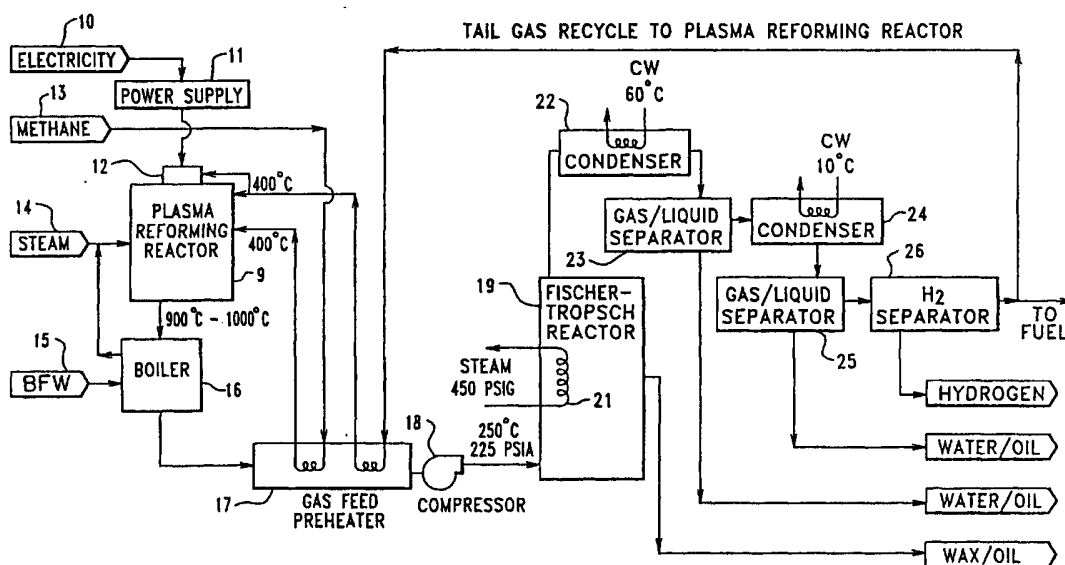


INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<b>(51) International Patent Classification <sup>7</sup> :</b> <b>C10G 2/00</b>	<b>A1</b>	<b>(11) International Publication Number:</b> <b>WO 00/64999</b> <b>(43) International Publication Date:</b> 2 November 2000 (02.11.00)
<b>(21) International Application Number:</b> PCT/US00/11769 <b>(22) International Filing Date:</b> 28 April 2000 (28.04.00) <b>(30) Priority Data:</b> 60/131,459 28 April 1999 (28.04.99) US <b>(71) Applicant (for all designated States except US):</b> RENTECH, INC. [US/US]; 12401 East 37th Avenue, Denver, CO 80239-3404 (US). <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> YAKOBSON, Dennis, L. [US/US]; 12544 W. 87th Avenue, Arvada, CO 80005 (US). VAVRUSKA, John, S. [US/US]; 872 Don Cubero Avenue, Santa Fe, NM 87501 (US). BOHN, Edward, M. [US/US]; 15722 14 Place SW, Burien, WA 98166 (US). BLUTKE, Andreas [GE/US]; 2456 Alki Avenue SW, Apt. 303, Seattle, WA 98116 (US). <b>(74) Agent:</b> MARTIN, Rick; Patent Law Offices of Rick Martin, PC, 416 Coffman Street, Longmont, CO 80501 (US).		<b>(81) Designated States:</b> AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>With international search report.</i> <i>Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>

**(54) Title:** PLASMA REFORMING/FISCHER-TROPSCH SYNTHESIS



**(57) Abstract**

Fischer–Tropsch (FT) products are formed in a plant utilizing a combination of a plasma reformer reactor (9) and an FT reactor (19). Feedstocks ranging from gases such as methane and natural gas to solids such as petroleum coke and coal are plasma reformed with water and/or CO<sub>2</sub> to produce one or more of hydrogen, oils, liquid alkanes and oxygenated alkanes, oil and waxes. The specific ancillary equipment, e.g., boilers (16), preheaters, condensers (22, 24), gas liquid separators (19, 25), compressors (18, 18a), etc. will be combined or omitted as needed for treatment of desired raw materials as shown by the Figures.

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1                   **PLASMA REFORMING/FISCHER-TROPSCH SYNTHESIS**  
2  
3

4                   **CROSS-REFERENCE TO RELATED APPLICATION**

5                   This application is a non-provisional application claiming the benefits of  
6                   provisional application No. S/N 60/131,459, filed 04/28/99.  
7

8                   **FIELD OF THE INVENTION**

9                   This invention relates to plasma reforming of feedstocks to provide a  
10                  syngas which is converted to higher molecular weight hydrocarbons using a  
11                  Fischer-Tropsch (FT) reactor and process.  
12

13                  **BACKGROUND OF THE INVENTION**

14                  Environmental, health and safety concerns are leading to requirements  
15                  that offshore oil production rigs cannot flare their low value hydrocarbon gases.  
16                  In such cases, the gases must be compressed for pipeline or shipboard transport  
17                  to on-shore facilities. Refinery flare gases and/or bottoms can also be upgraded  
18                  to more valuable products where feasible using a portion of the flare gas for  
19                  feedstock and heating the reactors where necessary.

20                  There have been a variety of approaches to reforming using plasmas.  
21                  U.S. Patent 5,993,761 to Piotr Czernichowski et al explores this area well.  
22                  Charles B. Benham et al explores FT synthesis as a mechanism for upgrading  
23                  reformer products, e.g., U.S. 5,504,118, U.S. 5,500,449; U.S. 5,620,670 and U.S.  
24                  5,621,155. Both groups are working in economic niches where tax incentives,

1 regulatory penalties, etc., must combine with other factors to contribute to the  
2 worth of the use of the processes. This is true even where there is a cheap raw  
3 material source, e.g., CO<sub>2</sub> availability from a nearby well.  
4

## 5 SUMMARY OF THE INVENTION

6 The invention combines new plants for the manufacture of FT products  
7 utilizing a plasma reformer to provide the syngas feed and the processes  
8 necessary to obtain the desired FT products. The new plants include the a)  
9 reformer and FT reactor combined plants in packaged form where the plants are  
10 integrated with a large barge or a ship and assemblable packages, i.e., kits for  
11 plant assembly on site.  
12

## 13 BRIEF DESCRIPTION OF THE DRAWINGS

14 Before explaining the disclosed embodiment of the present invention in  
15 detail, it is to be understood that the invention is not limited in its application to  
16 the details of the particular arrangement shown, since the invention is capable of  
17 other embodiments. Also, the terminology used herein is for the purpose of  
18 description and not of limitation.

19 Figure 1 depicts a combined plasma reformer and Fischer-Tropsch plant  
20 for the production of Fischer-Tropsch products from natural gas.

21 Figure 2 depicts a variation on the reactor of Fig. 1 adapted for the  
22 production of Fischer-Tropsch liquids from liquids such as H-Oil and solids such  
23 as petroleum coke slurries.

## DETAILED DESCRIPTION OF THE DRAWINGS

The process of Figure 1 is carried out in a plasma reforming reactor 9. The electrical feed 10 is conditioned by power supply 11 to operate within the frequency range of 0.37=0.44 MHz. The conditional feed 10 is supplied to plasma generator 12 which initiates and controls the plasma formation in the reactor 9. A methane gas or other low molecular weight gaseous hydrocarbon feed 13 is heated in the gas feed preheater 14 to about 400°C for purposes of this discussion and introduced into reactor 9 directly or through the plasma generator 12. Steam 14 is also fed to reactor 9. Carbon dioxide can also be introduced into reactor 9 as a substitute for steam to reduce to eliminate any carbon deposition on the catalyst.

Preconditioned "tap" or other water is stored in boiler feed water tank 15 before injection into boiler 16 where it is preheated by heat exchange with the hot gases from reactor 9 and introduced into reactor 9. The 900°-1000°C gases from reactor 9 are cooled in boiler 16 and introduced into gas feed preheater 17 where it is used to heat the gas feed. The cooled reactor 9 effluent is then run through compressor 18 and introduced into a FT reactor 19 at about 250°C and 225 psia. Reactor 19 temperatures are regulated, inter alia, by heat exchange coil 21.

The reaction products from FT unit 19 are cooled in condenser 24 with 60°C plant water. The cooled reaction products are then separated into gaseous and liquid fractions in separator 25. The gases are condensed in condenser 24 with about 10°C coolant and passed through gas/liquid separator 25 to break out

1 a water/oil fraction. The gases are passed through the hydrogen separator 26.  
2 The tail gas is recycled to the preheater 17 and fed to the reactor 9. The product  
3 fractions from the FT reactor 9 further include wax/oil, water/oil and hydrogen.

4 Computer runs were made to evaluate the operation of the plant of Fig. 1.  
5 In the case of natural gas, both tail gas recycle after hydrogen removal and  
6 carbon dioxide recycle were investigated. In the other two cases, tail gas recycle  
7 without hydrogen removal and carbon dioxide recycle were investigated. In all  
8 cases, the feedstock flow-rate was 1000 tons per day.

9 The outlet pressure of the plasma reactor was assumed to be 15 psia and  
10 the outlet temperature was 1832°F for natural gas and 2100°F for the other two  
11 feedstocks. It was assumed that the gases at the outlet of the plasma reactor  
12 were in equilibrium at the exit temperature. The efficiency of the plasma in  
13 converting electrical energy into thermal energy was assumed to be 70%. The  
14 FT reactor inlet pressure was assumed to be 250 psia. Therefore, compression  
15 of the synthesis gas exiting the plasma reactor was required. The compression  
16 power was calculated using an isentropic efficiency of 70%. It was assumed in  
17 all cases that the FT reactor converted 90% of the incoming carbon monoxide.  
18 The liquid hydrocarbon products ( $C_5+$ ) produced in the FT reactor were modeled  
19 assuming a dual-slope Anderson-Schultz-Flory carbon number distribution ( $\alpha_1 =$   
20  $0.69$  and  $\alpha_2 = 0.95$ ). a water gas shift constant of 10 was assumed. It was  
21 assumed that electrical power would be produced by a combined cycle unit from  
22 the tail gas (which was not recycled) at an efficiency of 55% based on lower  
23 heating value. It was further assumed that additional electric power would be

generated from steam derived from cooling the plasma and FT outlet gases and from cooling the FT reactor. The efficiency of the steam-generated power was assumed to be 33%.

The following composition of natural gas was used in the calculations:

CH <sub>4</sub>	89.00 vol % tail gas
C <sub>2</sub> H <sub>6</sub>	6.63
C <sub>3</sub> H <sub>8</sub>	0.71
CO <sub>2</sub>	2.95
N <sub>2</sub>	0.71

A diagram of a plasma-based system for reforming natural gas is shown in Fig. 1. In Table 1, results are tabulated for a natural gas feedstock with recycle of tail gas from the FT reactor and removal of hydrogen from the system. The first entry having 0% tail gas recycle is a baseline case wherein 30% of the hydrogen from the plasma reactor is removed upstream of the FT reactor to reduce the H<sub>2</sub>:CO ratio of the gas exiting the plasma reactor from 2.85 to 1.99 which is considered to be a practical maximum value for an iron-based FT catalyst. In the other cases in Table 1, 90% of the hydrogen is removed downstream of the FT reactor (from the tail gas). With the requisite amount of steam added to the plasma reactor, the minimum possible H<sub>2</sub>:CO ratio is 1.55 when 90% tail gas recycle is employed. It can be seen that increased steam addition increases the H<sub>2</sub>:CO ratio and decreases hydrocarbon yield.

TABLE 1. Plasma Reforming of Natural Gas with Tail Gas Recycle

Tail Gas Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.064	1.99	3.118	7.317	3.986
90	1.281	1.55	5.413	5.403	4.152
90	1.486	1.6	5.401	5.486	4.203
90	1.894	1.7	5.384	5.644	4.302
90	2.298	1.8	5.372	5.798	4.400
90	2.697	1.9	5.360	5.947	4.495

In Table 2 are shown the results for the case wherein CO<sub>2</sub> is removed from the tail gas and recycled to the plasma reactor. In this case no H<sub>2</sub> removal is necessary since the hydrogen reacts with the CO<sub>2</sub> in the plasma reactor. The minimum amount of steam required in this case is about 0.65 pounds per pound of natural gas fed to the plasma reactor. This gives a H<sub>2</sub>:CO ratio of 1.6. As additional steam is added to increase the H<sub>2</sub>:CO ratio to 1.9, the yield increases slightly but the energy required by the plasma increases significantly. The tail gas recycle case which produces the highest C<sub>5</sub>+ yield produces about 21% more yield than the best CO<sub>2</sub> recycle case, but this tail gas recycle case requires about 11% more electrical energy to be imported.

TABLE 2. Plasma Reforming of Natural Gas with CO<sub>2</sub> Recycle

CO <sub>2</sub> Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.064	1.99	3.118	7.317	3.986
98	0.647	1.60	4.413	5.623	3.322
98	1.073	1.70	4.443	5.797	3.476
98	1.492	1.80	4.461	5.964	3.621
98	1.851	1.90	4.467	6.132	3.740



1           A diagram of a system for reforming refinery bottoms (H-Oil) is shown in  
2   Fig. 2.

3           In the plant of Figure 2, the tail gas recycle loop and the hydrogen  
4   separator are eliminated. A condenser is added with the elimination of hydrogen  
5   as a product and the addition of alcohols. The same identification numerals used  
6   in Fig. 1 are utilized in Fig. 4 except as new elements are added. Modifications  
7   are indicated by the addition of alphabetic suffixes.

8           The H-Oil feed 13a is pumped into reactor 9 along with steam from source  
9   14. The reactor 9 products are piped to boiler 16 from whence steam is recycled  
10   to reactor 9 via source 14. The reactor 9 products are used to heat the recycled  
11   tail gas via the preheater 17a prior to its return to the inductively coupled plasma  
12   generator 12 and reactor 9. Where the H-oil is sour, it is desulfurized in  
13   separator 30, passed through compressor 18a and introduced into FT reactor 19.  
14   Boiler feed water 15 is passed through coil 21 to form 450 psig steam for recycle  
15   to reactor 9.

16           The FT products from FT reactor 19 are passed through boiler 27 to heat  
17   boiler feed water for recycle. The cooler FT products are then passed through  
18   condenser 22 for further cooling and then through separator 25a to separate oil,  
19   water and alcohols from the tail gas to be recycled for use as fuel and feed for  
20   reactor 9.

1           The composition of H-Oil used in the calculations is as follows:

	<b>Wt. %</b>
Carbon	84.33
Hydrogen	8.89
Nitrogen	1.12
Sulphur	5.56
Ash	0.10

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9           The higher heating value of the H-Oil is 17,084 Btu per pound. As in the  
10 natural gas case, calculations were performed for a) recycle of a portion of the tail  
11 gas to the plasma reactor and b) for separation of carbon dioxide from the tail gas  
12 and recycling a portion of the carbon dioxide to the plasma reactor. Due to the  
13 lower hydrogen content of H-Oil compared to natural gas, hydrogen removal from  
14 the system is not required. In Table 3, calculated results are tabulated for  
15 different amounts of recycle of tail gas. As tail gas recycle is increased, the  
16 amount of steam required is reduced and the hydrocarbon yield is increased by  
17 67%. Also, the plasma energy requirement drops by 21% as tail gas recycle  
18 increases. However, the amount of electrical energy imported increases by 44%  
19 as the tail gas recycle increases.

TABLE 3. Plasma Reforming of H-Oil with Tail Gas Recycle

Tail Gas Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.379	1.65	3.509	6.020	2.871
10	1.354	1.63	3.683	5.892	3.055
20	1.317	1.60	3.881	5.755	3.216
30	1.268	1.56	4.099	5.613	3.381
40	1.215	1.51	4.342	5.471	3.542
50	1.151	1.44	4.615	5.325	3.698
60	1.086	1.35	4.919	5.184	4.127
70	0.954	1.19	5.270	5.013	3.974
80	0.762	0.92	5.661	4.838	4.074
85	0.643	0.70	5.864	4.780	4.133

In Table 4 are shown the results for the H-Oil feedstock wherein CO<sub>2</sub> is removed from the tail gas and recycled to the plasma reactor. As CO<sub>2</sub> recycle is increased, the amount of steam required is reduce and the H<sub>2</sub>:CO ratio decreases. The yield increases by 27% and the amount of imported electrical energy increases by about 19%. The 85% tail gas recycle case which produces the highest C<sub>5</sub>+ yield produces about 31% more yield than the best CO<sub>2</sub> recycle case, but the tail gas recycle case requires about 21% more electrical energy to be imported.

TABLE 4. Plasma Reforming of H-Oil with CO<sub>2</sub> Recycle

CO <sub>2</sub> Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.379	1.65	3.509	6.020	2.871
10	1.353	1.57	3.580	5.953	2.922
20	1.304	1.47	3.661	5.868	2.971
30	1.235	1.37	3.753	5.768	3.019
40	1.188	1.27	3.851	5.689	3.085
50	1.092	1.15	3.970	5.575	3.142
60	1.024	1.03	4.100	5.490	3.227
70	0.903	0.90	4.260	5.373	3.310
80	0.741	0.75	4.457	5.240	3.404

Figure 2 provides for a solid feedstock. Petroleum coke is utilized here. The only difference between this process and the H-Oil process is that water must be used rather than steam to form the solid petroleum coke slurry. The latent heat of vaporization of the water must be supplied by the plasma; therefore, reforming of solids is less energy efficient than reforming liquids or gases. The assumed composition of petroleum coke used in the calculations is:

	Wt%
Carbon	88.94
Hydrogen	3.92
Oxygen	0.10
Nitrogen	1.51
Sulphur	5.53
Ash	0.50

The higher heating value of the petroleum coke is 15400 Btu per pound. As in the previous case, calculations were performed for a) recycle of a portion of the tail gas to the plasma reactor and b) for separation of carbon dioxide from the

tail gas and recycling a portion of the carbon dioxide to the plasma reactor. Due to the low hydrogen content of petroleum coke, hydrogen removal from the system is not required. In Table 5, calculated results are tabulated for different amounts of recycle of tail gas. As tail gas recycle is increased, the amount of steam required is reduced and the hydrocarbon yield is increased by 39%. Also, the plasma energy requirement drops 21% as tail gas recycle increases. Unlike the H-Oil case, the amount of electrical energy imported decreases as tail gas recycle increases.

**TABLE 5. Plasma Reforming of Petroleum Coke with Tail Gas Recycle**

Tail Gas Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.468	1.30	3.469	7.082	5.058
10	1.420	1.25	3.643	6.836	4.465
20	1.374	1.20	3.833	6.605	4.507
30	1.334	1.14	4.040	6.385	4.555
40	1.261	1.06	4.272	6.124	4.565
50	1.165	0.95	4.531	5.850	4.558
60	1.046	0.80	4.815	5.575	4.537

Figure 2 provides for the introduction of a petroleum coke or other slurry, e.g., a coal slurry, through slurry pump 13b.

In Table 6 are shown the results for the petroleum coke feedstock wherein CO<sub>2</sub> is removed from the tail gas and recycled to the plasma reactor. As CO<sub>2</sub> recycle is increased, the amount of steam required is reduced and the H<sub>2</sub>:CO ratio decreases. The yield increases by 18% and the amount of imported electrical energy decreases by about 17%. The 60% tail gas recycle case which

produces the highest C<sub>5</sub>+ yield produces about 17% more yield than the best CO<sub>2</sub> recycle case, but the tail gas recycle case requires about 8% more electrical energy to be imported.

**TABLE 6. Plasma Reforming of Petroleum Coke with CO<sub>2</sub> Recycle**

CO <sub>2</sub> Recycle %	Steam Fed to Plasma Lb/Lb Feed	FT H <sub>2</sub> :CO	Yield C <sub>5</sub> + Bbl/ton Feed	Plasma Energy kWh/Lb C <sub>5</sub> +	Imported Energy kWh/Lb C <sub>5</sub> +
0	1.468	1.30	3.469	7.082	5.058
10	1.415	1.21	3.547	6.917	4.391
20	1.371	1.12	3.629	6.775	4.373
30	1.292	1.02	3.727	6.568	4.312
40	1.216	0.92	3.835	6.379	4.271
50	1.132	0.82	3.958	6.184	4.235
60	1.022	0.70	4.103	5.959	4.186

Based on the calculations, the following conclusions can be drawn:

- i) Tail gas recycle is generally superior to carbon dioxide recycle.
- ii) Carbon dioxide removal prior to the FT reactor is unnecessary at the low plasma pressure assumed.
- iii) In all cases, imported electrical power will be required.

## GENERAL TEACHING OF THE INVENTION

Preferably, a natural gas feed is utilized as a raw material but refinery residuals such as H-oil, and coal or coke can also be utilized as feeds in variations of the overall process just described. The plant can be a prefabricated unit mounted on a barge or larger vessel, a unit assembled on an oil or gas offshore platform, or other site, or a "kit" made up of the components of a

1       predesigned plant packaged for usage under the conditions required to effectively  
2       recover FT products. The feedstocks are preferably hydrocarbons but can  
3       include oxygen, nitrogen, sulphur and various other elements to the extent that  
4       the substantially hydrocarbon characteristics of the feedstock remain present.  
5       Thus, where sulphur, various metals, or other materials are a component of the  
6       feedstock, the plant must include equipment and ancillary process steps  
7       necessary for removing these materials. Similarly, solid feedstocks must be  
8       ground to predetermined sizes for assembly at a coal field or other deposit.  
9       Where the feedstock is solid, e.g., coal or a coke, it must be ground to a powder  
10      of predetermined sized particles.

11           Although the present invention has been described with reference to  
12      preferred embodiments, numerous modifications and variations can be made  
13      within the scope of the invention. No limitation with respect to the specific  
14      embodiments disclosed herein is intended or should be inferred.

**WE CLAIM:****CLAIM 1**

In a plant for the conversion of a low value feedstock to at least one higher value Fischer-Tropsch (FT) product having at least one reformer and at least one FT reactor, the improvement wherein the at least one reformer includes an electric powered, plasma reforming reactor.

**CLAIM 2**

The plant of Claim 1 wherein the reformer includes an inductively coupled plasma generator.

**CLAIM 3**

The plant of Claim 1 wherein the plasma generator operates at frequencies within the range of 0.37-0.44 mHz.

**CLAIM 4**

The plant of Claim 1 wherein the plasma generator is inductively coupled and operates at frequencies within the range of 0.37 – 0.44 mHz.

**CLAIM 5**

The plant of Claim 4 further including equipment for injection and treatment of a gaseous substantially hydrocarbon feedstock.

**CLAIM 6**

The plant of Claim 4 further including equipment for injection and treatment of a liquid carbon-based feedstock.



**CLAIM 7**

The plant of Claim 4 further including equipment for injection and treatment of a substantially solid carbon-based feedstock.

**CLAIM 8**

The plant of Claim 1 attached to one of a barge and/or a ship.

**CLAIM 9**

The plant of Claim 1 attached to one of a barge and/or a ship and including an inductively coupled plasma generator which operates in the range of 0.37-0.44 mHz.

**CLAIM 10**

The plant of Claim 1 in a "kit" form for assembly including at least a prepackaged, electric plasma powered reformer and a prepackaged FT reactor, the reformer and the FT reactor being predesigned for forming FT products from at least one of a substantially hydrocarbon gas, liquid or solid.

**CLAIM 11**

The plant of Claim 10 wherein the plasma powered reformer includes an inductively coupled generator which operates at 0.37-0.44 mHz.

**CLAIM 12**

In a process for the production of products from at least one gaseous, liquid or solid, substantially hydrocarbon feedstock using a Fischer-Tropsch reactor, the improvement comprising conducting the reforming in an operating electric powered plasma reactor.

**CLAIM 13**

The process of Claim 12 wherein the feedstock is treated in an inductively coupled plasma.

**CLAIM 14**

The process of Claim 12 wherein the operating frequencies of the inductively coupled plasma are within 0.37-0.44 mHz.

**CLAIM 15**

The process of Claim 13 wherein the feedstock is treated in an inductively coupled plasma operating within the frequency range of 0.37-0.44 mHz.

**CLAIM 16**

The process of Claim 15 wherein the feedstock is substantially a hydrocarbon gas.

**CLAIM 17**

The process of Claim 15 wherein the feedstock is substantially a liquid.

**CLAIM 18**

The process of Claim 15 wherein the feedstock is substantially a solid.

**CLAIM 19**

All inventions taught herein.

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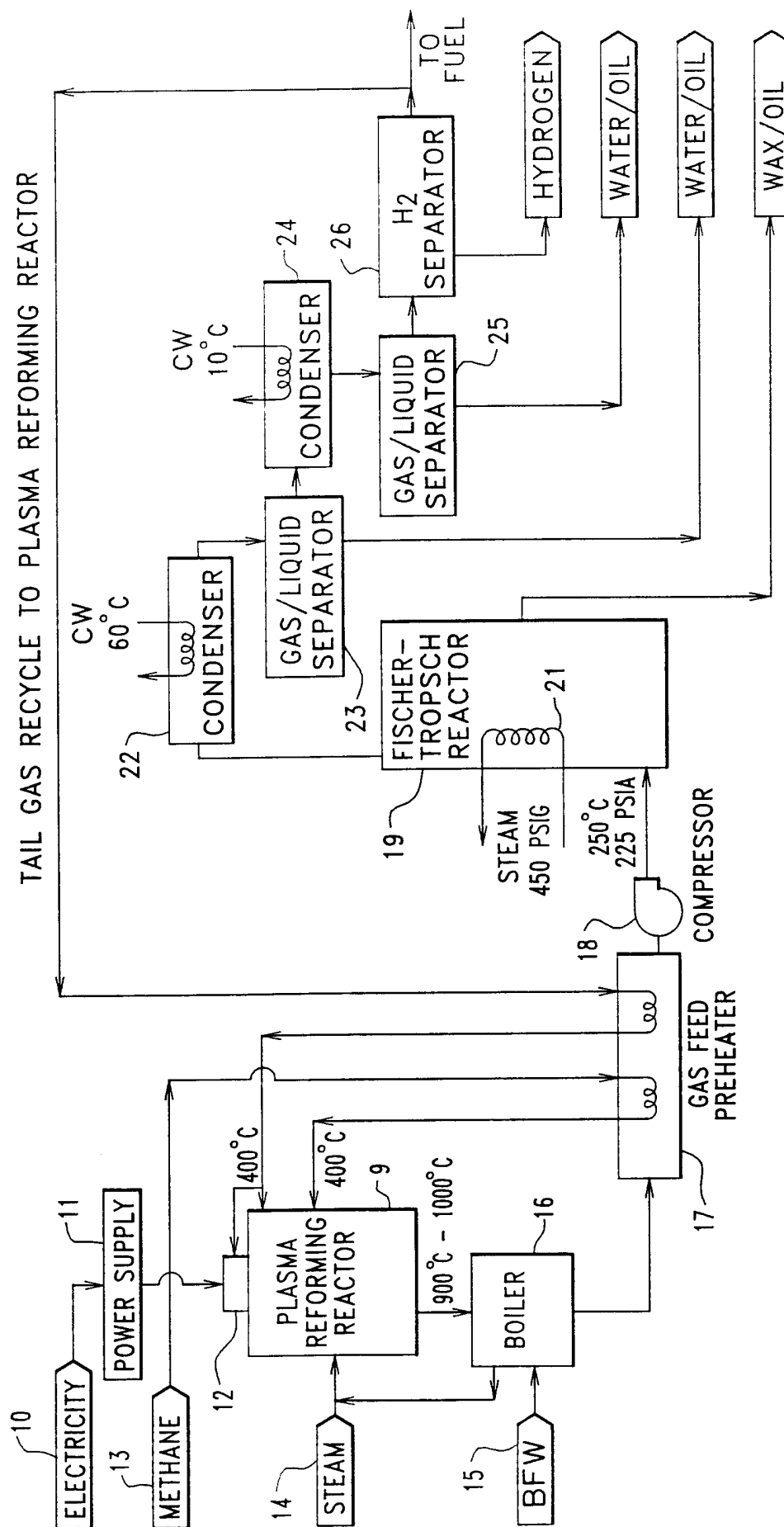


FIG. 1

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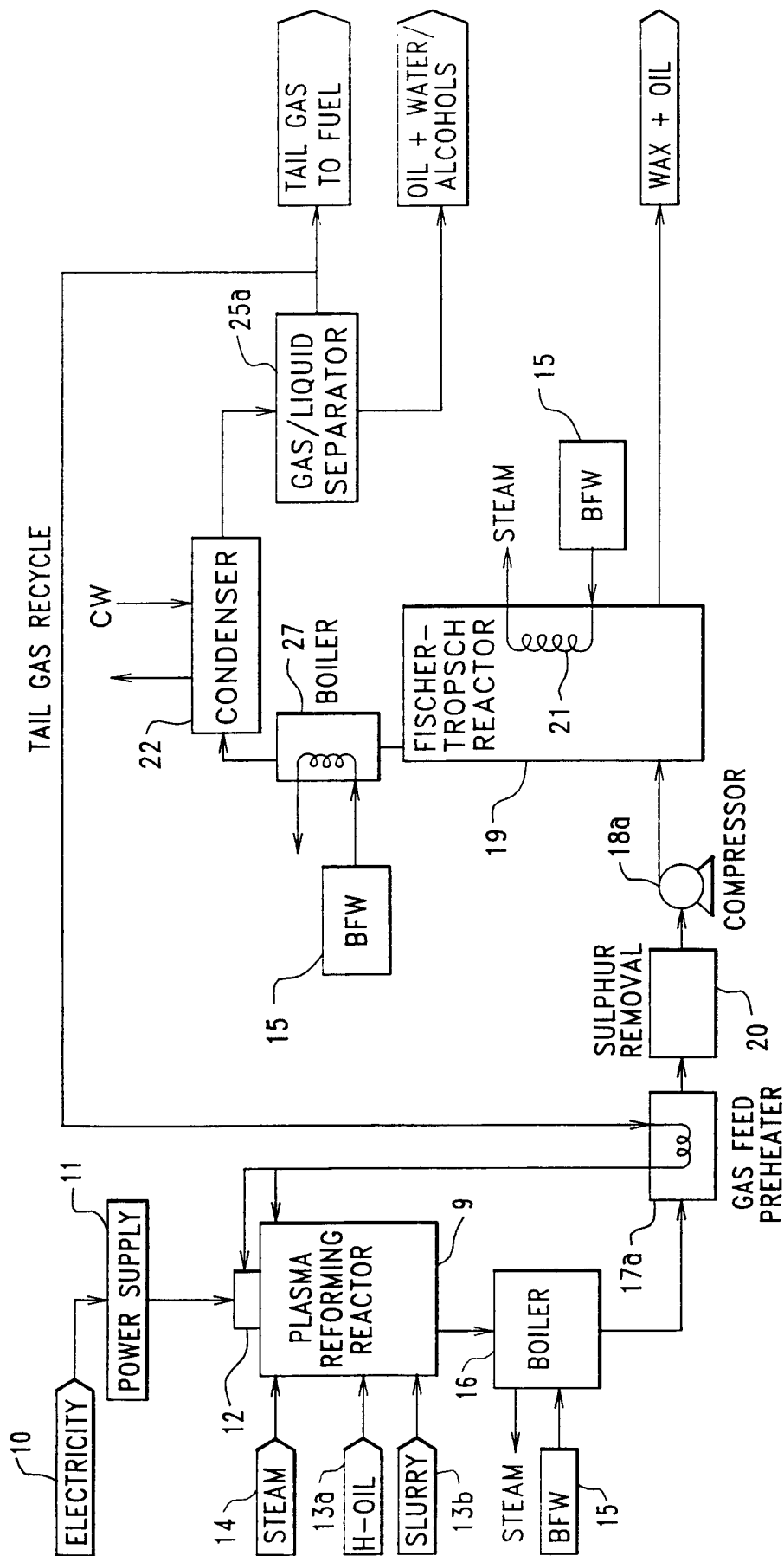


FIG.2

# INTERNATIONAL SEARCH REPORT

Int'l Application No

PCT/US 00/11769

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 C10G2/00 C01B3/34

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)  
IPC 7 C10G C01B

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 practical, search terms used)

EPO-Internal, WPI Data, PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 343 160 A (GUTEHOFFENUNGSHÜTTE OBERHAUSEN A.G.) 16 February 1931 (1931-02-16) the whole document ---	1,3,7, 12,14, 18,19
X	WO 98 30524 A (CARBON RESOURCES LTD) 16 July 1998 (1998-07-16) claims 1,9 page 1, line 15 - line 16 page 10, line 26 -page 11, line 1	1,12,16
P,X	& US 5 993 761 A (CZERNICHOWSKI ALBIN ET AL) 30 November 1999 (1999-11-30) cited in the application claims 1,11,21,23 column 7, line 65 -column 8, line 8 -----	1,12,16



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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Date of the actual completion of the international search

20 September 2000

Date of mailing of the international search report

27/09/2000

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 00/11769

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 343160	A	NONE	
WO 9830524	A	16-07-1998	
		FR 2758317 A	17-07-1998
		AU 8313998 A	01-04-1999
		EP 0914292 A	12-05-1999
		US 5993761 A	30-11-1999