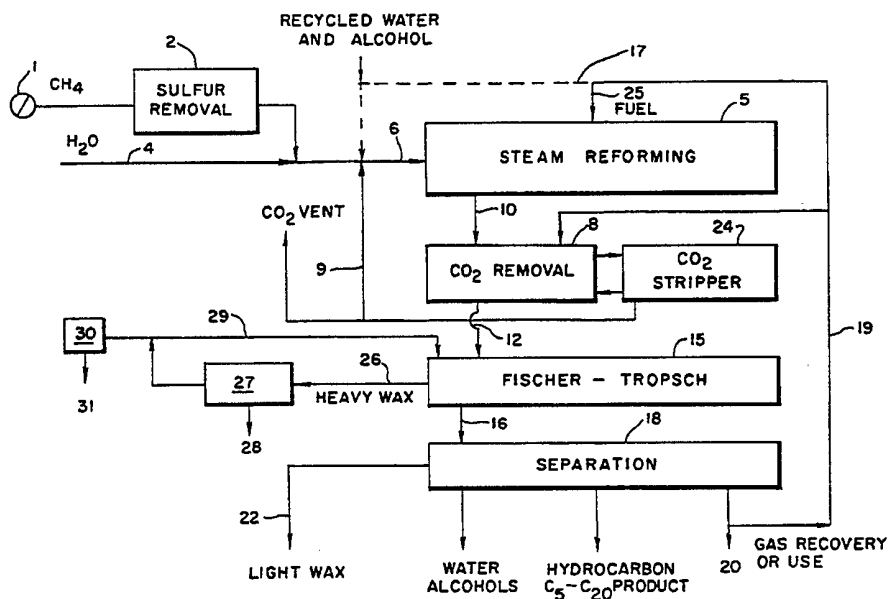




INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁵ : C07C 27/00, 27/06		A1	(11) International Publication Number: WO 95/20558
			(43) International Publication Date: 3 August 1995 (03.08.95)
(21) International Application Number: PCT/US94/00520		(81) Designated States: AT, AU, BB, BG, BR, CA, CH, CZ, DE, DK, ES, FI, GB, HU, JP, KP, KR, LK, LU, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SK, UA, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).	
(22) International Filing Date: 28 January 1994 (28.01.94)			
(71) Applicant (for all designated States except US): RENTECH, INCORPORATED [US/US]; Suite 300A, 1624 Market Street, Denver, CO 80202 (US).			
(71)(72) Applicants and Inventors: BENHAM, Charles, B. [US/US]; 12878 West 68th Avenue, Arvada, CO 80004 (US). BOHN, Mark, S. [US/US]; 1614 Tamarac Drive, Golden, CO 80401 (US). YAKOBSON, Dennis, L. [US/US]; 8847 Norwich Street, Westminster, CO 80030 (US).		Published With international search report. With amended claims.	
(74) Agent: BERKSTRESSER, Jerry, W.; Shoemaker and Mattare, Ltd., Crystal Plaza Building 1, Suite 1203, 2001 Jefferson Davis Highway, P.O. Box 2286, Arlington, VA 22202-0286 (US).			

(54) Title: PROCESS FOR THE PRODUCTION OF HYDROCARBONS



(57) Abstract

The invention is directed to the preparation of higher hydrocarbons starting with lower hydrocarbons. A hydrocarbon stream (1) is desulfurized in zone (2), mixed with steam in line (4), the total mixture is subjected to steam reforming in zone (5) to obtain a mixture of hydrogen, carbon monoxide and carbon dioxide, which is treated in zone (8) to remove carbon dioxide. The synthesis gas (12) is subjected to Fischer-Tropsch process in zone (15) with iron catalyst, promoted by an alkali metal, preferably potassium, and optionally copper. The effluent from the Fischer-Tropsch process is subjected to a separation process in zone (18) to obtain a gaseous stream (19) which is recycled to the steam reforming zone (5), a liquid gasoline boiling hydrocarbon stream, light wax (22) and water/alcohol mixture. Heavy wax (26) from the Fischer-Tropsch process is subjected to cracking.

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PROCESS FOR THE PRODUCTION OF HYDROCARBONS

Background of the Invention

This invention relates to a method and a system for the production of hydrocarbons and hydrocarbon compounds which includes the use of a Fischer-Tropsch synthesis reactor and process, utilizing an iron-based catalyst, in combination with processes for converting hydrocarbon-containing gases in general, and in particular gases rich in methane, into hydrogen and carbon monoxide from such gases.

Considerable research and development work has been undertaken in the past to commercially apply the Fischer-Tropsch synthesis of hydrocarbons, from a wide variety of carbonaceous and hydrocarbon starting materials.

A compendium of some of the prior work with Fischer-Tropsch synthesis technology is contained in the Bureau of Mines Bulletin 544 (1955) entitled Bibliography of the Fischer-Tropsch Synthesis and Related Processes by H.C. Anderson, J. L. Wiley and A. Newell.

The product distribution and yields from specific Fisher-Tropsch reactions with iron catalysts have also been examined by Charles N. Satterfield and George A. Huff, Jr. in an article entitled Carbon Number Distribution of Fischer-Tropsch Products Formed on an Iron Catalyst in a Slurry Reactor, Journal of Catalysis 73, 187-197 (1982), wherein the Shultz-Flory distribution is examined with respect to various catalyst systems.

In addition, the article entitled Fischer-Tropsch Processes Investigated at the Pittsburgh Energy Technology Center Since 1944 by Baird,

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Schehl, and Haynes in Industrial and Engineering Chemistry, Product Research and Development, 1980, 19, pages 175-191, describes various Fischer-Tropsch reactor configurations.

5 The foregoing articles describe in considerable detail how specific catalysts can be employed in various reaction vessel configurations under conditions which favor the conversion of carbon monoxide and hydrogen into specific product
10 groups.

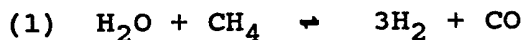
 There have only been a few instances wherein the Fischer-Tropsch reaction has been incorporated into a complete system, starting with a solid or gaseous feed stock. Germany placed several plants
15 in operation during the 1930's and 1940's using coal as the feed stock, referenced in Twenty-Five Years of Synthesis of Gasoline by Catalytic Conversion of Carbon Monoxide and Hydrogen, Helmut Pichler, Advances in Catalysis, 1952, Vol. 4, pp.
20 272-341. In addition to the foregoing, South Africa has been using Fischer-Tropsch technology based upon this German work for the past 35 years to produce gasoline and a variety of other products from coal, referenced in Sasol Upgrades Synfuels with Refining Technology, J.S. Swart, G.J. Czajkowski, and R.E. Conser, Oil & Gas Journal, August 31, 1991, TECHNOLOGY. There was also a Fischer-Tropsch plant built in the late 1940's to convert natural gas to gasoline and diesel fuel
25 described in Carthage Hydrocol Project by G. Weber, Oil Gas Journal, Vol. 47, No. 47, 1949, pp. 248-250. These early efforts confirmed that commercial application of the Fischer-Tropsch process for the synthesis of hydrocarbons from a hydrocarbon-
30 containing feed stock gas requires solving, in an

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economical manner, a set of complex problems associated with the complete system. For example, initially, it is important for the hydrocarbon-containing feed stock to be converted into a mixture consisting essentially of hydrogen and carbon monoxide before introduction of the mixture into the Fischer-Tropsch reactor. Economic operation of specific sizes of Fischer-Tropsch reactors, generally requires the ratio of hydrogen to carbon monoxide to be within well established ranges. The Hydrocol plant, referenced hereinbefore, used partial oxidation of natural gas to achieve a hydrogen to carbon monoxide ratio of about 2.0. An alternative approach to partial oxidation uses steam reforming for converting light hydrocarbon-containing gases into a mixture of hydrogen and carbon monoxide. In this latter case, steam and carbon dioxide, methane and water are employed as feed stocks and carbon dioxide can be recycled from the output of the reformer back to its inlet for the purpose of reducing the resultant hydrogen to carbon monoxide ratio.

There are therefore two primary methods for producing synthesis gas from methane: steam reforming and partial oxidation.

Steam reforming of methane takes place according to the following reaction:



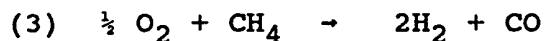
Since both steam and carbon monoxide are present, the water gas shift reaction also takes place:

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Both of these reactions are reversible, i.e., the extent to which they proceed as written depends upon the conditions of temperature and pressure employed. High temperature and low pressure favor the production of synthesis gas.

Partial oxidation reactions utilize a limited amount of oxygen with hydrocarbon-containing gases, such as methane, to produce hydrogen and carbon monoxide, as shown in equation (3), instead of water and carbon dioxide in the case of complete oxidation.



In actuality, this reaction is difficult to carry out as written. There will always be some production of water and carbon dioxide; therefore the water gas shift reaction (2) will also take place. As in the steam reforming case, relatively high temperatures and relatively low pressures favor production of synthesis gas.

The primary advantage of partial oxidation over steam reforming is that once the reactants have been preheated, the reaction is self-sustaining without the need for the addition of heat.

Another advantage of partial oxidation is the

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lower ratios of hydrogen to carbon monoxide normally produced in the synthesis gas which ratios better matches the desired ratio for use in the Fischer-Tropsch synthesis of hydrocarbon liquids in the overall process.

A still further advantage of partial oxidation resides in the elimination of a need for the removal of carbon dioxide and/or hydrogen from the synthesis gas before being fed to the synthesis reactors.

Adjustment of the hydrogen to carbon monoxide ratio can be achieved by removal of excess hydrogen using, for example, a membrane separator. However, this approach requires additional capital equipment and can result in lower oil or liquid hydrocarbon yields due to a loss of hydrogen to the process.

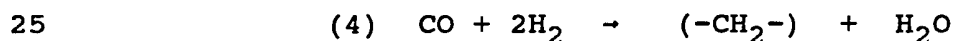
In order for the overall process considerations to be used in a manner which can produce economical results whether employing either steam reforming or partial oxidation of a feed stock, the Fischer-Tropsch reactor must typically be able to convert at least 90% of the incoming carbon monoxide. If a 90% conversion efficiency is to be achieved in single pass operation and hydrogen is not removed before introduction of the gas stream into the reactor, the build up of

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hydrogen due to the excess of hydrogen will necessitate a larger reaction vessel to maintain a sufficiently long residence time in the reaction vessel. Recycle of unreacted hydrogen and carbon monoxide from the outlet of the Fischer-Tropsch reactor back to its inlet is commonly employed to achieve the required conversion. However, when an excess of hydrogen is employed, an even greater excess of unreacted hydrogen will build up under such a recycle operation. This condition, in turn, can necessitate an even larger reaction vessel or alternatively the hydrogen removal described must be employed.

Major drawbacks to the commercialization of many of the prior processes were the high cost of product specific catalysts, and an unacceptable overall process conversion efficiency of the carbon input into liquid hydrocarbon output, particularly, when an inexpensive catalyst was utilized.

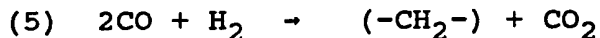
The two catalyst types attracting the most serious attention for the Fischer-Tropsch reaction are either cobalt based or iron-based catalysts. In practice, a cobalt-based catalyst will favor the following reaction:



While an iron catalyst will favor the

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following overall reaction (due to its high water gas shift activity):



Theoretically, cobalt-based catalysts can produce higher conversion yields than iron-based catalysts since cobalt can approach 100% carbon conversion efficiency, whereas iron tends toward 50% carbon conversion efficiency during the Fischer-Tropsch synthesis reaction since the reaction (5) favors the production of carbon in the form of CO_2 . The major drawbacks encountered are, first, that cobalt-based catalysts are very expensive compared to iron-based catalysts and, further, if the Fischer-Tropsch technology were embraced on a large scale worldwide, the higher demand for relatively scarce cobalt might drive the cost even higher.

The use of cobalt-based catalysts have typically included recycle of tail effluent back to the inlet of the Fischer-Tropsch reactor to achieve 90% conversion primarily because cobalt favors formation of water. Water is well known to be a strong inhibitor of either catalytic reaction schemes. Thus, as the reaction proceeds in the presence of water, not only is the concentration of reactants less, but the concentration of inhibiting

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water vapor is greater. In practice, generally 70% carbon monoxide conversion is the maximum attainable in single-pass operation using a cobalt-based catalyst. Iron-based catalysts, which favor carbon dioxide formation permit up to 90% of the theoretical conversion of carbon monoxide per pass without great difficulty, and without the formation of additional water, thereby eliminating the necessity for effluent recycle back to the inlet of the Fischer-Tropsch reactor.

It has generally been considered undesirable to form CO_2 in the Fischer-Tropsch synthesis reaction as happens using iron-based catalysts and therefore many process schemes use cobalt-based catalysts including the recycle of some of the reactor effluent directly back into the Fischer-Tropsch reactor. In summary, therefore, iron-based catalysts, while efficient in converting carbon monoxide into the products shown in equation (2), have previously been limited in overall carbon conversion efficiency since their use favors the production of carbon dioxide, and therefore, they were not as efficient in overall carbon conversion efficiency as the process schemes utilizing cobalt based catalysts.

The Fischer-Tropsch synthesis has therefore

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been used in combination with an up-stream steam reforming reactor which must then be followed by CO₂ removal from the carbon monoxide and hydrogen reaction products before the CO and H₂ produced by the steam reforming reaction are subjected to a Fischer-Tropsch reaction using cobalt-based catalysts.

In selecting a suitable catalyst for use in a system which favors reaction (5), several considerations are important. In the Fischer-Tropsch synthesis using appropriately designed equipment, the hydrogen to carbon monoxide feed ratio to the Fischer-Tropsch reactor will optimally be in the range of from 1.0 to 2.0 parts of hydrogen for every part of carbon monoxide. This is necessary in order to obtain reasonably acceptable percent conversion of carbon monoxide into hydrocarbon per pass through the Fischer-Tropsch reactor without the undesirable formation of carbon in the catalyst bed.

In order to adjust the H₂/CO ratio into the range of optimum ratios described hereinbefore for the catalyst selected, it is necessary and typical that an additional stage of hydrogen removal, by a membrane or the like, is inserted into the product stream between the steam reformer and the Fischer-

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Tropsch reactor. This hydrogen removal is necessary to produce the proper ratio of hydrogen to carbon monoxide in the steam reforming reaction product stream entering the Fischer-Tropsch reactor.

The present inventors have discovered that notwithstanding the foregoing difficulties, economic viability for a natural gas to oil conversion process using steam reforming or partial oxidation and a Fischer-Tropsch synthesis using an iron-based catalyst can be achieved. The present invention includes a solution to the problems of reducing the formation of excess hydrogen from the reformer or partial oxidation unit and increasing the overall carbon conversion efficiency for the entire carbon input to the system when using specifically prepared iron catalysts. As will be shown hereinafter, the carbon dioxide produced by such iron catalysts, which production contributes to the low carbon conversion efficiencies previously discussed, can be used to solve both the excess hydrogen and low overall carbon conversion efficiency problems.

Objects of the Invention

It is therefore an objective of the present

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invention to utilize specific low-cost catalysts which favor the formation of carbon dioxide, in a Fischer-Tropsch reactor to efficiently produce hydrocarbon products, with or without the necessity
5 for recycling gaseous effluent directly back into the Fischer-Tropsch reaction zone.

It is still a further objective of the present invention to utilize reactions which produce hydrogen and carbon monoxide, such as steam
10 reforming and partial oxygenation wherein the hydrogen to carbon monoxide ratios produced can be used directly in an appropriately designed Fischer-Tropsch synthesis reactor using specific iron-based catalysts, without the further step of removing
15 hydrogen.

It is still a further objective of the present invention to produce the hydrogen to carbon monoxide ratios required for specific equipment designs in a Fischer-Tropsch synthesis by the use
20 of sufficient carbon dioxide in the steam reforming or partial oxidation reactions to promote improved carbon conversion efficiency in the reactions of hydrocarbon-containing gases to hydrogen and carbon monoxide.

25 It is yet a further objective of the present invention to produce the requisite hydrogen and

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carbon monoxide necessary for a Fischer-Tropsch synthesis by recycling the carbon dioxide and optionally the light hydrocarbon gases formed in the Fischer-Tropsch reaction into the feed stream of either a steam reformer reactor or partial oxidation unit for producing after carbon dioxide removal a synthesis gas containing the desired ratios of hydrogen and carbon monoxide.

It is yet a further objective of the present invention to provide an overall process for the efficient conversion of hydrocarbon-containing gases and low B.T.U. gases, such as hydrocarbon-containing natural gas having relatively high concentrations of carbon dioxide into desired hydrocarbon-containing products having more than five carbon atoms, including liquid hydrocarbon products including naphtha, diesel fuel, and hydrocarbon waxes, which process is highly efficient in converting the total carbon input into the process into carbon in the hydrocarbon products.

It is yet a further objective of the present invention to increase the selectivity of the Fischer-Tropsch reaction towards higher molecular weight compounds and to increase the carbon conversion efficiency by recycling tail gases rich

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in olefins, alcohols and aldehydes back to the Fischer-Tropsch reactor inlet. The recycled olefins, alcohols and aldehydes are readsorbed on the catalyst and participate in further chain growth.

It is yet a further objective of the present invention to increase the selectivity of the Fischer-Tropsch reaction towards higher molecular weight compounds and to increase the carbon conversion efficiency by recycling naphtha which is rich in olefins and which contains a large amount of alcohols back to the Fischer-Tropsch reactor inlet. The recycled olefins and alcohols are readsorbed on the catalyst and participate in further chain growth. It is yet a further objective of the present invention to convert residual hydrogen and carbon dioxide which otherwise would be vented or used for fuel into liquid hydrocarbon product using a second Fischer-Tropsch reactor, thereby improving the carbon conversion efficiency.

It is a further objective of the present invention to produce a catalyst having high activity and selectivity for producing predominantly hydrocarbon containing products having more than five carbon atoms.

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Brief Summary of the Invention

The process of the present invention applies to the conversion of hydrocarbon-containing gases including low B.T.U. hydrocarbon gases, from whatever source derived, into liquid hydrocarbon products. Such gases, once obtained, are first converted into hydrogen and carbon monoxide in either a steam reforming reactor or partial oxidation unit and these gases are subsequently converted in a Fischer-Tropsch reactor utilizing a specific iron-based catalyst into carbon dioxide and hydrocarbon products containing more than five carbon atoms each, including gaseous hydrocarbons, liquid hydrocarbons, alcohols, and waxes. Some or all of the carbon dioxide from the Fischer-Tropsch reaction is preferably mixed with the starting hydrocarbon-containing gases, before conversion into hydrogen and carbon monoxide. In its preferred embodiments, carbon dioxide is removed from the resultant hydrogen and carbon monoxide stream before introduction of the gases into the Fischer-Tropsch reactor. The carbon dioxide thus removed can also optionally be added to the starting materials if desired or necessary to obtain the desired ratios of hydrogen to carbon monoxide.

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An overall system for the practice of the foregoing process has also been developed whereby a methane-containing gas stream can be converted to liquid hydrocarbon products utilizing equipment which can include: steam reforming means or partial oxidation means, to produce a gas stream containing hydrogen, carbon monoxide and carbon dioxide; carbon dioxide removal means for removing carbon dioxide from the gas stream; Fischer-Tropsch slurry reactor means utilizing an iron-based catalyst and employing conditions which will catalytically convert the hydrogen and carbon monoxide into hydrocarbon products having more than five carbon atoms, and carbon dioxide; carbon dioxide removal means for removing the carbon dioxide produced in the Fischer-Tropsch reactor means; and recycle means for introducing a predetermined quantity of the removed carbon dioxide to the gas stream entering the steam reforming means or partial oxidation means; whereby the hydrogen to carbon monoxide ratio entering the Fischer-Tropsch reactor means is selected in the system to produce an improvement in the overall carbon conversion efficiency of the process.

A second Fischer-Tropsch slurry reactor means utilizing an iron-based catalyst and employing

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conditions which will catalytically convert hydrogen and carbon dioxide into hydrocarbon products having more than five carbon atoms, and water and alcohols.

5 Brief Description of the Drawings

Figure 1 is a schematic of one embodiment of the process of the present invention;

Figure 2 is a schematic of another embodiment of the process of the present invention using partial oxidation;

Figure 3 is a more detailed schematic of the system of the present invention;

Figure 4 is a schematic of still another embodiment of the system of the present invention;

15 Figures 5 and 5a are illustrations of a cross-flow filter used for wax clean up in the present invention;

Figures 6 and 6a are illustrations of a catalyst filter apparatus useful in the practice of the present invention;

Figure 7 is a schematic showing a process according to the present invention employing steam reforming with no tail gas recycle and one carbon dioxide absorber;

25 Figure 8 is a schematic showing a process

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according to the present invention employing steam reforming with no tail gas recycle and two carbon dioxide absorbers;

5 Figure 9 is a schematic showing a process according to the present invention employing steam reforming with tail gas recycle with one carbon dioxide absorber;

10 Figure 10 is a schematic showing a process according to the present invention employing steam reforming with tail gas recycle with two carbon dioxide absorbers;

15 Figure 11 is a schematic showing a process according to the present invention employing steam reforming with tail gas recycle with two carbon dioxide absorbers; and

 Figure 12 is a schematic showing a process according to the present invention employing partial oxidations with hydrogen removal and optionally carbon dioxide removal.

20 Detailed Description of the Invention

 Referring to Figure 1, hydrocarbon-containing gases such as methane are introduced at 1. The gases used must be suitable for use in the process of the present invention, and are preferably made
25 to undergo sulfur removal 2 before being introduced

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into the steam reforming reactor 5. Conventional equipment for this sulfur removing step is utilized, such as a packed bed. Typically, a granular bed of zinc oxide such as 32-4 obtained from Katalco in 1/8 to 3/16 inch (3-5 mm) spheres can be used. System pressure can be used in the sulfur removal process which typically is operated preferably at between 200°C and 500°C and more preferably at between 350°C and 400°C and most preferably at about 375°C. The space velocity through the reactor should preferably be between 400 and 1000 cubic feet per hour per cubic feet of bed, and more preferably between 600 and 800 cubic feet per hour per cubic feet of bed, and most preferably about 700 cubic feet per hour per cubic feet of bed.

The hydrocarbon gas after sulfur removal is then mixed with stream 6 before introduction into the steam reformer 5.

A unique advantage of the present invention is the ability of the particular process described herein to tolerate, indeed to require, predetermined high levels of carbon dioxide in the process stream 6 entering the steam reformer, or other producer or source of hydrogen and carbon monoxide used. Hydrocarbon gases that are high in

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CO₂ concentration at a preselected system pressure can be employed with advantage. This permits the use of gases produced by pyrolysis of hydrocarbon sources as well as gases from wells that are low in B.T.U. content by virtue of having high concentrations of carbon dioxide. Typically the gas stream 6 entering the reformer can contain one atom of carbon in the hydrocarbon gases to a total of up to four molecules of carbon dioxide and water and more preferably about three molecules of carbon dioxide and water, where the number of carbon dioxide molecules is less than or equal to twice the number of carbon atoms in the hydrocarbons contained in the feed gas stream 6. These proportions are selected primarily to reduce the formation of elemental carbon in the steam reformer. Different proportions can be used where additional steam is employed. For example, less than four parts of carbon dioxide and water may be employed so long as the overall reaction does not promote the excessive formation of elemental carbon in the reformer. The recycle stream 9 containing carbon dioxide from the CO₂ removal and recovery stage 24 is combined with the stream 6 to produce a preselected ratio of carbon to water and carbon dioxide entering the reformer 5. Depending on the

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concentration of carbon dioxide in the original hydrocarbon gas 1 or the total amount of carbon dioxide from the original hydrocarbon gas 1 and the light hydrocarbon gas recycle 17, the addition of carbon dioxide to the gas stream 6 can be adjusted by control of the input of carbon dioxide 8 from the CO₂ removal and recovery stage 24.

The steam reforming reactor 5 can be of conventional design employing a commercial nickel catalyst such as obtained from Katalco and designated as 23-1. Preferably, the reactor should be operated at from about 1292°F (700°C) to about 1652°F (900°C) at system pressure of about 12 psia (82.7 kPa) to about 500 psia (3447 kPa). The flow of input gases through the reactor catalyst bed should be approximately 300 lbs/hr/ft³ catalyst.

The gas streams 6, 10, 12 and 16 can be operated, as previously described, at system pressure or at some other pressure by appropriate pressure reduction apparatus or with compression. The components of the system can be designed to tolerate a wide variation in operating pressure if desired. System pressure as described herein, has been found to produce the benefits and advantages described.

As shown generally in Figure 2, a partial

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oxidation reaction may be employed or may be substituted for the steam reforming stage of the process shown in Figure 1.

After the steam reforming step, the hydrogen, carbon monoxide and carbon dioxide-containing gas stream 10 is subjected to a carbon dioxide removal step by absorption. The gases having a reduced carbon dioxide content are then passed on as 12 to the Fischer-Tropsch reactor. Preferably, such a CO₂ removal apparatus should reduce the concentration of carbon dioxide in the gas stream 12 to less than about 5% by volume for optimum use in the Fischer-Tropsch reactor 15. One of the preferred practices for such CO₂ removal is the use of an aqueous potassium carbonate solution containing about 30% potassium carbonate through which the carbon dioxide-containing gas is bubbled. Preferably, the absorption should take place at a temperature of from about 100°C to about 115°C, and more preferably from about 105°C to about 110°C and most preferably at about 105°C, at the system pressure previously identified. Higher or lower pressures will, of course, require optimizing the temperature and throughput for a given absorber size to achieve the same or similar desired reduction in the concentration of the carbon

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dioxide in the gas stream 12. The potassium carbonate solution containing dissolved CO₂, i.e., the rich solution, is then heated in a separate vessel to drive off the absorbed carbon dioxide.

5 The resulting stripped, i.e., lean solution, is then returned to the absorption vessel to absorb more carbon dioxide from the gases 10 from the steam reformer 5.

Other CO₂ removal schemes can be employed such
10 as those using amines, but these generally require a significantly higher pressure to produce the required reduction in CO₂ concentration.

The hydrogen and carbon monoxide-containing gas stream 12 is then introduced into a Fischer-
15 Tropsch reactor which preferably employs a catalyst slurry using an iron-based catalyst and more preferably a precipitated iron catalyst and most preferably a precipitated iron catalyst that is promoted with predetermined amounts of potassium
20 and copper depending on the preselected probability of linear condensation polymerization and molecular weight distribution sought.

There are three fundamental aspects to producing a catalyst for a particular application:
25 composition, method of preparation, and procedure for activating the catalyst.

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Determining the "best" activating procedure for a catalyst is difficult even if it is known what changes in the catalyst are needed to give the desired activity, selectivity and stability.

5 The preferred catalyst is an unsupported precipitated iron catalyst promoted with copper and potassium. The catalyst is made using elemental iron and copper as starting materials.

10 The first step in the process is dissolution of the metals in nitric acid to form a mixture of ferrous nitrate, ferric nitrate and cupric nitrate in appropriate proportions. The ratio of water to acid is an important parameter and should be adjusted to give a weight ratio of about 6:1. The
15 dissolution of the metals in nitric acid is accompanied by evolution of nitrogen oxides, principally nitric oxide and nitrogen dioxide. Nitric oxide has limited solubility in the acid, but it can be readily oxidized to nitrogen dioxide
20 by contact with air or oxygen. Nitrogen dioxide dissolves in water producing nitric acid and nitric oxide. Therefore, in order to reduce nitrogen oxide emissions from the reaction vessel and at the same time to reduce the consumption of nitric acid,
25 oxygen is bubbled through the solution while the metals are being dissolved. The small amount of

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nitrogen dioxide which escapes from the vessel is scrubbed using a potassium hydroxide solution. The mixture is stirred until all of the metals have dissolved. The temperature of the solution
5 increases as the metals dissolve, but is controlled to a maximum temperature of about 150°C.

The next step in the process is precipitation of a catalyst precursor from the nitrate solution using ammonium hydroxide. Ammonium hydroxide is
10 prepared by dissolving anhydrous ammonia in water. Ammonium hydroxide at ambient temperature is added to the hot nitrate solution until the pH of the solution reaches 7.4. At this point, all of the metals have precipitated out as oxides. The
15 mixture is cooled to 80°F and the final pH is adjusted to 7.2.

After precipitation, the catalyst precursor must be washed free of ammonium nitrate using high quality water which is free of chlorine. The
20 slurry is first pumped from the precipitation vessel into a holding tank located upstream of a vacuum drum filter. The catalyst precursor is allowed to settle in the holding tank, and a clear layer of concentrated ammonium nitrate solution
25 forms above the solids. This layer is drawn off before the slurry is washed and filtered. A vacuum

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drum filter fitted with water spray bars is used for washing the catalyst precursor and concentrating the slurry. The electrical conductivity of the filtrate is monitored to ensure complete removal of ammonium nitrate from the slurry.

After the catalyst precursor has been washed, the last ingredient of the catalyst, potassium carbonate, is added in an amount appropriate for the quantity of iron contained in the batch. The potassium carbonate is dissolved in a small amount of water and this solution is mixed thoroughly into the slurry to distribute the potassium uniformly. At this point, the weight percent of catalyst in the slurry should be a value of between about 8 to about 12.

A spray dryer is used to remove most of the water from the catalyst and at the same time to produce roughly spherical catalyst particles having diameters in the range of 5 to 50 microns.

The last step in the process is heating the catalyst in air to about 600°F to remove residual moisture and to stabilize the catalyst. This step is carried out in a fluidized bed which is heated electrically. The annealed catalyst is then ready for induction or activation and use.

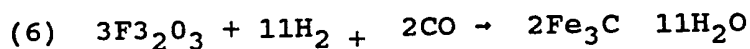
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Many different activating procedures for promoted iron Fischer Tropsch catalysts have been described in the literature. For example, one of the most definitive studies on activating iron Fischer Tropsch catalysts for use in fixed-bed reactors was published by Pichler and Merkel. (United States Department of Interior Bureau of Mines, Technical Paper 718, By H. Pickler and H. Merkel, Translated by Ruth Brinkley with Preface and Foreword by L.J.E. Hofer, United States Government Printing Office, Washington, D.C., 1949, Chemical and Thermomagnetic Studies on Iron Catalysts For Synthesis of Hydrocarbons). In this study, high activity of the catalyst was correlated with the presence of iron carbides after the activation procedure. The most effective procedure used carbon monoxide at 325°C at 0.1 atm. pressure. The study also showed how the presence of copper and potassium in the catalyst affected activation of the catalyst.

The following equations show the stoichiometry for some of the reactions which can take place during activation:

Production of cementite from hematite using hydrogen-rich synthesis gas:

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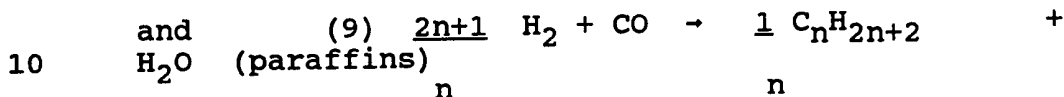
Production of cementite from hematite using carbon monoxide alone:



5 In the presence of an iron-based catalyst, the following reactions take place:



(olefin)



Water gas shift reaction:



15 One problem with using carbon monoxide or carbon monoxide-rich synthesis gas for activation is the possibility of over-carbonizing the catalyst whereby free carbon or non-carbidic carbon is produced thereby reducing the activity of the catalyst.

20 It is important in commercial plants using slurry phase Fischer Tropsch reactors that there be flexibility in the activation procedure during start-up of the plant. For example, when the wax and catalyst are loaded into the slurry reactor, it is necessary to have a fluidizing gas
25 flowing through the gas distributor to prevent catalyst settling. Also during heating of the

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slurry to activation temperature, gas flow must be maintained. It is, therefore, advantageous to use synthesis gas initially during start-up since it is being flared and inert gas (nitrogen or carbon
5 monoxide) may be difficult or expensive to obtain.

It has been discovered that the activity and selectivity of a Fischer Tropsch iron catalyst is improved if the catalyst is subjected to a hydrogen-rich synthesis gas at elevated temperature
10 and pressure. The reaction of carbiding of the iron catalyst precursor, principally hematite, using a hydrogen-rich synthesis gas and the subsequent Fischer Tropsch reaction both produce water. It is believed that the presence of this
15 water prevents over-carburization of the catalyst and thereby improves the activity and selectivity of the catalyst. (See "The Influence of Water and of Alkali Promotor on the Carbon Number Distribution of Fischer-Tropsch Products Formed
20 over Iron Catalysts" by L. Konig et al., Ber. Bunsenges. Phys. Chem. 91, 116-121 (1987) - c VHC Verlagsgesellschaft mbH, D-6940 Weinheim, 1987.)

It has also been discovered that this hydrogen-rich synthesis gas can be used in lieu of
25 an inert gas for maintaining the catalyst in suspension while the slurry is being heated to

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approximately 200°C. At this point, the synthesis gas is replaced by an inert gas (nitrogen or carbon dioxide) until the activation temperature has been attained at which time activation is carried out using synthesis gas.

It has also been discovered that the presence of a large amount (20%) by volume of nitrogen in the synthesis gas used for pretreatment of the catalyst has no detrimental effect on the activation procedure. The time for activation of the catalyst remained at two hours in the presence of 20% nitrogen.

The initial load of catalyst in a commercial-scale slurry reactor comprising several thousand pounds of catalyst is best pretreated in the full-scale slurry reactor. However, during operation, when only a few hundred pounds of catalyst need to be pretreated to replace a portion of the inventory in the reactor to maintain activity, a separate pretreatment reactor is required. The pretreatment reactor should be similar in design to the large Fischer-Tropsch reactor, but much smaller. The batch of slurry containing the pretreated catalyst is pumped into the large reactor.

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EXAMPLE 1

Conventional Activation Procedure

$$\text{H}_2:\text{CO} = 0.7$$

$$P = 35$$

$$5 \quad T = 280-290^\circ\text{C}$$

$$\text{SV} = 6 \text{ NL/g Fe/h}$$

$$\text{Time} = 3-5 \text{ hours}$$

EXAMPLE 2

Activation Procedure According to the Present

10 Invention

$$\text{H}_2:\text{CO} = 1.4$$

$$P = 150 \text{ psig}$$

$$T = 280^\circ\text{C}$$

$$\text{SV} = 4 \text{ NL/g Fe/h}$$

$$15 \quad \text{Time} = 2 \text{ hours}$$

Preheat slurry to 200°C using synthesis gas.

Heat from 200°C to 280°C using CO_2 .

Activate using synthesis gas.

20 Many different Fischer-Tropsch reactor designs can be employed in the process of the present invention. The preferred design is similar to that described in the article entitled Fischer-Tropsch Synthesis in Slurry Phase by M.D. Schlesinger, J.H. Crowell, Max Leva and H.H. Storch in ENGINEERING

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AND PROCESS DEVELOPMENT, Vol. 43, No. 6 (June, 1951) pp. 1474-1479. The descriptions contained therein of a synthesis reactor utilizing a precipitated iron catalyst suspended in a cooling oil are representative of the known state of this art. Such a reactor should be sized and operated under conditions to produce up to about 90% conversion of carbon monoxide into hydrocarbon products and carbon dioxide. Preferably, the reactor used in the present process should be operated at from about 100 psia (689 kPa) to about 500 psia (3447 kPa) at a temperature in the range of from about 428°F (220°C) to about 536°F (280°C). More preferably, the pressure used should be in the range of from about 150 psia (1034 kPa) to about 300 psia (2068 kPa) at a temperature of from about 464°F (240°C) to about 500°F (260°C) and most preferably at about 225 psia (1551 kPa) and about 482°F (250°C). The distribution of synthesis feed gas uniformly across the reactor cross section is necessary to achieve good mixing between the rising gas bubbles and the slurry medium containing the dispersed catalyst particles. The gas distributor can consist of orifices or porous metal spargers. A preferred design using orifices consists of concentric rings or torroidal manifolds nested in

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such a manner that the rings follow the contour of the bottom head of the reactor, i.e., the largest diameter ring at the highest elevation and the smallest ring at the lowest elevation. The orifices can be placed facing upward or downward or both. Each orifice should be placed near the center of equal areas of the reactor cross-section. The preferred porous metal sparger consists of an inner elliptical end closure at the bottom of the reactor oriented convex upward with small diameter porous plates welded into holes in the curved distributor plate. An alternate design utilizing a flat distributor plate would perhaps provide a more uniform distribution of bubbles but would require a larger thickness to resist bending. The preferred space velocity selected for optimal reactor conversion efficiency should be between 100 and 300 cubic feet per hour per cubic feet of expanded catalyst bed, more preferred between 200 and 270 cubic feet per hour per cubic feet of expanded bed, and most preferably about 240 cubic feet per hour, per cubic feet of expanded catalyst bed. The reactor diameter should be selected to give a feed superficial velocity (actual volumetric flow rate of feed gases divided by empty reactor cross-sectional area) between approximately 0.33 to 0.66

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feet per second (0.1 to 0.2 meters per second). These conditions should increase the height of the selected catalyst bed between 30% and 40% over the height of the bed without flow. In addition, the
5 slurry is an efficient heat transfer medium for the exothermic reactions taking place.

The preferred method for removing the large exothermic heat of reaction is a heat exchanger within the slurry reactor. The heat exchanger
10 tubes should extend from a height about 3 feet (1 m) above the gas distributor to the top of the expanded slurry. The preferred heat transfer medium is water introduced into the bottom of the tubes via concentric torroidal manifolds. The
15 water undergoes boiling in the tubes which provides a large heat transfer coefficient. The efficient heat transfer from the slurry to the boiling water allows the slurry temperature to be nearly uniform throughout the reactor. The temperature of the
20 slurry can be controlled by a combination of the height of water in the tubes and the steam pressure (and therefore steam saturation temperature) in the tubes.

Under the broadly preferred operating
25 conditions described herein, the iron catalyst particle size selected should have a large

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dimension of preferably between about 5 μ to 40 μ , more preferably 10 μ to 40 μ and most preferably about 30 μ .

It is expected that any of the catalysts which favor reaction (5) can be used effectively in the present invention. Preferably, the iron based catalysts described hereinbefore are utilized due to their low cost. Most preferably, a precipitated iron catalyst is employed and depending on the preselected alpha, i.e., the polymerization probability desired; where the weight ratio of potassium (as carbonate) to iron is between 0.005 and .015, more preferably between 0.0075 and 0.0125, and most preferably about 0.010. Larger amounts of alkali metal promoter cause the product distribution to shift toward the longer-chain molecules, while small amounts of alkali metal result in predominantly gaseous hydrocarbon product. The weight ratio of copper to iron is preferably between about 0.005 and 0.050, more preferably between about 0.0075 and 0.0125, and most preferably about 0.010. Copper serves as an induction promoter. The foregoing ranges are utilized to obtain the high conversion efficiencies hereinafter described is the Fischer-Tropsch slurry reactor, the product distribution obtained and the

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relatively long life of the catalyst.

The percent by weight of the foregoing iron catalyst is preferably between 5 and 15 percent by weight of iron in the slurry, more preferably
5 between 7.5 and 12.5 percent by weight and most preferably about 10 percent by weight of the slurry.

One of the characteristics of a slurry Fischer-Tropsch reactor designed to produce heavier
10 hydrocarbon products is the continuous increase in slurry height due to the low volatility of the heavier waxes. One method to maintain the slurry level to a constant value is to use a cross-flow
filter 27 (shown in Figure 1) to remove filtered
15 wax, stream 28, while returning the catalyst to the reactor through stream 29. The advantage of the cross flow filter is that a flow velocity of the slurry through the porous filter tubes of about 10 feet per second (3 M/S) will slow down the rate of
20 building of a layer of catalyst on the tube wall. When the flow rate of filtered wax through the porous tubes has diminished to a predetermined level, an inert gas such as carbon dioxide is used to pressurize the filtered wax on the shell side of
25 the cross flow filter to bump the layer of catalyst into the slurry stream 29, which flows back into

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the Fischer-Tropsch reactor 15. As an example of the flowrates involved for a commercially available cross-flow filter from Mott Metallurgical Corporation (Farmington, Connecticut) if the rate of removal of filtered wax through the tubes is 2 gpm, then the slurry flowrate from the Fischer-Tropsch reactor 15 to the cross-flow filter 27 would be 65 gpm and the flowrate of slurry back to the Fischer-Tropsch reactor would be 63 gpm in order to provide a velocity of 10 fps in the porous tubes to give the required shearing action to prevent catalyst buildup. A schematic diagram of a Mott cross flow filter and installation are shown in Figure 5. In order to periodically remove catalyst from the reactor, a slipstream of slurry, 30, is fed to another porous metal filter which collects catalyst on the inside of the porous tubes. the catalyst is periodically "bumped" into the bottom holding section using an inert gas. A schematic diagram of a Mott filter which can be used for catalyst removal is shown in Figure 6.

The separation stage 18, of the process can be configured in different ways to recover the different products and product distributions resulting from different gaseous hydrocarbon feeds, reaction conditions and catalysts.

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In the preferred embodiments described hereinafter, the separation stage 18 can employ a cold trap, and/or distillation apparatus. In this manner, the gases in stream 20 including carbon dioxide, can be recycled, via stream 19, and/or a portion of the gases can be used as a fuel stream 25 or feed stock stream 17 for the steam reforming stage 5.

Utilizing the reaction conditions described, the light hydrocarbon gases and carbon dioxide are separated and the higher carbon-containing products are separated from the pre-separation product stream 16. Advantageously, the gaseous product stream 20 after separation, is rich in light hydrocarbons and can be used directly as for process heat. The product stream 21 containing hydrocarbons having carbon contents between C_5 - C_{20} , generally a mixture of saturated and unsaturated aliphatic, hydrocarbon product, can be employed as a substitute for diesel fuel and the like. It has been determined that high cetane numbers are obtained from this product stream, which makes it particularly attractive either alone or blended with other diesel fuel stocks. Engine tests on the diesel fraction, typically containing C_{11} - C_{19} have demonstrated that the fuel burns

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much cleaner than commercially available diesel derived from crude oil. In addition, the particulate emissions are much lower than those produced with conventional diesel fuels partly
5 because the aromatic content is less than about 1% by weight compared to about 32% by weight for conventional diesel fuels.

Typically the diesel product produced by the process described herein has the following physical
10 characteristics compared with the specifications for ASTM diesel grades.

Finally, product stream 22 is rich in hydrocarbon products containing more than twenty carbon atoms, which product generally is useful as
15 paraffin wax. (See Tables I, II, III, IV and V.)

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TABLE I

	<u>Diesel</u>	No. 1 <u>Diesel</u> ASTM(1)	No. 2 <u>Diesel</u> ASTM(2)	<u>F/T</u>
5	Cetane Index ASTM 976-80 62	45 min	40 min	
10	Sulfur wt. % ASTM D129-80 <0.0001*	.50 max	.50 max	
15	90% Distillation Temperature °F 556°F ASTM D56	550°F-max	540°F-min 640°F-max	
	Viscosity @ 40°C cSt. 1.8 ASTM D445-82	1.4 min 2.5 max	1.9 min 4.1 max	
20	Conradson Carbon on 10%; ASTM D189-81 .02 wt. %	.15 max	.35 max	
25	Flash Point °F, min Corrected to 760 mm Hg 122°F ASTM D56-82	100°F	125°F	
30	Aromatic Content, Vol. %; ASTM D1319 0%	8% min	33%	
	API Gravity 48.7 ASTM D1298	38-41	34.7	
35	BTU/lb ASTM D240 19,371	16,000- 17,000	19,810	
	Oxygen Content, wt % 3.05%	N/A	N/A	

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*Analyses were below limits of detection.

- (1) ASTM D975-81 #1 Diesel
- (2) ASTM D975-81 #2 Diesel

5 The following is a more detailed analysis of
the diesel of Table I.

TABLE II

<u>TEST</u>		<u>METHOD</u>	
<u>RESULTS</u>			
10	Flash Point °F. 122	ASTM D56	
	API Gravity @ 60°F. 48.7	ASTM D1298	
	Sulfur Content, wt. % <0.0001	Horiba Analyzer	
15	Kinematic Viscosity 1.80 @ 40 °C., cSt.	ASTM D445	
20	Distillation Range 314	ASTM D86	IBP
	566		90%
	627		FBP
25	Conradson Carbon on 0.02 10% Residuum, wt. %	ASTM D189	
30	Saturates, wt. % 30	NMR/90 MHz	
	Alpha-Olefins 45		
	Internal-Olefins 9		
	Alcohols and Other 16		
35	Oxygen Content, wt. % 3.05	Elemental Analysis	
	Average Carbon Chain	GC/FID	

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^{C₁₄}
Length

Cetane Index
62

ASTM D976

5 Heat of Combustion,
19,371
BTU/lb.

ASTM D240

In addition to the foregoing, the F/T Diesel
of the present invention was further analyzed.

10 TEST RESULTS:

Relative percent (approximate) alcohols by Gas
Chromatography/Mass Spectroscopy for the specific
species of alcohols present

	<u>Alcohol</u>	<u>Percent</u>
15	<u>(approx.)</u>	
	Propanol	0.02
	Butanol	0.1
	Pentanol	0.3
	3-Methyl Pentanol	0.3
20	Hexanol	0.1
	Octanol	0.9
	Decanol	1.0
	Dodecanol	0.9
	Tetradecanol	1.0
25	Pentadecanol	0.9
	Hexadecanol	0.7
	Heptadecanol	0.2
	Octadecanol	0.6
	Nonadecanol	0.1
30	Other Branched Alcohols	1.0
	Total Alcohols	8-9

While the contribution of the presence of
alcohols to the superior performance of the F/T

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diesel with respect to emissions generally and particulate emissions in particular is not fully understood at the present time, the following analysis clearly shows the superiority of the performance of the F/T diesel fuel of the present invention.

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TABLE IIISYNTHETIC DIESEL FUEL

ASTM Distillation, °F		
5	IBP	332
	90%	514
	EP	555
	Cetane Index	62
	Sulfur Content, wt%	<.001
10	Cloud Point, °F	-2
	Pour Point, °F	-6
	Conradson Carbon on 10% Residuum, wt%	.05
	Flash Point, °F	146
	Bottom Sediment & Water, vol. %	<.025
15	Kinematic Viscosity @ 100°F, cSt	1.89
	API Gravity @ 60°F	48.5
	Aromatics, wt %	0
	Paraffins, wt %	47
	Olefins, wt %	41
20	Alcohols, wt %	6
	Other Oxygenates, wt %	6
	Heat of Combustion, Btu/lb	18,585
	Heat of Combustion, Btu/gal	
	128,230	

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TABLE IVEMISSION RESULTS
(g/bhp-hr)

	<u>NOx</u>	<u>BSP</u>	<u>HC</u>	<u>CO</u>
5				
	#1 DIESEL FUEL		.81	1.25
	4.89	.326		
	std. dev.		.01	.02
	.02	.001		
10	SYNTHETIC FUEL		.69	1.08
	5.19	.268		
	std. dev.		.01	.00
	.02	.008		

15 CLEAN AIR ACT AMENDMENTS OF 1990
U.S. HEAVY DUTY TRUCK ENGINE
EMISSION STANDARDS - g/bhp-hr

	<u>1990</u>	<u>1991</u>	<u>1994</u>	<u>1996</u>
HC	1.3	1.3	1.3	1.3
CO	15.5	15.5	15.5	15.5
20 NOx	6.0	5.0	5.0	4.0
PARTICULATE	0.6	0.25	0.10	0.10

From the data shown and with comparison to the standards in the Clean Air Act Amendments of 1990 there is a significant improvement when using the synthetic fuel F/T diesel of the present invention.

25 The enhanced emission performance strongly suggests that an oxygen containing additive could be formulated which would produce improved performance. The synthesis process of the present invention produces not only synthetic F/T diesel

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containing oxygenates but also a naphtha that contains several oxygen containing specie including alcohols. The following analysis shows some of the typical chemical and physical characteristics of the naphtha produced by the process of the present invention.

TABLE V

<u>TEST</u>	<u>METHOD</u>
<u>RESULT</u>	
10 API Gravity @ 60°F. 54.7	ASTM D1298
Distillation Range 220	ASTM D86 IBP
15 300	FBP
Saturates, wt. % 22	NMR/MHz
Alpha-Olefins 48	
20 Internal-Olefins 0	
Alcohols 26	
25 Water 4	
Oxygen content 73.5%	
Average Carbon Chain Cg	GC/FID
30 Length	
Alcohol Content, Rel. Percent (approx.)	
Octanol	4.5
Nonanol	7.4
Decanol	5.2
35 Dodecanol	0.9
3-Methyl-1-Butanol	4.4
3-Methyl-1-Pentanol	0.8
Hexanol	3.7
Heptanol	2.3

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1-Nonanol	0.6
Total Alcohols	30

It has been learned that the addition of a sufficient amount of the synthetic naphtha from the process of the present invention to produce an oxygen content of 2% or more by weight of conventional diesel fuel provides a significant improvement in the emissions produced in standard engine tests.

Such an addition must be judiciously made so as to provide the higher oxygen levels in the fuel without changing the other specification parameters sufficiently to exceed the permissible ranges specified for the suitability of the fuel for its intended function.

The wax product can either be used as produced or cracked to produce additional synthetic diesel fuel and naphtha.

Depending on the desired end product, where a wax is desired, a wax clean up step is contemplated to remove any entrained catalyst which is smaller than the pore size of the porous metal filter element (0.2 μ to 0.5 μ) in the cross flow filter,

Where additional diesel fuel is desired, the wax can be heated to 410°C (770°F) to produce

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additional naphtha and diesel fuel. The following are typical analysis of the results of a wax thermal cracking step as described. Other conventional procedures may be employed.

- 5 It will be seen in the following Tables VI and VII that the level of oxygen contained in the diesel and naphtha produced from a wax cracking step is quite low and may be adjusted if desired for the results described by blending with the
- 10 oxygen containing naphtha from the process or with the oxygen containing diesel fuel from the process.

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TABLE VI

DIESEL CRACKED PRODUCT

	<u>TEST</u>	<u>METHOD</u>
	<u>RESULTS</u>	
5	Flash Point °F. 138	ASTM D56
	API Gravity @ 60 °F. 47.5	ASTM D1298
10	Sulfur content, wt.% <0.0001	Horiba Analyzer
	Kinematic viscosity 2.49 @ 40 °C., cSt.	ASTM D445
15	Distillation Range IBP 348	ASTM D86
	90% 653	
	FBP 694	
	Conradson Carbon on 10% <0.01	ASTM D189
20	Residuum, wt.%	
	Saturates, wt.% 46	NMR/90 MHz
	Alpha-Olefins 46	
25	Internal-Olefins 8	
	Oxygen Content, wt.% 0.16	Elemental Analysis
30	Average Carbon Chain C ₁₅ Length	GC/FID
	Cetane Index 73	ASTM D976
35	Heat of combustion, 19,754 BTU/lb.	ASTM D240

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TABLE VII

NAPHTHA

	<u>TEST</u>	<u>RESULTS</u>	<u>METHOD</u>
5			
	Saturates, wt.%		NMR/MHz
		40	
	Alpha-Olefins		
		52 Internal-Olefins	
10		7	
	Alcohols		
		0	
	Average Carbon Chain		GC/FID
		C ₈	
15	Length		

A salient feature of this invention, as previously described, resides in the use of carbon dioxide in the steam reformer, or other reactor for producing hydrogen and carbon monoxide in order to improve the overall carbon conversion efficiency of the process when the source of the carbon dioxide is in part derived from the Fischer-Tropsch reaction.

The gas stream 19, containing light hydrocarbon gases and carbon dioxide is subjected to similar removal of the carbon dioxide by absorption and subsequent stripping as previously described generally at 8. Preferably, the separated carbon dioxide from the steam reforming and the Fischer-Tropsch reactors, stream 9, is then added to the incoming gas stream 6 into the steam reforming reactor 5 to achieve the proportions

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previously described. Excess CO₂ may be vented, or compressed and stored for later use or sale.

Light hydrocarbon gas stream 23, after separation from the carbon dioxide, can be recovered for use as a petrochemical feed stock or fuel, or used as a fuel for the steam reformer, recycled to the inlet gas stream 12 to the Fischer-Tropsch reactor to enable further chain growth of olefins and alcohols, or even recycled to the inlet gas stream 6 if desired, as shown by the dotted line 17, to improve overall carbon conversion efficiency and impart an adjustment in the yield of the higher hydrocarbon product stream 21.

The preferred system of the present invention employing the process previously described is shown schematically in Figure 3.

The incoming gas stream 100 is subjected to sulfur removal, if desired, at 102. The gas after sulfur removal and after introduction of steam in stream 106 for reaction in the steam reformer 105.

The reaction product stream 107 from the steam reformer containing primarily hydrogen, carbon monoxide and carbon dioxide is introduced into a carbon dioxide absorber 108. The product gases having preferably less than about 10% carbon dioxide and more preferably less than 5% by volume

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of carbon dioxide is then transferred via line 109 into the Fischer-Tropsch reactor 110. Preferably the lean carbon dioxide absorbing solution previously described, is introduced by pump 115
5 into the absorber via line 111 after removal from the carbon dioxide stripper 112 by line 113 and valve 114. The carbon dioxide rich solution created in the absorber 108 is transferred to the stripper 112 by line 116.

10 After reaction in the Fischer-Tropsch reactor 110, the reaction products are transferred via line 119 to a distillation column 120 where the hydrocarbon wax products are separated from the diesel fuel, water and alcohol, naphtha and the
15 light hydrocarbon gases, carbon dioxide, carbon monoxide and hydrogen.

The light hydrocarbon product stream is then transferred via line 121 to a carbon dioxide absorber 125 where the light hydrocarbon gases are
20 separated from the carbon dioxide for further use and the absorbed carbon dioxide is stripped in the stripper 112 and then recycled to the reformer 105 via lines 130 and 104. Optionally, the light hydrocarbon gases, stream 137, can be recycled back
25 to the inlet of the Fischer-Tropsch reactor in order to enable the olefins and alcohols contained

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therein to participate in further chain growth. In some instances, it may be desirable to combine the carbon dioxide absorber, 125, with the carbon dioxide absorber, 108, to reduce the cost and complexity of the plant. Any portion of stream 137 not recycled back to the Fischer-Tropsch reactor, stream 138, can be either used for fuel for the reformer or added to the reformer feed, 106.

The conditions selected for use in the various components of the system are subject to the same criteria previously described for the process.

The following examples were modeled using the conditions listed. The modeling is based on the experience with various conditions used in pilot plant studies and represents the expected results using the conditions employed.

Carbon conversion efficiency for the overall process is defined as the ratio of amount of carbon contained in the C_5+ product in the Fischer-Tropsch reactor.

The amount of C_5+ product produced by the Fischer-Tropsch reactor is calculated in the following manner.

A given quantity of hydrogen and carbon monoxide react to form a product stream consisting of hydrogen, carbon monoxide, carbon dioxide,

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water, hydrocarbons and oxygenates. Any gases other than hydrogen and carbon monoxide which enter the reaction vessel are assumed to act as diluent gases only. Determining the complete product stream involves solving for six (6) unknowns:

5 (i) moles of hydrogen; (ii) moles of carbon monoxide; (iii) moles of carbon dioxide; (iv) moles of water; (v) moles of hydrocarbons and oxygenates; and (vi) composition of the hydrocarbons and

10 oxygenates leaving the reaction vessel.

To solve for these six unknowns, six equations are required. The first three result from the requirement that carbon, hydrogen, and oxygen be conserved across the reactor. The

15 fourth equation results from the assumption that a given amount, 90% of the feed carbon monoxide is reacted. The fifth equation results from empirical pilot plant data which shows a that consumption of hydrogen by conversion to hydrocarbon product and

20 water depends upon input hydrogen-to-carbon monoxide ratio and carbon monoxide consumption:

$$\frac{\text{Change in Moles of Hydrogen}}{\text{Change in Moles of Carbon Monoxide}} = \frac{\text{Input Moles Hydrogen}}{\text{Input Moles Carbon Monoxide}}$$

25

The sixth equation results from a statement of

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the Schultz-Flory theory: the moles of hydrocarbon of carbon number n in the product stream equals the moles of hydrocarbon of carbon number $n-1$ multiplied by α , the chain growth probability which is a constant for a given catalyst system and set of operating conditions. As shown in the hereinbefore referenced article by Satterfield and Huff, the Schultz-Flory theory is only valid if all compounds of each carbon number are included. Thus, the minor quantities of alcohols and other oxygenates, predominately in the C_2 through C_4 range, produced by the Fischer-Tropsch reaction are included in the calculated product distribution.

It must be stated that the analyses based on the equations are approximations to what can be expected in actual practice. Interpreting the hydrocarbon product stream as including oxygenated compounds which are generally produced in small amounts relative to the hydrocarbon, particularly for carbon numbers greater than 4, the yields obtained from these analyses are valid for comparison purposes.

In Table 1 are listed parameters and results of analyses performed on the system described hereinbefore, operated in different modes and at different conditions.

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Example 1

Referring to Figure 3 one million standard cubic feet

(28,316 M³) per day of natural gas assumed to be
5 methane regulated to a pressure of 230 psia (1590 kPa) is heated to 700°F (371°C) in preheater PH1 and flows through sulfur removal bed S1 at a space velocity of 700 M³ per hour per M³ of catalyst. S1 is a fixed bed of commercially available zinc oxide
10 spherical pellets ranging in diameter from 1/8 inch (3mm) to 3/16 inch (5mm). This type of sulfur removal process is appropriate for low levels of sulfur compounds, e.g. less than 25 parts per million (ppm).

15 The natural gas leaving S1 has a sulfur content less than 0.5 ppm and is mixed with 1.46 MMSCF (41,343 M³) per day of carbon dioxide recycled from stripper ST1 and 1.73 MMSCF (48,987 M³ per day of steam. The mixture is preheated to
20 1292°F (700°C) in preheater PH2 by the gases leaving the reforming reactor R1. The heated gas mixture undergoes chemical reaction in the catalytic reforming reactor R1. The catalyst is a commercial reforming catalyst such as nickel
25 supported on aluminum oxide in the form of raschig rings (e.g. catalyst 23-1 available from Katalco).

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Since the chemical reactions taking place involving the methane, steam and carbon dioxide are endothermic, heat is supplied to the outside walls of the tubes containing the catalyst rings. Due to heat transfer limitations, tube diameters are kept small, e.g. 5 inches (12.7) cm) and several tubes are manifolded together. For the flow rates of this example, a total of 12 tubes of 5 inches (12.7 cm) inside diameter and 24 feet (7.3 m) long would be required.

The objective of the reforming reactor is to produce as much synthesis gas (a mixture of hydrocarbon and carbon monoxide) and particularly carbon monoxide as possible. The extent to which the carbon in the methane and carbon dioxide is converted to carbon contained in carbon monoxide is determined by the thermodynamic equilibrium of the water gas shift reaction:

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(11)

and the steam-methane reaction:



5

(12)

The equilibrium constants for these reactions depend on the temperature of the gases leaving the reformer. Since reaction (12) involves an increase in moles as the reaction consumes methane, higher pressures adversely affect the extent of conversion of methane. The water-gas shift reaction readily achieves equilibrium on the nickel catalyst whereas the steam-methane reaction approaches to within about 16°C (29°F) of equilibrium, and the projected results are based on this phenomenon. For the present example with an exit gas temperature of 850°C (1562°F) and a pressure of 225 psia (1550 kPa) the gas leaving the reformer is comprised of 2.15 MMSCFD (60,879 M³/day) of hydrogen, 1.52 MMSCFD (43,040 M³/day) of carbon monoxide, 0.80 MMSCFD (22,653 M³/day) carbon dioxide, 0.08 MMSCFD (2265 M³/day) of methane and 1.29 MMSCFD (36,528 M³/day) of water.

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These gases are cooled in preheater PH2 to about 200°C (392°F) and then to 25°C (77°F) in water-cooled condenser C1 where the water is condensed and removed in separator vessel SV1.

5 The large carbon dioxide content (approximately 18%) of the gases leaving SV1 is undesirable for the synthesis reactor feed. Therefore, the next step in synthesis gas preparation is reduction of the carbon dioxide
10 content to less than about 5% by volume, and in this example, to 2% by volume. This is accomplished in a carbon dioxide absorption column ABS1 using a hot aqueous potassium carbonate solution which is converted to potassium bi-
15 carbonate upon reaction with carbon dioxide. The solution is continuously regenerated by pressure reduction (flashing) to approximately 2 psig (138 kPa) and boiling in stripper column ST1. The carbon dioxide removed in ST1 is compressed to 230
20 psia (1590 kPa) and recycled back to the reformer inlet. The gases leaving absorber ABS1 are cooled from 105°C (221°F) to 25°C (77°F) in water-cooled condenser C2 where the water vapor is condensed and removed in separator vessel SV2.

25 Alternate means can be used for removing carbon dioxide such as ethanolamine systems.

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However, these systems generally require higher operating pressures and temperatures and require a significantly greater amount of steam for regenerating the solution. Commercial systems of either type are available. After carbon dioxide removal, gas flows are the same except for carbon dioxide which is reduced to 0.016 MMSCFD (453 M³/day). The gases enter synthesis reactor SR1 which is a bubble column slurry reactor of the type described in detail by Kolbel and Ralek in The Fischer-Tropsch Synthesis in the Liquid Phase, Catalyst Review -- Science Engineering, Vol. 21(2) pp. 225-274, (1980). Reactor SR1 contains a precipitated iron catalyst having a particle size in the range of 5 to 40 microns and suspended in a sulfur-free high melting point wax (m.p. > 60°C (140°F)). The slurry should contain about 10% by weight iron. The space velocity is 240 vol. per hour per volume of expanded catalyst slurry bed volume.

The overall reaction vessel size for this example is 4.5 feet (1.37 m) internal diameter and 45 feet (13.7 m) high. The reactor would contain approximately 20,000 pounds of wax and 3500 pounds of catalyst. This volume allows room for expansion of the slurry and a catalyst and wax disengaging

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section above the slurry. The reactor has internal cooling tubes for removing the large exothermic heat of reaction approximately 7000/Btu/Lb. of liquid produced (16,249 kj/kg). Water pumped into the tubes generates high pressure steam which can be used for process heat.

The gases entering the bottom of synthesis reactor SR1 flow through a nozzle plate which produces small bubbles less than 1mm in diameter. The bubbles rising in the slurry provide good mixing between the gas and liquid phases and between the liquid and solid phases. The reactor temperature is maintained at 250°C (482°F) and the operating pressure is controlled to 210 psia (1450 kPa) by back pressure regulator BPR. The products produced in SR1 along with the unconverted gases enter a fractionating tower where the products are separated into three fractions: 36.0 barrels of naphtha-comprising molecules having carbon numbers between C₅ and C₁₀; 27.7 barrels of diesel -- C₁₁ to C₁₉ and 17.0 barrels of wax - C₂₀⁺.

The overhead gases contain a large amount of carbon dioxide which is produced in synthesis reactor SR1. To recover this carbon dioxide for reuse, the gases are fed to carbon dioxide absorber ABS2. After the water is removed in condenser C4

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and separator vessel SV4, the remaining light hydrocarbon gases, hydrogen and carbon monoxide flow through back pressure regulator BVPR into the reforming furnace burner. Combustion air for the reformer is compressed with blower B1 and preheated in PH3 using flue gases.

Table VIII lists the product yields and carbon efficiency along with operating parameters for Example 1 and several examples discussed below.

10

Example 2

Example 2 is the same as Example 1, except that no carbon dioxide is recycled from either the reformer or the Fischer-Tropsch reactor back to the inlet of the reformer. In this case, the carbon conversion efficiency is only 36.8% and the yield of C₅+ product is only 51.8 barrels.

15

Example 3

Example 3 is the same as Example 1 except that only carbon dioxide from the reformer is recycled back to the reformer inlet. The carbon conversion efficiency in this case is only 43.6% and the yield of C₅+ product is only 61.3 barrels. Comparing Examples 1, 2 and 3 demonstrates the advantage of recycling carbon dioxide from the Fischer-Tropsch reactor back to the (Example 2) inlet of the

20

25

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reformer. If no carbon dioxide recycle is employed, the efficiency is low, 36.8% and the C₅+ yield is also low, only 51.8 barrels. Adding carbon dioxide recycle from the reformer, (Example 3), improves the carbon conversion efficiency and C₅+ yield slightly to 43.6% and 61.3 barrels, respectively. Only when carbon dioxide recycle from the Fischer-Tropsch is added as in the preferred system, Example 1, do dramatic increases in carbon conversion efficiency and C₅+ yield result. Note that in only the preferred system is the 50% carbon conversion efficiency as predicted by equation 2, exceeded.

Example 4

Example 4 demonstrates the effect of recycling a fraction of all Fischer-Tropsch tail gases not just carbon dioxide. Here, half of the Fischer-Tropsch tail gases are recycled to the reformer inlet in an attempt to improve system performance by utilizing carbon dioxide and light hydrocarbon gases in the tail gas. This performance improvement is realized as the carbon efficiency increases from 58.1% in Example 1 to 60.5% in Example 4. Yield of C₅+ increases from 80.7 to 85.2. The disadvantage of this scheme is that gas

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flow rate into the reformer and Fischer-Tropsch reactor increase by about 50% thus increasing equipment costs significantly. If more than half the tail gas is recycled, equipment sizes increase very rapidly. In addition, high hydrogen-to-carbon monoxide ratios (input to Fischer-Tropsch reactor) result. Another disadvantage of this approach is the olefins contained in the tail gases require more steam to prevent carbon formation in the preheat heat exchanger and reformer.

Example 5

In this example, an improvement is obtained over those obtained in Example 4 by utilizing practically all the carbon dioxide in the Fischer-Tropsch tail gas. Only 50% of the tail gases is recycled but after first separating the carbon dioxide from the tail gas stream. In this manner, 98% of the CO₂ present in the tail gas is recycled into the reformer. Once again, the expected carbon efficiency and C₅+ yield increase significantly, to 71.3% and 94.6 barrel, respectively. Note also that gas flow into the reformer and Fischer-Tropsch are reduced from those employed in Example 4, thereby not requiring increases in equipment size to obtain the improved yields. Moreover, the high

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hydrogen to carbon monoxide ratio of Example 4 has been reduced from 3.54 to 2.50.

Example 6

In this example, Example 4 is extended to 70%
5 recycle of all Fischer-Tropsch tail gases, which will produce significant increases in carbon efficiency and C_5+ yield result, but at the expense of very large gas flows and excessive hydrogen to carbon monoxide ratios. It is possible that in an
10 installation these C_5+ yields could not be practically realized in an economically designed system. This is because the reformer heat input would increase beyond that available from combustion of the tail gases not recycled to the
15 reformer inlet. A more practical economical limit appears to be closer to the 50% recycle of Example 4.

Example 7

This example demonstrates the results from the
20 use of the alternate method for reducing the high hydrogen to carbon monoxide ratios input to the Fischer-Tropsch reactor by removing some hydrogen from the gas stream with, for example, a membrane separator. Example 7 demonstrates the effect of

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removing sufficient hydrogen to restrict the hydrogen to carbon monoxide ratio to about 1.5 to 1. Comparing the results of Example 4, it can be seen that there is a loss of carbon efficiency and lower C₅+ yields. This can be attributed to the fact that the hydrogen is removed from the reaction stream and cannot contribute to production of hydrocarbons. A comparison with Example 5 shows how much more effective the method of recycling carbon dioxide from the Fischer-Tropsch reactor to the reformer is compared to this example. Not only is the hydrogen retained in the system in Example 5, but there is a better use of the carbon input.

Example 8

This example can be compared with Example 4 and demonstrates the effect of changes in alpha, i.e. the probability of linear condensation. The alpha (α) has been decreased to 0.7 and the effect is to significantly increase production of lighter hydrocarbons. The carbon efficiency and C₅+ yield decreased to 43.7% and 60.0 barrels, respectively because the reduction of alpha (α) to 0.7 significantly increases production of C₁ through C₄ hydrocarbons at the expense of C₅+ fraction. It is noted, however, that although the C₅ fraction

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decreases, these light hydrocarbons can be used as chemical feed stocks.

Example 9

This example, run as previous Example 4, increases the overall recycle of Example 4 to 70% retaining the low alpha (α) of 0.7 of Example 8. In addition, sufficient light hydrocarbons are recycled and reacted to produce C₅+ yields and carbon efficiency of 79.3 barrels and 54.6% respectively. A combination of reduced alpha (α) and overall recycle of Fischer-Tropsch tail gas is therefore a method of shifting the distribution of C₅+ hydrocarbons. Here again, one must consider the large gas flows which result and the limit imposed by reformer heating requirements as discussed under Example 6.

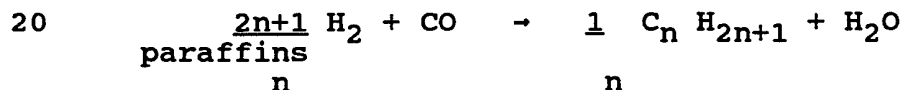
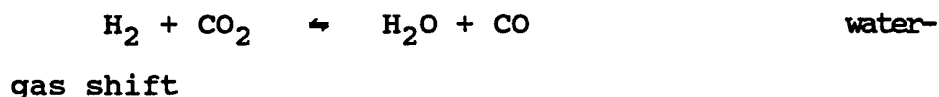
Example 10

This example demonstrates that increasing the reformer operating temperature increases its performance and, therefore, performance of the complete system. The reformer operating temperature of the preferred system, Example 1, has been increased to 875°C for this example. Comparing with Example 1, this produces

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approximately 5.5% more carbon monoxide thus increasing carbon efficiency to 61.4% and increasing C₅+ yield to 85.1 barrels. Practical implementation of this increase requires that one
 5 account for not only the higher energy cost of operating at the higher temperature, but also the decreased life of the reformer tubes, a major system expense.

An alternative method for improving carbon
 10 conversion efficiency by utilizing the carbon dioxide produced in the Fischer-Tropsch reactor has been discovered (See Figure 4) It was found that the tail gases from the Fischer-Tropsch reactor which consist chiefly of hydrogen and carbon
 15 dioxide can be converted to liquid hydrocarbons in a second Fischer-Tropsch reactor according to the following reactions:



25 In this case, the primary reaction is the water gas shift reaction which proceeds to

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equilibrium and corresponds to an extent of reaction from left to right of about 0/25 for temperatures of about 250°C. The carbon monoxide formed in the shift reaction reacts with excess hydrogen to produce hydrocarbons via the Fischer-Tropsch reactions. A test was conducted in a small slurry reactor using the same iron-based catalyst used in the normal Fischer-Tropsch synthesis. The temperature, pressure and space velocity were also kept the same. The carbon dioxide conversion was 25% for a feed having a hydrogen to carbon dioxide ratio of 2:1 and also for 1.5:1. Conversion of the hydrogen was 42%, and 88% of the carbon monoxide produced in the water gas shift reaction was converted to hydrocarbons in the Fischer-Tropsch reaction. The chain growth (α) was the same as in the normal Fischer-Tropsch synthesis.

This approach is particularly advantageous in systems which have excess carbon dioxide which would normally be vented to the atmosphere and which also have hydrogen removed in a membrane separator or pressure saving adsorption unit.

The following Table summarizes the various schematic illustrations in Figures 7 through 14 showing the expected yields possible in barrels per day.

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TABLE VIII

ALTERNATIVE PROCESS CONFIGURATIONS
EQUIPMENT REQUIREMENTS AND PRODUCT YIELDS

Conditions:

- 5 * 1.0 MMCFPD METHANE (CH₄)
 * 8% MAX CO₂ TO FT REACTOR VESSEL
 * 1.5:1 H₂ to CO RATIO

*** EQUIPMENT ***

FIG.	REO FORMER	PART OXID.	CO ₂ #1	ABS. #2	CO ₂ STRIP	CO ₂ COMP	H ₂ SCRUB	F-T GAS	TAIL COMP	F-T RECYCLE	DIST COI
7	Y	N	Y	N	Y	Y	Y	Y	N		N
8	Y	N	Y	Y	Y	Y	Y	Y	N		N
9	Y	N	Y	N	Y	Y	Y	Y	Y		N
10	1X	N	Y	N	Y	Y	Y	Y	N		Y
11	Y	N	Y	Y	Y	Y	Y	Y	N		Y
12	N	Y	N	N	N	N	N	Y	Y		Y
13	N	Y	Y	N	Y	Y	Y	Y	Y		Y

*** PRODUCTS ***

FIG.	<u>YIELD B/D (C7+)</u>	<u>SURPLUS ENERGY (MMBTUPD-LHV)</u>
7	39.97	226
8	69.38	0
9	60.98	0
10	77.96	0
11	2582.93	0
12	100.05	0
13	106.03	0

Finally, it has been observed that the aqueous phase removed

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from distillation contain a significant amount of alcohols and other oxygenated compounds (see Table ____). In general, it will not be economical to attempt to concentrate and recover the alcohols. One approach for disposing of this aqueous phase is to recycle it to the reprinter feed whereby the water will contribute to the steam requirement and the oxygenated compounds will undergo reaction in the reformer to produce additional hydrogen and carbon monoxide.

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TABLE IX

Typical Fischer-Tropsch Aqueous Phase Composition

Water Content, wt. %		87.5
ASTM E203		
Total Alcohols, Aldehydes and Ketones		
GC/MS, corrected by water content		
10	Methanol	0.13
	Ethanol	5.75
	1-Propanol	2.00
	1-Buranol	1.25
	1-Pentanol	0.63
	1-Hexanol	0.13
15	Hydrocarbons	0.63
	Acetic Acid	1.25
	Ethyl Acetate	0.13
	Acetaldehyde	0.13
Total Acid Number, mg KOH/g		26.5
ASTM D2849		
Iron content, mg/l.		<0.05
Atomic Absorption		

The foregoing description and examples are exemplary of the operation of the method and system of the present invention and the scope of the invention is not limited thereby. The appended claims, as limited only by the prior art, represent the intended scope of the invention described.

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WHAT IS CLAIMED:

1 1. A process for the conversion of
2 hydrocarbon gas feed stock into higher molecular
3 weight hydrocarbon products including liquid
4 hydrocarbon products suitable of use as a fuel or a
5 fuel additive comprising the steps of:

6 converting the feed stock hydrocarbon gases in
7 the presence of carbon dioxide into hydrogen and
8 carbon monoxide in predetermined ratios;

9 reacting the hydrogen and carbon monoxide
10 together in a Fischer-Tropsch synthesis reaction in
11 the presence of a promoted iron-catalyst in a
12 liquid hydrocarbon slurry;

13 recovering liquid gaseous hydrocarbon products
14 having more than five carbon atoms produced by said
15 Fischer-Tropsch reaction;

16 separating gaseous products including carbon
17 dioxide produced by said reaction from the liquid
18 products;

19 recycling at least a portion of the gaseous
20 product produced including carbon dioxide into the
21 feed hydrocarbon gases before the conversion to
22 hydrogen and carbon monoxide.

2. The process of claim 1 wherein the

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2 Fischer-Tropsch synthesis is conducted at a
3 pressures between about 100 psia (689 kPa) and 500
4 psia (3447 kPa) and at temperatures between about
5 220°C (428°F) and 280°C (536°F) and at space
6 velocities between 100 and 300 M³/hr per M³ of
7 expanded slurry volume.

1 3. The process of claim 1 wherein the
2 catalyst selected is a precipitated iron-copper
3 catalyst promoted with alkali metal salts.

1 4. The process of claim 3 wherein the alkali
2 metal salt is potassium carbonate.

1 5. The process of claim 4 wherein the amount
2 of catalyst employed is such that between 15% and
3 15% of the total weight of slurry is iron.

1 6. The process of claim 4 wherein the
2 particle size of the catalyst is between 5 μ and 40
3 μ.

1 7. The process of claim 5 wherein the liquid
2 hydrocarbon products recovered are characterized as
3 being substantially comprised of saturated and
4 unsaturated aliphatic hydrocarbons and alcohols

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5 having chain lengths of from between about 5 to
6 about 20 carbon atoms.

1 8. The process of claim 7 wherein the liquid
2 hydrocarbons recovered have a boiling range of from
3 about 122°F (50°C) to about 662°F (350°C).

1 9. The process of claim 8 wherein the
2 Fischer-Tropsch synthesis reaction produces up to
3 about 90% conversion of the carbon from the carbon
4 monoxide into hydrocarbon product and carbon
5 dioxide.

1 10. The process of claim 1 wherein more than
2 50% of the carbon introduced into the conversion
3 step in the form of hydrocarbons is converted into
4 carbon in the final hydrocarbon products containing
5 at least five carbon atoms.

6 11. A process for the conversion of
7 hydrocarbon gases into hydrocarbon products
8 including hydrocarbon products suitable for use as
9 a fuel or a fuel additive comprising the steps of:
10 converting the hydrocarbon gases in the
11 presence of carbon dioxide into hydrogen and carbon
12 monoxide in the ratio of from about 0.5 to about

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13 2.0 parts of hydrogen to one part of carbon
14 monoxide by volume;

15 removing carbon dioxide from the hydrogen and
16 carbon monoxide produced;

17 reacting the hydrogen and carbon monoxide by a
18 Fischer-Tropsch synthesis reaction in the presence
19 of a hydrocarbon slurry containing a promoted iron
20 catalyst;

21 recovering gaseous and liquid hydrocarbon
22 products produced by said Fischer-Tropsch reaction;

23 separating hydrocarbon containing gaseous
24 products produced by said reaction from the other
25 products;

26 recycling at least a portion of the gaseous
27 products produced into the Fischer-Tropsch
28 synthesis reactor for the conversion to hydrogen
29 and carbon monoxide.

1 12. A process for the conversion of a
2 hydrocarbon-containing gas stream into products
3 including liquid hydrocarbons having greater
4 molecular weight comprising the steps of:

5 first, catalytically reacting the hydrocarbon
6 gas in one reaction zone in the presence of water
7 and sufficient carbon dioxide to produce hydrogen
8 and carbon monoxide product in a preselected ratio

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9 of hydrogen to carbon monoxide;

10 second, catalytically reacting the hydrogen
11 and carbon monoxide in a second reaction zone in
12 the presence of a slurry containing an alkali
13 promoted iron-based catalyst under conditions
14 favoring the formation of carbon dioxide, light
15 hydrocarbon gases, and normally liquid hydrocarbons
16 containing at least five carbon atoms, and
17 hydrocarbon waxes;

18 third, separating the gaseous and liquid
19 hydrocarbons by distillation; and

20 fourth, recycling at least the light
21 hydrocarbon gases into the reaction of hydrogen and
22 carbon monoxide.

1 13. The process of claim 12 wherein the ratio
2 of carbon from hydrocarbon gas to carbon dioxide
3 and water is one part of carbon from the
4 hydrocarbon gas for up to four parts of carbon
5 dioxide and water.

1 14. The process of claim 13 wherein the
2 ratio of one part of carbon from hydrocarbon in the
3 feed stream to up to two parts by volume of carbon
4 dioxide is maintained where the overall ratio of
5 one part of carbon from hydrocarbon to up to four

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6 parts by volume of carbon dioxide and water is
7 maintained.

1 15. The process for the conversion of a
2 hydrocarbon gas stream into products including
3 liquid hydrocarbons comprising the steps of:

4 first, catalytically reacting the hydrocarbon
5 gas in one reaction zone in the presence of water
6 and sufficient carbon dioxide to produce hydrogen
7 and carbon monoxide product in a ratio of hydrogen
8 to carbon monoxide of from about 0.5 to about 2.0
9 to 1;

10 second, catalytically reacting the hydrogen
11 and carbon monoxide in a second reaction zone in
12 the presence of a slurry containing an alkali
13 promoted iron-based catalyst under conditions
14 favoring the formation of carbon dioxide, light
15 hydrocarbon gases, and normally liquid hydrocarbons
16 containing at least five carbon atoms, and
17 hydrocarbon waxes, and then separating the liquid
18 hydrocarbon products from the gaseous products; and

19 third, reacting the gaseous products in a
20 third reaction zone in the presence of a slurry
21 containing an alkali promoted iron-based catalyst
22 to produce additional liquid hydrocarbon product.

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1 16. The process of claim 15 wherein the ratio
2 of carbon from the hydrocarbon gases first reacted
3 to carbon dioxide is one part of carbon from
4 hydrocarbon gas to up to two parts of carbon
5 dioxide.

1 17. The process of claim 16 wherein the ratio
2 of carbon from hydrocarbon gas to carbon dioxide
3 and water is one part of carbon from the
4 hydrocarbon gas to four parts of carbon dioxide and
5 water.

1 18. The process of claim 17 wherein the ratio
2 of one part of carbon from hydrocarbon in the feed
3 stream to up to two parts by volume of carbon
4 dioxide is maintained where the overall ratio of
5 one part of carbon from hydrocarbon to up to four
6 parts by volume of carbon dioxide and water is
7 maintained.

1 19. A method for adjusting the hydrogen to
2 carbon monoxide ratio introduced into a Fischer-
3 Tropsch reactor without removal of hydrogen,
4 comprising the steps of:

5 separating carbon dioxide from the product
6 stream from a Fischer-Tropsch reactor; and

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7 introducing a preselected portion of the
8 separated carbon dioxide into a steam reforming
9 reactor in combination with a hydrocarbon-
10 containing feed stream and water in a predetermined
11 ratio of hydrocarbon to water to carbon dioxide to
12 produce a preselected hydrogen to carbon monoxide
13 ratio in the product stream from the steam
14 reforming reactor.

1 20. The process of claim 19 wherein the ratio
2 of carbon from hydrocarbon gases to carbon dioxide
3 is one part of carbon to up to two parts of carbon
4 dioxide.

1 21. The process of claim 20 wherein the ratio
2 of carbon from hydrocarbon gas to carbon dioxide
3 and water entering the steam reforming reactor is
4 one part of carbon to up to four parts of carbon
5 dioxide and water.

1 22. The method of claim 21 wherein the ratio
2 of one part of carbon from hydrocarbon in the feed
3 stream to up to two parts by volume of carbon
4 dioxide is maintained where the overall ratio of
5 one part by volume of carbon to up to four parts by
6 volume of carbon dioxide and water is maintained.

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1 23. The process of claim 22 wherein the steam
2 reformer conversion of hydrocarbon gas to hydrogen
3 and carbon monoxide is conducted at a temperature
4 of from about 1292°F (700°C) to about 1652°F
5 (900°C).

1 24. The process of claim 23 wherein the steam
2 reforming reaction is conducted at a pressure of
3 from about 12 psia (82.7 kPa) to about 500 psia
4 (3447 kPa).

1 25. A system for converting hydrocarbon gases
2 into products including liquid hydrocarbon products
3 containing five or more carbon atoms wherein the
4 conversion of carbon from the hydrocarbon gases
5 into hydrocarbon product containing five or more
6 carbon atoms is at least 50% comprising:

7 catalytic conversion means for converting
8 hydrocarbon gases, water and carbon dioxide into
9 hydrogen, carbon monoxide and carbon dioxide and
10 including means for introducing gases into said
11 conversion means and means for removing product
12 from said conversion means;

13 Fischer-Tropsch synthesis means for converting
14 hydrogen and carbon monoxide into liquid

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15 hydrocarbon compounds and carbon dioxide.
16 recycle means for taking at least a portion of
17 the carbon dioxide produced by the Fischer-Tropsch
18 synthesis means and introducing said carbon dioxide
19 into the catalytic conversion means in preselected
20 amounts sufficient to prevent elemental carbon
21 formation in the catalytic conversion means while
22 producing a ratio of from about 0.5 to 1 to about
23 2.0 to 1 of hydrogen to carbon monoxide entering
24 the Fischer-Tropsch synthesis means.

1 26. The system of claim 25 wherein said
2 recycle means comprises:

3 carbon dioxide absorption and recovery means
4 for absorbing and recovering carbon dioxide from
5 the product stream of the Fischer-Tropsch synthesis
6 means.

1 27. The system of claim 26 further
2 comprising:

3 additional carbon dioxide absorption and
4 recovery means for absorbing and recovering carbon
5 dioxide from the product stream from the catalytic
6 conversion means for introduction into the feed
7 stream of the catalytic conversion means.

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1 28. The system of claim 27 further comprising
2 separation means for separating liquid hydrocarbon
3 product from the Fischer-Tropsch synthesis means.

1 29. The system of claim 28 wherein said
2 catalytic conversion means is capable of converting
3 hydrocarbons into carbon monoxide and hydrogen
4 starting with a ratio of one carbon atom up to two
5 moles of carbon dioxide.

1 30. The system of claim 29 wherein the ratio
2 of carbon to water and carbon dioxide is one part
3 carbon to up to four parts of carbon dioxide and
4 water.

1 31. In a method for inducting a catalytically
2 active promoted iron catalyst for use in a Fischer-
3 Tropsch slurry reactor, which method comprises
4 activating an inactive catalyst precursor
5 comprising iron oxide and a promoting amount of
6 potassium and copper, said iron oxide being
7 selected from the group consisting of hydrous iron
8 oxides and precipitated iron oxide comprised
9 predominantly of hematite, said activation being
10 effected by contact of said inactive catalyst
11 precursor with a mixture of gaseous hydrogen and

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12 carbon monoxide, at elevated temperature and
13 pressure, the improvement which comprises:

14 activating said catalyst precursor by
15 conducting said contacting under a combination of
16 conditions including a temperature of about 250°C
17 to 300°C, for about 0.5 to 5 hours, with a water
18 vapor partial pressure of about 1 psig, and a
19 hydrogen to carbon monoxide ratio of about 1.3 to
20 1.5, said combination of conditions being effective
21 to increase the selectivity of the activated
22 catalyst in the subsequent formation of liquid
23 hydrocarbons in a Fischer Tropsch reaction.

1 32. In a method for preparing a catalytically
2 active Fischer Tropsch promoted iron catalyst,
3 which method comprises activating an inactive
4 catalyst precursor comprising iron oxide and a
5 promoting amount of potassium and copper, said iron
6 oxide being selected from the group consisting of
7 hydrous iron oxides, and precipitated iron oxide
8 comprised predominantly of hematite, said
9 activation being effected by contact of said
10 inactive catalyst precursor with a mixture of
11 gaseous hydrogen and carbon monoxide, at elevated
12 temperature and pressure, the improvement which
13 comprises:

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14 activating said catalyst precursor by
15 conducting said contacting under a combination of
16 conditions including a temperature of about 250°C
17 to 300°C, for about 0.5 to 5 hours, with a water
18 vapor partial pressure of about 1 psig, and a
19 hydrogen to carbon monoxide ratio of about 1.3 to
20 1.5, said combination of conditions being effective
21 to increase the selectivity of the activated
22 catalyst in the subsequent formation of liquid
23 hydrocarbons in a Fischer Tropsch reaction.

1 33. A method of making a promoted iron
2 catalyst useful in a slurry Fischer-Tropsch reactor
3 comprising the steps of:

4 dissolving at less than 150°C predetermined
5 quantities of copper and iron in nitric acid to
6 form a solution of ferrous nitrate, ferri nitrate
7 and cupric nitrate;

8 sparging the solution with oxygen-containing
9 gas during the step of dissolving;

10 precipitating a catalyst precursor by the
11 addition of sufficient ammonium hydroxide to the
12 solution formed;

13 removing the ammonium nitrate formed during
14 the precipitation step;

15 washing the catalyst precursor;

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16 adding by mixing a water slurry containing
17 potassium carbonate to the catalyst precursor in an
18 amount sufficient to promote the catalyst,
19 drying the mixed catalyst precursor and
20 potassium carbonate promotor and sizing to a
21 particle size of from about 5 to about 50 microns,
22 heating the solids obtained in air to a
23 temperature of about 600°F for a sufficient time to
24 drive off residual moisture and anneal the catalyst
25 to render it suitable for induction activation and
26 subsequent use in a Fischer Tropsch slurry
27 reaction.

1 34. A diesel fuel additive for reducing
2 particulate emissions comprising a synthetic slurry
3 naphtha or diesel or mixtures thereof containing
4 alcohols containing at least five carbon atoms
5 produced by Fischer Tropsch reaction with a
6 promoted iron-based catalyst said additive to be
7 added with the diesel fuel in sufficient quantity
8 to produce an oxygen content in the diesel fuel of
9 at least 2% by weight, without exceeding diesel
10 fuel specification limits for viscosity.

1 35. A method of cracking a wax produced by a
2 Fischer Tropsch synthesis reaction utilizing a

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3 promoted iron-based catalyst in a slurry reaction
4 comprising the step of heating the wax to a
5 temperature of about 770°F (410°C) for a sufficient
6 period of time to produce a diesel fraction, a
7 naphtha fraction, and residual wax.

AMENDED CLAIMS

[received by the International Bureau on 11 July 1994 (11.07.94); original claims 1 and 5 amended; remaining claims unchanged (2 pages)]

1 1. A process for the conversion of
2 hydrocarbon gas feed stock into higher molecular
3 weight hydrocarbon products including liquid
4 hydrocarbon products suitable of use as a fuel or a
5 fuel additive comprising the steps of:

6 converting the feed stock hydrocarbon gases in
7 the presence of carbon dioxide into hydrogen and
8 carbon monoxide in predetermined ratios;

9 reacting the hydrogen and carbon monoxide
10 together in a Fischer-Tropsch synthesis reaction in
11 the presence of a promoted iron-catalyst in a
12 liquid hydrocarbon slurry;

13 recovering gaseous products, wox, and liquid
14 hydrocarbon products produced by said Fischer
15 Tropsch reaction;

16 separating the gaseous products and wox from
17 said liquid products comprising hydrocarbon
18 products containing more than five carbon atoms;

19 recycling at least a portion of the gaseous
20 product produced including carbon dioxide into the
21 feed hydrocarbon gases before the conversion to
22 hydrogen and carbon monoxide.

1 2. The process of claim 1 wherein the
2 Fischer-Tropsch synthesis is conducted at a
3 pressures between about 100 psia (689 kPa) and 500

1 psia (3447 kPa) and at temperatures between about
2 220°C (428°F) and 280°C (536°F) and at space
3 velocities between 100 and 300 M³/hr per M³ of
4 expanded slurry volume.

1 3. The process of claim 1 wherein the
2 catalyst selected is a precipitated iron-copper
3 catalyst promoted with alkali metal salts.

1 4. The process of claim 3 wherein the alkali
2 metal salt is potassium carbonate.

1 5. The process of claim 4 wherein the amount
2 of catalyst employed is such that between 5% and
3 15% of the total weight of slurry is iron.

1 6. The process of claim 4 wherein the
2 particle size of the catalyst is between 5 μ and 40
3 μ.

1 7. The process of claim 5 wherein the liquid
2 hydrocarbon products recovered are characterized as
3 being substantially comprised of saturated and
4 unsaturated aliphatic hydrocarbons and alcohols
5 having chain lengths of from between about 5 to
6 about 20 carbon atoms.

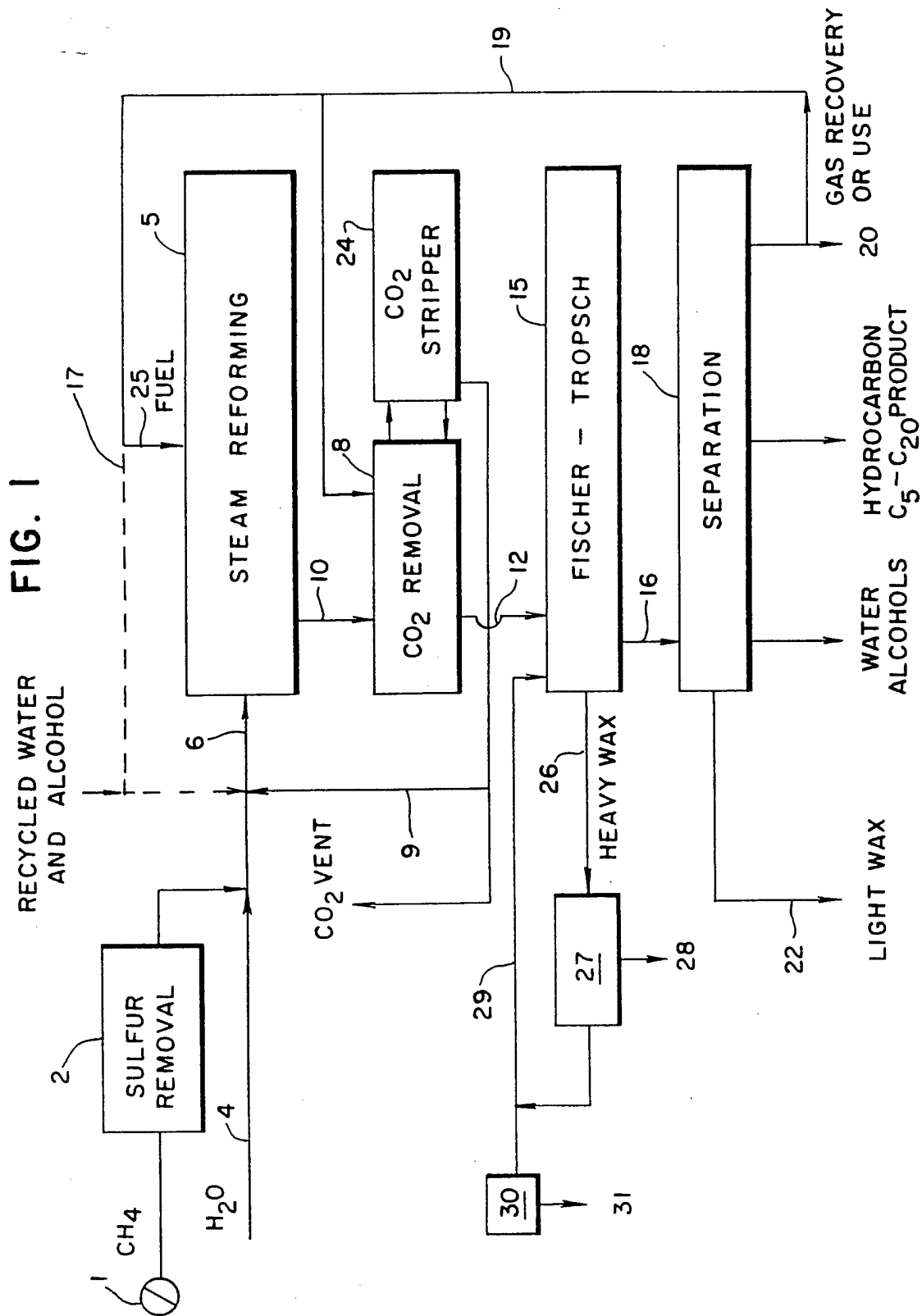


FIG. 2

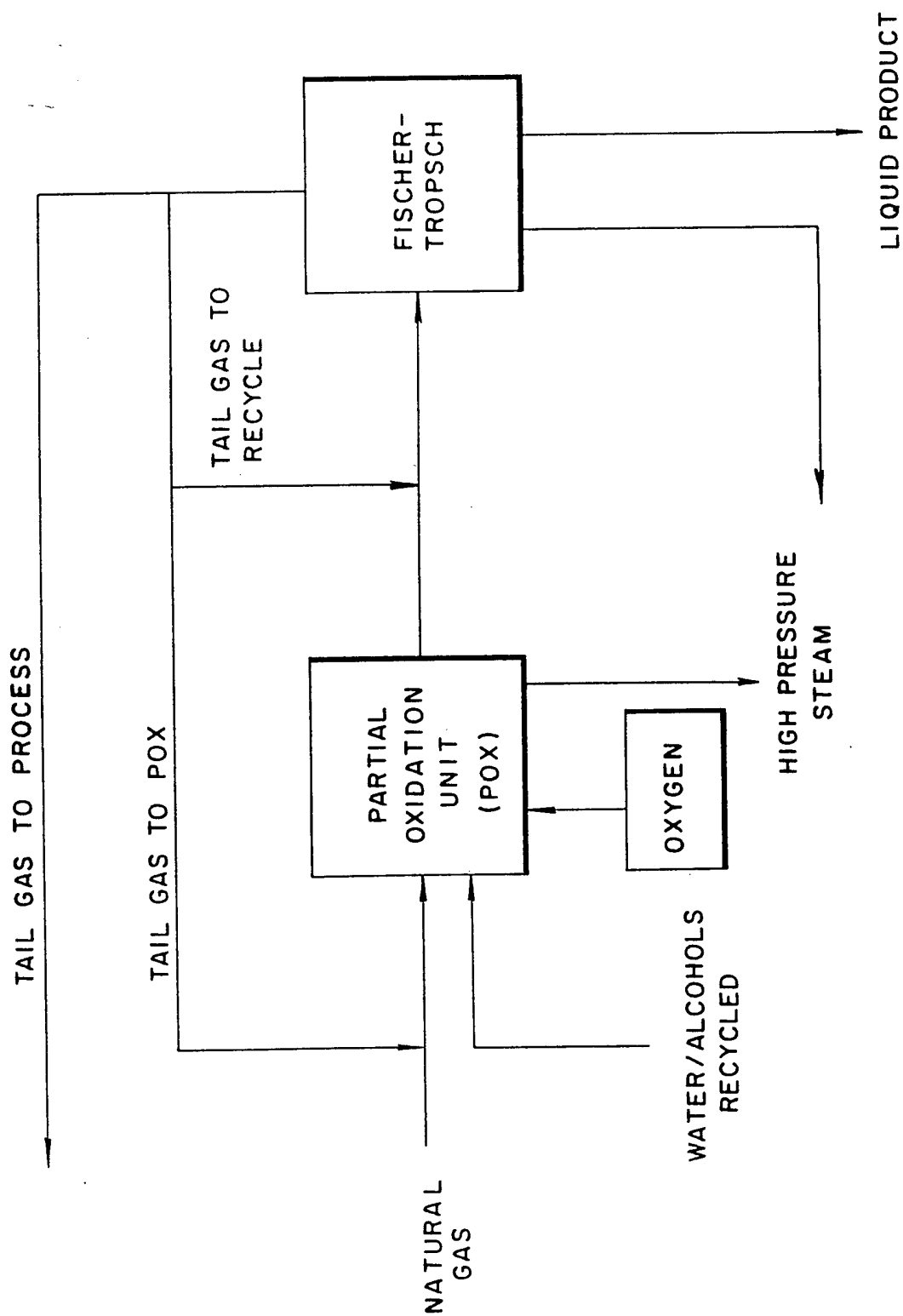


FIG. 3

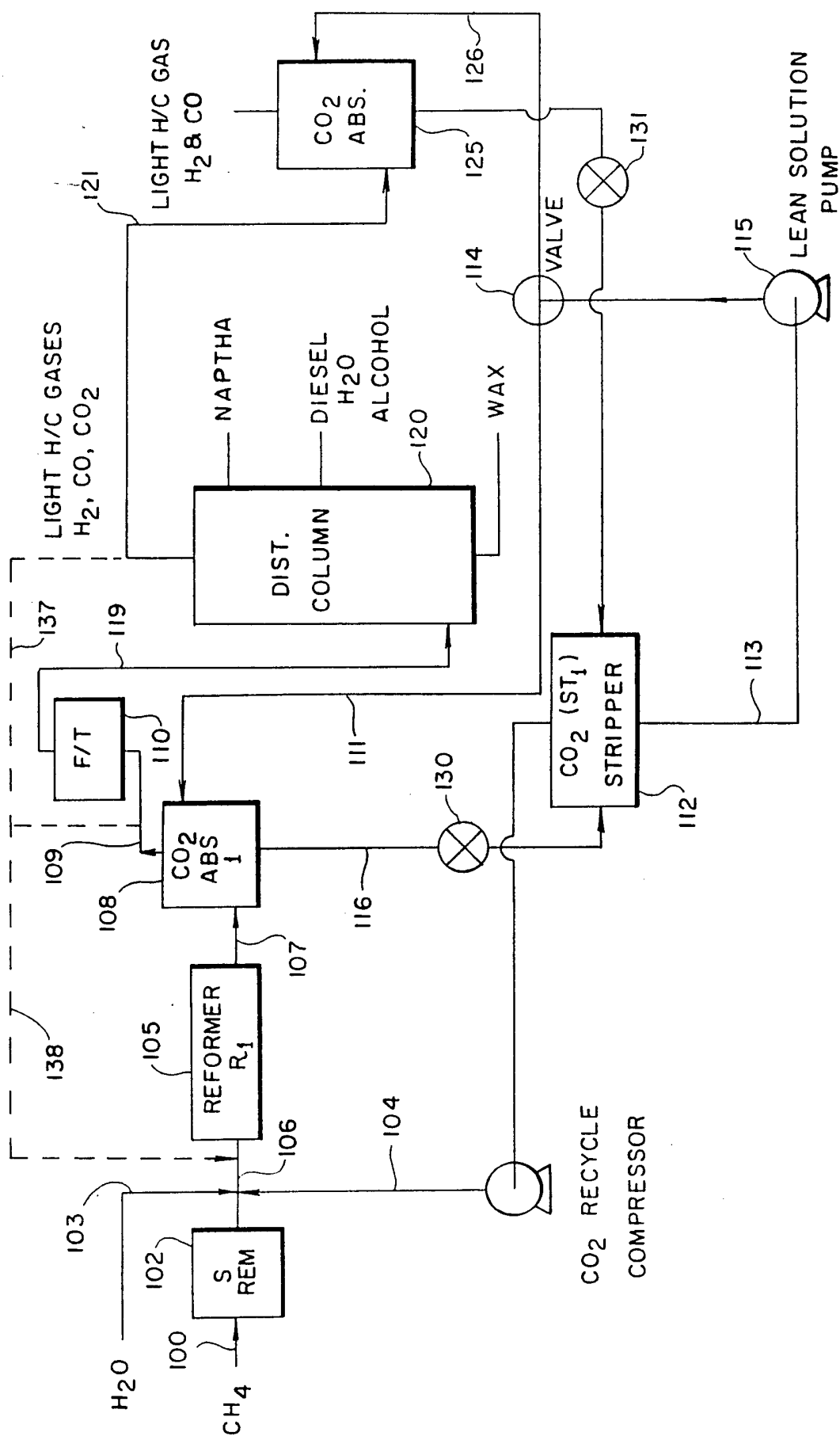


FIG. 4

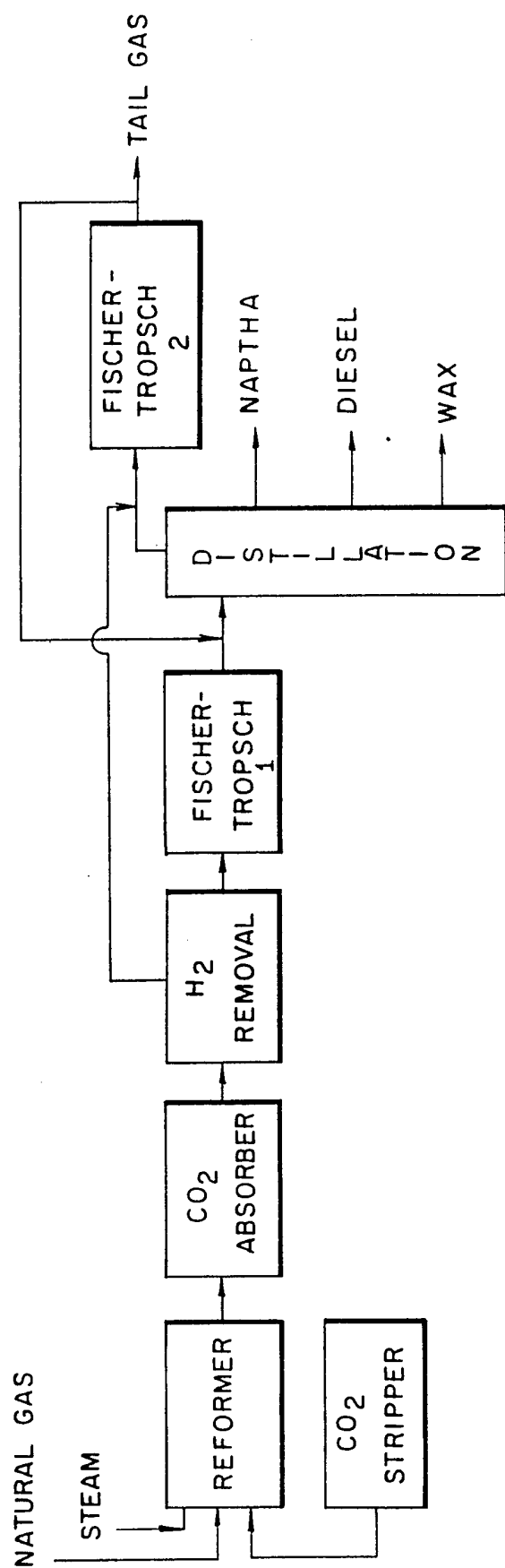


FIG. 5a

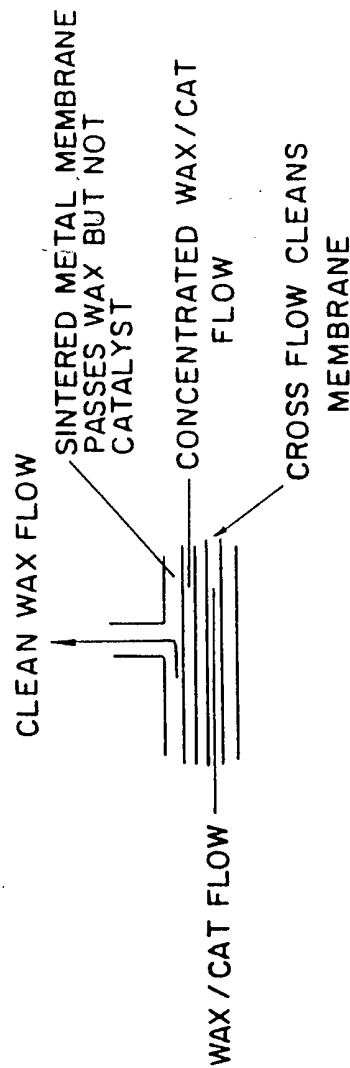


FIG. 5

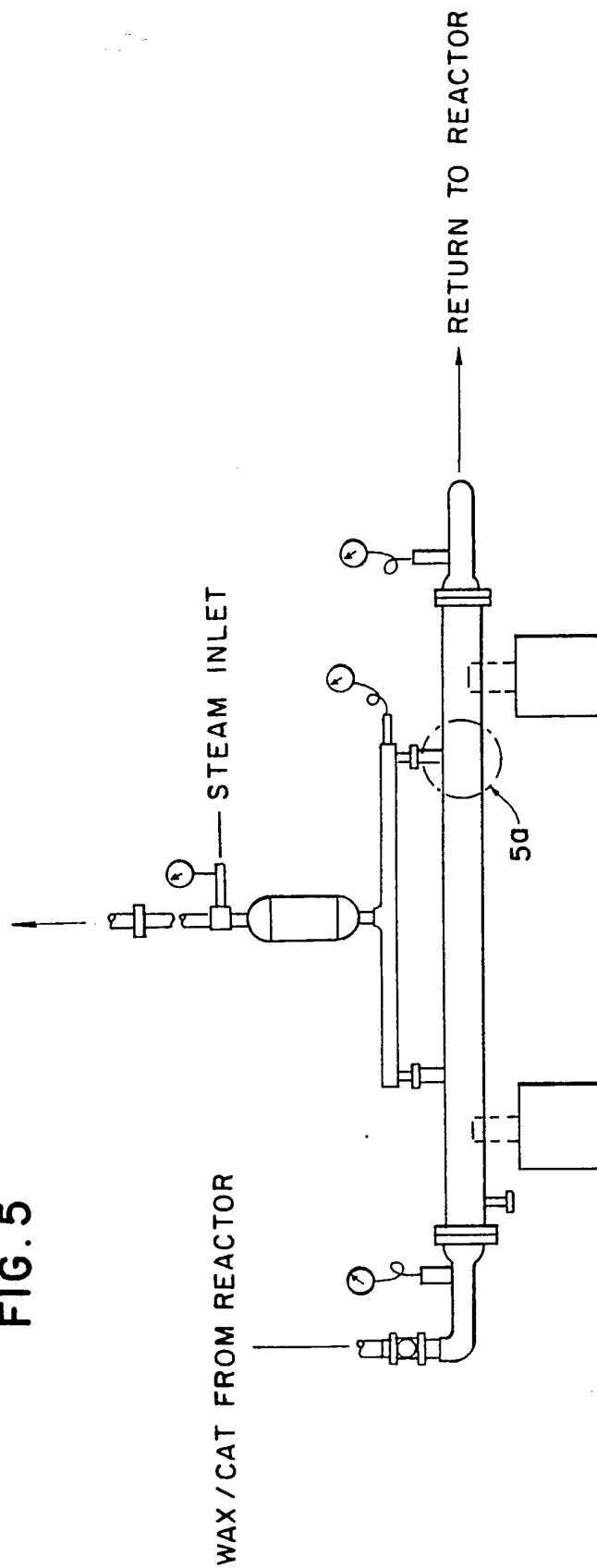


FIG. 6a

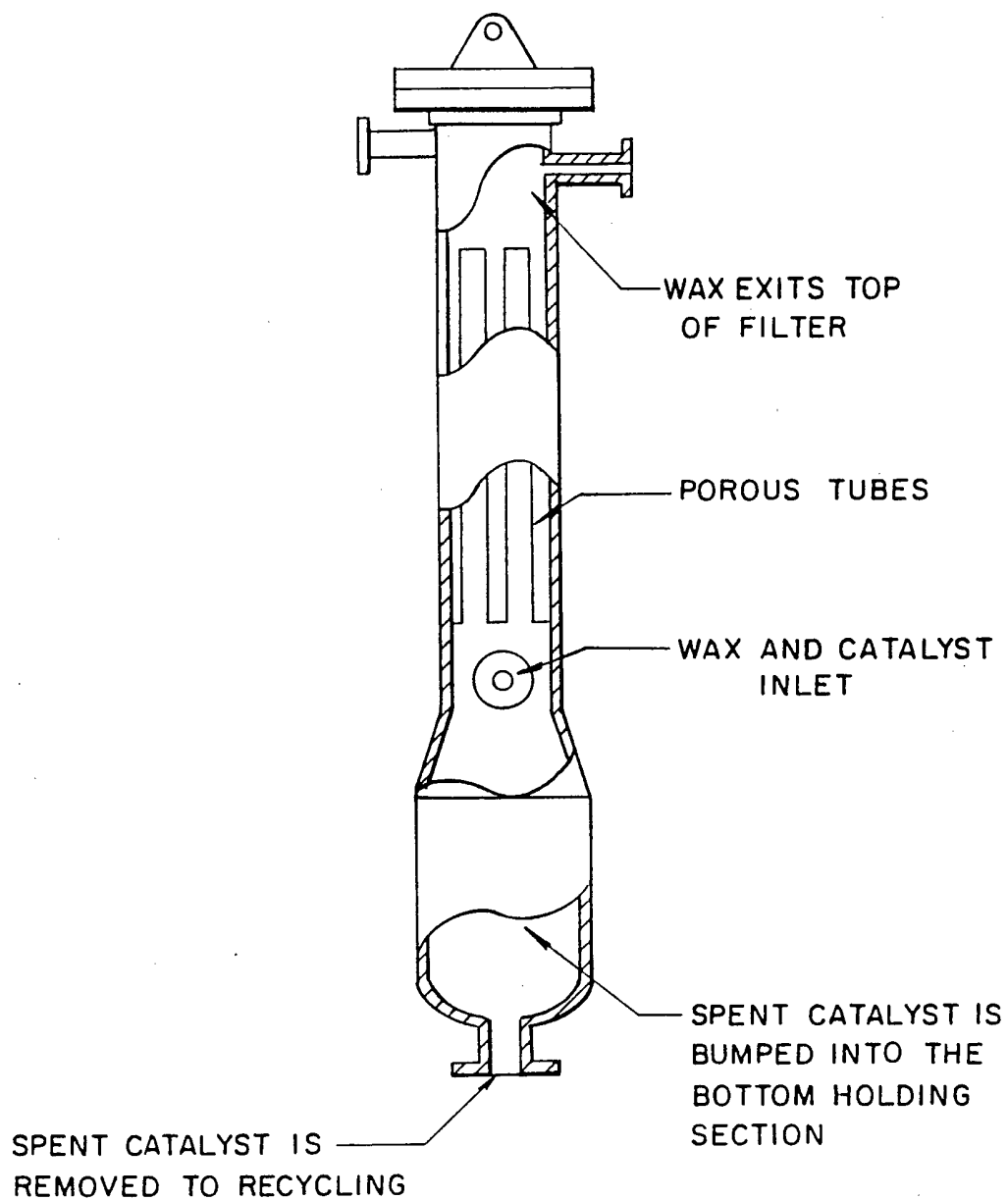


FIG. 6

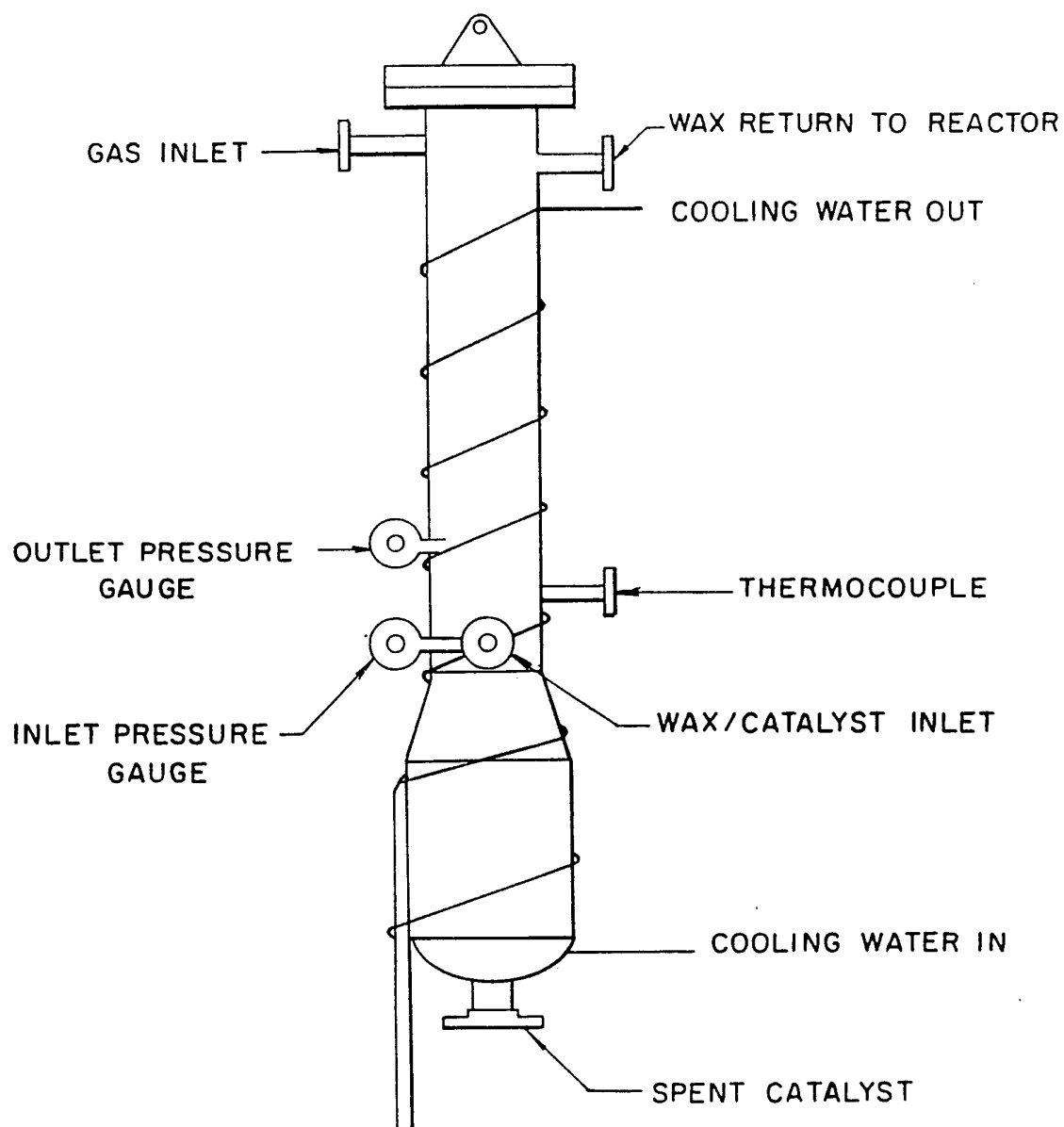


FIG. 7

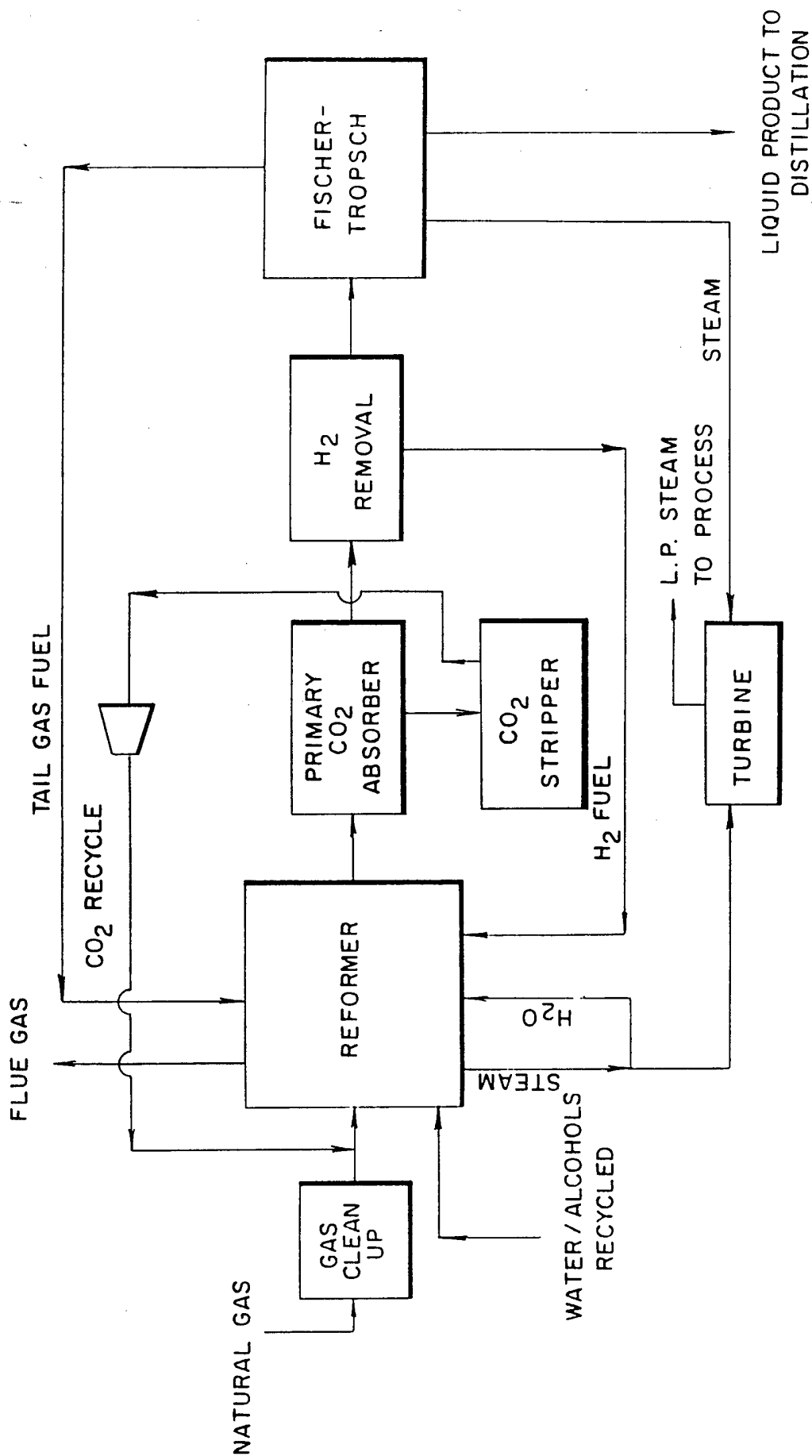


FIG. 8

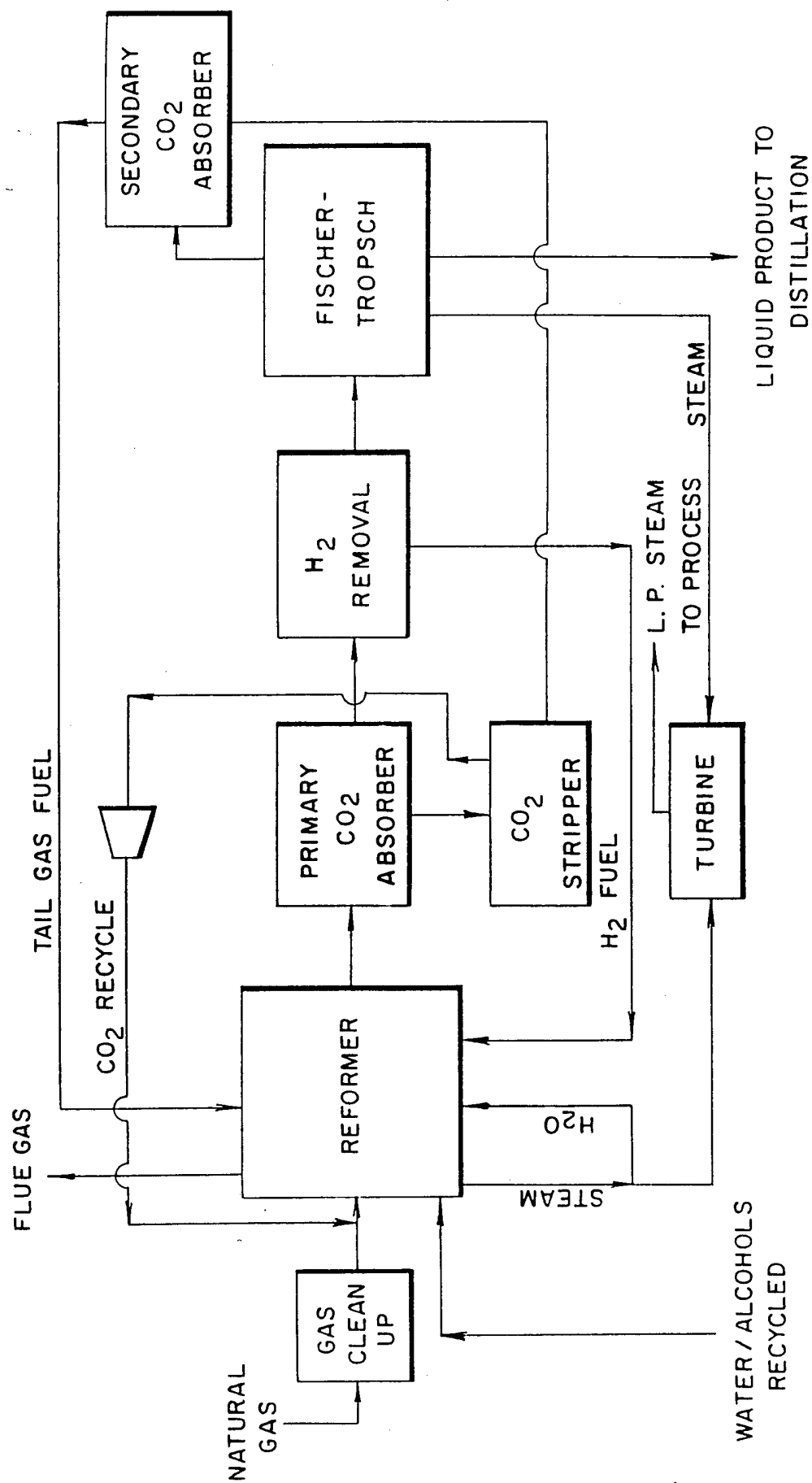


FIG. 10

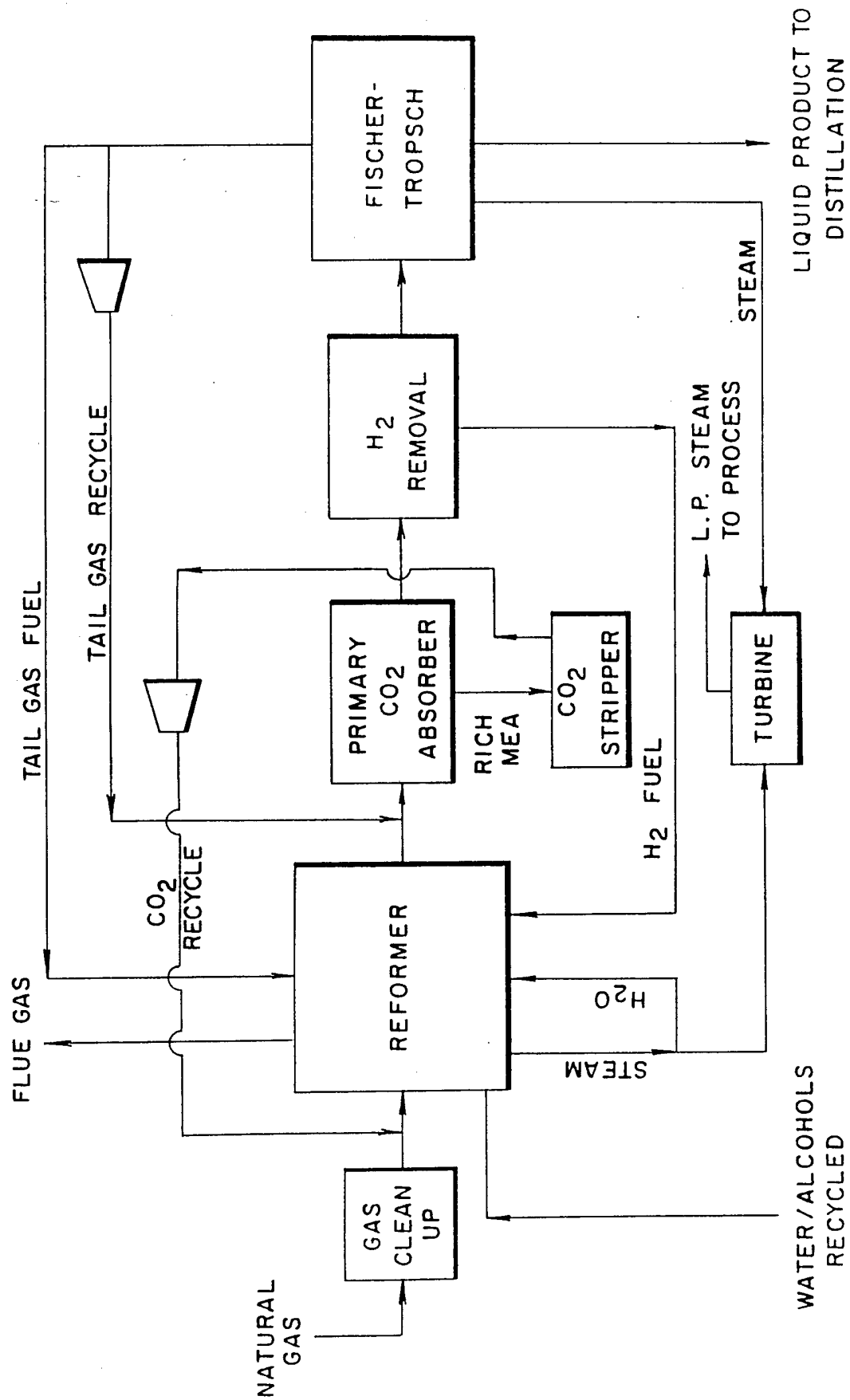
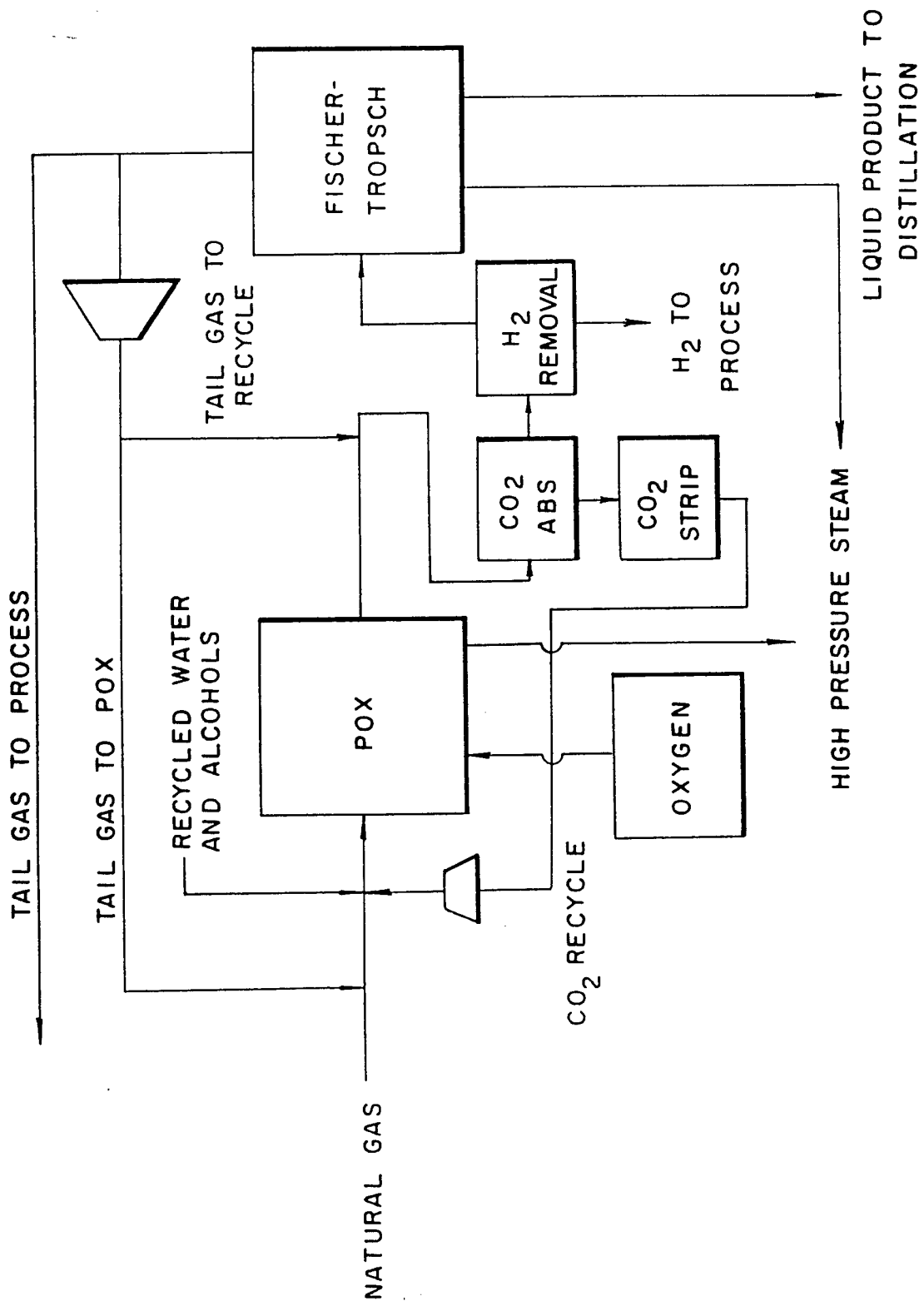


FIG. 12



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/00520

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) : C07C 27/00, 27/06

US CL : 518/704, 706, 709, 713, 717, 721

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 518/704, 706, 709, 713, 717, 721

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 2,434,537 (Barr et al.) 13 January 1948, Columns 2-5	15-18
Y	US, A, 2,483,771 (Holder) 04 October 1949, Figure, columns 2-6	15-18
Y	US, A, 2,561,244 (Sweetser) 17 July 1951, Figure, columns 3-5	15-18
X	US, A, 2,616,915 (Watson) 04 November 1952, Figure, columns 2-5, claims	3-9, 31-33
Y	US, A, 2,620,313 (Odell) 02 December 1952, Figure, Columns 3-4	31-33
Y	US, A, 2,727,056 (Gross et al.) 13 December 1955, Column	3-9, 31-33

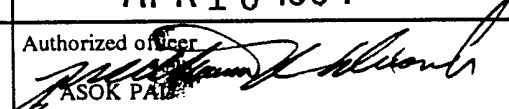


Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	*T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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*E earlier document published on or after the international filing date	*Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
*L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*G document member of the same patent family
*O document referring to an oral disclosure, use, exhibition or other means	
*P document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 01 April 1994	Date of mailing of the international search report APR 18 1994
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	Authorized officer  ASOK PAI Telephone No. (703) 308-3809

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/00520

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 2,758,128 (Rottig et al.) 07 August 1956, Columns 2-3, claims	1-35
Y	US, A, 4,154,751 (McVicker et al.) 15 May 1979, Columns 2-5	1-35
Y	US, A, 4,172,842 (Schlinger et al.) 30 October 1979, Columns 2-4	1-35
Y	US, A, 4,242,234 (Schlinger et al.) 30 December 1980, Columns 3-5	1-35
Y	US, A, 4,640,766 (Post et al.) 03 February 1987, Columns 3-6	1-35
X	US, A, 4,973,453 (Agee) 27 November 1990, Figure, Columns 3-6	25-30
Y	US, A, 5,023,276 (Yarrington et al.) 11 June 1991, Figure, Columns 4-7, Claims	1-35