R &D OF ENERGIES TECHNOLOGIES

ANNEX A I-Fossil Energy

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AI-1 POWER GENERATION WITH CO₂ CAPTURE AND STORAGE

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AI-1.1 The Effect of Climate Gas Emissions

The last 100 years has seen a significant warming of the earth's surface, as shown in the graph in Figure 1. This warming basically started around 1900, and the first 40 years of the twentieth century saw an increase in the average temperature of about 0.3-0.4°C. During the next 40 years, the temperature stabilized, but during the last 20 years there has been another rapid increase of about 0.3°C. This increase and the consequences that according to meteorological research follows from this, in the form of more extreme weather conditions, more frequent droughts, floods and extreme temperatures have serious implications on human life. Perhaps the most devastating effect of all is the meltdown of the ice cap on Greenland and Antarctica, leading to a sea level increase that can flood island states and low delta areas. All this has led to a growing concern about how to control and hopefully reduce this temperature increase.



Figure 1- Variation of the Earth surface temperature for the past 140 years

In 1988 the Intergovernmental Panel on Climate Change (IPCC) was established and is presently recognised as one of the most authoritative bodies in the world with regard to climate change. A large research effort has been undertaken, and models for the future trends in surface temperature have been established. Although uncertain, they give an impression about the future.



Figure 2- Variation in Earth surface temperature for the past 240 years with model projections up to year 2100 (IPCC, Climate change 2001, The Scientific Basis)

Figure 2 shows these scenarios predicted by a large number of models, using a variety of assumptions with regard to reduction in the increase of climate gas emissions. However, they all agree on one thing; there will be a dramatic increase in the earth's surface temperature if the emissions of climate gases, or at least the increase in emissions, are not reduced significantly. The most important climate gases are given in the figure below, and also the relative importance of them.



Figure 3- Climate gases and their relative importance

As can be seen, CO₂ is the most important climate gas because of the enormous size of the emissions. The total natural cycle of carbon on earth is about 100 Gigatons of carbon/year. Anthropogenic sources of carbon add about 6-7 GtC/year to this, and deforestation another 2 GtC/year. This may seem a small part of the natural cycle, but it has a great impact on the climate change. This is demonstrated in the graph below, where researchers have tried to separate the variation in temperature due to natural sources from that caused by anthropogenic carbon.



Figure 4- Warming attributed to human activity (Harald Dovland 2004)

AI-1.2 The Magnitude of the Problem

Transformation of 1 t of Carbon generates about 3,67 t of CO₂, so that the present level of total CO₂ emissions created by man made activity is around 24 Gt per year. The annual emissions from major industries, as an average for the years 1994-96, are given in the table below, showing a total of 17,5 Gt of CO₂ per year.

Table 1 CO ₂ emissions by major industries		CO ₂ emissions Million tonnes/year
Sources: IEA GHG	Iron and steel production	1440
(individual industries), OECD Environmental	Cement manufacture	1130
Data 1997 (overall),	Oil refining	690
EA World Energy Dutlook 1998 (power	Petrochemicals	520
generation).	Other industry	1320
	Overall industry	5100
	Power generation	7660

Table 1- Total CO ₂ emissions by major industrial sources ("Pu	utting Carbon	Back into	The
Ground", IEAGHG Report Feb. 2001	01)		

To put this number in perspective, one typical existing CO_2 capture plants in the USA remove about 50-60.000 tons CO_2 /year, and the Sleipner CO_2 capture plant removes about 1 million tons CO_2 /year. So we have just started to scratch the tip of the iceberg.

The challenges facing us are formidable. Simulations indicate that the total emissions we can allow in the next century are below the level of what the present annual emissions would produce. So we have to do something even if we could freeze the level of energy use today. There is already an overwhelming need to install CO₂ capture plants in existing power industry.

In addition we have to take into consideration that we need more energy desperately, to feed a growing population, and improve standard of living for all. Security of supply is a number one priority. To have access at a reasonable price to the energy you need to live a good life (food, housing, clothing, transportation, health++) is a "quality" that will receive higher attention. At present about 2 billion people lack access to sufficient amounts of energy in a form that does not pollute the nearby environment. There is therefore a drive for increasing large-scale energy production in these regions of the world. According to New Scientist (2003), China is putting a new coal fired power station on stream every two-three weeks.

The predictions from the World Energy Technology Outlook 2030 state that the world electricity demand will rise by 3% per year, much relying on coal and gas. The use of oil will increase by 65% from 2003 to 2030 and the use of gas and coal will double in the same period. This leads to the forecast that the emissions of CO₂ will grow even more rapidly than the world energy demand (2.1% p.a.). In 2030, the world will still rely by 90% on fossil fuels. And since we cannot increase the level of CO₂ emissions, this energy must come from renewable energy, nuclear energy or fossil energy with CO₂ management.

The question of availability and price will here be important. The renewable energy sources will have a formidable increase in development, but the price has to be reduced by R&D. This makes CO₂ management a most strategic technology, because it will make it possible to utilize low cost fossil fuels, until the price of the renewable has come down to the level where they may utilized fully.

The bottom line is that however we look at the situation and almost however optimistic one may be regarding the development and introduction of renewable energy, one must learn to live with fossil fuel. This implies that in order to avoid an uncontrolled climate change, the world will have to learn how to handle, i.e. capture and store, CO₂.

AI-1.3 International Agreements

The United Nations Framework Convention on Climate Change was established in Rio de Janeiro in 1992 and led to the development of the Kyoto Protocol in December 1997, which Norway signed in 1998. The Kyoto Protocol covers the gases CO_2 , CH_4 , N_2O , PFK, SF₆ and HFK, all calculated into CO_2 equivalents. The basis year 1990 was chosen, and the aim for each country is individual and pertains for the year 2012. This protocol needs to be ratified before it can enter into force, and this will happen 90 days after:

-a minimum of 55 partners of the convention have ratified the protocol and

-those ratifying the protocol represents a minimum of 55% of the CO₂ emissions of the Annex 1-countries in 1990.

At the start of this year (2004), 119 partners had ratified the protocol, representing 44.2% of the CO₂ emissions. A lot hinges now on whether Russia will ratify or not.

International agreements seem a necessary prerequisite to the global management of CO₂ emissions since such management involves considerable costs in terms of developing and implementing new technologies as well as reorganising energy production. No single country can on its own carry such costs, unless mechanisms are found that implies that the economic conditions of international trade are maintained. Such mechanisms might be taxes, e.g., on CO₂ emissions. However, one has also proposed some new solutions like tradable CO₂ quotas and green certificates. Tradable CO₂ quotas means that investments in CO₂ management may at least be funded by selling the amount of captured CO₂ to actors that in principle need to reduce their CO₂ emissions, but for some reason are unable to realise CO₂ capture. Green certificates represent a mechanism that allows for subsidies in new sustainable energy technologies. Presently, CO₂ capture is not supported by green certificates.

There is considerable disagreement regarding the efficiency of such instruments, in terms of their economic effects as well as whether they would work in practice. A critical issue is compliance with the international agreements and how such compliance may be measured and verified.

Presently, the prospects of getting an international agreement in place that would safeguard an efficient regime of CO₂ management look bleak. In spite of widespread scientific agreement about the greenhouse effect and considerable man-made impact on the ongoing global warming, policymakers in many countries still deny that this is an important problem that needs to be addressed by international agreements.

AI-1.4 Global CO₂ Mitigation Options: A Technological Review

AI-1.4.1 Introduction

Several choices are available to combat global warming, options being more efficient use of energy, trying to manage atmospheric up take of energy, use of carbon-less fuels or carbon neutral fuels, renewable energy sources (hydro, wind, wave, solar, tidal..), capture and storage CO₂ and last but not least to adapt to a warmer climate. Figure 2 depicts the various options (Bolland, 2003). To adapt is an option we should not pursue due to the severe consequences we will be facing- endangering biodiversity, changing patterns of wind and water and increasing the sea level, just to mention some of the malign effects. The magnitude and scope of challenges we face means that we have to look at a broad, complicated research agenda.



Figure 6- Options for reducing global warming (Bolland, 2003)

In this foresight context, we will particularly discuss the options available in the so-called carbon sequestration route or CO_2 management. By capturing CO_2 from large point sources, transporting it by suitable means and then safe storage underground or –sea we would take out CO_2 from the cycle and reduce the man made CO_2 emissions to the atmosphere. From a carbon exchange point of view, we would be taking the carbon found underground, use the energy content by oxidizing it and then put the carbon back into the ground.

However, the methods that will be discussed have limitations, they add cost to the conversion of energy, it is not feasible to collect all the carbon from our operations and the storage needs to be safe for thousands of years in terms of leaks and sudden changes in the geology and they are less energy efficient. Figure 3 shows different scenarios for storage underground with various leak rates in a business as usual case. Clearly we would demand very long residence times for CO₂ underground to have a real effect on global warming. Residence times exceeding 7000 years would be needed. The ability to



Figure 7- Needed residence time for CO2 storage (Lindeberg, 2003)

guarantee anything in such timescales are speculative, however putting carbon back into the ground offers a technical solution that is feasible.

AI-1.4.2 Technology options- CO₂ capture

Capture of CO₂ usually contributes for 70-80 % of the total costs in CO₂ management. Capture of CO₂ is usually divided into the groups of pre-combustion, post combustion and oxy-fuel. The classification is independent of the fuel used and reflects how CO₂ is taken out of the process. The three capture routes are shown in Figure 8.



*Figure 8- CO*² *capture routes. Red* (1) = *Post combustion, Blue* (2)= *Pre combustion, Green* (3) =*Oxy-fuel* (Bolland 2003)

In **Post-combustion**, the CO_2 is removed from the exhaust gas after the power plant. The advantage is that this technology may be used on existing power plants, and that the process may be used as it is. The disadvantage is the CO_2 must be removed from an atmospheric flow, with high volume and low CO_2 concentration, so that the separation units are expensive.

In **Pre-combustion**, the CO₂ is removed from the fuel before it enters the gas turbine. The disadvantage is that new equipment is needed in the power plant (reforming and water shift). The advantage is that CO₂ is removed from a lower volume flow with higher pressure, reducing the size and costs of the separation equipment

In **Oxy-fuel**, we use pure oxygen as reacting gas, so that only CO_2 and H_2O is formed by the combustion. We get clean CO_2 just by condensing the water. The disadvantage is that we need an oxygen plant

AI-1.4.3 Transport of CO₂

After the CO_2 has been captured, it will need to be conditioned for further transport. In case of pipeline transport, the gas is compressed to a level suitable for the transport distance, and dried to avoid dry-icing, clogging and corrosion. Typically, pressures of 100-200 bars are needed. Another option is to condense the CO_2 to liquid form and transport it by trailer or ship.

Large scale CO₂ management requires an infrastructure that is yet not available in Europe. As mentioned earlier, the EU15 countries have a collectable CO₂ potential of about 1Gt/year, thus 1000 millions of tons of CO₂ will need to be handled. Such systems are not available for the time being, and it is indeed a logistic challenge to plan, build and operate them.

Also the industrial opportunities involved in building such a system should be an attractive opportunity for Norwegian industry. Through Gassco we are today operating the most complicated gas pipeline system in the world, and Norwegian shipping manages abt. 80 % of the international liquid gas transportation market.

AI-1.4.4 Storage/use of CO₂

Studies of the storage potential for the North Sea have indicated safe storage capacity of 600 Gt of CO₂. Most of the storage potential is within aquifers, salt or fresh water layers found deep underground. Other options are abandoned gas and oil fields or the use of CO₂ for enhanced gas or oil recovery (EGR and EOR). EOR with CO₂ is the most commercially interesting option and has been utilized with great success in the US. Studies have shown that the potential for EOR in the North Sea is substantial and if such schemes are introduced, the market for CO₂ will be considerable. A CO₂ supply of 5-10 million tonnes of CO₂ would be needed per year. Clearly this shows that the CO₂ sources will have to be found outside Norway be or not be a go-ahead for gas fired power plants in Norway.

It should be noted that Statoil undertakes CO₂ capture and storage at the Sleipner field in the North Sea. CO₂ is removed from the produced natural gas and injected in the Utsira saline aquifer. A similar scheme will materialise in the Melkøya Snøhvit plant, where CO₂ is removed from the produced gas onshore, and returned by pipeline to be injected in a saline aquifer close to the Snøhvit gas field.

AI-1.4.5 Paving the way for CO₂ management

In addition to the many scientific and technological challenges emerging from engagement with CO₂ management, there are a lot of economic, social and political issues that has to be dealt with. For example, in order to facilitate effective international agreements, a lot of work is needed to find cost-efficient instruments that provide sufficient incentives for countries and companies to engage in CO₂ management. The obvious problems are legal and economic, but we know CO₂ management is hampered seriously by laissez-faire attitudes. Of considerable importance in this respect is the way the environmental movement may be able to influence politicians, business and the public opinion.

On a more concrete level, implementation of CO₂ management raises many important strategic issues. Some of these emerge from the ongoing discussions in Norway about the construction of gas-fuelled power stations. For example, what would be the consequences of starting with modest ambitions, like 5 % capture of CO₂, compared to aiming for much higher levels of CO₂ capture? There is also need to develop transition strategies to secure CO₂ management, on company level as well as for countries.

AI-1.5 R&D Needs

There is a need to reduce the costs within the CO_2 chain regardless of any income CO_2 may achieve as an asset for enhanced hydrocarbon recovery or tax/quota systems that will come soon into operation. The cost distribution of capture versus transport and storage points towards focusing on reducing capture cost as most imminent. For the near term technologies like post combustion and pre combustion refinement is needed. Improved system integration, smarter processes and reducing capital investment are key items together with improved solvents. It is believed that by commercialising these technologies on broad basis will yield substantial cost reductions in terms of less expensive materials, designs and building codes- safety codes. For mid term technologies, eg. oxy-fuel CC more research is needed in the operational aspects, the design of new turbomachinery and safety is instrumental. Combustion technology advances are needed for both H₂ based systems and oxy-fuel systems, it is not acceptable to trade-off CO_2 emissions with NO_x emissions for instance and high-pressure operation for oxy-fuel is also a relatively new field.

Membrane research is a field with great promises, both for oxygen production, CO_2 separation, H_2 separation and high temperature applications. There is clearly a need for more R&D in this field with high potential improvements, in both cycle efficiency and cost. The same applies to fuel cell systems.

To improve the knowledge base for the development of international agreements, policy instruments to support CO_2 management and transition strategies, substantial research efforts have to be undertaken within the humanities and the social sciences, including legal studies and economics.

AI-1.6 What May Happen – 2020-2040?

In general, global economic growth is likely to continue. In particular, Asian countries, like China and India, will be developing rapidly in terms of production as well as consumption. This will mean that the emission of CO₂ will increase substantially, and the contribution to the increase from power generation is about 40%.

Based on the predictions from "World Energy Technology Outlook 2030" the demand for electricity will increase by 3 % p.a. and this increase will be covered by natural gas. This causes the use of natural gas and coal to double from now to 2030. Natural gas, because it is a convenient energy source, making it possible to utilize advanced gas technology equipment with high efficiency. Coal is, however, also present in great quantities, because technological development, has made gasification of coal economic, so that this abundant resource may be used in the same high efficient gas technology equipment. So the coal industry is still very busy.

In Norway, the oil production has dropped somewhat since the turn of the century, but thanks to increased efforts in research on increased resource utilization in the PetroMax program, we were able to follow a higher production curve. The high oil price makes it still economically interesting to produce oil from small offshore fields.

Natural gas is produced in large quantities from offshore fields in the Norwegian Sea and the Barents Sea. The cooperation with Russia in this area has proved to be successful. Despite strong environmental concern and a long public debate, the gas exploration in the Norwegian Sea and the Barents Sea has emerged. Large resources have been found, and are now being produced as LNG and traded on the world market. All the five large-scale LNG plants do have facilities for capture and storage of CO₂ from the natural gas, and three have installed CO₂ capture from the in-plant heat and power generation systems.

With respect to climate changes and our responses to them, there are many possible outcomes. The following four outlines show how CO₂ management may have quite different actuality and success:

1) Climate research shows stronger and stronger evidence that man-made emission of greenhouse gases results in unwanted climatic changes. A UN resolution on greenhouse gas emission reduction is passed with a narrow majority. Trade barriers are used to penalise countries not complying with the resolution. Rich and developed countries make significant efforts in technology development and implementation of CO₂ capture and storage, as well as other greenhouse gas reduction measures. CO₂ capture in power generation systems takes place both in coal and natural gas fired plants.

2) Climate research shows stronger and stronger evidence that man-made emission of greenhouse gases results in unwanted climatic changes. However, it turns out to be impossible to implement any international agreement on greenhouse gas reduction. Among the rich and developed countries the attitude is to adapt to the climatic changes rather than trying to reduce man-made emissions of greenhouse gases. CO₂ capture and storage is applied in a limited number of plants, but not on a commercial basis

3) Climate research shows stronger and stronger evidence that man-made emission of greenhouse gases results in unwanted climatic changes. However, it turns out to be impossible to implement any international agreement on greenhouse gas reduction. Increasingly, nuclear power is used, and public acceptance has grown considerably. Breeder reactor technology has made a breakthrough, and also in the area of nuclear fusion some significant progress has finally happened. It is believed that fusion technology may be used for large-scale power generation before 2050. The interest for CO₂ capture and storage technology is high in many countries, but not in those who do not have access to CO₂ storage facilities. There is a heated dispute about nuclear power, and the countries are split into two groups on this issue.

4) Climate research shows that observed climatic changes can be explained by mechanisms other than changes in the atmospheric concentration of CO₂ and other greenhouse gases. The interest for CO₂ capture and storage is reduced to a minimum.

If one decides to venture into a concerted research effort related to CO₂ management, one has to be aware of the risks involved in such an effort – not just the risk of not succeeding in the scientific work but also the chances that the context of CO₂ management may change to make such effort unnecessary.

Both in Europe, North America, Japan and Australia there has been and still is a growing interest for CO₂ capture and storage. Only during the last five years the attitude towards CO₂ capture and storage has changed from being a curiosity to a technology that can be taken into large-scale use. There are various reasons for this:

-Climate research in the last two decades has shown increasing evidence that man-made emission of greenhouse gases may result in unwanted climatic changes.

-CO₂ capture and storage is gaining support, both in industry and among politicians, as a potential realistic measure, both economically and technologically, in order to follow Kyoto commitments.

-New nuclear power has currently very low support, and is not looked upon as the technology for supplying energy to society with very low or zero emission of CO₂.

-Most people accept that renewable energy (wind, hydro power, biomass, solar) cannot be used as a substitute for fossil fuels, but rather as a supplement.

Based on this, it is likely that CO₂ capture and storage will play a role in society and for the industry. The time perspective of this is uncertain. A horizon of 10-20 years should be used. Scenario 1) and 2) should be regarded as most likely.

AI-2 FUTURE NEEDS FOR FUNDAMENTAL RESEARCH IN THE OIL AND GAS INDUSTRY

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The infusion of new technology and knowledge provide tremendeous benefits to the oil and gas industry. The recognition of dwindling hydrocarbon resources and that the exploitation of the remaining resources are of a more demanding character accentuate the need for new technological solutions. Heavy oils, tar sands and oil shales constitute more than 50% of the initial oil reserves on the earth, and strong efforts are made to exploit these resources. Similarly, efforts are made to economically produce diesel based on natural gas and coal and also to be able to produce gas hydrates found subsurface and even on the sea floor in some geographical positions. The economic enablers to exploit these types of energy resources are heavily dependant on new technological solutions. It is also recognised that most of the challenges in the oil industry are of a multidisciplinary kind.

The most important exploration tool used today is seismic, and seismic methods have also become more and more important for monitoring the reservoir behaviour during production. Besides the acoustic methods, the introduction of electromagnetic surveys for the direct detection of subsurface hydrocarbon accumulations has shown very promising results. In spite of the progress made, there is still a challenge to come up with geophysical methods that have sufficiently high resolution to image remaining oil reserves in the reservoirs; e.g. electromagnetic or acoustic tomography between (instrumented) wells.

The use of bacteria to enhance the recovery of oil from the reservoirs is in its infancy, in that the fundamental understanding of the mechanisms involved is meagre. It is also foreseen that microbiological processes will have a more widespread application within the oil industry in the future, e.g. in processes to improve the quality of oil for transportation and refining.

Fundamental research is a necessary prerequisite to a successful progress within such applications of microbiology.

A trend within materials technology is to develop materials that possess an integrated set of mechanical and functional properties to specific applications. The set of properties may be obtained by e.g. producing composite solutions with existing or new materials. The challenge is to characterise the performance of the new materials in complex systems to ensure their required robustness. Applications of new materials in the oil industry is comprising the entire value chain; from materials in drilling and well constructions, to production equipment, pipelines and refinery facilities. The development of these kinds of new materials requires fundamental research in multidisciplinary environments; comprising physics, chemistry and materials technology as a whole.

AI-3 OCEANIC HYDRATES, A DYNAMIC RESERVOIR OF METHANE WITHIN THE MARINE ENVIRONMENT

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AI-3.1 Introduction

Gas hydrates are non-stoichiometric compounds (Sloan 1998). Water molecules form cage-like structures in which gas molecules are enclosed as guest molecules. Therefore, they are also called cage compounds or clathrates (latin clatratus for cage). Generally speaking, a gas hydrate can contain different types of gas molecules in separate cages, depending on the mixture of gas molecules in the direct environment. In addition to CH₄ in naturally occurring gas hydrates these gases will mostly be H₂S, CO₂ and, less frequently, other hydrocarbons.

To date gas hydrates of three different crystal structures occur (Sloan 1998); structures SI and SII both crystallize into a cubic system, whereas the third structure (also denominated H) crystallizes into a hexagonal system, like ice (Fig. 1). The structure of a gas hydrate can be seen as a packing of polyhedral cages. All three structures occur naturally. Structure I is most frequent. Its unit cell consists of 8 cages of two different types. Structure I cages can enclose gas molecules that are smaller in diameter than propane molecules, such as CH₄, CO₂ or H₂S. Therefore, the natural occurrence of this crystal structure mainly depends on the presence of biogenic gas, as commonly found in sediments of the ocean floor. A unit cell of structure II consists of 24 cages, i.e. 16 small cages and 8 large ones (Fig.1). The latter are larger than those of structure I. Hence, structure II contains natural mixtures of gases with molecules bigger than ethane and smaller than pentane.



Figure 1- Gas hydrate of type I structure. Small spheres are water molecules forming cages; large spheres are gas molecules (left). Cage types and the number of cage individuals forming the three common hydrate crystal structures (right).

It is usually confined to areas where a thermogenic formation of gas takes place in the sediment. H is a more complicated structure. Apart from smaller cages, it contains a cage type which requires very large gas molecules such as methyl cyclohexane.

Recognition that natural gas could form gas hydrate deposits by Russian scientists (Vasil'ev et al. 1970) led to the idea that natural gas hydrate should occur globally wherever the pressure and temperature conditions were favourable. These ideas were followed by gas hydrate discovery, first in permafrost regions of Russia (Makogon et al. 1971). Hydrate was then observed in sediment of the Black Sea (Yefremova and Zhizhchenko, 1974) and inferred by seismic surveys to occur in sediments of the Blake Ridge, of the western Atlantic Ocean (Stoll et al. 1971). By the early 1980s, hydrate 'had been found in sediments of Middle America Trench offshore Mexico (Shiply and Didyk, 1982). Since then, hydrate had been recovered from many places in the ocean (Kevenvolden et al. 1988) as well as in near-surface environments (Suess et al. 1999).

Recent hydrate assessment, concluded that methane hydrates might represent the most important gas resource for the next century since resources are twice the conventional fossil energy (recoverable and non-recoverable fossil fuels; Kevenvolden 1993). Hydrate-related gas resources were estimated at 10^{13} and 20×10^{15} m³ (at standard conditions) in onshore and deep offshore, respectively (Kvenvolden 1993). Recent estimates from Milkov (2004) confirm these estimates in principle. This fact explains a serious interest in gas hydrates as a potential future energy resource. However, other important issues raised in connection with gas hydrate: 1) How are the interaction of methane hydrate and climate 2) How is the role of methane hydrate in the carbon cycle and 3) how important are gas hydrate as a factor in the stability of sediments on continental slopes?

AI-3.2 Global occurrence of natural gas hydrates

Naturally occurring gas hydrates can be based on various gases, e.g. in the Greenland ice sheet, there is nitrogen hydrate. CO_2 hydrate has been shown to exist on other planets. A frequent type of gas hydrate is methane hydrate. The conditions required for its stability can be present in marine sediments as well as in permafrost soil of the polar areas. Physical conditions (temperature and pressure) required for the stability of methane hydrate in a marine environment are shown in Fig. 2. Assuming a constant temperature of 0°C, e.g. in polar areas, methane hydrate cannot be stable at a water depth of 100 m. It may occur in a seafloor which is more than 400 m below sea level. The thickness of the hydrate zone will depend on the temperature gradient. However, with an increasing depth below the seafloor, temperatures get too high for a formation of gas hydrate, so that one can find free gas and water. Given an average temperature increase by 3°C per 100 m sediment depth, when drilling at a water depth of 300 m, we can expect to find a 300-m-thick hydrate layer. At 1000 m water depth, the layer will be 600 m thick (Fig. 3). If, however, sediments are characterized by a stronger increase in temperature, which can be the case e.g. at active continental margins (4-6°C per 100 m depth), the hydrate zone will generally be thinner. Gas hydrate has been found in sediments up to 1100 m below the seafloor (Kvenvolden et al. 1998).



Figure 2- Stability and phase boundaries of methane hydrate on depth-temperature distribution in sea water and the upper sediments. Also shown are the phase boundary of pure methane hydrate at normal seawater salinity (1) and the phase boundary of methane hydrate with 3 mol-% H₂S at seawater salinity (2). Intersections of temperature profiles with the phase boundaries define the hydrate stability zone, and depths of the bottom-simulating reflector (BSR) for each of the hydrate compositions.



Figure 3 - Typical examples of geothermal regimes in a marine well (left) and a permafrost well showing the methane hydrate stability conditions and the potential presence of hydrate for various ground-thermal scenarios (after Dallimore et al. 1999).

Apart from adequate temperature and pressure conditions, gas hydrate formation depends on how much gas, primarily CH₄, is available. Most of the methane found in the oceans is produced by fermentative decomposition of organic components or by bacterial reduction of CO₂ in sediments (Claypool and Kaplan 1974). Sometimes it may also be a product of thermo-catalytic alteration processes in deeper sediments. CH₄ production is highest at the continental margins (Whiticar 1999). Along continental margins high

plankton productivity and high sedimentation rates yield large amounts of organic matter, which becomes the basis for a production of gas in the sediment. Therefore, gas hydrate is found at almost all passive and active margins (Henry et al. 2002, Macdonald et al. 2004, Charlou et al. 2004). However, there are also deposits in the Caspian Sea, the Black Sea (Ginsburg and Soliviev 1998; Bohrmann et al. 2003), the Mediterranean (Woodside et al. 1998) and Lake Baikal (DeBatist et al. 2002).

In permafrost areas, the temperature gradients are considerably lower. As shown in figure 3, the temperature can be expected to change by 1.3°C per 100 m within the permafrost zone, compared to 2°C per 100 m in layers below the permafrost zone. The ambient temperature and the thickness of the frozen layer are of paramount importance for the stability of gas hydrate. If the permafrost base is located at a depth of 100 m or less (case 1), the physical conditions will not be adequate for a formation of gas hydrate. The situation is different in case 2, where the permafrost basis is located at greater depth. In polar areas, methane hydrate can occur at depths ranging from 150 to 2000 m (Fig. 3).

Keith Kvenvolden and Thomas Lorenson (U.S. Geological Survey) have compiled all the <u>gas hydrate deposits</u> known so far (Kvenvolden and Lorenzen 2001). Samples of gas hydrate have been taken at approximately 20 different sites. Further occurrences have been identified by geochemical analyses, e.g. of chloride anomalies in pore waters. There are at least 80 sites where the existence of gas hydrate has been confirmed by bottom-simulating reflectors (BSRs). BSRs are seismic reflectors with a negative reflection coefficient. They occur at the interface between sediment containing methane hydrate and sediment containing free methane. BSR structures are roughly parallel to the seafloor morphology along isotherms. They do not follow the trend of stratigraphic horizons, but may intersect them. The reflector occurs in depths of several hundred meters below the seafloor, indicating the lower boundary of gas hydrate stability. Consequently, gas hydrate exists above the BSR, whereas below the BSR there is free gas.



Figure 4 - Seismic record from Blake Ridge (Kvenvolden, 1998), showing the presence of methane hydrate within sediments (right). Variations of the weak reflections above the BSR correspond to a varying content of gas hydrate in the pores. Below the BSR there are strong reflections caused by free gas in the pores. A seismic velocity model (left) shows the strong contrast of velocity in the BSR zone.

The <u>Ocean Drilling Program</u> has sampled various BSR horizons on the continental slopes off Peru, Chile, Costa Rica, Oregon/Washington and at Blake Ridge off North Carolina.

Although some details of the signatures are not yet fully understood, it appears to be clear that the strength and the characteristics of BSRs are determined by free gas below the gas hydrate zone. Seismic velocity is an important feature in this respect; it is higher in sediment cemented by gas hydrate than in un-cemented sediment. The existence of free gas below the BSR causes a further drastic decrease of seismic velocity, sometimes to levels lower than the seismic velocity of sea water (1500 m/sec). If there is no free gas below a deposit of gas hydrate, there will not be a BSR and thus it will be impossible to detect the deposit by means of conventional seismic. The fact that geophysical methods sometimes fail to detect gas hydrate may indicate that the total volume of gas hydrate worldwide is still underestimated.

Seafloor samples confirm the existence of gas hydrates in sediments, as indicated by BSRs. Most of the samples were obtained by the drilling ships of the international programmes DSDP and ODP, or they were retrieved by research vessels from shallow sediment. Once exposed to the temperature and pressure conditions on board, gas hydrate is not stable. It dissociates, and for this reason it is very likely that it often was not even noticed in the past. The only way to study gas hydrate samples in the laboratory is to either use pressurized sampling devices or to ensure extremely quick sampling and processing on board, preserving the gas hydrate in liquid nitrogen so that it can later be processed in a laboratory.

AI-3.3 Hydrate Ridge/Cascadia Margin

A particularly large quantity of gas hydrate was sampled by means of a TV-guided grab from a water depth of 780 m at the southern peak of the submarine Hydrate Ridge off Oregon (Suess et al. 1999, 2002). Hydrate Ridge is an elongated accretionary ridge, extending about 30 km from north to south and 15 km wide. It was formed by subduction of the oceanic Juan de Fuca plate beneath the North American continent. At its southern peak, gas hydrate occurs directly at the seafloor. A specific faunal community has settled here, supporting, for example, calyptogenic bivalves which perform chemosynthesis with microorganisms and thus use the methane of the hydrate as an indirect source of energy and food (Sahling et al. 2002). Samples from Hydrate Ridge as well as from other sites in the Gulf of Mexico, the Sea of Okhotsk or the Black Sea, show a very heterogenous, interlocking structure of mostly white gas hydrate and sediments. Generally, gas hydrate occurs in various forms, ranging from finely dispersed lumps to massive, pure layers which are several cm thick. Other structures may consist of layers that wedge out, interlayers with thicknesses only in the mm or cm range or irregularly branching gas hydrate that completely dissolves the original sedimentary structure and leads to a formation of clastic sediments (Bohrmann et al. 1998; Suess et al. 2002). Microscopic analyses of thin sections of pure gas hydrate show a sponge-like structure with strongly varying pore sizes (Kuhs et al. 2004). The pore structure is due to the upward movement of gas bubbles in the sediment. It is presumed that during this process a thin film of gas hydrate forms at the interface of the bubble with the pore water. Gas bubbles migrating upward from the seafloor have been observed by submersibles and robots and have also been recorded in the water column by means of echo sounder systems (Heeschen et al. 2003).

Annex A - Section 1.3



Figure 5- Distribution of hydrates beneath southern Hydrate Ridge, and average hydrate concentrations of the pore space developed from various drilling data during ODP Leg 204 (from Tréhu et al. 2004). The map (lower left) shows the average hydrate contents for the entire hydrate stability zone. Other images of seismic profiles contain average hydrate concentrations for specific horizons or environments.

Accurate quantitative estimates of how much hydrate is present in the sediments are rare and difficult to obtain because much of the gas hydrate has dissociated by the time samples have been retrieved. ODP Leg 204 was only the second ODP leg dedicated to quantifying the abundance of gas hydrates and understanding the dynamics of their formation in marine sediments (the first was Leg 164 to the Blake Ridge offshore North Carolina; Paull et al. 1996) and provided an opportunity to test several new techniques for sampling, preserving and quantifying gas hydrates (Tréhu, Bohrmann, Rack et al., 2003). Nine sites were drilled and cored on or near southern Hydrate Ridge, a topographic high in the accretionary complex of the Cascadia subduction zone, located approximately 80 km west of Newport, OR. All sites fell within a previously-acquired, high-resolution 3D seismic survey, which imaged the "plumbing" of this gas hydrate system and served as a road map to guide site selection. By integrating results from several techniques with different spatial scales and sensitivity to in situ gas hydrate content, the authors were able to obtain the first well-constrained quantitative estimates of how gas hydrate and free gas are distributed throughout this system (Tréhu et al. 2004). Gas hydrate distribution is very heterogeneous. Massive gas hydrate, comprising ~25% of the total volume, is restricted to the upper 20-30 meters beneath the seafloor at the summit, where bubbling methane vents and authigenic carbonates had previously been observed. Coexistence of gas hydrate, free gas and highly saline pore waters in this

region requires that gas hydrate formation here be rapid; seismic and geochemical data indicate that an anomalously permeable stratigraphic horizon channels gas-rich fluids from deeper within the accretionary complexing to form this focused deposit (Torres et al. in press). Elsewhere, gas hydrate occurs primarily in patchy clusters of veins and lenses up to a few cm thick. The regional average gas hydrate content of the sediments (~2%) is lower than previously thought (Tréhu et al. 2004). These multiple scales of observed heterogeneity in gas hydrate and free gas distribution provide constraints for a new generation of models for how gas hydrates form in marine sediments and their impact on slope stability global climate change.

AI-3.4 Stability of submarine slopes

When enclosed in sedimentary pore space, gas hydrate acts like cement, compacting and stabilizing the seafloor. However, if formed in deposits that are still unconsolidated, gas hydrate prevents the normal increase of compaction with increasing lithostatic pressure. If exposed to variations of pressure and/or temperature, interstitial gas hydrate decomposes. In this case, the compactness of the seafloor decreases, which may cause submarine land slides (Paull et al. 2002). Seismic, bathymetric and side-scan sonar mapping of the seafloor has shown that slides of different order of magnitude characterize all continental slopes.



Figure 6 - Thickness of the zone of hydrate stability in the seafloor (assuming a geothermal gradient of 30° C/km) depending on water depth (bold line). The bar charts show the equally depth-dependent increase in volume (number = factor by which the volume increases) if a given volume of gas hydrate dissociates (according to Paull et al., 2000).

There is hardly any immediate evidence for submarine slides triggered by gas hydrate dissociation. Still, the hypothesis seems to be corroborated by some observations (Driscoll et al. 2000). For instance, near slide scars one can often find traces of gas and fluid flux that move upward along seismically registered paths. The seafloor itself shows crater-like depressions, so-called pock marks, or bivalve and bacterial mats (cold vents) that indicate fluid venting. At the upper shelf edge there are slopes of more than 4°. Gravitational slides appear likely if such a slope becomes less stable due to gas hydrate dissociation. One important factor seems to be the expansion of the released gas, which increases with decreasing water depth. For example, at 650 m water depth, the volume of released gas and water is almost three times the original gas hydrate volume (Fig. 6). Gas hydrate decomposition at the upper shelf edge thus results in an enormous pore pressure that

leads to a massive loss of compactness while the large pore space makes the sediment highly deformable. Bottom simulating reflectors, with their slope-parallel trend, are another potential factor triggering submarine slides. When gas hydrate dissociates, they will be weak layers parallel to the slope.



Figure 7- The Storegga slide off shore of Norway has a total volume of 5608 km³. and is one of the largest known Holocene slides. It triggered a large tsunami, dated to 7250-7350 14C yr BP (Bondevik et al. 2003). Dots show where the tsunami deposits have been mapped, and numbers show the elevation of the deposits above the contemporaneous sea level.

Gas hydrate dissociation at the upper shelf edge can be caused by reduced pressure due to a lower sea level. During the Last Glacial Maximum 18,000 years ago, the global sea level was approximately 120 m lower than at present. This should have led to gas hydrate dissociation and, subsequently, to destabilization of the upper shelf edge. Many slides indeed happened during this period or later. However, they may also have been caused by higher sedimentation rates at the continental slope. The famous example is the Storrega slide offshore Norway. The mass moved by the Storegga slide had a total volume of 5608 km³. It took place in several stages, starting about 7000 years ago. The most massive mass movement happened during the first slide which triggered a tsunami from which a wave high > 20 m is documented in deposits from the Shetland Islands (Fig. 7). Depending on coastal morphology and population density, such a tsunami could nowadays cause severe damage.

In conclusion, recent observations seem to indicate that submarine slides and mass movements are triggered by gas hydrate dissociation. However, up to now we can only speculate about causes such as the short-term release of mechanic energy, the amount of methane or the long-term effects on the environment.

AI-3.5 Effect on global climate

When methane is released into the atmosphere, it acts as a greenhouse gas just like carbon dioxide, but 30 times more effective. Therefore it is a factor in the global warming of the atmosphere (Dickens 2003). Although the atmosphere stores as much as 760 gigatons of CO₂, a release of methane from an estimated 10,000 gigatons of gas hydrate deposits could alter its properties to a great extent. An increased release of methane from gas hydrate could affect the glacial/interglacial cycle (Kvenvolden 1998). A positive feedback would be caused by permafrost gas hydrate on land due to its temperature sensitivity, whereas oceanic gas hydrate would cause a negative feedback as it is controlled by sea level changes.



*Figure 8: Carbon isotope records across the LPTM in different phases at three oceanic sites. Original records have been placed on a common depth scale with the delta*¹³*C minimum at 0,0m (from Dickens 2003).*

The recently published hydrate gun hypothesis thoroughly documents evidence for Late Quaternaty climate change caused by hydrates (Kennett et al. 2003). The concept is that, as little as 15,000 yr ago, methane from hydrates caused significant global warming. Although the hydrate gun hypothesis seems to be controversial (Maslin and Thomas, 2003) it is analogous to a global scenario around the Late Paleocene Maximum (LPTM) proposed by Dickens et al. (1995, 1997). They suggested that 55.5 M years ago (around the LPTM), massive methane hydrate dissociation at the ocean floor might explain a 4-8°C temperature rise over a brief geological time interval of 1.000 years. This distinct event is documented in ODP samples as a prominent negative carbon isotope sequences $(\delta^{13}C = -2.5\%)$. This isotope shift is also documented in fossil tooth enamel and in carbonates and organic sediments in terrestrial sequences (Katz et al. 1999). In the LPTM hypothesis, the evolution of a large amount of methane from hydrates $(1.12 \times 10^{18} \text{g of})$ methane; Dickens et al. 1995) is the only plausible explanation that has been presented to explain the environmental perturbation. The change in isotopic carbon ratio to low values indicates that the source was external to the normal ocean-atmospheric-biomass carbon pool and hydrates in the ocean sediments are the most possible candidates (Dickens 1997). Recent discussions on the hydrate gun hypothesis mentioned that the Quaternary atmospheric methane spike was due to emissions from wetlands and peat bogs (Maslin and Thomas 2003). The theory requires a glacial-interglacial vegetation time shift of 1,000 Gt carbon, which seems to be difficult. However, even this counter hypothesis requires some hydrate-derived methane for a mass balance, along with a shift in time for the wetlands.

AI-3.6 Concluding remarks

A significant role for methane hydrates in the stability of continental slopes, in the longer-term greenhouse forcing and abrupt climate change scenarios and as a major contributor of carbon in global carbon cycle remains contentious. These issues can only be resolved with comprehensive, multidisciplinary studies on hydrates. Such studies are important before we increase exploration on gas hydrates in natural environments in order to use hydrates for fuel. The insights of such studies may well lead to recognition of an important role for methane hydrates in global climate change, and through it, as an agents of biotic evolution.

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AI-4 PRESENT STATUS OF WORLDWIDE R & D ON THE UTILIZATION OF GAS-HYDRATES FOR POWER PRODUCTION

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Gas-hydrate is a crystalline form of water and low molecular weight hydrocarbons (mainly methane) that forms at elevated pressures and moderately low temperature. The study of gas-hydrates has attracted the attention of the entire scientific community because of their widespread occurrences in permafrost and outer continental margins; potential energy content; role in climate change and geo-hazard. The energy content of gas-hydrates is estimated to be more than two times the amount of total fossil fuel (oil, natural gas and coal) reserves. To meet the ever-increasing demand of energy, gashydrates seem to be the best alternate source of cleanest fuel. Parameters like bathymetry, seabed temperature, rate of sedimentation, sedimentary thickness and total organic content are the guiding factors to look for places suitable for the occurrence of gashydrates. A systematic approach, based on various geological, geochemical and geophysical tools is required to establish the presence of gas-hydrates and to evaluate the resource potential. Mining strategy is to be then developed keeping in mind the impact on environment caused by extraction and dissociation of hydrates.

Presence of gas-hydrates in an area can be inferred through remote seismic experiments. However, today not much is known about the nature of distribution of hydrates, as they are not stable at STP like minerals. Hence quantification of gas-hydrates has remained elusive, though a number of empirical methods exist. A concerted scientific effort is on throughout the world with a view to evaluate the resource potential and hazard assessment.

Presence of gas-hydrates increases the seismic velocity that again depends on concentration and distribution of hydrates. On the other hand, presence of free-gas underneath decreases the seismic velocity. Thus accurate velocity determination across the bottom simulating reflector (BSR), associated with the base of hydrate stability field, provides very vital information for quantitative assessment of gas-hydrates and/or freegas. Traveltime tomography of wide-angle seismic data, acquired by 3-component ocean bottom seismometers (OBS), helps to demarcate the prospective zones of gas-hydrates and underlying 'free-gas' if present. Since the base of gas-hydrates is a good conversion point, converted waves recorded by OBS provide good constraint to the depth of BSR. The detailed velocity tomogram can reveal structures related to faults which, in turn, help to understand the migration path of fluid flow and hence the mechanism for the formation of gas-hydrates. The velocity field, derived from the OBS data can be used to improve the seismic image of multi-channel seismic (MCS) data, through a process called pre-stack depth migration. Both P- and S- wave velocity information derived from multicomponent wide-angle seismic data would bring out the nature of distribution of hydrates in the pore spaces of sediments, and hence would help in quantifying the amount of gas-hydrates.

Amplitude versus offset (AVO) analysis of both large offset MCS and wide-angle OBS data serves as a powerful tool to differentiate whether the BSR is caused by hydrated sediments underlain by brine or partially hydrated sediments underlain by free-gas.

Hydrates reduce the reflectivity by cementing the pore spaces of sediments. This phenomenon, termed as 'blanking', can also be used in quantifying the amount of gashydrates. However, we need to understand the effect of homogenization of lithology on amplitude reduction. Velocity-amplitude (VAMP) attribute, observed as a series of pushdown directly below the pull-up over a seismic section, can also be used to indicate presence of massive gas-hydrate deposit in an area.

Identification of BSR becomes difficult in places where bedding planes are parallel to the BSR, as is observed in the western continental margin of India. Normal incidence reflection amplitude versus frequency (AVF) serves as an important attribute in identifying BSR in such a geological situation. The decrease in BSR amplitude with increasing frequency, particularly with high-resolution seismic data, is due to the BSR being a gradational velocity contrast over a depth interval.

High-resolution multi-channel bottom seismic data also provide very high resolution image and layer velocities that may result in improved structural detail including delineation of fractures or conduits through which upward migration of fluids and methane gas can take place from down below to the zone of gas-hydrate stability field. This helps to understand the genesis of gas-hydrates.

Regarding the origin of gas-hydrates, geochemical tools provide supplementary information. The molecular composition of hydrocarbon gases and carbon isotropic composition of methane can distinguish between biogenic and thermogenic origin of gas-hydrates. Higher ratio of methane to higher molecular weight hydrocarbons or low concentration of δC^{13} indicates biogenic origin of methane.

As the resistivity of hydrated sediments is higher than that of normal oceanic sediments within the zone of gas-hydrates, the resistivity-depth function can also be used as a complimentary method to quantify the amount of gas-hydrates. In some situation BSR may not be prominently observed on seismic section. Transient electric dipole-dipole method can be aimed at deriving the resistivity-depth function of submarine sediments for demarcating the zone of gas-hydrate bearing sediments.

Study of seafloor compliance, defined as the transfer function between the vertical displacement of the seafloor and the seafloor pressure as a function of frequency, is sensitive mainly to the shear modulii, and thus high shear wave velocity above the BSR can be interpreted as due to gas-hydrates.

Heat flow measurements along with seismic study help to determine the thermal conductivity of rock materials. This information is useful in planning exploitation strategy to dissociate gas-hydrates by supplying heat from external source. If the thermal conductivity is low, absorption of energy from surroundings will be a slow process.

Due to lack of precise relationship between seismic velocity or resistivity of hydrated sediments and hydrate content, translation of velocity or resistivity build-up against the background trend in terms of concentration of hydrates has been difficult. So a theory is to be established between physical properties and concentration of hydrates in a porous medium by taking into account various factors like microstructure, anisotropy and multiple phases, and to validate the theory using drilling data.

For quantitative assessment of gas-hydrates, calculation of very accurate seismic velocity or resistivity is very essential. Sophisticated waveform inversion of MCS and OBS data is a powerful tool in extracting the fine-scale velocity variation across a BSR including delineation of thin layers that may contain gas-hydrates and/or free-gas. There is an urgent need to develop a 2-D waveform inversion of wide-angle OBS or very large offset shot gather of streamer data to derive spatial distribution of gas-hydrates in a prospective area.

As the amount of gas contained in hydrates differs depending on the structure of hydrates, a lot of research based on X-ray diffraction, NMR (nuclear magnetic resonance) and Raman spectroscopic methods is going on to study the crystal structure of gas-hydrates.

Experiment with synthesizing methane hydrates at laboratory with different composition and structure will provide fundamental data that will be extremely valuable in developing natural methane hydrates as an energy resource. Laboratory study of various physical properties (density, heat conductivity, sound wave characteristics, electric resistance etc) of methane hydrates with a variety of compositions and crystal structures is to be carried out to provide valuable information for the future development of natural methane hydrates. Kinetics of gas-hydrate dissociation from the solid to the gaseous form needs to be investigated to understand the production process. A field situation is to be simulated where change in physical properties for the formation and dissociation of gas-hydrates and their impact on surroundings will be studied.

Though gas-hydrates are a vast storehouse of natural gas, commercial production of gas from gas-hydrates has been a distant prospect. Three methods such as (i) thermal stimulation, (ii) depressurisation and (iii) inhibitor injection can be considered for production of gas from gas-hydrates. However, no method has been proved economically viable so far. With the fast growth of technology, it is expected that methane tapped below the gas-hydrates can be exploited economically. Therefore, we should look into 'gas traps in hydrate-seals' at places of seafloor hills, domes extending from below towards the seafloor, dipping strata intersecting the seafloor. It is claimed that gas from gas-hydrates has been produced in the Messoyakha field of Western Siberia, but there is no report of actual recovery and analysis of gas hydrates sample. If it is true, similar strategies can be adapted to the marine environment and the technique should be developed indigenously. The advanced countries, due to their abundant hydrocarbon potential, would not like to invest huge exchequer to promote exploitation technology for gas-hydrates, which is very expensive. No technical method will be developed if the costs of involvement and recovery are too high relative to potential gains of exploiting a limited resource potential. So there is a strong need to prepare

suitable strategies to assess the resource potential systematically before exploitation. A concerted effort is required to study the gas-hydrates in a scientific manner, and efforts are on throughout the world in this direction.

To assess the true potential of methane hydrates or to develop them as a resource, test drilling and recovery of gas-hydrate samples are must. Drilling in the Mackenzie Delta and Nankai Trough has been carried out with a view to developing methane hydrates as a resource. The drilling will also facilitate cross-hole tomography and vertical seismic profiling as well as measurement of in-situ formation conditions, and help for calibration purposes.

Suggested References

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AI-5 EXPLORATION OF MARINE GAS HYDRATES AROUND JAPAN Islands

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AI-1.5 Background

Gas hydrate is a solid, ice-like substance composed of gas and water molecules. Water molecules form cage structures in which various kind of gases such as methane, ethane, propane, hydrogen sulfide, carbon dioxide, etc, are incorporated to form a clathrate structure (Fig. 1).



*Figure 1-Structure of gas hydrate (CH*₄*.- 5.75* H₂O).

Naturally occurring gas hydrates are largely composed of methane and water, then properly called as *methane hydrate*, but often referred as *gas hydrate*. Since marine gas hydrates were first suspected in gassy sediments on the Blake Ridge (Lancelot and Ewing, 1972), northwest Atlantic, in 1972, extensive distribution of gas hydrates have been observed in the continental margin sediments and permafrost worldwide. The total amounts of gas hydrates in shallow geosphere were roughly estimated to be ~10,000 Gt as carbon (Kvenvolden, 1988), which is almost 17 times as much as the atmospheric carbon.

In 1995, the Ministry of International Trade and Industry (MITI) (later named the Ministry of Economy, Trade and Industry or METI) launched a five years R&D program to explore marine gas hydrates offshore Japan islands, responding to (1) the current energy security issue and (2) 6% reduction of CO₂ emission by the Kyoto Protocol. Under the supervision of METI, Japan National Oil Corporation (JNOC) has been conducting the program including seismic surveys and exploration drillings offshore Japan islands, in the

MacKenzie Delta, Canada (e.g., Dallimore et al., 1999), and laboratory experiments and technology development since 1995. Among these, exploration in Nankai Trough is the main task of the program.

The Nankai Trough runs SW-NE at the convergent margin of the Philippine Sea plate offshore southwest Japan islands. Because of wide distribution of BSRs (~32,000km²) (Fig. 2), which indicate the existence of subsurface gas hydrates (Fig. 3); Nankai Trough has been the focus of gas hydrate studies for the last decades.



Figure 2. Distribution of BSRs, which indicate the existence of subsurface gas hydrates, around Japan islands.

In 1999 to 2000, JNOC and Japan Petroleum Exploration (JAPEX) drilled exploratory wells in the site survey area as the first integrated efforts of drilling/coring dedicated to explore marine gas hydrate. The program successfully penetrated through the base of gas hydrate stability zone at around 270 meters below sea floor, identified gas hydrate zones, and recovered a number of gas hydrate bearing sands with extremely high saturation.



Figure 3-Bottom simulatingReflectors (BSRs) of the Nankai Trough.BSRs occur at around 270m in this area.

AI-5.2 Results of the Nankai Trough Gas Hydrate Drilling

Exploratory wells in the MITI-Nankai Trough encountered gas hydrate-bearing sandstone about 30 m thick, at 250 m below the sea floor (Figure 4).Interstitial pore space of the sandstones is largely filled by gas hydrates (the pore saturation is nearly 80 %), then the calculated amount of gas hydrates stored in the sands is 1.84 km³(0.07 TCF) CH₄ per km².

As the areal distribution of BSRs has been estimated to be 32000 km³, a simple calculation gives 2100 TCF for the total amount of methane in gas hydrates.

AI-5.3 Current and Future Program

Following the success of the first five year program (1995-2000), METI launched a 16 year program (2001-2016) with an intention to pave road toward a commercial production of natural gases from gas hydrate deposits (Fig. 5). 2D and 3D seismic surveys, on-land drilling and production test, and offshore exploration drillings are being conducted for the first phase (2001 to 2006). In 2002, JANOC/JAPEX and international consortium drilled research wells in the MacKenzie delta, northern Canada, and succeeded in the production test of from gas hydrate deposits below the permafrost (Fig. 5). For the second phase (2007 to 2011), offshore production test is the major target. An improvement of the production performance to pave road toward the commercial production will be the target of the last phase (2012 to 2016) of the program.



Figure 4- Depth profile of gas hydrate amount in sediments. The amounts (=pore saturation of gas hydrate; Sh%) were estimated from the chloride concentration of the "interstitial waters".



Figure 5- Flare of methane from the subsurface gas hydrates, Mackenzie delta.

AI-5.4 Integration of Academic and Industry Efforts

Japan's gas hydrate studies have been strongly supported and led by government projects. However, recently, university-based projects have been contributing lots to understand and model the nature and origin of gas hydrates in active margin settings. Among these, ODP (Ocean Drilling Program) to drill deep ocean floor and submersible dives to observe methane seeps and related phenomena on the ocean floors are expected to deepen our understanding of gas hydrates and the potential importance on global environments. New drilling ship "Chikyu", which is under construction, will serve as deep-earth drilling facilities to explore gas hydrates in active margins.



Figure 6- Current R&D program of gas hydrate exploration in Japan