically limited systems.

2. ALTERNATE FUEL FORECAST

2.1 Prediction of Major Alternate Fuel Types

In this section of the report the major alternate fuels of the future are analyzed so as to identify the non-petroleum crude based fuels which will probably play the greatest role in the future, which then will be subjected to detailed analysis. The time frame of concern is the years 1975 to 2000 with major emphasis on the 1985 to 2000 time frame. This analysis and prediction of alternate fuels is focused on the commercial point of view. Since the Army is committed by policy to use commercially available fuels the development of the commercial sector will also influence the Army's selection of conventional fuel type. This analysis draws heavily on a concurrent program carried out by Exxon Research and Engineering Company for the Environmental Protection Agency entitled "Feasibility Study of Alternate Fuels for Automotive Transportation"(1). The broad outline of the analysis and its conclusions are summarized here. For more detailed information the reader is referred to the final report describing the Alternate Automotive Fuel study (1).

2.1.1 Fuels and Selection Factors Considered

The fuels selected for preliminary analyses (1) were as follows:

1. Coal liquids (gasoline or distillate)
2. Shale liquids (gasoline or distillate)
3. Methanol
4. Ethanol
5. Higher Oxy Compounds
6. Hydrogen
7. Methane
8. Ammonia
9. Hydrazine

The criteria used in evaluation of these fuels were as follows:

Economic Criteria

1. Cost of production and distribution
2. Operating cost (in vehicle)

Technical Criteria

3. Technological status
4. Production efficiency
5. Environmental impact in production

Performance Criteria

6. Compatibility with engines
7. Toxicity
8. Safety
9. Driver acceptability - convenience
10. Environmental impact during use
11. Efficiency of use

Strategic Criteria

12. Fuel shift and entry compatibility
13. Resource availability
14. International considerations

The analysis(1) identified the following synthetic fuels as the most feasible and practical fuels of the future:

- Shale derived gasoline
- Shale derived distillate
- Coal derived gasoline
- Coal derived distillate
- Methanol as a product from gasified coal

The Environmental Protection Agency(1) study was restricted to the United States. It did not consider fuels derived from tar sands, since the U.S. tar sand resources are very small. Tar sand derived liquids are presently being produced outside the U.S. Since the present study is concerned with the worldwide alternate fuel situation the following fuel types were added:

- Tar sand derived gasoline
- Tar sand derived distillate

In addition to the detailed analysis whose results were summarized above, it is useful to consider the restrains inherent in the elemental composition of liquid combustion fuels, which at present represent our major source of energy for portable power plants.

The elements most common in the compounds composing fuels are carbon, hydrogen, nitrogen, sulfur and oxygen. Oxygen has no heating value for combustion, and sulfur and nitrogen pose severe environmental problems because of the formation of sulfur oxides and nitrogen oxides. Thus, the most desirable elements for combustion in fuel molecules are carbon and hydrogen because of the high heat of combustion of these elements and the non-polluting nature of their products of complete combustion (i.e., CO_2 and H_2O).

Also it has been suggested that hydrogen itself be used as the fuel of the future. At present, hydrogen can be produced via the following processes.

- Steam reforming of hydrocarbons
- Partial oxidation of hydrocarbons
- As a by-product during platinum reforming of naphthenes and paraffins in petroleum naphtha to produce aromatics for gasoline
- Pyrolysis of hydrocarbons
- Reaction of coal and water
- Electrolysis of water
- Thermochemical splitting of water
- Steam-iron process

All of these processes for hydrogen production are fossil fuel based with the exception of water electrolysis and thermochemical splitting and the steam-iron process. Indeed, only if non-fossil fuel energy generating sources (e.g., nuclear) are used as the source of energy for water electrolysis, water splitting or to drive the steam-iron process can these hydrogen producing fuel processes become truly carbon independent. Thus, the elements carbon and hydrogen derived from fossil sources and contained in compounds which are liquid at ambient conditions will be the major components of fuels used for combustion powered mobile power plants for the next 25 years.

References Cited in Section 2.1

(1) F. H. Kant et al., "Feasibility Study of Alternate Fuels for Automotive Transportation," U.S. Environmental Protection Agency, Contract 68-01-2112, Final Report, June 1974.

2.2 Anticipated Future Trend Regarding Petroleum and Alternative Fuels

It has been estimated that 75-85% of the original petroleum resource base remains unused(1). In the U.S. the American Petroleum Institute figures indicate an approximate 10 year crude oil proven reserve based on present U.S. production(2). Energy conservation measures dictated by economic and/or political policy, shifts from petroleum to coal and nuclear energy sources for electric power generation, discovery of addition crude reserves in presently unexplored areas, more efficient crude recovery methods, and the use of heavy crude oil reserves not presently economic to produce will all help to extend U.S. petroleum resources. Much larger reserves are present outside the U.S., particularly in the Middle East, upon which the other major users, i.e., Western Europe and Japan, are largely dependent(3). It was noted in June 1973 that quantitative energy forecasts are difficult to make(4). They would appear even more difficult to make in light of the major changes which occurred following the October 1973 Middle East War.

In response to economic and/or political factors, and ultimately to the overwhelming pressure of reduced petroleum production as the world approaches the exhaustion of petroleum reserves, a major synthetic fuel industry will be born and grow. Present production of synthetic fuels is non-existent in the U.S. and worldwide is extremely small compared to petroleum production throughout the world. (Total production from tar sands in Canada, from shale in the U.S.S.R. and China and from coal in South Africa is estimated to be equivalent to less than 1/2 of 1% of world petroleum production.)

Predictions of where and at what pace a transition from crude oil derived fuels to synthetic derived fuels will occur are difficult to make. In June of 1974, the Alternate Fuel Study(5) concluded that initial production of shale and/or coal derived fuels would occur in the U.S. within five to seven years, would approach 800,000 bbl/day total shale and coal derived liquids in 1985, and 6,000,000 bbl/day of shale and coal derived liquids in the year 2000. The National Petroleum Council(6) forecast predicted in 1980 a 100,000 bbl/day of synthetic liquid production in the U.S. (plus 400,000 bbl/day in Canada and 300,000 bbl/day in Latin America), and predicted for 1985 a 500,000 bbl/day synthetic liquid production in the U.S. (plus 1,000,000 bbl/day in Canada and 800,000 bbl/day in Latin America). In early 1974 U.S. automotive fuel consumption approximated 6,000,000 bbl/day. Thus, under these predictions synthetic fuels could make only a minor contribution to total automotive fuel supplies in 1985, but would have the potential to become a major factor in subsequent years. Cost analyses also made by the Alternate Fuel Study(5) for June 1974, building upon previous National Petroleum Council study economics, predicted for the time period 1982 to 1985 a \$5 to 7 per barrel cost for shale syncrude and \$8 to \$11 per barrle costs for coal syncrudes (in 1973 dollars). Based on the sudden dramatic increase in foreign crude oil prices to well over $10 per barrel, following the oil embargo, a synthetic fuel oil industry appeared economically feasible, and its rate of development limited by other factors such as environmental constraints, water availability and rate of government leasing of shale and coal lands. Indeed, at the time major investments were made in oil shale leases by private industry which leased a number of shale rock containing tracks from the government whereas a previous leasing attempt had failed(7). Hanging over this apparent economic advantage for synthetic liquids was the ever present possibility of a sharp drop in crude oil prices, whose actual production costs have been stated to vary from $0.10 to 3.00 per barrel(8). Long lead times for the development of a synthetic fuel industry and the large capital requirements for its construction further intensified the uncertainty regarding the economic viability of synthetic fuels relative to petroleum derived fuels.

In October 1974 it was announced by the Colony Department Operation, a joint venture of Atlantic Richfield Company, Shell Oil Company, Ashland Oil Company and the Oil Shale Corporation, that its plans for the U.S. first commercial oil shale plant (50,000 bbl/day) has been suspended indefinitely(9). The following reasons were cited:

- Inflation increased costs- e.g., product costs increasing from $7 per barrel to $11 per barrel and higher with plant investment costs increasing from $450 million to 800 million in one year.
- Government energy policy uncertainties, i.e., the failure to get government protection against the possibility of a drop in crude oil prices.
- Stronger than expected environmental opposition to shale oil development.
- Tight money.

Similarly, plans for synthetic crude production from tar sands in Canada experienced difficulties(11,12,13). Shell Oil withdrew from a planned 100,000 bbl/day plant in Alberta (11). Syncrude Canada Ltd.(11,12,13) experienced a halt in construction following withdrawal by Atlantic Richfield Canada Ltd. Construction was resumed after their replacement by the Canadian federal and provincial governments in the consortium (other members are Imperial Oil Ltd., Canada City Services and Gulf Canada, Ltd.)

In November 1974, it was reported from the American Petroleum Institute's annual meeting(10) that in general, petroleum industry interest in commercial synthetic fuel plants was decreasing because of inflation increased costs and the lack of government guarantees against the possibility of lower crude oil costs.

Thus, the details of the timetable for the development of a synthetic fuels industry is clouded at the time of the writing of this report, and would appear to be largely dependent on the initiation of a government policy designed to create such an industry, at least until such time as a substantial depletion of world petroleum reserves creates a clear economic incentive for synthetic fuels. Indeed, in such areas where a shale rock and coal derived synthetic fuel industry exist at present, i.e., U.S.S.R., China and South Africa, it would appear to be a product of government policy rather than world economic conditions.

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(3) Oil and Gas Journal, 71, No. 46, p. 119, November 12, 1973.

(4) M. H. Farmer, "Energy Scenarios - Supply Considerations," submitted to Environmental Protection Agency, Energy Analysis Branch, June 12, 1973.

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(6) M. W. Nichols, "Balancing Requirements for World Oil and Energy," Chemical Engineering Progress, 70, No. 10, p. 39 (1974).

(7) H. A. Meshlein, World Oil, 179, No. 1, p. 27 (1974).

(8) Forbes, November 1, 1974, p. 74.

(9) Wall Street Journal, October 7, 1974, p. 7.

(10) Wall Street Journal, November 14, 1974, p. 1.

(11) Oil and Gas Journal, April 14, 1975, p. 39.

(12) Oilweek, 26, #5, pages 26,27 & 32 (March 17, 1975).

(13) Forbes, May 1, 1975, pages 18 & 19.

2.3 Anticipated Trend Regarding General Army Fuel Requirements

In order to identify missing technology which will necessitate R&D effort resulting from future alternate fuels, it is necessary to assess the impact of the introduction of synthetic fuels in the coming years upon U.S. Army operations.

To accomplish this objective,for the purposes of the STAF only, a simplified analysis of U.S. Army fuel situation was formulated for the years 1975 to 2000. This prediction was developed principally from discussions with various experts, but also drew from material in a number of reports(1-4). Some major points are as follows:

(1) Army power plants require approximately 5 years to develop and then are employed in service for 20 years. Thus, the power plants to be used over the next 25 years are essentially fixed by decisions that have already been made or will be made in our current time frame.

(2) Army policy requires conventional combat fuels to be procured from commercial sources.

(3) Both the nature of commercial vehicle fuel types expected to be available and the nature of mobile Army power plants in use and in development lead to the conclusion that liquid hydrocarbon fuels will be dominant over the period 1975 to 2000.

(4) The major fuels of Army interest in their order of importance are and will be:

    (a) middle distillates

    (b) motor gasoline

    (c) aviation turbine fuel (JP-4 or JP-8 if the Air Force changes fuel).

(5) DOD policy is to procure fuels locally as much as possible. Thus, both U.S. and foreign produced fuels impact on Army requirements.

(6) The need for good storage stability is more important to the Army than to civilian users as combat fuels must be designed for a storage life of 3 to 5 years. Moreover, the policy of prepositioning fuels by storage at terminals suggests an advantage for fuels capable of even longer storage life.

(7) War-time demand levels (general, maximum, non-nuclear war) for conventional fuels could range up to a volume equivalent to 12% of maximum U.S. refinery output (approximately 5 times military peacetime demand).

(8) Emergency fuels need only provide a short life time operation since it is expected that the combat life of the equipment will be short.

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(2) "Executive Summary on the AMC Long Range Fuels R&D Program," The Army Fuels and Lubricants Research Laboratory (AFLRL), revised. Draft, 22 August 1973.

(3) R. A. Block, "Impact of the National Energy Crisis on the Defense Department," Advanced Research Projects Agency, October 12, 1972.

(4) R. D. Quillian, Jr., "A Report on the Energy Crisis," USAMC Laboratory Directors Conference, Charlottesville, Virginia, 22 March 1973.

3. ANALYSIS OF FUEL TECHNOLOGY

In this part of the STAF, those alternate fuels identified as the most feasible synthetic fuels in the future were subjected to detailed analyses. The analyses included factors such as resource availability, present status of processes to convert the resource (i.e., shale rock, coal) to a synthetic crude material, and the anticipated secondary processing required to convert the synthetic crude to a commercial fuel. Since the transition from petroleum derived fuels to synthetic fuel will necessarily be gradual and employ power plants presently using petroleum fuels, factors such as the composition of petroleum crude oil and present petroleum derived fuels and existing petroleum refining technology were also discussed to provide a basis for comparison with corresponding synthetic crudes and liquid products. An effort was made to make these comparisons as much as possible on a chemical composition basis rather than solely on a petroleum technology basis, which it was felt would generate both the greatest insight into alternate fuel problems and provide the resultant information in a more universal language for the reader.

3.1 General Overview of Synthetic Fuel Technology

A variety of processes for the production of liquids from shale rock and coal have been developed at different times and different countries, some of which actually predate the development of the present petroleum based fuel industry. In this section of the report, a brief general history and overview of shale and coal synthetic fuel developments is presented. A detailed analysis of current technology, resource availability and nature of synthetic liquid products is contained in other sections of this report.

In the late sixteenth century and early seventeenth century, the depletion of the once extensive forests used for the production of charcoal for ironmaking led to the development of processes for the production of coke from coal(1-3). In these carbonization processes, the coal was heated in ovens in the absence of added air to produce coke, the earliest form of a coal pyrolysis process. The development of coal pyrolysis processes for the production of illuminating gas began in the eighteenth century. Pitch and tar were often recovered as by-products. Coal tar was used in England to replace American wood tar during the American Revolution. It was not until the middle of the nineteenth century, however, that liquid by-products were generally recovered from coal pyrolysis processes, producing low yields by present standards of light aromatics and coal tars chemicals. The resultant coal derived benzene, toluene, naphthalene, anthracene, phenol, cresols and aniline became the basis for the modern chemical industry, starting with the development of the dyestuff industry in Germany. During World War I coal pyrolysis processes provided both toluene for TNT production and phenol for picric acid production.

Work on the direct hydrogenation of coal under presure was undertaken in Germany starting in 1913(1), and extensive liquefaction research was conducted in Germany during the 1920's and 1930's(4). Coal liquefaction research was carried on in the U.S. during the 1930's and again in the late 1940's and early 1950's(4).

Coal derived liquids may also be produced via the Fischer-Tropsch process where the coal is first gasified to carbon monoxide and hydrogen(5). In 1902, Sabatier and Senderens first reported the synthesis of a hydrocarbon, i.e., methane, by the reaction of carbon monoxide and hydrogen over nickel. In 1913, Badische-Anilin and Soda-Fabrik patented the possibility of producing liquid hydrocarbons and other chemicals such as alcohols, ketones, aldehydes and fatty acids by reacting carbon monoxide and hydrogen over various catalysts. Similarly in 1923, it was discovered that by the use of the proper catalyst and conditions, carbon monoxide and hydrogen can be selectively reacted to essentially only methanol. This work was the forerunner for the present and proposed processes to produce methanol from either natural gas or coal (after conversion to carbon monoxide and hydrogen).

The only present commercial process to produce liquids from coal is in South Africa at the SASOL plant(6). The coal is first gasified to carbon monoxide and hydrogen and then reacted to liquids using Fischer-Tropsch type catalytic processes. Products produced include gasoline, diesel oil, kerosine and waxes. In 1955, its production was indicated at approximately 5,000 bbl per day(6), but was expanded in 1966(7). A number of countries had Fischer-Tropsch processes to produce synthetic liquids, which, however, are not now commercially active(5,8). These processes were operated in France in 1937 (1,000 bbl/day) and in Japan in 1938 (two plants for a total production of 2,500 bbl/day) and in Germany starting in the 1930's (production from nine plants reached a high of 18,000 bbl/day during World War II). Processess for the direct hydrogenation of coal to liquids were built in England in 1935, and in Germany starting in the late 1920's(9,10). The English plant was designed to operate on both coal or creosote oil produced from coal but switched completely to creosote oil during World War II because of bomb hazards. At its peak production in 1941, it produced approximately 5,000 bbl/day of gasoline(9). The largest commercial coal hydrogenation industry to date existed in Germany during World War II where it has been estimated that up to half of Germany's total oil requirements and all of her aviation gasoline were synthesized from coal. Total production from 12 plants using either coal or coal derived tar and pitch was approximately 100,000 bbl/day(9,10).

Shale rock deposits are widely distributed, and the earliest processes involving the pyrolysis of shale rock to produce liquids predates the industrial revolution(12). During the nineteenth century, a wide spread shale oil industry developed replacing whale oil as an illuminant only to itself to be replaced by petroleum. Intermittent and now terminated shale oil industries include those in France starting in 1858, Scotland in 1850, Australia in 1865, Brazil in 1881, New Zealand in 1900, Switzerland in 1915, Sweden in 1921, Spain in 1922 and South Africa in 1935(12-14). It is interesting to note that the Scotish oil-shale industry spanned approximately a hundred years, and in 1890 produced approximately 8,000 bbl/day of synthetic product(14).

At present, commercial shale oil processes are only operated in the U.S.S.R. and in China(12,15). The U.S.S.R. based shale oil industry was established in Estonia in 1921, operated continuously since then, and was expanded by the Russians after World War II(15). The Chinese based oil shale industry was established in Manchuria in 1929, expanded both by the Japanese during World War II and the Chinese during the Korean War and several years ago estimated at approximately a 44,000 bbl/day size(13). Early Estonian emphasis on shale products was for use only as fuels (gas or furnace oil). More recently, U.S.S.R. emphasis is on the production of chemicals(15). Estonian production was cited as 25 million tons in 1973(16), which would be equivalent in size to approximately a 48,000 bbl/day operation (assuming it were all converted to liquids with 30 gallon per ton yield). Products from the U.S.S.R. shale operations include fuel oil, diesel fuel, kerosene, asphalt, benzene, toluene, xylene and specialty products such as solvents, drying oils and paints. The Russian shale oil industry is supported by an active R&D effort.

Major shale rock deposits exist in Brazil and it has been stated that Brazil will establish a commercial sized shale industry(17-18). West Germany has also indicated interest in establishing a shale oil industry(19).

It can be seen that processes for the production of liquids from shale rock and coal have been operated in a number of countries in the world, and actually predate the development of the present petroleum industry. A tar sand process has also been developed, thus, there is no basic technological barrier to the development of coal,shale and tar sand conversion processes by resource owning countries. Because of the difficult solids handling problem it would appear that liquefaction processes, particularly shale rock and tar sand processes, will be located near the source of feed material. Thus, for the purposes of this study, it will be assumed that coal and shale rock derived liquid fuels will be potentially produced in any country possessing the basic resources.

The availability of coal, shale and tar sand resources is discussed in detail in the following section. The U.S. and world reserves of both shale rock and coal are very large. The U.S. contains approximately two-thirds of the world's oil shale reserves. The only other country with shale reserves approaching this magnitude is Brazil which has approximately one-quarter of the world's reserves. Significant deposits, however, are found in the U.S.S.R., China, Canada, Sicily and Africa The major world coal reserves are in the U.S. (approximately one-third) and the U.S.S.R. and China (approximately one-quarter each). Other countries with significant reserves include Germany, U.K., Poland, India, Union of South Africa, Australia and Canada. Tar sand reserves are much smaller than either coal or shale reserves and are essentially found only in two countries (approximately 80% in Canada with the rest in Venezuela).

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