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GAS HYDRATE EXPLORATION: ITS TECHNOLOGY-ENVIRONMENT INTERFACE IN THE WORLD AND JAPAN

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Abstract

Ice-like gas hydrates under deep ocean bottom and permafrost have been attracting vigorous attention of geologists and energy industries world-wide in recent years. Such clathrate compounds are expected to become an environmentally sound, future source of energy. However, its research and development, if recklessly made, may cause such hazards as disturbance of marine environment, additional green house effect due to methane escape into the atmosphere and so on. After glimpses at the world and Japanese histories of natural gas utilization and at the Jevons' law on economy of fuel, this paper will investigate the current state of technology-environment interface of deep ocean drilling to gas-hydrate-containing sediments. A tentative map of gas hydrate evidences around Japan Archipelago is shown. Finally, needs for disclosure of empirical data and extensive environmental assessment will be discussed in the context of new drilling and related technologies.

I. *Introduction - From Titan to the Earth*

Methane hydrate occurrence on Titan. Ground-based remote sensing techniques have been so advanced that they are now accumulating the data on the chemical structures of the solar system and beyond to astonishingly fine details. As to the surfaces of the satellites of Saturn, Cruikshank and Brown (1993) suggest that volatile compounds such as methane (CH_4), ammonia (NH_3), and carbon monoxide (CO) may be incorporated into water ice to form clathrate hydrate structures. In addition to the ground-based techniques, the contemporary sciences have gained significant amount of information from the technology of spacecraft which carry a wide spectrum of observation and data-transmission equipments. Lunine (1994) tells that the data sent from *Voyager* I indicate the occurrence of methane hydrate layer near the surface of Titan, the largest satellite of Saturn.

Compared with the rapidly compiling scientific knowledge on the outerspace, the one of the inside of the Earth on which we live appears to be rather modest. As far as the deep oceans are concerned, however, recent progress of oceanographic research has been remarkable, largely owing to the U.S.-initiated Deep Sea Drilling Project and its international outgrowth called the Ocean Drilling Program. In these research efforts, it has been revealed that many parts of continental margins of the Earth are also endowed with vast amounts of gas hydrate. Independently of this, the scientists of the former Soviet Union too accumulated great amount of information of the gas hydrate in permafrost regions and inland seas such as Caspian Sea.

Technology-environment interface in gas hydrate R & D. While these findings of gas hydrate certainly have their own importance of the comparative planetary scientific perspective, they are also directly relevant to our economic lives on the Earth in that the gas hydrate exploration is becoming one of the most acute manifestations of technology-environmental interface today. Facing the global environmental problems such as increase in greenhouse gases in the atmosphere, marine pollution, acid rains/mists, decrease in tropical rainforests and so on, public interests in natural gas have grown more than ever before in the world history. The share of natural gas in the total consumption of primary energy sources has been increasing in many countries in recent years. In such a situation, it sounds to be a good news to hear that we have additional clean energy resource base. Not a few geologists now estimate that the total amount of heat value of natural gas partly entrapped in clathrate hydrate structures and partly stored under them as free gas are competitive with the one of conventional fossil fuels combined [Matsumoto, Okuda & Aoki (1994)], and some suggest that it may be even much larger [Kvenvolden (1988), MacDonald (1990)]. Regardless whether it is naturally occurring or due to human interference, gas hydrate formation/decomposition is now recognized as of an innegligible part of global carbon cycle.

From a more technical point of view, the modern technology has come to such an advanced level that it can widely be deployed to drill deep seabeds to extract methane hydrate and free methane beneath it. However, such attempts may pose serious threats not only to marine but to atmospheric environments, if the exploration is recklessly made. It then is urgent for policy makers and researchers to assess the implications of gas hydrate exploration both from technological and environmental viewpoints. Such assessments would become meaningful only if its knowledge and information held by specialists would be widely disclosed to the public. In what follows, we first characterize both histories of conventional natural gas utilization and of more recent gas hydrate research and development in the world. Then, we proceed to investigate the current state of its research in Japan. Problems associated with the widening of energy resource base will be discussed in the light of Jevons' law on economy of fuel, and the paper will be concluded by a presentation of major issues toward the coming century.

II. *Brief History of Energy Resources Augmentation*

Early human encounters with natural gas. Human use of natural gas has a long history, if longer, but not much shorter than the ones of coal and oil. In several parts of China, people had dug deep wells to obtain brine water for salt production. It is said that this practice dates back to quite olden times, i.e., some 1,000 B.C. A byproduct of this brine water well was natural gas. People exploited it as a fuel to heat brine water evaporated for salt to remain in the pan. It sometimes happened that only natural gas was obtained from a well. Such well became to be known as the fire well. Where a well and a heating site were apart, the gas from the former was sent to the latter by series of bamboo pipes. Since the 11th century, sophisticated, new technology of digging narrow, much deeper well, instead of traditionally wide, shallow well has been highly developed together the extensive system of bamboo pipelines in Szechwan Province and others (Shen, 1993).[1]

On the other hand, the rising flames of natural gas fire near Baku on the east coast of the Caspian Sea have attracted fireworshippers of Asia for more than 2,500 years. With respect to such 'eternal fires,' Peebles has noted the custom that ".....the temple contained a crematorium where the bodies of faithful devotees [to the cause of Zoroaster-author's addition] were consumed by the sacred fires of natural gas" (1980, p.148). As of this area, the observation by Mas'udi (896?–956?, Maçcoudi in French), a Bagdad-born Islamic traveller to many parts both of Islamic and non-Islamic worlds, is impressive. In his celebrated work; *The Meadows of Gold*, he writes as of his voyage to the coasts of the Caspian Sea sometime in the 930s: "..... In the basin also fronting on Djîlân and Deïlem, and between these two provinces and Amol, we find constant movement of commercial ships, which come and go with merchandises. Other ships leave the same points of the coast for Baku, where we find springs of white naphtha and of another kind; it is said that white naphtha only exists on the coast of kingdom of Chirwan [one of the then Islamic kingdoms]. On the land occupied by these springs of naphtha, we find a volcano or a spring of fire, from which fire eruptions never stop, and which always eject burning jets into the atmosphere. Facing this part of the coast, there are many islands. One of them, located at a distance of three days' travel from the land, has a big volcano. For certain epochs of years, its sides have been roaring and ejecting flames which elevate in the atmosphere up to the height of the steepest mountains and project, on the sea, live light which can be recognized from the land at a distance of 100 parasanges [one parasange = some 5250 m, a unit of distance in ancient Persia – author's note]."(Maçoudi, 1914, pp. 25–26)[2]. The flames which he witnessed there are now considered to have been the ones of natural gas. Later on, we will again encounter the Caspian Sea from a viewpoint other than fire worship. As far as Europe was concerned, however, the utilization of sizable amount of gas started only toward the end of the 18th century.

Manufactured gas in the age of coal civilization. As charcoal became costly with the decrease in forests in Britain, some people strengthened their efforts to manufacture iron by means of coke instead, as a reduction agent. The first commercial success of coke iron was brought about in 1709 by Abraham Darby (1678?–1717), and his ancestors expanded his business. This meant that dry distillation of coal to obtain coke left coal gas behind as a byproduct. The age of coke iron development was also the age of invention and improvement of coal-fired steam engine, the first successful one of which was built by Thomas Newcomen (1663–1729) in 1712. The heat efficiency of such engine was magnified by James Watt (1736–1819) in the 1760s. The company of Watt with his business promoter, Matthew Boulton, employed the Scotch engineer, William Murdock (1754–1839). It was he who invented a gas light in 1792 and

[1] Though Shen (1993) tells the most thorough history of natural gas utilization in China in the ancient times up to the 19th century, Needham (1962, p. 66) and Peebles (1980, pp. 4–5) briefly mention it too.

[2] This quotation is the author's tentative translation from French in the Arabic-French comparative text; Maçoudi (1914). The French part reads: "A ce bassin appartiennent encore le Djîlân et le Deïlem; entre ces deux provinces et Amol, il y a un mouvement perpétuel de bâtiments de commerce qui vont et viennent avec des marchandises. D'autres bâtiments partent des mêmes points de la côte pour se rendre à Bakou, où se trouvent des sources de naphte blanc et d'autre espèce; le naphte blanc n'existe, dit-on, au monde que sur la côte du royaume de Chirwân. Dans le terrain occupé par ces sources de naphte se trouve un volcan ou une source de feu dont les éruptions ne cessent jamais, et qui lance en tout temps dans les airs des jets enflammés. En face de cette partie de la côte sont situées plusieurs îles: l'une d'entre elles, distante de la terre ferme d'environ trois journées, renferme un grand volcan; à certaines époques de l'année, ses flancs mugissent et lancent des flammes qui s'élèvent dans les airs à la hauteur des montagnes les plus escarpées, et projettent sur la mer une vive lueur que l'on aperçoit du continent à une distance d'environ cent parasanges."

opened the door to the age of industrial as well as domestic uses of coal gas. It is noteworthy that early forms of internal combustion engine made in Britain, France and Germany also used coal gas as their fuel.

Jevon's law on economy of fuel. During the time when the number of steam engines were multiplying with increased heat efficiency and the traditional charcoal iron was being replaced by new coke iron both in Britain and Continental Europe, William S. Jevons (1835–82), the English economist, published a controversial book; *The Coal Question*, in 1865. Among many important issues raised in his book subtitled; 'an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines,' one particular point with contemporary relevance must be noted . He stresses: "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth" (Jevons, 3rd edition, 1906, p. 140). He also argues that "economy of fuel leads to a great increase of consumption" (1906, p. xxxiv). Economy of fuel means increase in energy efficiency, and it in turn leads to increased convenience of that fuel use. And this would increase the absolute level of its consumption, instead of decreasing it. Jevons has thought that this would almost universally hold in human life. We shall then call this the Jevons' Law on Economy of Fuel.

And in fact, coal consumption was increasing in Britain, the United States, and elsewhere as the heat efficiency of steam engine increased. Moreover, the distillation of crude oil, the method of which was elaborated by Abram Gesner, a Canadian geologist, became fashionable to get kerosene for lighting in the United States. This, however, resulted in the unwanted byproduct; gasoline, highly volatile and dangerously flammable. Some German engineers took note of it and invented a variety of the gasoline-fuelled internal combustion engines toward the end of the 19th century. The 20th century was thus fermented to become the age of the oil civilization. In a way, manufactured gas could be seen as of having bridged the coal civilization to the oil civilization.

Gas pipeline and liquefaction under the oil civilization. Oil fields development in the United States and elsewhere were often associated by natural gas seepages. Such gas was recognized to be useful as a household fuel in nearby areas. But its huge volume per unit of heat value compared with coal and oil posed difficulty both in its storage and long-distance transportation, and delayed its massive worldwide uses. A change came with the development of modern pipeline technology. Development of tightly welded iron pipelines, which were more efficient than the above mentioned bamboo pipes of China, made long distance transportation of natural gas economically feasible by the 1920s. The difficulty still remained, however, in terms of its overseas trade.

Liquefying gas was potentially a solution to this. After the experimental liquefaction of nitrogen, methane and others by the French chemist, Louis P. Cailletet (1832–1913) in 1877, the first attempt of liquifying natural gas on a practical scale was made and patented by the United States Bureau of Mines in 1917. Afterawhile, a commercial plant for liquefied natural gas (LNG) was constructed in Cleveland by East Ohio Gas Company. While this business was successful more than three years, the fourth tank of the plant was broken in October 20, 1944. The leaked LNG vaporized and entered the city's sewer system. Ignited by an unidentified source, it widely exploded and killed some 130 people and damaged quite a bit of properties (Tussing & Barlow, 1984). Since then, the LNG commercialization almost stopped for decades.

But the postwar, rapidly increasing demand for oil in the world also resulted in the welling of associated natural gas regardless one liked it or not. Coupled with the progress of storage technology, overseas natural gas trades found economic prospects and liquefaction became a promising business for the countries with big oil/gas fields toward the end of 1950s.

Gas industry in Japan. While Japan has fairly large deposits of coal, the endowments with oil and natural gas has been considered to be very small. The gas industry there, as in the cases of other countries, has developed with manufactured gas from coal. Since Japan opened the door to overseas after two-centuries long, national seclusion in 1854, western technologies started to rush into the country. The first gas use as an application of such imported technologies, dates back to 1857, when the Satsuma-han (one of the influential clans under the Tokugawa shogunate) in southern Kyushu extracted gas out of coal for lighting purpose. The Meiji Restoration of 1868 ended the shogunate politics and accelerated the modernization of the country based on European and American models. The first public gas lighting business was undertaken in Yokohama by Kaemon Takashima (1832–1914), a man of modern entrepreneurship in 1872, followed by the one in Tokyo in 1874. But the growth of gas industry was slow due to relatively rapid development of electric light business despite of its rather late start–introduction of arc light in 1878 and the first commercial lighting by incandescent lamps in Tokyo in 1887 (Murota, 1993). As far as the indigenous natural gas was concerned, it had been discovered in the Niigata area facing the Japan Sea in 1645, but its public use within the area came as late as 1907. The economic boom after the World War I, however, favoured the development of manufactured gas industry. The Gas Utility Act of 1925 helped it to become a part of modern public utilities (Sekijima, 1987). Although the demand for lighting sources had been almost totally taken over by public electric utilities and municipal electric undertakings by the mid 1930s, urban homes increasingly found it convenient to use gas for cooking and bath water heating, while firewood, charcoal and coal remained to be major energy sources in rural areas.

The damages of almost all big cities during the World War II severely hit the gas industry equally to other industries. But the postwar recovery was rather quick. The importance of gas in homes and industries has increased especially since the late 1950s when the oil civilization was rapidly catching up with the coal civilization. The age of mass production and consumption of the so-called 'consumer durables' came and more and more people inclined to take advantage of convenient life style using a plenty of gas and electricity mix. From the viewpoint of gas industry, feedstock for manufactured gas shifted from coal to crude oil, naphtha, liquefied petroleum gas (LPG) and indigenously produced natural gas. This shift was quickly followed by another shift, *i.e.*, the shift from manufactured gas to natural gas, as we will see later.

III. *Identifications of Gas Hydrates*

In the age of increasing natural gas consumption in the world and Japan, some scientists started conducting research of naturally occurring gas hydrate. But what is gas hydrate, to begin with? Water usually turns into ice when it freezes. If water is saturated with a certain kind of gas and if pressure and temperature are in certain ranges, however, it happens that water molecules crystallizes into a cage-like structure to host the gas molecules inside, resulting in gas hydrate (or clathrate ice).[3] It has been known that gases which can form such compounds are methane (CH_4), ethane (C_2H_6), carbon dioxide (CO_2), hydrogen sulfide (SO_2), and so on. Among naturally occurring gas hydrate, the major part of them is the methane hydrate. Since the main ingredient of natural gas is methane, the methane-dominated hydrates are also called natural gas hydrate.

Structures of gas hydrate. It is widely known that there are two types of water molecules' cage-like structure which form gas hydrate. They are often called Structure I and Structure II, of which Structure I is smaller than II. One unit of Structure I consists of 46 water molecules and becomes ready to stabilize by including a certain number of small gas molecules such as methane, ethane, hydrogen sulfide, or so within their interatomic spaces (or cavities). Maximum number of gas molecules hosted in this manner is 8 for Structure I, but it does not have to be fully filled for hydrate formation. One unit of Structure II consists of 136 water molecules and can include 8 larger gas molecules such as propane, iso-butane, or so at a maximum. But there still remain small cavities and they can additionally host 16 smaller gas molecules. If we only consider the fully filled methane hydrate of Structure I for the sake of simplicity of discussion, it density is 0.91 g/cm^3. This means that one cubic meter of it contains such an enormous amount of methane gas as 170.7 cubic meters if it is put at an ambient condition. Even if it is the 90% filled methane hydrate, one cubic meter of it contains 156 cubic meters of methane gas (MacDonald, 1992, p. 475). In this sense, gas hydrate is a storage of natural gas in a very compressed state, and such a fact is the reason why not only geologists but energy industries have shown great interests in naturally occurring gas hydrate.[4]

Temperature and pressure are, among others, the main factors which determine either formation or decomposition of gas hydrate. If the pressure is 25 atm or more (*i.e.*, if the site in question is deeper than 250 meters from the sea surface, for example), methane hydrate can form with the temperature 0℃ (273.15 K). If the pressure becomes larger, an environment with higher temperature than that allows hydrate formation. For example, an environment of 100 atm and 12℃ is within the stability zone for methane hydrate.[5]

From an unwelcome agent to a bonanza? The early age of gas lighting which we have seen before was also the time of birth of cryogenics. Humphry Davy (1778–1829), the English chemist, was the first to have noticed that certain kinds of gas combined with water could form an icy solid. This finding in 1810 was followed by Michael Faraday (1791–1867) who, in 1823, made chroline gas and water form a hydrate under cold winter weather of London,[6] which is now considered to be a chlorine-inclusion compound $Cl_2 \cdot 6H_2O$. However, no one had thought about the possibility that such a substance or a similar kind could be occurring under natural

[3] Such a compound has often been called a clathrate by chemists, while geologists tended to call it a gas hydrate, the term which we use in this paper. For details, see Englezos (1993).

[4] A new structure of hydrate is also known (Ripmeester, Tse, Ratcliffe, & Powell, 1987) and named Structure H, though it does not seem to have a direct relevance to the natural gas question in this paper.

[5] Other factors such as salinity of water, types of gases contacted with water and so on affect the stability of gas hydrate. Under the existence of sodium chloride (NaCl), a stability curve shifts toward lower temperature under the same pressure than otherwise, or the same temperature with higher pressure.

[6] Faraday writes, in his diary of January 16, 1823, that "A little water put into a jar of chlorine and left in a cold place. Hydrate of chloline formed, a little water added and the hydrate washed together–was in a criystalline plates and films–sometimes it shoots out in long prismatic or needle crystals into the atmosphere of a bottle of chlorine; at other times forms an arborescent film on its inner surface. The substance is of a bright yellow colour, ..." (Faraday, 1932, p. 89). With this kind of experiment, Faraday (1823) confirmed that a peculiar substance which Davy had obtained in 1810 (Davy, 1811) was a hydrate of chlorine.

conditions. The turning point only came in the 1930s when engineers of the former Soviet Union started to encounter the incidents of pipeline choking in Siberia, where chemical plants were developed and many pipelines were constructed as means of transporting various kinds of gas, oil, and chemical products among such plants. After repeated incidents, it became known that highly pressurized gas formed gas hydrate when it contained water if small in amount, and that it choked the pipelines. In the United States too, natural gas pipeline choking in the winter months called attentions of researchers in the 1930s. Hammerschmidt (1934) demonstrated that the formation of gas hydrate, not the freezing of water, in the pipelines, was the cause of such problems. Since then, intensive research on the temperature-pressure conditions of natural gas hydrate formation began both in the former Soviet Union and the United States. Theoretical prediction of natural occurrence of gas hydrate on such planets as Uranus and Neptune as well as on the satellites of Saturn was made by Miller (1961).[7]

The development of Messoyakha gas field in Western Siberia was an epoch-making event in the research and development of naturally occurring gas hydrate on the Earth in the former Soviet Union. It was discovered under the usual program of developing conventional gas fields in 1967. However, it has eventually become clear that the natural gas obtained from the field came up from the gas hydrate and from free gas zone beneath it. This finding around 1970 placed the Messoyakha field as the position of the world-first methane-hydrate gas field, quite different from the conventional gas fields in the world therein known (Makogon, 1981). A few years later, Soviet scientists also discovered gas hydrates in the sediments of the Black Sea [Yefremova & Zhizhchenko (1974)]. Furthermore, they found the traces of gas hydrate occurrence in the Caspian Sea and obtained their samples to analyze their crystalline structures in 1979. A strikingly interesting aspect of the Caspian Sea has been more recently found in that crystalline hydrate was taken up, by using the technique of gravity corer, from the crater-like summits of mud volcanoes[8] named 'Buzdag', 'Elm' and others at the depths of 475–600 meters [Ginsburg *et al.* (1992)].

Such findings have not been limited within the former Soviet Union. The recovery of terrestrial methane hydrate was made during the boring by two U.S. oil companies in Northwest Eileen Well No. 2, Prudhoe Bay, Alaska in 1972. Shortly after this, sonic logs taken from some exploration wells showed definite evidences of gas hydrate occurrence in some areas of MacKenzie Delta, Northwestern Territories, Canada [Billy & Dick, (1974), Judge & Majorowitz (1992)].

Research progress under DSDP and ODP. Toward advancement of joint research of deep

[7] At that time, however, it was not thought that there could be such gas hydrates on the earth. Miller (1961, p. 1798) wrote: "The gas hydrates .... are not known to occur naturally on the earth because of the unfavourable combination of temperatures, pressures, and gases that are poor hydrate formers in the earth's atmosphere." At the same time, he was cautious enough to add: "Hydrates of air may be formed in the high clouds of the earth either from metastable ice or super-cooled water." (Miller, 1961, p. 1807) In 1982, naturally occurring hydrate of air was discovered in the deep ice cores taken at the Dye-3 observatory in Greenland, though not in the high clouds.

[8] A mud volcano is different from a land or submarine volcano in the usual sense. While the latter is a product of the activity of hot magma originated from the mantle of the deep Earth, the former is a product of rather cool seepages of methane, water and so on from a shallower part of the Earth crust. Hovland & Judd (1988. p. 283) simply define it as "volcano-shaped structure composed of mud that has been forced above the normal surface of the sediment, for example by diapiric action." The author speculates that high-rising jets of flames of natural gas which Mas'udi witnessed and thought of volcanic eruptions on some coast of the Caspian Sea sometime in the 930 s might have been related to gas hydrate and that such jets might have left mud volcanoes in that area.

oceans, four institutions in the U.S. were united in 1966 to form the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES).[9] Scientists of this new organization started the Deep Sea Drilling Project (DSDP) under the sponsorship of the National Science Foundation in 1968. The drill ship *Glomer Challenger* began its first drilling in August of that year, and it travelled more than 600,000 kilometres with the collected core of 97 kilometres long until 1983 (Maxwell, 1994/94). In the meantime, DSDP attracted the attentions of international scientific communities so that it became known as the International Phase of Ocean Drilling (IPOD) in 1975. The former Soviet Union, the former Federal Republic of Germany, Japan, the United Kingdom and France participated in it. The U.S. members of JOIDES increased around that time and they were incorporated to become the Joint Oceanographic Institutions Incorporated (JOI) in 1976.

In 1983, a proposal was made by Texas A & M University whose College of Geosciences and Maritime Studies was a member of JOI. It was the plan to use the drill ship SEDCO/BP 471 better known as *JOIDES Resolution*, which could offer greater research capability than *Glomer Challenger*. The DSDP was then transformed to the Ocean Drilling Project (ODP). The *JOIDES Resolution*, which was an assembly of highly capable laboratories by itself, started its ODP cruises in January 1985. The ODP gradually changed its character from an American project to an entirely international program during the period between 1987 and 1993. As of 1993, its participants are Canada-Australia,[10] France, Germany, Japan, the United Kingdom, and the European Science Foundation (Sweden, Finland, Norway, Iceland, Denmark, Belgium, the Netherlands, Spain, Switzerland, Italy, Greece, and Turkey), beside the United States. Each voyage has been serially recorded with Leg number, and so has been each specific place visited with Site number.

The DSDP and ODP, which have had a wide scope of oceanographic research, have not been intended to narrowly investigate ocean gas hydrate only, of course. But it is true that they significantly have contributed to the progress of gas hydrate research in the world. Two, among others, of the major outcomes of subaquatic gas hydrate research under DSDP and ODP are; (1) direct recovery of gas hydrate in cores, and (2) establishment of a new geological concept of bottom simulating reflector (BSR). Starting from (2), some scientists of the U.S. Geological Survey observed abnormal seismic reflections from the ocean floor in Blake Outer Ridge northeast off Florida Peninsula in 1970. Further studies have shown that the bottom of gas-hydrate-containing sediment often has parallel stretch to the ocean floor usually a few hundred meters above it. Exploration of hydrate has been mostly made by sending seismic waves (artificially caused by air guns) from ocean surface down toward bottom and analyzing the travel times and waveforms of their reflection. Then, reflection by ocean floor and the one by hydrate-containing sediment bottom often show detectable differences in velocities and in wave forms (polarity inversion). From these differences and the above-mentioned parallelism, the hydrate-containing sediment bottom was named bottom simulating reflector (BSR, hereafter) in 1974. It is sometimes occurs that a reservoir of free gas (mostly methane) exists underneath the BSR (Bangs, Sawyer & Golovchenko (1993) and others). In such a case, it is considered that stable gas hydrate with little permeability is

[9] Its members were Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, University of Miami Institute of Marine Sciences, and Lamont Geological Observatory of Columbia University.

[10] Due to the limit of each budget, Canada and Australia formed a consortium to participate in the program as a single unit.

performing the role similar to the cap rock in conventional oil and/or gas fields. This means that if one observes BSR in some sea area then the probability is high that one can find gas-hydrate-rich sediment above it and possibly a free gas reservoir below it.[11]

This outcome (2), together with other search methods, has led the outcome (1) in well more than ten ocean sites in the world. Direct recoveries of suboceanic gas hydrate in the early stages were made in DSDP Leg 66 (Central Pacific coast of Mexico) in 1979, DSDP Leg 67 (Middle America Trench off Guatemala coast) in 1979, DSDP Leg 76 (Blake-Bahama Outer Ridge, North Atlantic) in 1980 and others. As to Leg 67, a core sample of almost pure gas hydrate of 1 meter long was obtained. Examples of recent, direct recoveries are in ODP Leg 127 (Okushiri Ridge, Japan Sea) in 1989 and ODP Leg 146 (Cascadia Subduction Zone, off Vancouver Island of Canada) In 1992. As to Leg 127, gas hydrate samples were recovered from Site 796, or more exactly one from Hole 796A and another from Hole 796B at the places of 2571 and 2623 meters deep from the sea surface, respectively and both some 90 meters sub-bottom.

By 1993, there are over 60 places in the world; ocean sites, inland sea sites and permafrost sites, gas hydrate occurrence of which are confirmed, either by direct sampling, or BSR observation or other means under DSDP/ODP, other independent research, or commercial exploration [Matsumoto et al. (1994, p. 106, Table 5–1)].

IV. *Jevons' Law in View of Japanese Demand for Natural Gas*

Japan in the period between the late 1950s and early 1970s was the 'rising sun,' *i.e.*, the country of rapid economic growth. Such a growth was made possible at least through two things; accelerated consumption of energy sources most of which were imported from overseas (mainly West Asian countries) and severe pollution both in air and water. As to the latter, the so-called 'kogai-byo' (pollution diseases) were very intense in many parts of Japan; the Minamata Disease and the Yokkaichi Asthma, to name only a few. This bitter experience was forcing the central government of Japan and local governments as well to take strict regulations against air and water pollution.

Reap forward of LNG imports and gas-fired CHP. In such a sociopolitical context, natural gas came to be considered as better source of energy among the industry circles. But this concern with pollution was not the only reason why Japan started the imports of liquefied natural gas (LNG). There was another reason which was purely economic. That is to say, long-term contracts with precisely set volumes and prices were possible to make with exporting countries or companies in the case of LNG while such securities could not be guaranteed in the case of crude oil.

A distinct feature of Japan's LNG imports has been in that not only gas industry has been interested in shifting its sources of gas supply from the above mentioned mix to natural gas derived from LNG but electric power companies had been planning to use LNG for power generation. Thus, the first contract of LNG import was made as early as 1966 by Tokyo Gas Company and Tokyo Electric Power Company (TEPKO) with two U.S. companies to import

[11] The BSR in the Cascadia Subduction Zone off Vancouver Island, British Columbia, Canada, is one of the most intensively studied cases (Hyndman & Davis, 1992; Singh, Minshull & Spence, 1993).

LNG from Alaska. Its first delivery to Japan was made in 1969. Following this successful delivery, the LNG ships started to come from Brunei, Abu Dhabi, and others in the 1970s. Following TEPCO, other electric power companies such as Kansai Electric, Chubu Electric and Kyushu Electric also started to use LNG for their thermal power generation.

Another new move was the rapidly arisen interest in CHP (combined heat and power–usually called 'cogeneration' in Japan). The two oil crises in 1973 and 1979 motivated industries and service sectors to take strong measures of energy conservation to avoid cost increase. This economic incentive has led an increasing number of manufacturing factories and service undertakings (hotels, public baths, and others) to adopt CHP systems of one type or another to satisfy their own heat and electricity needs, partially independently of electric power companies, if not totally. For such systems, natural gas has been considered to be most suitable (as fuels for gas turbine and gas engine).

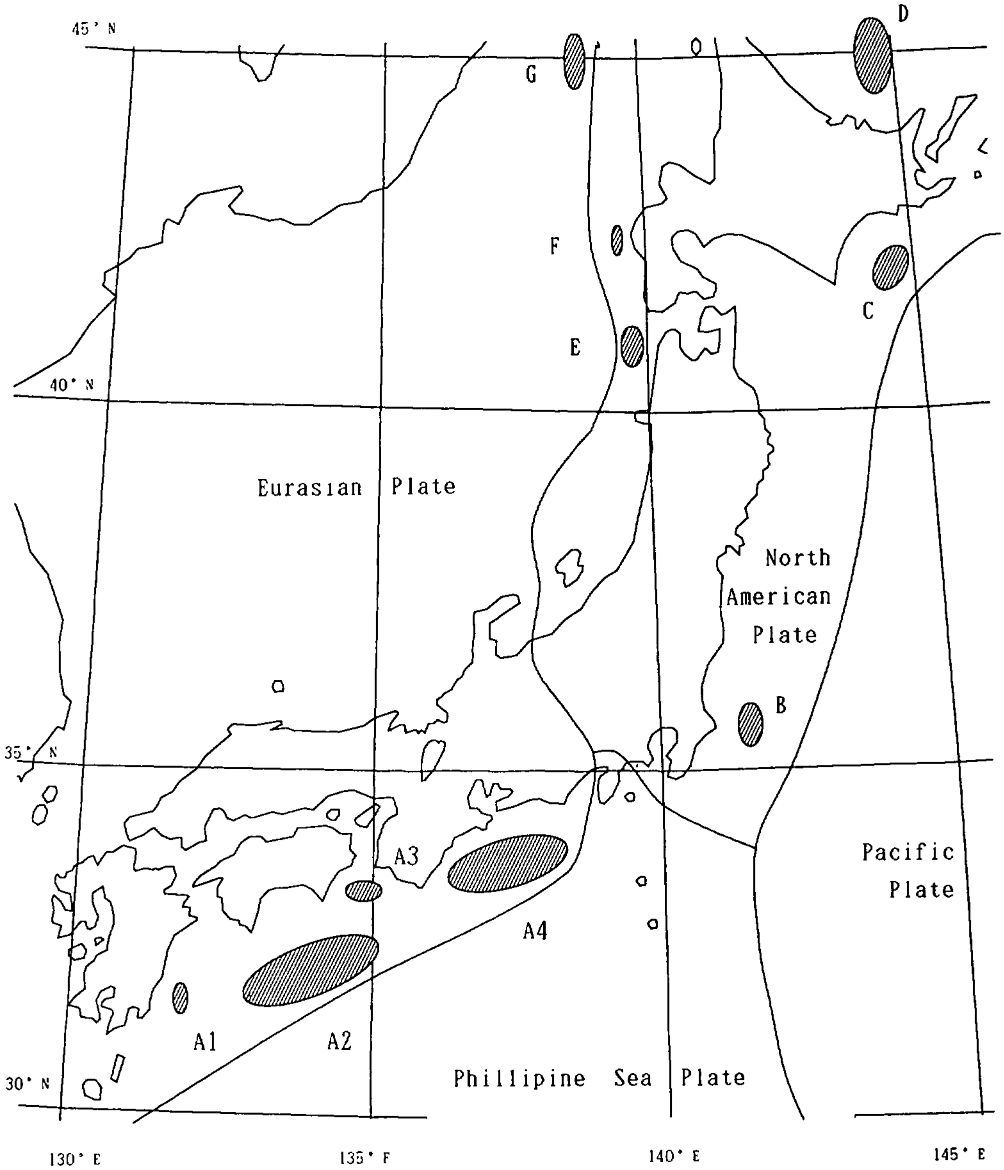
Jevons' law at work. Sequence of these new events resulted in the increase in demand for natural gas much faster than the one for oil. While total consumption of natural gas in Japan was only 3.9 billion cubic meters (bcm) in 1970, it rose to 9.6 in 1975, 25.1 in 1980, 36.8 in 1985, and 39.8 bcm in 1989. Its forecasts for 2000 and 2010 are as high as 63.0 and 77.5 bcm, respectively (International Energy Agency, 1991, p. 229). Such an impressive growth of demand for natural gas can be considered to fit with the Jevons' law on economy of fuel in view of the three-fold increase in efficiencies of natural gas utilization. That is to say, we have the following three facts: (1) Thermodynamic heat efficiencies of internal combustion engines have increased much higher than the ones of their early ages, and such engines include natural-gas-fired ones; (2) Economic efficiency in gas transportation and storage increased due to the advancement of pipeline and liquefaction technologies; And (3) the CHP has a potential of increasing the overall efficiency of gas use up to 80% or so, instead of at most 40% or so if gas is used solely for power(electric or motive) generation. These three factors together have been and are being creating more and more demand for natural gas in the aggregate sense, though energy consumption for one unit of work has decreased due to the said increase in an individual efficiency. The Jevons' law on economy of fuel is clearly at work here.

Increased interests in gas hydrate research. As far as Japan's indigenous supply of natural gas is concerned, it was only 2.1 bcm against the total 48.3 bcm of natural gas supply in 1989. The government forecasts of corresponding figures for the year 2000 are 2.3 against 71.1 [International Energy Agency (1991, p.230)]. This poor situation calls for the need of developing unconventional sources of natural gas if technologically and economically possible. The publication of *Power from the Earth* by Thomas Gold (1987) had a certain impact on some specialists in Japan. The book had been devoted to assert an abiotic origin of oil and natural gas and to suggest a vast availability of natural gas in the form of methane gradually rising up from deep parts of the Earth. It was quickly translated into the Japanese and published in 1988. Under the sponsorship of Agency of Resources and Energy, the Ministry of International Trade and Industry (MITI), the Institute of Energy Engineering set up a committee for investigating such unconventional sources of natural gas. It is known that the result of intensive research by this committee was summarised in a voluminous report titled *Research Report on the Availability of Deep Earth Natural Gas* and presented to the sponsor in 1990. It was unfortunate, however, that this report was restricted to be of a limited circulation so that the general public could not see its content. Soon after this, however, the Institute of Energy Engineering initiated another committee; the research committee on unconventional natural

TABLE 1. GEOGRAPHICAL DISTRIBUTION OF GAS HYDRATE EVIDENCES AROUND JAPAN ARCHIPELAGO

Location		Evidence	Main Source
The Pacific			
A1	Nankai Trough (Off eastern Miyazaki)	BSR	Aoki, *et al.* (1983)
			Machihara (1983)
A2	Nankai Trough (Off southern Shikoku)	BSR, Sample Chemical Analysis	Taira, *et al.* (1991)
A3	Nankai Trough (Muroto Trough)	BSR	Sato (1994)
			Matsumoto, *et al.* (1994)
A4	Nankai Trough (Kumano-nada through off Omaezaki Cape)	BSR	Okuda (1995)
			Gas Epoch (1995)
B	Offshore Chiba Basin	BSR	Arato, *et al.* (1995)
C	Kuril Trench (Off Tokachi/Hidaka)	BSR	Sato (1994)
Okhotsk Sea			
D	Off Abashiri (Kitami-Yamato Mount)	BSR	Matsumoto, *et al.* (1994) Sato (1994)
Japan Sea			
E	Western Tsugaru Basin	BSR	Sato (1994)
F	Okushiri Ridge	Sample BSR	Tamaki, *et al.* (1990) Kuramoto, *et al.* (1995)
G	Tatar Trough	BSR	Sato (1994)

FIG. 1 MAP OF THE AREAS OF GAS HYDRATE EVIDENCES AROUND JAPAN ARCHIPELAGO*



* Constructed based on the data in the sources listed at the rightmost column of Table 1.

gas, which had a sub-committee on methane hydrate. A part of the result of research in this methane hydrate sub-committee is published, this time openly, as *Methane Hydrate: Gigantic Source of Natural Gas for the 21st Century* by Matsumoto *et al.* (1994). This will help to narrow the knowledge gap between the specialists and the general public as to Japan's potential of gas hydrate R & D in the future.

As mentioned above, Japan participated in the ODP in 1975, the year of its commencement. The geologists at the Ocean Research Institute, University of Tokyo; Noriyuki Nasu, Kazuo Kobayashi and Asahiko Taira have successively taken turns to be in charge of the ODP operations in Japan. Through international joint studies under ODP and partly due to Japan's own research efforts, seven sites of gas hydrate occurrence thus far have been confirmed around the Japan Archipelago. According to Matsumoto et al. (1994), Sato (1994), Arato, Akai, Uchiyama, Kudo & Sekiguchi (1995), Gas Epoch (1995) and many others, they are;

A: Nankai Trough (stretching from the east of Miyazaki, Kyushu Island and the south of Shikoku Island to the souths of Kii Peninsula and of the Tokai region near Cape Omaezaki, Honshu Island, Pacific Ocean),
B: Offshore Chiba Basin (the east of Choshi, Pacific Ocean),
C: Southern part of Kuril [Chishima] Trench (Off Tokachi-Hidaka, the south of Hokkaido Island, Pacific Ocean),
D: Off Abashiri (Kitami-Yamato sea mount, the east of Hokkaido Island, Okhotsk Sea),
E: Nishi-Tsugaru Basin (west of Tsugaru Peninsula of Honshu Island, Japan Sea),
F: Okushiri Ridge (the west of the southern part of Hokkaido Island, Japan Sea),
G: Tatar Trough (the west of Hokkaido Island, Japan Sea).

Their locations with associated evidences are described in Table 1. Fig. 1 is their geographical map.[12]

As to F: Okushiri Ridge, the occurrence came to be directly known by gas hydrate sample collections from the sediments (ODP Leg 127, Site 796A and B) as mentioned before. As to four other cases B, C, D, E and G, the seismic observation of clear BSRs seem to have confirmed their occurrences. Its confirmation in D: Off Abashiri was very recently made by The Geological Survey of Japan (Nihon Keizai Shimbun, 1993). The seismic profile of its BSR is given in Matsumoto (1994, p. 152). The discovery of BSR in C: Offshore Chiba Basin is more recent (Arato *et al.*, 1995).

The case of A: Nankai Trough has been most widely studied since the 1980s. Its marine geology was studied by Aoki, Yamano & Kato (1983) and many others. Machihara (1983) conducted chemical analyses of sea water and sediment in a part of this ocean bottom to find high concentration of light hydrocarbons. In addition, Taira, Hill & Firth (1991) as a part of ODP program report that gas hydrate was recovered, together with some plant debris, in the wash core 4W at Hole 808F in ODP Leg 131 to this area in 1990. In another part of the ocean

[12] Geologically speaking, the area A is located in the zone where the Philippine Sea Plate subducts under the Eurasian Plate. The area B seems to locate near the triple junction of the Philippine Sea, Pacific, and North American Plates. The area C locates in the boundary between the Pacific and North American Plates. The area D is peculiar (relative to others) in that it does not seem to be related to any of such plate boundaries. The areas E, F, and G are clearly lined up in the boundary between the Eurasian and North American Plates. It may be worth noting that the northward extrapolation of this line approximately hits the area of 10 gas vents off northeastern coast of Sakhalin Island, the area described by Cranston (1994) and others.

bottom of Nankai Trough, a hydrothermal vent was also discovered with rich organic and inorganic activities including the propagation of tube worms and others (Matsumoto *et al.*, 1994). This region of gas hydrate occurrences is segmented into four subregions, A1, A2, A3, and A4 as Tables 1 and 2 show. With these preliminary findings, Japan is now entering into an active stage of gas hydrate research and development, the plan of which we will mention later.

V. *New Technologies in North America and Japan's Move to Gas Hydrate Exploration*

It has been believed that gas hydrate, where it existed, was forming a dense layer immediately above the corresponding BSR. However, recent drilling experiences rather suggest that they are forming discontinuous layer, lens-like, or nodule-like pockets, or so. Sophisticated methods of research and exploration are then needed.

Horizontal drilling in Canada and the United States. In this circumstance, it must be noted that drilling technology has entered into a new age in North America. Traditionally, drilling was made vertically down. But now, some studies (Davenport, 1992; Cooper, 1994) demonstrate that horizontal and any other directional drilling is technologically feasible. This method can bring up oil and/or gas in a much more exhaustive way than the case of vertical drilling. Only problem is that this technology is very expensive. Then, the question is the matter of comparison between high capital investment and high rate of recovery of oil and/or gas from a discovered well. If the monetary return from the latter greatly exceeds the former cost, then this new technology is adopted. Many practices have been already made in the United States and Canada. Cooper (1994) emphasizes its economic and environmental merits. In the case of gas hydrate R & D, it is too early to discuss economic aspects of such a new drilling method. But if one can obtain horizontal cores in addition to vertical cores as before, they will help scientists to investigate further details of geological distribution of gas hydrate occurrences.

Technology of enhanced oil recovery. As means of exhaustively recover oil in the conventional fields, a whole variety of schemes of enhanced oil recovery (EOR) is also well known among the oil industry. The EOR means the injection of mechanical force and/or heat into an oil reservoir to ease the oil flow by changing geological conditions around oil concentrations. For this, various kinds of chemicals are often used. Injection of water into a well is the simplest of EOR. But there are many others. Trollope (1994, p. 11) lists nitrogen flooding, oxygen fire flooding, polymer flooding, carbon dioxide flooding, cyclic steam stimulation, alkaline flooding, hydrocarbon flooding, steam flooding, micellar polymer flooding. If the gas hydrate research would turn into a stage of its active development, the technologies similar to these may be adopted. In the Messoyakha gas field in Western Siberia, methanol has been injected into gas hydrate layers to promote the dissociation of methane gas from the clathrate cage structures.

Emerging exploration projects in Japan. In the energy-hungry Japan, keen attention have been paid especially on the Nankai Trough, because it is very close to one of the major natural gas consumption centres of Japan, *i.e.*, to the Kansai economic zone with such densely populated cities as Osaka, Kobe and Kyoto. The off-Abashiri site, which was just discovered in 1993, is also significant in that the implied gas hydrate locates in the sea of 500–3,000 meters deep and occurs in the vertical range of only 0–800 meters beneath the ocean bottom. The area of its distribution is estimated to be as large as 5,000 square kilometres (Nihon Keizai Shimbun, 1993). It is known that the offshore drilling technology of Japan is not so advanced and that it can drill only down to 500 meters. Even so, the off-Abashiri site still is within a reach of the ready-made drilling technology of Japan.

Although an independent ground for gas hydrate R & D in Japan has been weak, the situation is changing. The Agency of Science and Technology has a plan; Geo-Marine Frontier Project (a tentative name), under which the Japan Marine Science and Technology Centre (JAMSTEC) will promote the construction of a deep sea drill ship of 15,000 tons class, the drilling and other capacities of which will be comparable to the ones of *JOIDES Resolution*. Moreover, it will have a riser and BOP. The riser length is planned to be 2000 meters at an initial stage and to eventually reach 4000 meters. The drill pipe will be 10,000 meters long (Nasu & Kobayashi, 1993/94).[13] Another plan is also set in motion.

That is to say, Japan Geological Survey under Institute of Industrial Technology, the Ministry of International Trade and Industry (MITI), together with Tokyo Gas Company, Osaka Gas Company and others are commencing a joint research on deep ocean gas hydrate from 1994 (Nippon Keizai Shimbun, 1994). Okuda (1995) mentions that an unidentified R & D body is planning to start demonstrative drilling into the sea bottom off Omaezaki Cape, i.e., the subarea A4 in Table 2, from 1999 to find natural gas potential associated with gas hydrate deposit and free gas there. At the same time, costs for oil import expectedly continue to be low relative to the ones for LNG import (Toichi, 1994). If this trend does not change into the coming century, development of gas hydrate aroung Japan Archipelago may not materialize so fast because extraction of natural gas from gas hydrates still seems to cost even higher than LNG import. It is then safe to say that basic research is more important than rushing into quick development as far as the presentday Japan is concerned.

VI. *Discussion and Conclusion*

Recommendations for decision makers and for researchers. Admittedly, natural gas is an environmentally superior fuel to coal and oil. From this reason, not only conventional gas fields will continue to be developed as in the past but subaquatic gas hydrate deposits will invite more attentions of engineers, scientists, and energy industries than ever toward the coming century. In the country like Japan, which does not have significant reservoirs of conventional oil and gas of its own, this trend seems to be particularly the case. But it is also true that the world history of energy resources development and utilization have been tainted with a vast, lengthy series of accidents, pollution, and environmental disruptions; the Cleveland LNG explosion, the Chernobyl nuclear plant eruption, and the Valdez oil spill, only to cite a few. This tells that extensive technology/environment assessments of international nature are mandatory for a further research and development of gas hydrate. And there is a precondition for this. That is to say, its knowledge and information held by specialists must be widely open to the public, since future benefits and potential risks of gas hydrate development will

[13] It is recently reported (Butler, 1996) that France and the United Kingdom are considering to withdraw from the ODP. If this happens, Japan's role in deep ocean research will become greater than ever before in the international scene.

commonly prevail on us and on the generations yet to come. In Japan, almost no precise data have been open to public as to the above stated locations B, C, D, E, and G. It is of vital importance for the general public to know what happens if its stability condition is violated by one reason or another and it starts dissociating.[14]

Judge & Majorowitz (1992, p. 252) characterize the process of gas hydrate dissociation in the following sequence. Firstly, it results in the formation of shallow gas fields. Secondly, such fields turn into shallow high pressure zones under the sea bottom, or high methane concentrations in gas bubbles in ground ice in permafrost areas. From such zones, then, gas blowouts may occur. We additionally think that the second stage may be associated with gas seepages toward the sea floors and then to the water columns of the sea or toward the permafrost surfaces. This sequence, which may naturally proceed under a global warming trend, could be accelerated by human drilling activities into the gas-hydrate-bearing sediments. In what follows, we list several points to which the technology/environment assessments are recommended to address.

[a. Slow process of gas hydrate dissociation] — Without human interference, a certain amount of methane is considered to be escaping into the atmosphere from the permafrost soils and the sedimental hydrates under the sea bottoms in the world. Judge & Majorowitz (1992) present a qualitative analysis of gas hydrate dissociation under the permafrost area of Beaufort-Mackenzie Delta in northern Canada. As to the Okhotsk Sea, the occurrences of gas vents from the sea floors known to have gas hydrate deposits underneath have been intensively studied by Russian and Canadian scientists. One of such zones locates near Paramushir Island, south of Kamchatka Peninsula. From the sea floor of 770 m deep, a flare of gas bubbles was observed to be standing up as high as several hundreds meters [Zonenshayn (1987) and Zonenshayn *et al.* (1987)]. Another zone situates off the northeast coast of Sakhalin Island. In this zone, 10 active gas vents were discovered [Ginsburg, Soloviev, Cranston, Lorenson & Kvenvolden (1993)]. Although gas bubbles rising has been detected within water columns under the sea surface in most of the cases, Cranston, Ginsburg, Soloviev & Lorenson (1994) report that, in one of those vent areas, small gas bubbles of 1 mm in radius were seen to reach even the sea surface 700 m above it when the sea was exceptionally calm. The detailed drill core studies of the cases off Paramushir Island and off Sakhalin Island are available in Cranston (1991) and Cranston and Standing (1992). Based on the studies of these two areas of gas vents, Cranston (1994) estimates a global amount of gas-hydrate-oriented methane escape into the atmosphere.

According to Clarke, Amand & Matson (1986), on the other hand, the U.S. climate satellite of *NOAA* has observed water plumes rising in the Arctic Sea near Bennett Island (76° 7'N, 149° 3'E) some 500 kilometres off East Siberia coast more than 150 times since 1974. The analysis of picture images has revealed that the temperature of water plumes was - 45℃ (228 K). They then presented a hypothesis that such a low temperature is due to the decomposition of gas hydrate. This hypothesis is repeated in Judge & Majorowitz (1992, p. 1992), Matsumoto *et al.* (1994, p. 228) and others. In response to the author's inquiry on this possibility, however, Ginsburg (1994) answers that no Russian scientists have confirmed such

[14] Below the bottom of Okinawa Trench, hydrates of carbon dioxide were discovered (Sakai, Gamo, Kim, Tsutsumi, Tanaka, Ishibashi, Wakita, Yamano, & Oomori, 1990). The formation and dissociation processes of such hydrates also seem to be important from the global change viewpoint.

a phenomenon of gas-hydrate-generated water plumes near Bennett Island. As this disagreement of opinions shows, qualitatively and quantitatively reliable data of the world-wide amount of methane released from land surfaces in the permafrost regions and from ocean surfaces are not available up to the current state of knowledge of science, except only a few studies such as Cranston (1994).

[b. Implication to the global climate change] — International Energy Agency (1991), however, gives estimates of the global, annual methane emission data. Animals, rice paddies, landfills, coal mining and others are sources of such emissions, and the global total is said to amount to 540 teragrams/yr with the range 440–640. Contribution of hydrate decomposition to this is tentatively given as 5 teragrams/yr with the range 0–100, *i.e.*, one per cent of the total or so. In this regard, the above mentioned study of Cranston (1994) is also important. In addition to these, if drilling to hydrate fails in one way or another, it will increase methane escape further. If global warming would become real, then it would work to melt permafrost to result in gas hydrate decomposition (a positive feedback). But it might also cause sea level rise to result in increase in pressure on ocean bottoms and this would function as a stability increasing factor (a negative feedback). MacDonald (1990) and many others have studied a possible relationship between gas hydrate and climatic change. But there are still so many uncertain factors in this question and further studies are awaited.

[c. Violent, natural process of pressurized gas venting] — In many regions of the world, submarine slumps and slides have been observed by geologists. McIver (1982) presented a hypothesis that some of such geological deformations had been due to the massive dissociation of gas hydrate succeeded by pressurized gas venting toward the sea floor. Such a hypothesis finds supports from Kvenvolden (1993) and others. McIver (1982) further noted that a large volume of gas bubbles released from the hydrate and ascending to the sea surface (and then to the atmosphere) might even sink a ship and/or hit down a low flying aircraft. Although such a possibility of accident was denied by Sweet (1983), a late Canadian chemist, D. W. Davidson was affirmative to it. Since then, the opinions which relate the unexplained ship/aircraft disappearances under the name of the Bermuda Triangle to the massive dissociation of submarine gas hydrate have been increasing (Sokolov, 1988; Miller, 1990; Canadian Chemical News, 1990). Destructive nature of gas blowout, whether it is related to the gas hydrate or not, should not be underestimated.

[d. Gas blowout due to drilling failure] — The subbottom structures of the continental slopes of the northern and western Gulf of Mexico are rich in gas-charged sediments. According to Bryant & Roemer (1983, pp. 176–7), a mechanical failure in drilling occurred in the Pennzoil's A-5 well in High Island Block A-563 on November 6, 1976. A massive blowout of natural gas then caused the whole part of platform of US$ 27 million worth sink into the crater created by the gushing streams of gas and seawater. Through seismic records, the size of the crater was measured as of almost 1500 ft in diameter and 320 ft deep. Some 155 million ft^3 of sediment was ejected from this crater. Hovland & Judd (1988) documented similar cases of drilling-triggered gas blowouts in the North Sea in the 1980s. Bryant & Roemer (1983, p. 177) also noted that gas blowouts could naturally occur at the sea floor to form a crater and briefly described an example of such a case in Ship Shoal Area Block 300 in the Gulf of Mexico. In addition to the crater fields of the formerly mentioned mud volcanoes; Buzdag and Elm in the Caspian Sea (Ginsburg & Soloviev, 1994), the seemingly natural formation of sea floor craters is also reported by Prior, Doyle & Kaluza, (1989) as to the Gulf of Mexico, and Solheim &

Elvehoi (1993) as to the Barents Sea. Fine cautions have to be taken in order for drilling not to stimulate such volcanic eruptions.
[e. Technology selection to prevent geohazards] — For commercial offshore development of oil/gas fields, the drilling with a riser and BOP became a commonplace in the 1980s (Mason, 1983). By a riser, mud fluids are recycled to control the outflow of oil or gas from the well. A BOP is placed below a riser and above the well so that it can prevent pressurized gas from unexpectedly blowing out from the well. DSDP and ODP had a policy of not drilling through a BSR to deeper parts in order to preserve the marine geology there. At the same time, it was considered that deep ocean environment with gas hydrate was not likely to be the place under which conventional oil and/or gas occurred so that a possibility of oil seepages or gas blowout would be minimal if any. Due to these considerations, the *JOIDES Resolution* was equipped neither with a riser nor BOP. Where it is judged to be safe to do so, however, deeper drilling through a BSR may come into gas hydrate research. In fact, the BSR-through drilling was made in ODP Leg 141 (Chili Triple Junction) in 1991 [Bangs, Sawyer & Golovchenko (1993)]. If such attempt would become a commonplace instead of remaining to be an experimental few, much more caution must be required. As to terrestrial, commercial drilling, an earthquake potential has already been alarmed. Kosub (1993) has mentioned such a case associated with water injection into gas wells in Rangeley, Colorado. Subaquatic gas hydrate often occurs in subduction zone with faults. If its exploration would reach a stage of development beyond research, then technologies similar to the previously mentioned EOR would be extensively deployed. Then, the development in such geologically active zones would require greatest cautions. Also note that experiences of gas kick and fire on a rig in MacKenzie Delta and gas burst to the earth surface in Siberia are known [Matsumoto *et al.* (1994, p. 165)].

VII. *Issues for the 21st Century*

Among many points to be investigated, let us focus our considerations on the following two points; [A] implications of natural gas, including gas hydrate, for environmental economic question, and [B] themes for broader scientific research.
[A. Implications of natural gas for environmental economic question] — Keeping a threat of global warming in mind, Matsumoto *et al.* (1994, p. 242) mentions the following three targets as of possible directions toward environmental betterment:

(1) Reduction of the absolute level of energy consumption
(2) Shift of energy sources toward natural gas, nuclear power and so on which emit less carbon dioxide than others,
(3) Fixation of combustion-generated carbon dioxide without letting it escape into the atmosphere.

Let us take these three targets as reference points for our discussion. Toward the goal (1), attempts of increasing energy efficiency are usually cited to meet it. CHP is one of such examples. But it is worthwhile to look back the above introduced Jevons' Law on Economy of Fuel. If this law works, then attempts of technological advancement in energy efficiency, though they are certainly important, may not be enough to hit the target (1). Not only technological but some institutional arrangements are necessary to meet it.

With regard to the above target (2), natural gas emits about one third less carbon dioxide (CO_2) and much less sulfur oxides (SO_x) than coal and oil for each unit of heat generation. When it is applied to internal combustion engine of one type or another, its emission of nitrogen oxides (NO_x) is not much different from the case of gasoline and others. Hence, the world still is at a stage of waiting for NO_x-prevention technology. Nuclear power options have often been mentioned in many countries including Japan as of reducing CO_2-emission. However, it must be noted that multiple processes of nuclear fuel fabrication from uranium ore, building and maintenance of power station, long-term management of radioactive waste, and so on require a certain amount of inputs of oil and/or coal as it was demonstrated by Chapman (1975). Its amount of CO_2-emission may be less than the case of oil- or coal-fired power generation, but it certainly is not zero, to say the least [Murota (1992, p. 260)].

As to the target (3), it is perfectly possible to transform a small amount of CO_2 into other carbon compounds of not having a greenhouse effect at a chemical laboratory basis. Making CO_2 clathrate hydrate is one of the examples under investigation in Japan. Aya (1993) and Okuda & Matsumoto(1994) review the current state of technology of deep sea storage of CO_2 in such a form. When one faces CO_2 in bulk and attempts to change it to clathrate or some other forms by means of an industrial process, however, requirements of energy and equipments to do so will be enormously large. Afforestation in extensive scales may be more realistic than this.

[B. Themes for broader scientific research] — One of the themes of importance is the conservation and documentation of mud volcanoes and seabed pockmarks. As the knowledge of deep sea has recently increased, hitherto unknown world-wide occurrences of small-crater-like pockmarks (Hovland & Judd, 1988; Ginsburg *et al.*, 1992; Kelley, Dickson & Belknap, 1994; Vogt, Crane, Sundvor, Max & Pfirman, 1994) have become known to scientists, in addition to the knowledge of mud volcanoes. Not only all of these are precious for geological studies on the evolution of our water planet, but some may even be important for the biogeochemical studies on the origin of life, complete theory of which we do not have yet. Since there are cases where gas hydrate ayers situate in the vicinities of such occurrences, cares have to be taken for gas hydrate exploration not to disturb them.

Another theme of importance is the investigation of the origins of natural gas. The majority of scientific opinions supports the biotic origin of natural gas. The biotic gas is usually classified into the two major types; biogenic and thermogenic ones. The former is the result of anaerobic decomposition of organic matter, and the latter is considered to come from kerogen or n-alkene which has a biotic origin by itself. Against this, Mango, Hightower & James (1994) have proposed a catalytic formation of what is usually thought of thermogenic gas and emphasized the role of transition metals as agents of such catalysis. Then, thermogenic versus catalytic controversy of the origin of natural gas has to be studied further. Moreover, it is still too early to totally forget an abiotic hypothesis on its origin presented by Gold (1987). The research of gas hydrate can also be considered to be a research as of where such gas comes from. Soloviev & Ginsburg (1994) suggest that further studies of mud volcano may be helpful to find deep sources of gas supply as well as the pathways through which such gas migrates up to gas hydrate stability zones. Our present knowledge on the atmospheres and insides of Titan and other satellites of Saturn is still very limited despite of recent progress of astronomical research, and remains to be largely speculative after all. But so is our knowledge of natural gas and its hydrates on the Earth yet to be deepened.

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