The Challenge of Japan Oil, Gas and Metals National Corporation [JOGMEC] to develop the new GTL process,
- GTL process utilizing CO$_2$ contained in the natural gas to explore stranded gas reserves -

1. Abstract
2. The outline of JOGMEC’s project
3. Characteristics of JNOC-GTL process
4. Characteristics of GTL products
5. Performances of both Syngas and FT catalysts
6. Process development with scale-up methods
7. Project roadmap viewing feasibility study: JOGMEC and PERTAMINA

Kazuhito Katakura, Masaru Ihara and Yoshifumi Suehiro: Japan Oil, Gas and Metals National Corporation [JOGMEC] (*1),
Toshiya Wakatsuki: Japan Petroleum Exploration Co., Ltd. [JAPEX],
Mitsunori Shimura: Chiyoda Corporation [CHIYODA],
Toshio Shimizu: Cosmo Oil Co., Ltd. [COSMO],
Kenichiro Fujimoto: Nippon Steel Corporation [NIPPN STEEL],
Atsushi Sakamoto: INPEX Corporation [INPEX],
Shigetada Kataoka: Tomen Corporation [TOMEN] and
Suhardiman and Kusmiyati: PT. Pertamina (Persero) [Pertamina]


1. ABSTRACT

Natural gas with clean characteristics in combustion is expected to be the alternative energy resources to oils in the near future, but the natural gas resources more than 5Tcf, which is only around 2% of the discovered natural gas fields as appears Figure 1, are mainly developed for LNG market, nevertheless further promotion of its utilization will also be beneficial to environmental preservation. The balance around 98% of the natural gas fields are left undeveloped due to almost stranded natural gas reserves, which is generally small or medium range of natural gas fields inappropriate to LNG supply.

JOGMEC has been tackling the research and development of the natural gas conversion technology from the year of 1998 till 2004 in collaboration with five Japanese private companies for JAPEX, CHIYODA, COSMO OIL, NIPPON STEEL and INPEX, in order to aim at establishing the option technology to explore stranded gas reserves.

The JNOC-GTL process differs from other conventional GTL processes in two main sections:
1) The synthetic gas ("Syngas") production applies the steam (H$_2$O)/CO$_2$ reforming rather than Auto-thermal Reforming ("ATR") or Non-catalytic Partial Oxidation ("POX") used in other processes ("conventional GTL processes"), and
2) The Fischer-Tropsche ("FT") synthesis employs the slurry reactor with noble metal or non-noble metal catalysts, as compared to the Co or Fe based catalysts used in the conventional GTL processes.

Thus, JNOC-GTL process is expected to prominently get effective in energy efficiency as applied against the natural gas reserves containing relatively high CO$_2$. 

1/17
JNOC-GTL process is capable to utilize CO₂ contained in the natural gas and does not require any O₂ supply. Namely, the characteristics of JNOC-GTL process in contrast to those of the existing ones using ATR or POX are (1) no use of the O₂ generator, (2) no use of the CO₂ removal unit, and (3) no use of the H₂ conditioning unit for Syngas. Such facility savings will bring about the remarkable reduction of the plant cost for its election and operation. The suitable conditions for the JNOC-GTL process will meet with the plant scale of 5,000 to 15,000 BPSD and the case of CO₂ contents being 20 to 40mol% in the natural gas. The economic evaluation does indicate that the JNOC-GTL process is more economical than the conventional ones when applied under those conditions.

Our challenges conducted until the end of 2003 have delivered the outcomes (1) recorded around 5,000 operation hours by the identical catalyst of Syngas production and (2) produced GTL products at continuous daily rate 7.3BPSD exceeding the design capacity of 7BPSD at the Yufutsu GTL pilot plant in September 2003, supported by the promising catalysts of Syngas production and FT synthesis and the attained efficient total process. Our new challenges also have been commenced focusing on (1) the enhancement of the promising catalysts of Syngas production and FT synthesis through the evaluation of the long run reliability and (2) the development of scale-up methods for the total process.

This paper introduces the outline and the characteristics of JNOC-GTL process, characteristics of GTL products, the catalysts performance of Syngas production and FT synthesis viewing the current test results derived from the Yufutsu GTL pilot plant, process development with scale-up methods, and the project roadmap viewing the economic evaluation in the feasibility study between JOGMEC and Pertamina.

2. THE OUTLINE OF JOGMEC’S PROJECT

One of the characteristics of JNOC-GTL process is capable of utilizing CO₂ contained in the natural gas and it does not require any O₂ supply. Thus it is an attractive measure to widely and efficiently monetize even stranded gas reserves including around 40mol% of CO₂, which are located far from an existing gas market and have been left undeveloped due to mainly high-cost De-CO₂ plants and gas transportation methods such as a gas pipeline and LNG.

To enable GTL products to compete in the existing oil markets and in the worldwide trend of strict environmental restriction on emission, improvements to the GTL technology are required in three items:

1) Reduction of the construction and operation costs for a GTL plant,
2) Enhancement of energy efficiency, and
3) Reduction in CO₂ emission.

In addition to the above three items deeply concerning the total process, the followings are two essential issues on advancing the planning of a demonstration plant equipped with 500BPSD of the design capacity as the post-Yufutsu GTL pilot plant:

1) Enhancement of the promising catalyst performance such as the productivity and the long-run reliability of both Syngas catalyst and FT catalyst to achieve high efficient conversion from gas to liquids, and
2) Development of scale-up methods for the total process applicable to a demonstration plant and a further commercial plant.

Assistance by gas producing countries, such as the supply of low cost feed gas, a tax preference and/or a subsidy to GTL projects and/or products, would boost the competitiveness of GTL products, comparing to the oil products in the existing oil markets, which have desirable
characteristics such as no sulfur content and no aromatic content. The above assistance will provide GTL technology with an opportunity to supply competitive oil products to the existing oil markets.

3. CHARACTERISTICS OF JNOC-GTL PROCESS

Figure 2 compares the main features of JNOC-GTL process compared to the existing ones. The main characteristic of JNOC-GTL process is to apply the steam/CO\textsubscript{2} reforming in the Syngas production. This is able to efficiently use CO\textsubscript{2} included in the natural gas, and to produce the H\textsubscript{2}/CO molar ratio of 2/1 composed Syngas suitable for FT synthesis with one pass reaction. Such a process will make it feasible to eliminate, from a full set of the Syngas production facilities, O\textsubscript{2} generator, CO\textsubscript{2} removal unit and H\textsubscript{2} conditioning unit, which will take a high cost.

3.1 STEAM/CO\textsubscript{2} REFORMING

Figure 3 illustrates the equilibrium reactions occurred in the steam/CO\textsubscript{2} reforming, which consists of three equilibrium reactions relating to reforming and two carbon formation reactions. Syngas composition suitable for FT synthesis should be H\textsubscript{2}/CO=2/1, because FT synthesis produces straight-chained hydrocarbons. Since the steam reforming of natural gas makes the Syngas composition changed to over H\textsubscript{2}/CO=2/1, it is necessary to remove excessive H\textsubscript{2} from Syngas or to input CO\textsubscript{2} into feed gas in order to make the favorable condition for such Syngas composition. An appropriate amount of natural gas, H\textsubscript{2}O and CO\textsubscript{2} under the given reaction temperature and pressure to produce the Syngas of H\textsubscript{2}/CO=2/1 is uniquely determined because CH\textsubscript{4}/steam/CO\textsubscript{2} reaction is under the equilibrium reaction.

The horizontal axis of Figure 4 shows the feed gas composition of CH\textsubscript{4}, H\textsubscript{2}O and CO\textsubscript{2} required to produce Syngas of H\textsubscript{2}/CO=2 under the reaction condition in temperature of 850 deg-C and in pressure of 2.1 MPa. The ratio of total feed gas volume to produce the unit Syngas volume is also presented in the vertical axis of Figure 4. In view of energy efficiency and gas volume, the most suitable condition is the point of the maximum production of Syngas with the minimum amount of feed gas. In Figure 4, for example, that is the feed composition of CH\textsubscript{4}:CO\textsubscript{2}:H\textsubscript{2}O=1:0.4:1, which will produce one unit of Syngas by one unit of feed gas. However, this reaction is under the carbon decomposition condition based on equilibrium. The carbon formation causes catalyst deactivation. Therefore, it is to be avoided for conventional steam reforming catalysts to be used, where two or three times of the appropriate amount of steam will be introduced into the reactor to suppress the carbon formation. This will make the conventional steam reforming to decrease the production and energy efficiencies and to enlarge the reactor size. JOGMEC overcame these difficulties and developed the new GTL process, which produce one unit of Syngas by one unit of feed gas in CH\textsubscript{4}:CO\textsubscript{2}:H\textsubscript{2}O=1:0.4:1 ratio with no formation of carbon, in spite of carbon deposition conditions.

This new GTL process contributes the reduction of CO\textsubscript{2} emission. Our calculation of CO\textsubscript{2} emission shows that JNOC-GTL process features the lowest CO\textsubscript{2} emission among the conventional GTL processes; e.g. amount of CO\textsubscript{2} emission from JNOC-GTL process corresponds to 60-90\% of ATR and 60\% of POX in De-CO\textsubscript{2} before Reforming and 20-40\% of POX in De-CO\textsubscript{2} after Reforming as appears in Figure 5.

At the Yufutsu GTL pilot plant, JNOC’s Syngas Reformer uses the externally heated reactor, in which the reformer tubes of 11cm-I.D. and 12m-height are laid out in vertically parallel and heated by burners in the oven. The catalyst is filled inside the tubes. The reformer tube is similar to that used in the conventional steam reforming process, therefore, the Syngas
production capacity is restricted by number of tubes.

Reforming reaction will occur in the catalysts bed temperature of 800-900 deg-C, pressure of 2.0MPa, and GHSV (Gas Hourly Space Velocity) of 2,000-3,000hr⁻¹. The key parameters of the Syngas catalysts suitable for this type of reformer are heat stability, resistance of carbon formation, heat transfer efficiency, and mechanical strength.

3.2 FT SYNTHESIS

The following reaction occurs in the FT synthesis.

\[ \text{CO} + 2\text{H}_2 \rightarrow -(1/n)(\text{CH}_2)_n - + \text{H}_2\text{O} + 167 \text{kJ/mol} - \text{CO} \]

As for FT synthesis process we employ the slurry phase reactor, it enables to remove exothermal energy and to prevent wax from covering the surface of FT catalysts. We developed FT catalysts of the noble and/or non-noble metal for the reactor in order to study harder by competing against each other. A sedimentation vessel is adopted to circulate the slurry phase and it is located outside the FT Reactor. An internal filtration device in the reactor should be considered for high efficiency in a commercial scale plant.

At the Yufutsu GTL pilot plant, JOGMEC’s FT Reactor utilizes a slurry bed. The shell and tube type reactor employs cooling water in the tube side and slurry in the shell side to remove the heat effectively occurred in the reaction. Reaction will take place in the slurry temperature of 230-270 deg-C, pressure of 2.0-3.0 MPa, and Syngas feed rate of 10-50 cm/sec. The first slurry is composed of mineral oils as solvent and powdered catalysts as suspension material. Once Syngas enter at the bottom of the reactor in the shape of dispersed bubble, the mineral oils will be replaced with GTL products at the first level of reaction. The slurry is continued circulating in the reaction and separated into GTL products and powdered catalysts. Therefore, the key issue of FT catalysts suitable for this type of reactor is physical and chemical stabilities. The C5+ yield is important among the reaction parameters and its target value is set as 85% at the Yufutsu GTL pilot plant.

4. CHARACTERISTICS OF GTL PRODUCTS

Photo 1 shows the first light oil and heavy oil products derived from the Yufutsu GTL pilot plant in November 2002. Subsequently GTL production, 7.3BPSD has been operated by non-noble metal FT catalysts since September 2003. The overview of the plant is shown in Photo 2.

Tables 2 and 3 list characteristics of GTL products from the Yufutsu GTL pilot plant. GTL products are demonstrated to be super clean fuels supported by sulfur containing in light oil, which is less than 1 mass ppm. Density is lower than those of crude oil based products. Cetane Index is relatively higher than we expected. Smoke point of GTL kerosene is 26 mm so that JOGMEC regards our products as applicability for equipment for conventional kerosene such as stove.

Our collaborator has commenced demonstrating a hydrogen station in Yokohama, which produces hydrogen reformed from GTL Naphtha supplied by the Yufutsu GTL pilot plant. Comparing to the conventional method using de-sulfur gasoline, it has the feature that GTL Naphtha can be utilized until the composition of the higher distillation points as appears in Table 4.

GTL gas oil has superior properties; i.e. (1) zero sulfur contents, (2) zero aroma contents, and
higher Cetane Index, over the requirements of automobile industry. In fact an automobile industry reported that it would meet the fuel for diesel engines with lower emission and higher efficiency in the future in the following viewpoints:

1) The emission of particulate matter ("PM") is restrained due to no aroma contents and secondarily no sulfur contents. This will link to improve the active performance of the diesel particulate filter ("DPF"), because the PM attack is reduced and the sulfur attack is eliminated from the catalysts of DPF.

2) Higher Cetane Index has a potential to make diesel engines decrease a compression ratio and increase efficiency due to the improvement of ignitability. It will be expected to develop visionary diesel engines with a lower NOx emission.

3) It has an obvious advantage that GTL gas oil is compatible to the existing gas oil and also it is applicable to the blending use with the existing gas oil on the condition of the utilization of existing infrastructures such as gasoline service stations.

The running test applying GTL gas oil to the micro gas turbine generating the electric power, 27kW, demonstrated that GTL gas oil could reduce the NOx emission from the exhaust gas as appears in Figure 6. It is presumed that no aromatic contents in the GTL gas oil is generally restrained from generating the heat spots in the combustion flame. Less heat spots in the combustion flame is restrained from generating the thermal NOx. It is recommended to evaluate GTL gas oil from the viewpoints of stability of supply, lubricity, low temperature fluidity, mileage, adaptability of sealing material and so on toward an earlier practical use.

5. PERFORMANCES OF BOTH SYNGAS AND FT CATALYSTS

Performances of both Syngas and FT catalysts have been viewed from the bench plant and the test results of the Yufutsu GTL pilot plant.

5.1 PERFORMANCE OF SYNGAS CATALYST

Figure 7 shows the life test data of Syngas catalyst at the bench plant, which was developed by CHIYODA. Syngas production under the equilibrium composition of $\text{H}_2/\text{CO}=2/1$ was maintained for over 8,000 hrs in the feed gas ratio of $\text{CH}_4/\text{CO}_2/\text{H}_2\text{O}=1:0.38:0.85$, which is more negative conditions of carbon decomposition, under an effluent gas temperature of 850 deg-C and reaction pressure of 2.1MPa.

Figure 8 is an example of operation data of Syngas catalyst at the Yufutsu GTL pilot plant till December 2003. Methane conversions calculated from product gas composition in comparison with those of equilibrium value were almost constant at 100% during 5,000 hrs. It is suggested that the catalyst performed satisfactorily at the pilot plant level.

5.2 PERFORMANCE OF FT CATALYST

Figure 9 is an example of operation data of non-noble metal FT catalyst at the bench plant reviewing the FT reactor reliability for over 800 hrs. We plan to evaluate the long-run reliability of the FT catalysts in May to September 2004 at the Yufutsu GTL pilot plant.

Table 1 lists the typical performance of non-noble metal FT catalysts named C’ newly developed by NIPPON STEEL. Parameter $\alpha$, that means a hydrocarbon chain growth probability, of 0.91 and the productivity, which defines grams of $\text{C}_5^+$ products by one kg of catalyst per one hour (g/kg-cat-hr), of 1,325 g/kg-cat-hr are achieved in the reaction of a feed gas composition of $\text{H}_2/\text{CO}=2/1$, temperature of 240 deg-C, pressure of 2.2 MPa, and CO conversion of 62.3% at the Yufutsu GTL pilot plant in September 2003, confirming the validity.
of FT catalyst and process. Subsequently changing the reaction conditions, all the target values were cleared; i.e. the catalyst C’ recorded GTL oil production of 7.3BPSD, CO conversion of 75.3% and C₅⁺ selectivity of 88.7%. FT reactor size is about 0.25m-I.D. and 15m-height for 7 BPSD production capacity of GTL products.

6. PROCESS DEVELOPMENT WITH SCALE-UP METHODS

Figure 10 illustrates the typical JNOC-GTL process flow in the target production range of 5,000 to 15,000 BPSD of liquids from a natural gas feedstock that contains 20-40 mol% CO₂. Input amounts of steam and CO₂ into the Syngas Reformer shall be adjusted according to CO₂ content of natural gas in order to produce Syngas of H₂/CO=2/1 per one pass at the Syngas Reformer condition of 2.0 MPa and 850 deg-C.

Our challenge has been commenced developing scale-up methods for the total process applicable to a demonstration plant and a commercial plant. On the purpose of delivering speedy and accurate outcomes in a low cost, the computational simulation for the process development of the major equipments such as Syngas Reformer and FT Reactor has been developed. The process development of FT Reactor, employing the bubble column reactor (“BCR”) with three-phase mixed model of gas, liquid and solid and also the flow pattern in the churn turbulent flow, will be more complex than one of Syngas Reformer. We focus the computational simulation on the process development of FT Reactor.

The conventional design methods, placing the assumptions such as a complete mixed model and a plug flow model will not provide the accurate information on the complex flow pattern in the BCR like FT Reactor. These assumptions limit the process development to scale up FT Reactor. However it is an advantage that the computational fluid dynamics (“CFD”) simulation does not require these assumptions. Therefore it has been introduced in lieu of the conventional design methods. The CFD simulation generally has characteristics to directly handle the complex phenomena with three-phase mixed model and also the complex structures loading a plenty of cooling tubes in the FT Reactor.

The CFD model on the basis of the CFD simulation needs the information on the laboratory scale studies, the cold model studies and the engineering data such as rising gas velocity of bubbles and gas holdup derived from the Yufutsu GTL pilot plant as appears in Figure 11, showing the CFD applied to FT Reactor.

The flow pattern on the cold flow experiment in the cold model studies can be observed when the pressurized air is so injected from the bottom plate with plenty of 1mm diameter holes as to catch up a churn turbulent flow into the water filled in the vessel, 0.58-meters diameter and 3-meters height made from transparent acryl and loaded adequate cooling tubes to provide the similar condition as the FT Reactor at the Yufutsu GTL pilot plant.

The macro process model incorporating chemical reaction and heat transfer into CFD model will boost the accuracy in the future in advancing scale-up of FT Reactor as appears in Figure 12, showing the scale-up procedure for the FT Reactor.

Our developed CFD model can so precisely describe the complex hydrodynamics in BCR as to well match the cold flow experiment. We have already begun to develop the macro process model aiming at the efficient scale-up methods of FT Reactor more than 5,000BPSD at the moment.
7. PROJECT ROADMAP VIEWING FEASIBILITY STUDY: JOGMEC & PERTAMINA

As part of a collaborative study into the development and monetization of stranded gas reserves, JOGMEC and Pertamina have been jointly conducting a “desk top” feasibility study for the applicability of JNOC-GTL process to certain Pertamina gas fields since December 2001. We have originated the feasibility study phase-II (“FS-II”) since September 2003 under our scenario to supply GTL products to the market based on the feasibility study phase-I (“FS-I”) at completion, which contains eight (8) steps as appears in Figure 13 for the purpose of organizing a flexible and efficient study. The 8 steps of FS-I and the current progress information on FS-II are summarized as follows:

7.1 Feasibility study phase-I

1) Steps 1-3 Identification of Potential Gas Fields
   - After screening Pertamina’s list of proposed gas fields, both parties agreed to conduct a detailed study into the application of JNOC-GTL technology to two selected gas fields, denoted “A” and “B.” Pertamina provided a pre-development plan for two selected gas fields, denoted “A” and “B.”

2) Step-4 Conceptual Design and Cost Estimation for GTL plant
   - Conducted Conceptual Designs with capacity of 5,000BPSD GTL plant at both “A” and “B” fields for cost estimation.
   - Estimated cost for a GTL plant, 5,000 BPSD and GTL product-handling facilities for both “A” and “B” field options.

3) Step-5 Marketing of GTL Products
   - Investigated (i) the short and long-term prospects for GTL products as alternatives for petroleum products, (ii) the demand for GTL Products, and (iii) the premiums for GTL Gas Oil.
   - Concluded that Singapore would become a more promising market than Japan for GTL products.

4) Step-6 Law, Regulation and Tax Regime to be applied for GTL Project
   - Both parties have investigated the influence of 2002 Petroleum and Natural Gas Law in Indonesia (“new law”) on constructing a possible business model. GTL plant had a possibility stipulated as a downstream activity under the new law. However it still has a little possibility stipulated as an upstream activity as well as the case of LNG plant as an upstream activity.

5) Step-7 Economic Evaluation with Sensitivity Analysis
   - Sensitivity analysis indicated the following key parameters:
     - The purchase price for the natural gas feedstock is the most intensive factor to the GTL product cost.
     - The second and the third intensive parameters are the level of investment and plant cost required for the GTL plant respectively.
   - Key parameters such as natural gas price, investment and IRR are indicated as the breakdown in three kinds of natural gas price, US$25, US$30 and US$35 as appears in Figure 14.

7.2 Feasibility study phase-II

1) Project scenario
   - FS-II targets the planning of a demonstration plant as the post-Yufutsu GTL pilot plant on the basis of the outcomes from the FS-I. Our project scenario contains the following three stages:
     a) The 1st stage is the Yufutsu GTL pilot plant, which successfully produced GTL products, 7.3BPSD from the natural gas feedstock.
b) The 2nd stage is a demonstration plant equipped with around 500BPSD of design capacity. It features the scalability to more than 500BPSD and the intention of chain strategies to the 3rd stage of commercial plants. It is important to establish the scaled up procedure of JNOC-GTL process in this stage.

c) The 3rd stage is to advance commercial plants organizing GTL network in view of the world trend and the size of natural gas reserves.

2) Evaluation of project value

We have evaluated the GTL business process with the internal rate of return ("IRR") and the net present value ("NPV"). It is proper that the increase of natural gas sales price results in the increase of IRR of upstream business ("upstream IRR") categorized as natural gas producing, but the decrease of IRR of downstream business ("downstream IRR") categorized as natural gas consuming, GTL producing and GTL sale, because the upstream IRR has a trade-off relation to the downstream IRR.

Therefore we consider the model integrating upstream and downstream in order to improve the trade-off relation in view of the GTL business process. The IRR integrating upstream and downstream definitely shows the trend getting closer to the downstream IRR, but the NPV integrating upstream and downstream will be more increased even though the downstream IRR and IRR integrating upstream and downstream could be the same value as the total investment grows up by means of merging upstream investment on the downstream investment, which is more than double size of the upstream investment.

We have a business principle that the business process integrating upstream and downstream could maximize the NPV. It is more effective index rather than IRR for a total evaluation of GTL business scheme, as the IRR does not consider any amount of investment.

3) Strategy to Business

(1) On evolving our scenario to a business process, it will be important to promote the practical use of core competence for both parties and key factor for success. The followings are the core competence for both parties, JOGMEC and Pertamina:

a) JOGMEC has a business process and management resources complimenting each core competence, which is capable to produce GTL products to directly make the most of CO₂ up to 50% included in the natural gas without removing CO₂ in light of the technical predominance at the downstream.

b) At mainly upstream portion, Pertamina has a business process and management resources complimenting each core competence, which is capable to develop small and/or medium classes of undeveloped and stranded natural gas fields, which Pertamina possesses, combining with the geological predominance.

(2) The followings are the key factors for success ("KFS") linking to the core competence:

a) Total optimum conditions in the GTL business process:

The sensitivity analysis conducted in the FS-I has required decreasing the natural gas price as the first priority to raise the competitiveness of GTL products even in the existing oil market. The value added of GTL products will be increased when low priced sales natural gas is supplied; i.e. the production cost of GTL products is decreased. JNOC-GTL technology is capable to bear a value added on a low value of stranded natural gas fields including high CO₂ content on the condition that upstream business and downstream one are so integrated as to structure the organic system. Total
optimum condition at first must apply to the organic system, which aims at maximizing the profit born by the GTL products. The partial optimum conditions do not always link to the total optimum conditions, as partial optimum conditions often include the party’s intention beyond the economical efficiency.

b) Architecture of a profitable mechanism:
In the case of the price cut of sales natural gas, the source of profit is the key issue for both parties. If both parties could reach the consensus to maximize the total profit born by the sales of GTL products on the condition of minimizing the internal profit simply born by selling the natural gas from the upstream to the downstream, it is obvious that the low priced natural gas will originate a crucial value as GTL products in the series of the organic system.

It brings out the value chain in the organic system. The value chain is the source of profit and it will lead to a profitable mechanism such as a supply chain management (“SCM”) or a demand chain management (“DCM”). Either of them will construct such the best practical architecture of profitable mechanism between upstream and downstream as to attain the total optimum conditions in the organic system. One of the effectiveness of SCM or DCM is to improve a throughput that aims at the vast increase of sales. It will initiate increasing cash flow in the GTL business.

8. CONCLUSIONS
1) The enhancement of the promising catalysts performance and development of scale-up methods for the holistic JNOC-GTL process have been systematically conducted in view of the CFD model, the macro process simulation model and the results derived from the Yufutsu GTL pilot plant until December 2003.
2) JOGMEC has reviewed a profitable path to monetize gas fields using the JNOC-GTL process, in view of three stages of project scenario, the evaluation of project value utilizing IRR, NPV and strategy to business including core competence and KFS through the completed FS-I and the ongoing FS-II.

9. ACKNOWLEDGEMENT
JOGMEC cordially appreciates five private partners in the JNOC-GTL technology development project (JAPEX, CHIYODA, COSMO OIL, NIPPON STEEL, and INPEX) and Pertamina and TOMEN, the partner in the feasibility study, for allowing presentation and publishing in this project.

10. REFERENCES
**World's Gas Fields By Size**

(Total: 4,448 Fields)

50,000 BPD size plants
Fit only 2% of fields

Fig. 1 World's gas fields by size

**Conventional Process**

<table>
<thead>
<tr>
<th>Natural Gas (containing CO2)</th>
<th>CO2 removal</th>
<th>Sulfur removal</th>
<th>FT synthesis</th>
<th>Product upgrading</th>
</tr>
</thead>
</table>

**Syngas Production**
- Non-catalytic Partial Oxidation
- Autothermal Reforming

**FT Synthesis**
- Co or Fe Based Catalyst

**JNOC**

<table>
<thead>
<tr>
<th>Natural Gas (containing CO2)</th>
<th>CO2 removal</th>
<th>Sulfur removal</th>
<th>FT synthesis</th>
<th>Product upgrading</th>
</tr>
</thead>
</table>

**Syngas Production**
- CO2/Steam Reforming

**FT Synthesis**
- Noble and Non-noble Metal Catalysts

**Fig. 2 Comparison with Conventional Process**

**Steam/CO2 reforming reaction**

1. \( CH_4 + H_2O \Leftrightarrow CO + 3H_2 -206kJ/mol \)
2. \( CO + H_2O \Leftrightarrow CO_2 + H_2 +42kJ/mol \)
3. \( CH_4 + CO_2 \Leftrightarrow 2CO + 2H_2 -248kJ/mol \)

**Carbon formation reaction**

4. \( CH_4 \Leftrightarrow C + 2H_2 \quad -75kJ/mol \)
5. \( 2CO \Leftrightarrow C + CO_2 \quad +172kJ/mol \)

**Fig. 3 Equilibrium Reaction in Steam/CO2 reforming**
Fig. 4 Optimal $\text{H}_2\text{O}/\text{CH}_4$ and $\text{CO}_2/\text{CH}_4$ Molar Ratio in Feed to Produce Syngas ($\text{H}_2/\text{CO}=2$)

Fig. 5 Estimated $\text{CO}_2$ emission in comparison with ATR, SMR and POX
Fig. 6 Comparison of NOx emission from the micro gas turbine
(By courtesy of Idemitsu Kosan Co., Ltd.)

Fig. 7 Life test data of Syngas Catalyst with CO₂/H₂O Reforming (Bench Plant)

Fig. 8 Operation data of Syngas Catalyst (Pilot Plant)
Reaction conditions: 503K, P=2.2MPa, H2/CO=2.0
Catalyst performed a high-activation and stability in 800 hours at the bench plant.

Fig. 9 FT Operation data of FT Catalyst (non-noble metal) (Bench Plant)
**Fig. 10 JNOC-GTL Process Flow Diagram**

- Labo. Scale Studies
  - Development of Catalyst
  - Kinetics (Reaction data)
  -...

- Cold Model Studies (Experimental Studies)
  - Hydrodynamics
  - Bubble behavior
  - Effect of solids loading
  -...

- Pilot Plant (at Yufutsu)
  - Operating Data
  -...

- Engineering Tool
  - CFD Model
  - Macro Process Model

- Commercial Plant
  - Commercial scale design & Evaluation
  - Design study

**Fig. 11 Correlation map to Computational Fluid Dynamics applied to FT Reactor**

**Fig. 12 Scale up procedure for FT Reactor**
**Fig. 13 Feasibility Study Flow Scheme**

**Fig. 14 Breakdown Cost based on the Sensitivity Analysis**

**Table 1 Typical Performance of JOGMEC developed FT Catalyst (Pilot Plant)**

<table>
<thead>
<tr>
<th>Cat Name</th>
<th>Temp (°C)</th>
<th>CO conversion (%)</th>
<th>C₅+ selectivity (%)</th>
<th>μ</th>
<th>Productivity (g/kg-cat h)</th>
<th>BPD (bbld)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>≥ 60</td>
<td>≥ 85</td>
<td>≥ 0.9</td>
<td>—</td>
<td>—</td>
<td>(5~7)</td>
</tr>
<tr>
<td>C’</td>
<td>240</td>
<td>62.3</td>
<td>85.2</td>
<td>0.91</td>
<td>1325</td>
<td>5.0</td>
</tr>
<tr>
<td>C’</td>
<td>230</td>
<td>75.3</td>
<td>88.7</td>
<td>0.91</td>
<td>689</td>
<td>2.6</td>
</tr>
<tr>
<td>C’</td>
<td>230-239</td>
<td>87.6</td>
<td>79.9</td>
<td>0.92</td>
<td>768</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Note: Catalyst C’ stands for Cat. C by mass production, P=2.2MPa, H₂/CO=2/1
### Table 2 Properties of Light Oil and Heavy Oil

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Light Oil</th>
<th>Heavy Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density g/cm³</td>
<td>0.7564</td>
<td>Solid</td>
</tr>
<tr>
<td>Kinematic Viscosity mm²/s</td>
<td>1.443</td>
<td>-</td>
</tr>
<tr>
<td>Flash Point deg C</td>
<td>&lt;25 °C</td>
<td>-</td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10% deg C</td>
<td>109.5</td>
<td>400</td>
</tr>
<tr>
<td>50% deg C</td>
<td>196.5</td>
<td>485</td>
</tr>
<tr>
<td>90% deg C</td>
<td>317.5</td>
<td>615</td>
</tr>
<tr>
<td>CHN C mass%</td>
<td>82.5</td>
<td>84.9</td>
</tr>
<tr>
<td>H mass%</td>
<td>14.9</td>
<td>15</td>
</tr>
<tr>
<td>N mass%</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>Water mass ppm</td>
<td>4940</td>
<td>-</td>
</tr>
<tr>
<td>Aromatic mass%</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
<tr>
<td>Nitrogen mass ppm</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
<tr>
<td>Sulfur mass ppm</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
<tr>
<td>Color (Saybolt)</td>
<td>+7</td>
<td>-</td>
</tr>
<tr>
<td>Cloud Point deg C</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>Pour Point deg C</td>
<td>7.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Both Light and Heavy Oils are before hydrocracking process. Both Light and Heavy Oils are aromatic free as well as sulfur free. N.D. stands for “Not Detected”.

### Table 3 Properties of Kerosene and Gas Oil from Light Oil

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Kerosene</th>
<th>Gas Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillation T10/T90 °C</td>
<td>160/193</td>
<td>260/309</td>
</tr>
<tr>
<td>Density g/cm³</td>
<td>0.7541</td>
<td>0.7827</td>
</tr>
<tr>
<td>Kinematic Viscosity mm²/s</td>
<td>1.211</td>
<td>3.430</td>
</tr>
<tr>
<td>Flash Point °C</td>
<td>42</td>
<td>90</td>
</tr>
<tr>
<td>Color</td>
<td>+30</td>
<td>+22</td>
</tr>
<tr>
<td>Cloud Point °C</td>
<td>-50</td>
<td>5</td>
</tr>
<tr>
<td>Pour Point °C</td>
<td>-50</td>
<td>+5.0</td>
</tr>
<tr>
<td>Smoke Point mm</td>
<td>26.0</td>
<td>-</td>
</tr>
<tr>
<td>Cetane Index</td>
<td>57.8</td>
<td>88.1</td>
</tr>
</tbody>
</table>

Note: Light Oil is before hydrocracking process. Pour point of Gas Oil is -7.5degC at the Japanese Industry Standard (JIS) No.2

### Table 4 Comparison of the raw material for hydrogen production

<table>
<thead>
<tr>
<th>Items</th>
<th>unit</th>
<th>GTL Naphtha (*1)</th>
<th>De-sulfur Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density 15deg</td>
<td>g/cm³</td>
<td>0.6906</td>
<td>0.6748</td>
</tr>
<tr>
<td>Distillation 10%</td>
<td>deg</td>
<td>93.5</td>
<td>52.0</td>
</tr>
<tr>
<td>Distillation 50%</td>
<td>deg</td>
<td>102.0</td>
<td>72.0</td>
</tr>
<tr>
<td>Distillation 90%</td>
<td>deg</td>
<td>116.5</td>
<td>90.0</td>
</tr>
</tbody>
</table>

Note: (*1) GTL Naphtha was produced from the GTL products supplied from the Yufutsu GTL pilot plant.
Photo 1 Heavy Oil (left) and Light Oil (right)

Photo 2 Yufutsu GTL Pilot Plant (7 BPSD)