JOIDES Journal

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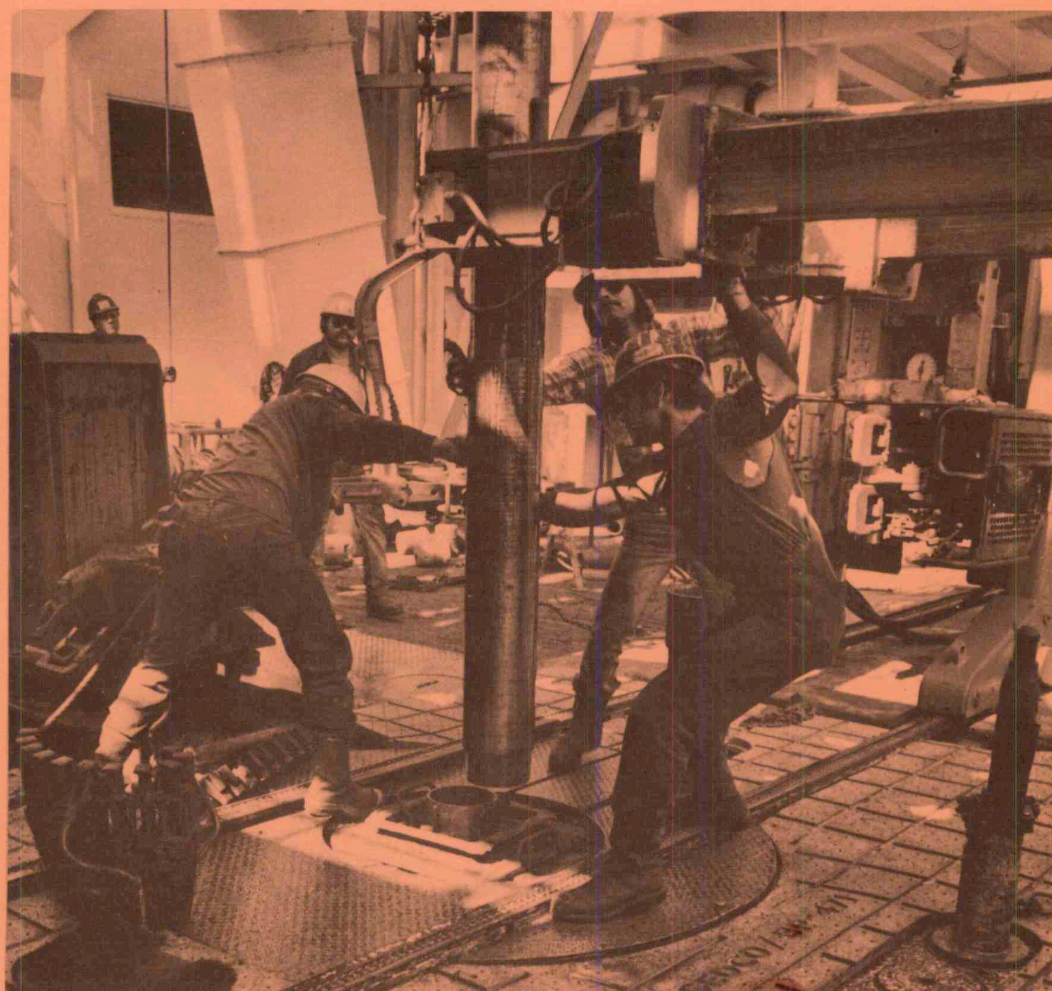
March 1986

Ocean Drilling Program
Guidelines for Pollution Prevention and Safety



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This revised edition of the Guidelines for Pollution Prevention and Safety was compiled by George E. Claypool (Chairman) and the JOIDES Pollution Prevention and Safety Panel, and was edited by A.E.S. Mayer and M.M. Burdett, JOIDES Office, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882-1197.

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PREFACE

All drilling operations involve the chance of accident or pollution and this has been recognized from early on in the Deep Sea Drilling Project (DSDP). Policies to minimize the risk of hazards during drilling developed by DSDP have been updated and implemented for the Ocean Drilling Program (ODP).

This Special Issue is devoted to a new edition of the guidelines for pollution prevention and safety which have been developed by the JOIDES Pollution Prevention and Safety Panel. The Panel is composed of petroleum geologists, geophysicists, and organic geochemists drawn from industry, government, and academia who are recognized authorities in the fields of marine research and offshore oil exploration and who provide independent advice to the Program.

March 1986

INTRODUCTION

The only way to be absolutely certain of safety and of freedom from hazards of pollution in connection with drilling in the oceans is to do no drilling at all. Any drilling must involve some risk. The value of the scientific objectives that are sought in the Ocean Drilling Program (ODP) must be balanced against potential hazards so that the Program will achieve these objectives so far as is possible without falling below acceptable standards either of safety or for the prevention of pollution. By diligent planning and careful operational procedures, it is usually possible to minimize the risks and achieve the desired goals of the Program.

It is emphasized that adherence to the old adage of "An ounce of prevention is worth a pound of cure" offers the surest route to safety and pollution prevention. The money and time spent on extra care in preliminary site surveys, site location, and in planning of the drilling program may forestall an accident which could not only cause lamentable loss of life and property and damage to the environment, but could also cause the abrupt termination of this major international scientific endeavor.

This edition of the Guidelines for Pollution Prevention and Safety has been prepared with recognition of the transition from the Deep Sea Drilling Project (DSDP) to the Ocean Drilling Program, which began drilling operations on January 31, 1985. The diverse sites planned for ODP drilling will involve additional hazards over those of previous DSDP drilling, in that deeper sediment penetrations (with re-entries) are scheduled for many continental margin sites, and on these margins more holes may be drilled in shallower water than before. Moreover, it now seems probable that, at least for the first five years of ODP, JOIDES RESOLUTION (SEDCO/BP 471) will be operating in a riserless mode. The ODP must, therefore, continue to face the safety hazards inherent in such an operation with the lack of a drilling riser to the surface, lack of return circulation, and lack of blowout preventers. However, improved seismic surveying, a full borehole logging program, and the hydrocarbon monitoring capabilities on JOIDES RESOLUTION should provide additional information for decisions on safety and pollution matters. In any case, it seems evident that emphasis on pollution prevention and safety matters should be at least as great, if not greater, in ODP compared with DSDP.

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PRINCIPAL HAZARDS

Oil and Gas Escape and Blowouts

The principal hazard in ocean drilling, with respect to pollution prevention and safety, comes from the possibility of opening up reservoir strata which would allow oil or hydrocarbon gas to escape in large quantities into the sea or the atmosphere.

Because natural submarine seepages, both of oil and of gas, exist in many parts of the world apparently with little deleterious effect on the environment, it is difficult to say what amounts of oil or gas released into the sea water or the atmosphere by drilling operations should be termed hazardous as regards environmental considerations. Certainly as a pollutant, escaping oil must be considered far more serious than escaping gas.

On the other hand, as a hazard to safety of personnel and property, hydrocarbon gas may be more dangerous than oil because of its mobility, highly flammable nature, adverse effect on sea water buoyancy, and the difficulties in its pressure control.

Offshore drilling for oil is currently taking place along much of the world's marine coast line and, on the whole, a remarkable safety record has been demonstrated. However, it must be recognized that in any drilling operation release of hydrocarbons can occur if adequate precautions are not taken, and that this release can be hazardous both as regards pollution and safety. Since ODP drilling is particularly vulnerable in this respect because of the limited controls available from JOIDES RESOLUTION, it has seemed particularly important both for pollution and safety considerations to try to avoid entirely any substantial release during drilling operations of either oil or gas into the sea or the atmosphere, whether through quiet escape or through violent blowouts.

a. Hydrocarbon origin and occurrences

The term petroleum may be applied to any dominantly hydrocarbon substance -- liquid, gas, or solid -- originating in the rocks of the Earth, although it is popularly reserved for the crude oil, natural gas, and asphalt of the so-called petroleum industry.

Mixtures of petroleum hydrocarbons exist as gaseous, liquid, and solid phases depending on the temperature, pressure, and composition of the system. Under earth surface conditions, C_1-C_4 hydrocarbons (methane, ethane, propane, butane) are predominantly in the gas phase while C_5 and larger hydrocarbons are predominantly liquid.

Hydrocarbon gases, largely methane (C_1), may be generated in significant quantities from organic matter in sediments either under near-surface conditions by bacterial action or at greater depths by thermochemical action. Liquid petroleum (oil), however, is almost exclusively the product of thermochemical generation from hydrogen-rich organic matter in deeply buried sediments. This generation appears to become quantitatively important only as temperatures reach 50° to 150°C (typically at burial depths of 1500-5000 m for average geothermal gradients). Hydrocarbon gases are generated with the oil and, although consisting largely of methane, usually include significant quantities of ethane (C_2), propane (C_3), butane (C_4), and higher hydrocarbons. Thermochemical conversion of organic matter to hydrocarbons continues at accelerating rates with increasing depth and temperature until all organic matter and the oil itself has been converted largely to methane and carbon-rich residues.

The apparent relation of gas and liquid hydrocarbons of different modes of genesis to depth and temperature is shown diagrammatically in Figure 1. It should be stressed that while biogenic hydrocarbons are

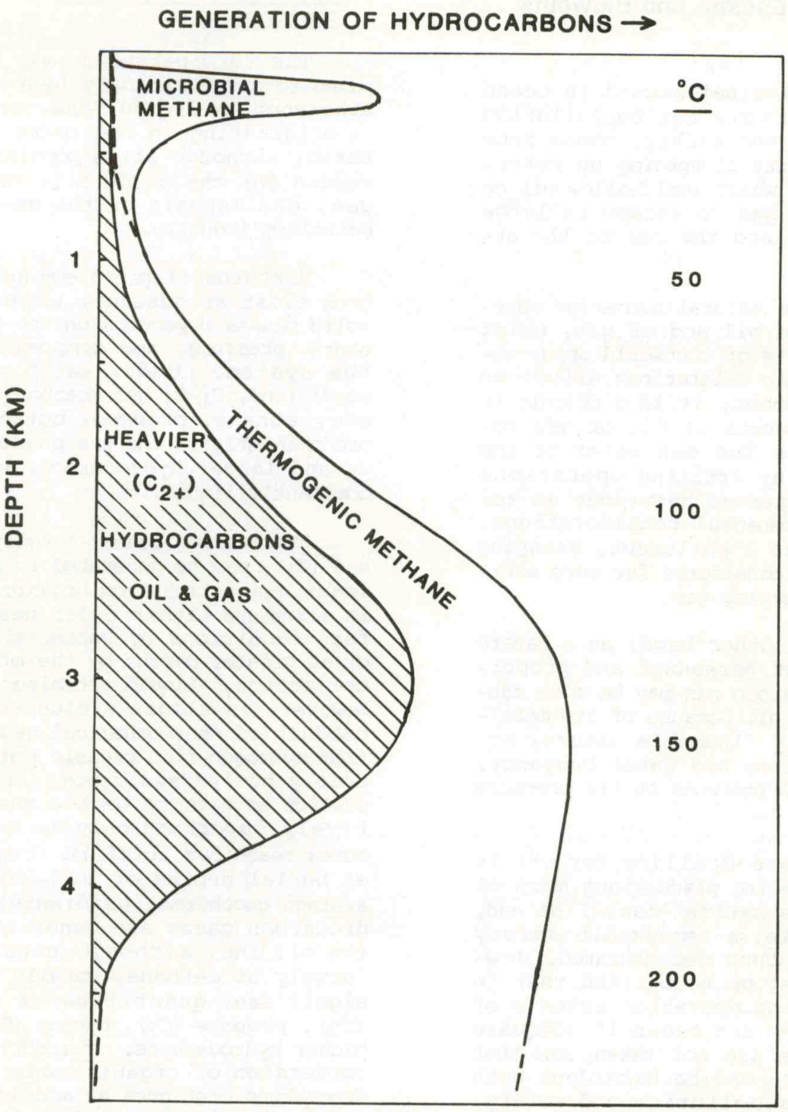

Figure 1: Relation of generation of methane and heavier hydrocarbons to depth of burial and temperature and the relation between the genesis of microbial methane and thermogenic methane. (After Hedberg, H., 1974. Amer. Assoc. Petrol. Geol. Bull., 58, 661-673.)

generated at relatively shallow depths and thermochemical hydrocarbons at relatively greater depths, either may be found at any drilling depth in the sedimentary section because of migration, subsequent burial, or exhumation.

Biogenic methane is commonly found in swamps where it is known as "marsh gas," but it is also formed in marine sediments with sufficient contents of organic matter. Biogenic methane usually can be distinguished from thermochemical methane by means of isotope ratio mass spectrometry; the biogenic form has a distinctly greater abundance of the light carbon isotope ^{12}C relative to the heavy carbon isotope ^{13}C. Also, thermochemical methane is formed along with ethane and heavier hydrocarbons in the early stages of hydrocarbon generation, thus the ratio of methane-to-ethane gradually decreases as hydrocarbons of thermochemical origin become more abundant.

More complete discussion of geologic factors involved in the origin and occurrence of petroleum is given in the following reference works:

Tissot, B.P. and Welte, D.H., 1984. Petroleum Formation and Occurrence (2nd ed.). Berlin: Springer-Verlag.

Hunt, J.M., 1979. Petroleum Geochemistry and Geology. San Francisco: W.H. Freeman and Co.

Both biogenic and thermochemical methane may be found in ODP boreholes. There is no difference in their common physical and chemical properties. Both can cause blowouts, both can catch fire, both can be associated with some ethane, and both can occur in substantial quantities at very shallow depths. About the only major difference in significance is that the conditions which produce thermochemical methane may also produce liquid oil, whereas oil of direct microbial origin is unknown. (See Figure 2.)

There is a common fallacy that if methane can be identified as biogenic, it can be disregarded as a threat to safety. At least one serious blowout has occurred in offshore drilling operations (Cook Inlet, Alaska) due to gas of apparent biogenic origin. In addition, one of the world's largest gas fields and more than 20% of the world's gas reserves are of apparent biogenic origin. It has been mistakenly suggested that if methane/ethane or $^{12}C/^{13}C$ ratios are greater than a certain value, gas dangers can be dismissed because it is then a question of only "marsh gas," not "true petroleum gas." It is the quantity of hydrocarbons possibly present in subsurface reservoir strata, rather than the origin of those hydrocarbons, that is of primary concern.

The JOIDES Pollution Prevention and Safety Panel (usually known as the Safety Panel) is and has been strongly in favor of getting as much information as possible on the character of the hydrocarbons encountered in ocean sediments. However, it would deplore, as a menace rather than an aid to safety, the setting of "magic numbers" as substitutes for balanced judgment based on the multitude of geological, geochemical, operational, and experience factors which should enter into the decision in any specific case. It believes that such arbitrarily imposed numerical guidelines for interpretation are dangerous because the values must vary so much with other factors and circumstances and because they are so likely to be used blindly as crutches to avoid more sound and reasoned judgment.

b. Cause and explanation of blowouts

In oil well drilling operations, formation fluids (water, oil, or gas) will flow from reservoir strata into the well bore whenever a substantial pressure-differential exists between the formation fluid and the drilling mud in the hole; that is, whenever the pressure of the fluid in the interstices of a reservoir formation substantially exceeds the adjacent pressure in the drill hole resulting from the weight of the column of drilling fluid filling the hole. The formation

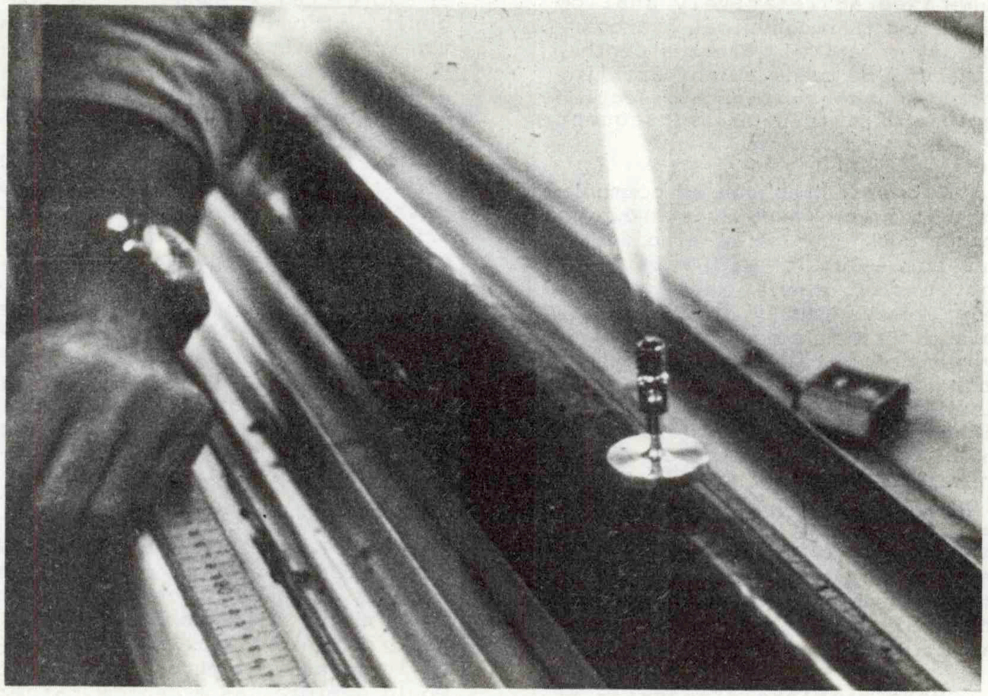

Figure 2: Core of Pliocene hemipelagic sediment taken from DSDP Hole 397 (Leg 47A-N.W. Africa) which contains biogenic methane. A gas sampler inserted in the core allowed methane to "flare" when lit. After the core warmed on deck, the expansion of gas caused the bursting of the core section endcaps. (Photo courtesy of M. Arthur, University of Rhode Island.)

fluid entering the well bore is generally less dense than the drilling fluid and therefore will tend to move upward in response to buoyancy once it has entered the hole.

When the formation fluid is gas, gas-charged oil, or gas-charged water, the gas, on entering the hole, may permeate the drilling fluid causing it to become "gas-cut" (filled with gas bubbles), thus greatly diminishing its density and its ability to cause back-pressure on the formation. Likewise, when gas enters the well bore, it undergoes rapid expansion due to pressure reduction while traveling up the hole. Because the drilling fluid is confined by the narrow diameter of the bore hole (commonly less than 10 inches), the increasing expansion of the gas bubbles in the drilling fluid as they move upward will cause a flow of displaced drilling mud from the mouth of the hole with consequent reduction of the total weight of the fluid column in the hole, resulting in further reduction of the restraining pressure on the entry of formation fluid. The consequence is a type of chain reaction. Gas will tend to enter the hole at an ever-accelerating rate as the pressure differential between formation and hole is increased. If not promptly brought under control, this process may quickly result in violent ejection of all drilling fluid from the hole which in turn will result in "wild" or unrestrained flow of gas or gas-charged formation fluid at the surface. Such a calamitous event is called a "blowout" and may be extremely dangerous to life, property, and the environment. Elaborate measures are employed by the petroleum industry to prevent its occurrence -- weighting of drilling muds, application of back pressure by pumps, use of mechanical blowout preventers, etc.

c. Differences in blowout risks between ODP and oil well drilling operations

In current ODP operations, conditions are quite different from those of customary oil well drilling, principally due to lack of means for return circulation, the common use of sea water instead of heavy mud as a drilling fluid, the lack of a drilling riser, and the much greater water depths involved. In current ODP operations, any gas encountered under pressure sufficient to cause it to enter the hole and permeate the drilling fluid, would, as it traveled upward, be confined only until it reached the ocean floor (top of the bore hole), or until it reached the base of such soupy, fluid sediment as might locally lie immediately below the ocean floor. Above this point, the gas, although continuing its upward course, would probably also tend to dissipate away from the vicinity of the bore hole and would reach the ocean surface, if at all, in less concentration and over an increasingly broad area in proportion to the water depth through which it had to pass.

Considering the usually much greater water depths involved in ODP drilling than in normal oil well drilling, there is relatively much less danger in ODP drilling of a violent outbreak of gas at the surface with accompanying hazards to the drilling vessel. However, at the same time, the means of control over the results of a gas flow into the hole are also much less effective under current ODP operating conditions. It is entirely possible that a blowout could occur even with drilling operations in water depths of 500 m or more. Moreover, even though the escape of gas or oil at the ocean surface from holes drilled in water depths of several thousand meters might be so diffuse as not to be readily discernible, the total pollution of ocean waters by hydrocarbons might be even greater than in a more violent blowout. It is even possible that a continuing substantial escape of hydrocarbons into the ocean waters from an ODP hole could occur so quietly as to completely evade notice from the drilling vessel.

A true gas blowout could imperil the vessel and crew in several ways -- by release of noxious gases, by fire, or by causing a loss of the vessel's buoyancy due to charging of the surrounding sea water with gas bubbles.

Hydrogen sulfide is the principal highly noxious gas that might be encountered. It is easily detected by several commercial devices and is identifiable in low concentration by its characteristic odor (rotten eggs).

The greatest fire danger from a gas blowout on JOIDES RESOLUTION would occur if a blowout of hydrocarbon gas took place through the drill pipe. However, in relatively shallow water, gas escaping to the surface from around the drill pipe at the sea floor also may present a fire hazard to the vessel. JOIDES RESOLUTION drill crews are trained in the standard oil field practices for avoiding or controlling these possibilities.

Aeration of the sea by gas to the point where buoyancy is seriously impaired could hardly occur in the water depths usually encountered at ODP sites. However, this buoyancy decrease has happened twice with vessels drilling for oil in shallow water and the possibility should not be ignored at the shallower ODP sites.

Intercommunication between Reservoirs and Exchange of Fluids

A situation may occur when formation fluids (oil, gas, or water) from deep, high-pressure zones, in the process of flowing up the bore hole, pass shallower zones with lower, normally-pressured formation fluids. A real danger exists that under these conditions, hydrocarbons may enter a zone that opens to the sea floor by outcrop of fracture, resulting in an uncontrollable leak.

Furthermore, high-pressure fluids from deep zones may, in the same way, charge shallow zones with fluids above normal hydrostatic pressure and thus make even shallow future drilling in the area hazardous. It is also possible, though not very likely under ODP conditions, that deep saline formation water might in this way contaminate shallower fresh water aquifers.

Drilling Active Ridges

High temperatures encountered in hydrothermal systems or close to magma chambers may present special hazards for deep sea drilling. The behavior of water in marine hydrothermal systems is governed by the pressure-volume-temperature relations of water. On the accompanying graph (Figure 3) the specific volume of water at constant temperature is plotted as a function of pressure. Below the critical temperature of water (374°C) there is an abrupt change of slope corresponding to the phase change resulting from boiling. Above the critical temperature, the rate of change of specific volume with pressure is more gradual. With regard to possible drilling hazards, it is important to avoid drilling

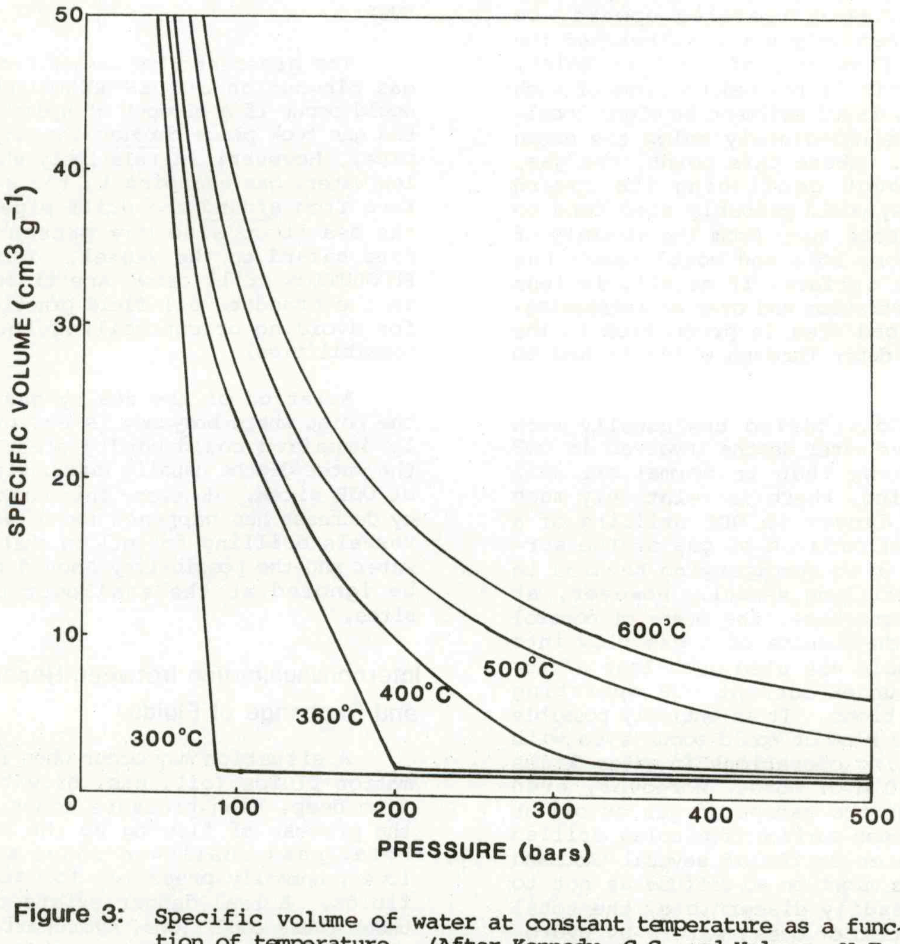

Figure 3: Specific volume of water at constant temperature as a function of temperature. (After Kennedy, G.C. and Holser, W.T., 1966. Geol. Soc. Amer. Mem., 97, sect. 16.)

into rocks where the pressure and temperature conditions indicate that a rapid increase in the specific volume of water would occur with further increase in temperature or decrease in pressure. For example, drilling into a 360°C hydrothermal system at a pressure of 200 bar (about 2000 m total sub-sea depth) would be unwise because a small movement of water up the drill pipe could cause the water to flash to steam. In summary, the upper limit of temperature that is safe to drill will depend on the pressure or the total depth (water depth plus depth of penetration) at that temperature. For a given water depth, it will be necessary to set a maximum temperature to which drilling should be attempted. This requirement emphasizes the need to know the temperature at the bottom of the hole in order to ensure that conditions for drilling are safe.

Other Hazards

Hazards of storms, hurricanes, ice, collisions, etc. are common to all vessels and consequently are not detailed here. Likewise, the hazards involved in the mechanical operation of drilling equipment are common to all offshore drilling operations and do not require special mention.

While not detailed here, it is of course, mandatory that conventional safety measures used in oil field operations and on drilling vessels, such as the wearing of safety hats, no smoking areas, and emergency blowout and fire procedures, be observed. It is also essential that measures be taken to prevent pollution of the environment by any of the operations incidental to the Program.

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GENERAL OBSERVATIONS OF PRECAUTIONARY MEASURES, RESPONSIBILITIES, INFORMATION REQUIREMENTS, AND PANEL PROCEDURES

Subjects considered by the Safety Panel to be the most important to stress for purposes of safety and to prevent hazards to the environment are treated below under the following five topics:

1) Choice of reasonably safe drill sites
2) Proper planning of the drilling program for each site
3) Early detection or anticipation of hydrocarbons or high fluid pressures during drilling
4) Measures for coping with flows of fluids encountered or anticipated during drilling
5) Measures for abandoning holes

Care in the first of these -- choice of reasonably safe drill sites -- probably offers the greatest return in insurance against trouble.

It is the responsiblity of those who plan each leg and its drilling sites (JOIDES thematic and regional panels) to consider each of these topics, both in advanced planning and in connection with shipboard operations. It is also their responsibility to propose, to the best of their ability, only drilling sites and drilling programs which they themselves can conscientiously support as reasonably safe. The function of the Safety Panel is to review proposals of sites and drilling programs from the safety angle.

Those who are responsible for initially planning a leg should do so only after thoroughly considering the possible hazards and the precautions outlined in these Guidelines and adjusting their proposals accordingly. There should not be an attitude by those involved in the Program that their involvement is only with science and that safety matters are exclusively the concern of the Safety Panel. Decisions on risks should be made with the recognition that it is not one site or one leg that is concerned but the future of the whole Ocean Drilling Program which could be jeopardized by an accident or a pollution incident.

The co-chief scientists or the ODP Science Operator staff representative of each leg are responsible for presenting sufficient data to the Safety Panel to allow a thorough evaluation of each of the above-listed safety components for that leg and for each drill site proposed. Unless adequate data are provided, the Safety Panel must refuse to consider a proposed site or drilling program. Moreover, these data should be provided in time to allow review by individual Panel members in advance of the meeting at which a leg is scheduled for review by the Safety Panel. Only definitely identified and supported locations can be approved by the Panel; if a location approved by the Panel is subsequently moved, it cannot be considered to be supported by the Panel. Further information on the data requirements for review of proposed drill sites by the Safety Panel is given in Special Issue No. 4 of the JOIDES Journal, September 1985 (pages 72-74).*

Once drilling operations are started on a hole, the responsibility for safety and pollution measures, including cessation or abandonment of drilling, should be clear-

*JOIDES Journal, Special Issue No. 4 (September 1985) is available from JOI Inc., 1755 Massachusetts Avenue, NW, Suite 800, Washington, DC 20036.

ly fixed on the Science Operator's shipboard Operations Superintendent. He will, of course, consider the recommendations of the co-chief scientists. The Operations Superintendent relies to a large extent on the scientific staff for prompt hydrocarbon analysis of all cores and for interpretation of the analyses. Accordingly, the responsibility for hydrocarbon monitoring should be clearly fixed on the co-chief scientists who are in overall charge of the scientific staff and laboratories on the vessel. The co-chief scientists should never allow operations to continue if at any time, in their judgment, they feel the safety guidelines detailed in this issue are not being met. Further advice on hydrocarbon monitoring is given in Appendix 1.

It is desirable that the designated Operations Superintendent for a particular leg and at least one of the co-chief scientists should be present at the Safety Panel meeting held to consider that leg. Furthermore, on any leg where the geology of the region is known to be generally favorable for petroleum occurrence, the scientific staff on board the vessel should include a petroleum geologist with a significant amount of experience in the planning and evaluation of exploratory and development wells drilled for oil and gas.

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PRECAUTIONS IN CHOICE OF DRILL SITES

Thickness and Character of Underlying Rock Strata

It is basic both to the general program and to pollution prevention and safety to make, in advance, the best possible estimate of the total thickness of the sedimentary section at a proposed drill site and the probable nature of the rocks to be penetrated. Thickness of sedimentary strata above igneous or metamorphic basement is one of the most useful factors in initially deciding whether or not the section at a drill site has potential petroleum hazards resulting from thermochemical action on organic matter in the sediment. It is difficult to predict in advance of drilling whether or not there has been an adequate supply of organic matter in a section to have allowed substantial petroleum generation. However, seismic information can usually provide reasonably accurate advance information on the sedimentary thickness at a proposed drill site. If there is a lack of any definite information on the absence of petroleum source material, thick sedimentary sections (1500 m or more) must always be looked on as possible progenitors of petroleum and should be drilled with appropriate caution.

For purposes of considering petroleum hazards, oceanic areas may generally be divided into those with more than 1000 m of sediment above basement (most of the shelves, slopes, and rises adjacent to continents or islands; many of the small ocean basins and oceanic troughs; and a few sediment-filled basins far from land in the main oceans), and those with less than 1000 m of sediment (constituting most of the vast central areas of the major oceans, the mid-ocean ridges, and many trenches and local areas nearer to land).

Sedimentary columns less than 1000 m thick usually have not experienced sufficient geothermal heating to generate abundant <u>in situ</u> liquid petroleum. Such areas of thin sediments are thus relatively free of petroleum hazards provided that the following conditions are also fulfilled:

a) These areas should be so situated that there is no possibility of them having once been more deeply buried.

b) Such areas should not be at the wedging-out margins of adjacent sedimentary basins with thicker columns of potential oil-generating sediments from which lateral migration could have taken place.

c) Such areas should not have experienced greater than normal heat flow than in basins developed over areas of initial sea floor rifting.

In general, the Safety Panel considers the vast central oceanic areas with only 500 m or less of sediment above basement to be nearly free from petroleum hazards. Even in such areas, however, consideration must be given to the possibility that thick, older sedimentary sections may underlie the present acoustic basement (usually oceanic basalt) or that accumulations of biogenic methane may be present.

Obviously, hydrocarbon hazards are greatly increased if there are good potential reservoir strata in the section. This factor has an important modifying effect bearing on safety conclusions based purely on thickness and probable organic content. Seismic data and regional geologic considerations may give helpful information on the probability of substantial reservoirs being present.

The anticipated presence of evaporites, over-pressured shales, gas-hydrate zones, and other tight seals, below which hydrocarbons may be trapped, has an important bearing on the depth to which a drill hole can be carried safely. Likewise, the presence of diapirs is a danger signal.

Structural Attitude and Probability of Traps

Equally as pertinent as the "thickness of sediment" factor in evaluating the risk of drilling a site is whether or not the hole is likely to penetrate a trap capable of holding hydrocarbons. It is required by the Safety Panel that at least one continuous seismic profile be obtained across any prospective deep sea drilling site and that two intersecting profiles approximately at right angles be obtained for any prospective drilling location on the shelf, slope, or rise or at any site where a single profile suggests the possibility of local trap closure. Features of structural significance to be considered on the seismic profiles include folds, faults, pinch-outs, unconformities, and diapirs. Any sort of structural or stratigraphic trap within the section to be penetrated should be avoided in the choice of drilling locations. While reliance must be placed primarily on seismic sections for the identification of traps, additional available lines of evidence such as gravity, magnetics, and detailed bathymetry may also be helpful.

If drilling is proposed in regions where the thickness and character of the rock sequences suggest adequate hydrocarbon source possibilities, then quality of seismic control is a critical factor. Migrated or depth seismic sections may be required to evaluate faults as migration pathways. Maps on key horizons are necessary to document local structure and structural trapping possibilities. Other types of maps based on regional depths of intersecting surfaces (pinch-outs) may be needed to evaluate possible stratigraphic traps.

It often happens that site proponents tend to put drilling locations at the crests of structural highs because such sites represent minimum drilling distances to stratigraphic objectives. These sites are, however, the most hazardous places to drill because of the danger that they or their flanks may trap petroleum. The site proponents and the JOIDES scientific panels are urged that, in their initial selection of locations, they should seek places off-structure where the desired objectives can be reached, even if this action means some extra drilling distance.

Known Oil and Gas Occurrences

In planning a drilling leg, information on all known or suspected oil and/or gas seepages or other hydrocarbon occurrences close to the proposed sites of that leg should be obtained. This information is most important with respect to prospective locations on continental margins, and both on-shore and offshore data are desirable. Shallow piston cores at proposed sites may yield useful advanced information on hydrocarbon concentrations in the surface sediments of these areas. Petroleum companies who hold or have held acreage in the general vicinity are a good source for this type of information.

Abnormal Pressures

Areas and stratigraphic intervals in which fluids are under greater than normal hydrostatic pressure should be avoided as they represent hazards to safety because of their common association with gas or oil and because of the danger of blowouts. The presence of undercompacted shale is a warning that fluids will be encountered at more than normal hydrostatic pressure. (An undercompacted shale is one in which fluid expulsion has not kept pace with increased fluid pressure, so that the formation fluid in the shale and associated sands are not only under hydrostatic pressure but also carry part of the weight of the overlying rock column.) Fluid pressures within such shales could also have a component of pressure generated internally by buoyant forces related to contained gas. Undercompacted shales often may be identified in advance of drilling by means of velocity inversions or decreases in seismic interval velocity due to their abnormally high fluid content.

They may also appear in seismic sections as distorted bedding, usually strongly convoluted. Undercompacted shales may show up on gravity profiles because of their lower density. Absence of a velocity inversion does not, of course, preclude abnormal formation pressure, nor does the presence of a velocity inversion always result from an undercompacted shale section. Consequently, drill sites at which marked velocity inversions are detected should be avoided unless the inversion can be related to some other lithologic change.

High Geothermal Gradients

If possible, heat flow data should be acquired at prospective drilling sites because higher than normal temperatures are commonly associated with above normal pressures and hydrocarbon accumulations.

Water Depth

The dangers of oil and gas blowouts to the safety of the vessel and its personnel diminish greatly with increasing depth of water. Thus, while violent surface blowout might occur in water depths as great as 500 m, there would appear to be little likelihood of such blowout dangers at 2000 m or more. However, quiet escape of oil or gas into the sea with consequent risk of pollution of ocean waters and loss of valuable hydrocarbon resources can occur while drilling in any water depth.

Significance of Gas Hydrates to Safety of Drill Sites

Certain gases, including the light C_1-C_3 hydrocarbons, hydrogen sulfide, and carbon dioxide can combine with water to form a stable solid clathrate (gas hydrate) structure under the low temperatures and high fluid pressures of sediments just below the deep ocean floor. Because of steadily increasing temperatures downward below the ocean floor, the clathrate structure is stable only within a limited thickness of the upper part of the sediment column. At greater sediment depths, temperatures are such that gas hydrates cannot exist in spite of the increasing pressure with depth. The thickness of the potential gas-hydrate zone varies with water depth (pressure), local bottom water temperatures, local geothermal gradients, and gas composition. In very deep water, gas-hydrate stability zones may extend to sub-bottom depths of up to about a thousand meters. In the sediments above the depth of critical decomposition temperature, any excess methane will theoretically be combined with water to form the solid clathrate. Below this critical depth, solid gas hydrates will not be formed, and those which may have been formed at shallower depths will decompose as deposition and subsidence, or deposition alone, bring about temperatures at which gas hydrates are unstable.

The phase change at the depth of gas-hydrate decomposition is associated with velocity and density changes that may result in a pronounced seismic reflector which mimics sea floor topography. Such reflectors have been referred to as "bottom simulating reflectors" or "BSRs." A BSR caused by a gas hydrate is commonly associated with an inversion in seismic velocity resulting from the denser, faster sediment containing a gas hydrate overlying the less dense, seismically slower sediment containing free gas. A BSR that cuts across bedding reflectors at a sub-bottom depth that increases slightly with increasing water depth, and that occurs at a depth that is consistent with temperatures of gas-hydrate decomposition, can provide an indirect geophysical means of predicting the presence of a zone containing a gas hydrate.

Small quantities of carbon dioxide, ethane, and propane have a stabilizing effect on the gas-hydrate structure while increased salinity has a destabilizing effect. In deep sea sediments, the best estimates of gas-hydrate stability are given by experimental work on the pure methane (CH_4)-pure water system because methane is, for practical purposes, the only gas present and salts are excluded during gas-hydrate crystallization.

The phenomenon of methane-hydrate formation provides both a safety factor and a hazard in ODP drilling. Over much of the ocean area at water depths greater than about 300 to 1000 m (depending on latitude and bottom-water temperature), any excess methane present in the sediments within the gas-hydrate stability zone should be immobilized in the form of a gas hydrate. In theory, the gas-hydrate stability zone may be drilled without danger of gas release.* Beneath the gas-hydrate stability zone, however, a gas-hydrate layer may cap and seal reservoir rocks which are filled with gas in large volume and at high pressures. Moreover, such trapping may occur not only in geologic structures or pinch-outs, but also in flat-lying beds, merely due to possible temperature-related irregularities in the lower surface of the gas-hydrate stability zone. Dangerous, high-pressure gas accumulations may be expected particularly where previously formed gas hydrates have decomposed in porous and permeable sediments at the base of the gas-hydrate stability zone.

In view of these considerations and the limited pressure control equipment of JOIDES RESOLUTION, the Safety Panel policy has been that drilling should not be carried into the strata underlying the gas-hydrate stability zone in a section where there is evidence for the occurrence of abundant methane and the presence of reservoir strata. For each hole where gassy sediments are expected and penetration of more than 250 meters is planned, calculations should be made based on bottom-water temperatures, overburden pressures (water and rock), and the probable geothermal gradient to show the lower limit of the theoretical methane-hydrate zone (see Appendix 2). The drilling program should be planned accordingly and presented for review to the Safety Panel.

*Although drilling operations may increase local temperatures and release some gas into the hole, it seems probable that such release will be so narrowly limited to the immediate proximity of the hole that there will be little possibility of any substantial gas escape or gas blowout.

Although drilling within the gas-hydrate stability zone usually offers a margin of safety against gas blowouts or gas escape, two additional important factors should be borne in mind:

a) Gas generated within or entering the gas-hydrate zone from below will be stabilized in the solid form only so long as sufficient water is present. If all the available water is used to form gas hydrate, then any additional methane would be present as gas.

b) Even within the zone of gas-hydrate stability, the normal dangers of oil leaks and oil blowouts persist wherever there are possibilities of encountering oil accumulations.

Coring of gas hydrates has confirmed their existence within continental margin sediments in three regions: the Blake Outer Ridge off southeastern United States, the upper landward slope of the Middle-America Trench off Mexico, Guatemala and Costa Rica, and the Gulf of Mexico and offshore Louisiana. Other areas where geophysical evidence (BSR) and the geologic setting suggest that gas hydrates may be well developed are offshore Peru-Chile, on the upper landward slope of the Japan Trench and the Nankai Trough, and in the northern Indian Ocean. Under conditions of active marine sedimentation, the main requirement for gas-hydrate development appears to be preservation of sufficient organic matter to sustain prolonged microbial methanogenesis in the sediments. Oceanic regions with high organic productivity and oxygen depletion in the water column are places where this requirement is most likely to be fulfilled. Site surveys in such regions should be tailored to provide maximum seismic resolution in the uppermost 1 km of sediment in order to evaluate the possibility of gas hydrate occurrence. (See Figure 4.)

Figure 4: Hydrate-cemented vitric sand recovered in DSDP Hole 498A (Leg 67-Middle America Trench) - Sample 498A-15-2, 110-125 cms. As the hydrate melts, sand grains are incorporated into a clay-rich slurry. This shows the vents for gases released by the melting of the hydrates. [From Harrison, W.E. and Curial, I.A., 1982. Gas hydrates in sediments of Holes 497 and 498A. In Aubouin, J., von Huene, R., et al., Init. Rpts. DSDP, 67: Washington (U.S. Govt. Printing Office), 351-382.]

Weather

Acquisition of data on weather conditions throughout the year is essential for choosing the optimum season for drilling in a particular area. The JOIDES Planning Committee and the Science Operator should be familiar with anticipated weather and sea conditions at the sites of a proposed leg so that timing can be adjusted to minimize hazards which might occur because of weather or to avoid the need for abrupt termination of drilling due to anticipated weather. In high latitudes, information on ice conditions is, of course, an important safety consideration.

Political Considerations

Questions of political jurisdiction over areas in which the ODP is operating may involve problems due to conflicts between various national claims and due to uncertainties regarding national boundaries at sea. Different countries may also have different standards with respect to pollution prevention. It is not appropriate for the Safety Panel to take responsibility for problems of this nature because their solution involves international law and top-level policy for the ODP. The Safety Panel would like the JOIDES Planning Committee, the Science Operator, and the Co-chief Scientists to supply information on distances of sites from shore and probable political jurisdictional control at each site. This information will enable the Safety Panel to call attention to possible political difficulties.

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PRECAUTIONS IN PLANNING DRILLING PROGRAMS FOR INDIVIDUAL HOLES

Depth of Penetration

In general, a penetration to no more than 50 m of section or to refusal of the advanced piston corer, even on top of a structure, is not considered hazardous because a high pressure hydrocarbon accumulation would be unlikely at such shallow depths in relatively unconsolidated sediments. However, any deeper penetration should depend on the assurance with which the absence can be established of a dangerous combination of hydrocarbon sources, structures, and potential reservoirs.

Coring Program

The current standard policy for ODP drilling is continuous coring of all holes unless the site has been drilled before. Deviation from this policy requires approval by the JOIDES Planning Committee for possible science omissions, and by the JOIDES Pollution Prevention and Safety Panel and the Science Operator for safety reasons. Examination of cores and fluids obtained from the hole is the only means currently available for direct monitoring of hydrocarbons or other indications of potential hazard.

Re-entry

The greater depths of penetration provided by re-entry capability obviously increase the chance of encountering hydrocarbon reservoirs and the risk of blowouts. The re-entry cabability, however, may also be of some value in aiding pollution prevention and safety because it facilitates the utilization of well logs before reaching final depth in a hole and can be a means of testing cement plugs in the drilled holes.

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MEASURES FOR EARLY DETECTION OR ANTICIPATION OF HYDROCARBONS DURING DRILLING

Prompt Examination of All Cores and Samples of Drilling Fluid for Shows of Oil or Gas

Every new ODP hole drilled is to a large extent a venture into the unknown, no matter how carefully the site was picked and the drilling program planned, or how assured its prognosis seems to be. Constant vigilance with regard to detection of hydrocarbons and the approach to hydrocarbon accumulations should be observed throughout the drilling at every site where such accumulations are a possibility.

Routinely, a visual examination should be made of each core as soon as it is removed from the barrel. A designated member of the shipboard scientific party should promptly examine all cores and fluid recovery for obvious hydrocarbon shows, and those shows which appear to be significant should be analyzed immediately by qualified personnel. In addition, appropriate samples should be removed regularly and quantitatively analyzed for the content of dissolved hydrocarbon gases in the sediments. Examination of sediments by qualitative solvent extraction, ultra-violet fluorescence, or pyrolysis assay may also indicate the presence of migrated hydrocarbons.

The principal questions to be answered promptly from the examination of samples are: 1) Have hydrocarbon-bearing strata been penetrated that could pollute ocean waters or adjacent strata or cause a hazard to safety?, and 2) What warning signals regarding safety and pollution prevention can be found that may bear on the advisability of discontinuing drilling?

The significance of hydrocarbon shows with respect to the above questions is obviously very great, but this significance can be evaluated properly only in the light of many other factors such as:

a) the general geologic background of the region

b) the probable lithologic and lithogenetic character of the section to be penetrated and that already penetrated

c) the petroleum indications elsewhere in the region

d) the records of other holes drilled in the vicinity

e) the probability of encountering reservoir rocks

f) the probability of source rocks

g) the probability of evaporites or undercompacted shales in the section

h) the observed or estimated temperature-pressure conditions with respect to gas-hydrate formation

i) the probability of structural or stratigraphic traps

j) the water depth

k) the proposed drilling and coring program

Probably the best guideline that can be given is that drilling should be stopped immediately whenever hydrocarbons or hydrocarbon indications are encountered under circumstances which suggest the presence of, or proximity to, substantial accumulations of either hydrocarbon gas or oil.

There are several features of the chemical composition of the hydrocarbons detectable in cores or samples of drilling fluid that may contribute importantly to a proper understanding of the processes involved, and on the basis of this understanding an intelligent decision on where to drill can be made. Although no one of these features by itself provides the basis for any hard and fast rule for deciding when drilling a hole should be stopped, these features, taken together, are so significant that acquisition of such geochemical information from all samples is strongly urged.

The identification and determination of the chemical and physical properties of any gas, liquid, or solid petroleum or petroleum-like substance will, of course, be critically important with respect to whether dangerous accumulations have been encountered or may be imminently expected. The composition of hydrocarbon gas shows may be of significance in distinguishing gases of biogenic origin (or other origin not associated with oil) from thermochemical hydrocarbon gases which have leaked from some underlying oil and gas accumulation. Gases which have been associated with liquid petroleum commonly have a C_2-C_5 (ethane through pentane) content of several percent of the total hydrocarbons in the gas phase. Between this extreme and the more frequent occurrences of gas consisting of methane as the only hydrocarbon detectable by thermal conductivity-gas chromatography, there have been sediment gas shows in holes in which the methane is accompanied by very small but significant quantities of ethane (C_1:C_2 is on the order of 10^6 to 10^3:1). In many of these cases, the relative ethane content has shown increases in an erratic but overall exponential fashion with increasing depth of penetration. Ethane appears to result from slow in situ generation by thermochemical processes beginning at relatively low near-surface temperatures and increasing with depth. It has also been postulated that, under certain conditions, bacteria may have been capable of generating minor amounts of ethane. In any case, it should be emphasized that it is primarily the quantity of hydrocarbon gas and the possibilities of its accumulation and trapping that pose the potential danger. Of secondary importance is the origin or composition, both of which are useful for an understanding of the nature of the occurrence.

Because the degree of generation of petroleum liquids and gases from organic matter in source rocks is closely related to the temperatures which these source rocks have experienced, it is important to determine the stages of temperature alteration (thermal maturity) which the organic matter in ODP core samples has attained. Thermal maturity may be estimated from the chemical composition of sediment gas, the distribution of solvent-extractable hydrocarbon constituents, pyrolysis assay, and by the coloration and reflectance of detrital organic particles. The use of these techniques to determine maturation of organic matter is discussed in the reference works cited on Page 5 and especially in Pages 515-540 of Tissot and Welte, 1984.

The general level of thermal maturity of the organic matter in the sediments being drilled must be known in order to evaluate the significance of hydrocarbon shows encountered during ODP drilling. The presence of petroleum of high temperature origin, such as wet gas or typical crude oil, in a sedimentary sequence containing thermally immature disseminated organic matter, implies that a migration pathway from a deeper, hotter sediment source has existed. In contrast, sequences that are unusually rich in organic matter sometimes contain locally migrated immature bitumens. However, it would be difficult using shipboard geochemical techniques to distinguish between an immature bitumen and a biodegraded mature crude oil residue.

It is the recommendation of the Safety Panel that ODP drilling be stopped immediately if migrated hydrocarbons are detected. It is possible that knowledge of the geologic circumstances could sufficiently mitigate the risk of a spill or blowout to permit the resumption of drilling. However, a decision to resume drilling should be made only after a thorough evaluation by re-

sponsible shipboard personnel, and in consultation with shorebased ODP operations.

In addition to thermal maturity and origin of hydrocarbons, it is important to make some estimate of the quantity of hydrocarbons associated with a given quantity of sediment. A quantitative estimate of hydrocarbon content (either gas, liquid, or solid) is critical to the evaluation of whether hydrocarbons are migrated or indigenous. Abrupt changes in hydrocarbon contents of cores could also signal the presence of a hydrocarbon accumulation at greater depth. Recommended procedures for routine quantitative monitoring of hydrocarbon contents of sediments cored by JOIDES RESOLUTION are summarized in Appendix 1 of these Guidelines.

Continuous Observation of Drilling Rate

The drilling rate should be continuously monitored for changes which might indicate potential hazards. For example, sudden increases in the drilling rate may be a warning of entry into an undercompacted shale, with associated conditions favorable to hydrocarbon entrapment.

Temperature and Pressure Determinations

To a certain extent, hydrocarbon accumulations have been noted to be associated with abnormal temperature gradients. With a temperature measuring device available, it should be possible to detect anomalously high geothermal gradients. The pressure core barrel may be useful for confirming the presence of over-pressured shales as well as gas hydrates.

Well-logging

One of the principal values of routine logging (electrical, sonic, or nuclear) is that it provides a continuous record of the hole through intervals that were drilled without coring and through intervals where core recovery was poor. The probable increase in the number of holes where change of bits and reentry will be required to attain objective depths makes it advisable for pollution prevention and safety purposes, as well as for other reasons, to have a well-logging capability on board and to consider logging each stage of penetration before resumption of drilling. Such logs will provide a means of detecting oil and gas reservoirs in the section and should be a "must" for holes requiring deep penetration into thick, potentially hydrocarbon-generating sedimentary sections.

At deep continental margin sites, the running of well logs from time to time during drilling may be very helpful in determining the depth to which a hole can be carried safely. The ODP logging program of Lamont-Doherty Geological Observatory will provide invaluable scientific records of the holes for future reference.* In addition the program will be of value with respect to pollution prevention and safety through help in the identification of reservoir and sealing rocks, undercompacted shales, detection of hydrocarbons, and determination of the character of fluids filling the pore spaces of the rocks penetrated.

*For further information on the logging program see the Wireline Logging Manual by the Borehole Research Group of Lamont-Doherty Geological Observatory, March 1985.

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MEASURES FOR COPING WITH FLUID FLOWS ENCOUNTERED OR ANTICIPATED DURING DRILLING

Drilling Practices

Rapid pipe or tool movements which may either induce flow into the hole or fracture the formation are to be avoided.

Early Abandonment

If hydrocarbons are detected under conditions suggestive of substantial accumulations or imminent approach to such accumulations, drilling should be stopped and the hole immediately plugged.

Plugging and Abandonment Procedures

a. With cement

The hole should be filled with viscous gel barytes mud of about 75 pound per cubic foot allowing extra volume for hole enlargement and loss during displacement. The hole should be filled to the uppermost competent layer and a cement plug spotted. A minimum size plug should be 200 sacks and 12 to 15 lb./gal. Where possible, a plug catcher or calibrated displacement tanks should be used in placing the cement.

If hydrocarbons have been encountered or are suspected and the hole has penetrated semi-consolidated or consolidated formations, the proper placement of the cement should be confirmed by feeling for it with the drill string or recovering a cement sample with the core barrel. The cement plug should be calculated to be no less than 15 m in length in the appropriate hole size and preferably closer to 30 m in length.

b. Without cement

The hole should be filled with viscous gel barytes mud of about 75 pound per cubic foot, allowing extra volume for hole enlargement and loss during displacement.

Standard Abandonment Procedures

a) All holes drilled in consolidated or semi-consolidated sediments which are on the shelf, slope, or continental rise should be plugged with cement.

b) All holes drilled in unconsolidated sediments on the shelf, slope, or continental rise and all other holes in unconsolidated sediments in which shows of oil or gas are encountered should be filled with mud.

c) Holes in the deep ocean beyond the continental margin in unconsolidated sediments in which no shows of oil or gas are encountered or holes in igneous rocks may be abandoned without plugging.

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APPENDIX 1
HYDROCARBON MONITORING IN ODP HOLES

The JOIDES Pollution Prevention and Safety Panel traditionally has encouraged vigilance and care in the monitoring of hydrocarbons in DSDP and ODP cores. Previously, the Panel has not given any specific advice about actions to be taken when hydrocarbons are observed and has not provided detailed guidelines for termination of drilling because of the difficulty of specifying in advance all the possible factors that influence such a decision. Moreover, it has been felt that the Safety Panel's proper role is pre-drilling site review, and that to extend too far beyond general advice in the area of shipboard operations might interfere with informed and balanced judgments by responsible parties facing real rather than hypothetical situations.

It is now considered that it should be possible to provide guidelines in certain areas that will make it easier to follow the general safety advice. This Appendix attempts to do this in the area of hydrocarbon monitoring.

These Guidelines advise that drilling should be stopped when hydrocarbons or hydrocarbon indications "are encountered under circumstances which suggest the presence of, or proximity to substantial accumulations of either hydrocarbon gas or oil" (P.22). Hydrocarbons are ubiquitous in sediments and detection is limited only by analytical sensitivity. Therefore, it is the amount and composition of the hydrocarbons, in relation to the mode of occurrence in the core and the general geologic setting, that must be evaluated rather than presence or absence of hydrocarbons. Two key factors in the evaluation of hydrocarbon shows are determining whether occurrences are normal or anomalous and whether these shows are indigenous or migrated. (This information is only background for safety evaluation, however, because normal, indigenous hydrocarbons still can be hazardous.) Normal or anomalous refers to whether or not the hydrocarbon occurrence is what would be expected under the prevailing geologic circumstances. Evaluation of indigenous or migrated nature of hydrocarbon occurrences requires quantitative and qualitative assessments. If hydrocarbons are present in amounts that are too large for the level of total organic matter in the sediments (e.g. as measured by total organic carbon), then this result indicates that the hydrocarbons are likely to have migrated. In addition, a hydrocarbon occurrence with composition indicative of origin at higher temperatures than have been experienced by the sediments being drilled also implies migration.

The Safety Guidelines specify that all forms of hydrocarbons, whether gas, liquid, or solid, should be monitored visually in the cores, and advise that routine instrumental monitoring should be employed. In the past it was common that laboratory analyses for hydrocarbons were performed only in the case of visual evidence such as gas pockets, oil-stains, or asphalt-filled veins or vugs. In ODP, a program of routine analyses of organic matter has been implemented so that analyses are performed at regular intervals, in addition to those places where visual evidence for hydrocarbons occurs. This program consists of head-space gas analysis, measurements of organic carbon content, and thermal analysis/pyrolysis (Rock-Eval). Collection of data in a systematic fashion helps to establish normal trends against which anomalous hydrocarbon occurrences can be recognized.

During the past history of ocean drilling, the most frequently used hydrocarbon monitoring technique has been the analysis of gas pocket (vacutainer) samples and interpretation of methane/ethane (C_1/C_2) ratios. Formation of sufficient gas to result in a gas pocket when cores are brought to the sea surface usually depends on the process of microbial methanogenesis occurring in the sediments. This microbial methane provides the gas phase into which any migrating petroleum-related hydrocarbons could partition and be detected by subsequent analysis. In contrast to the analysis of gas pocket samples, the headspace gas analysis employs helium as the gas phase to extract hydrocarbons from sediments. Proper interpretation of results of the headspace gas technique requires that a background of experience be developed.

In contrast to the headspace gas technique, which has only been used infrequently in ocean drilling, there is an extensive body of data showing trends of hydrocarbon composition with depth for gas pocket (vacutainer) samples. These generalized trends are summarized in Figure 1-1 as C_1/C_2 ratios vs. depth. For indigenous gas of biogenic origin, C_1/C_2 decreases with increasing depth of burial. The magnitude of the ratio and the rate of decrease depend on the thermal gradient and the organic matter content. These trends result from the progressive addition with depth of small amounts of ethane and heavier hydrocarbons to pure methane of microbial origin. The presence of migrating petroleum hydrocarbons also causes an anomalous decrease in the C_1/C_2 ratio. Figure 1-1 (selected from a review of gas pocket samples analyzed through Leg 84 of the Deep Sea Drilling Project) shows only a few cases where C_1/C_2 ratios drop below 500 at shallow depths.

Sediments with C_1/C_2 ratios significantly lower than 500 were cored in DSDP Holes 88, 477, 481, and 570. Hole 88 was drilled above a salt dome in the Gulf of Mexico. The high ethane content of Hole 88 gases undoubtedly indicates the

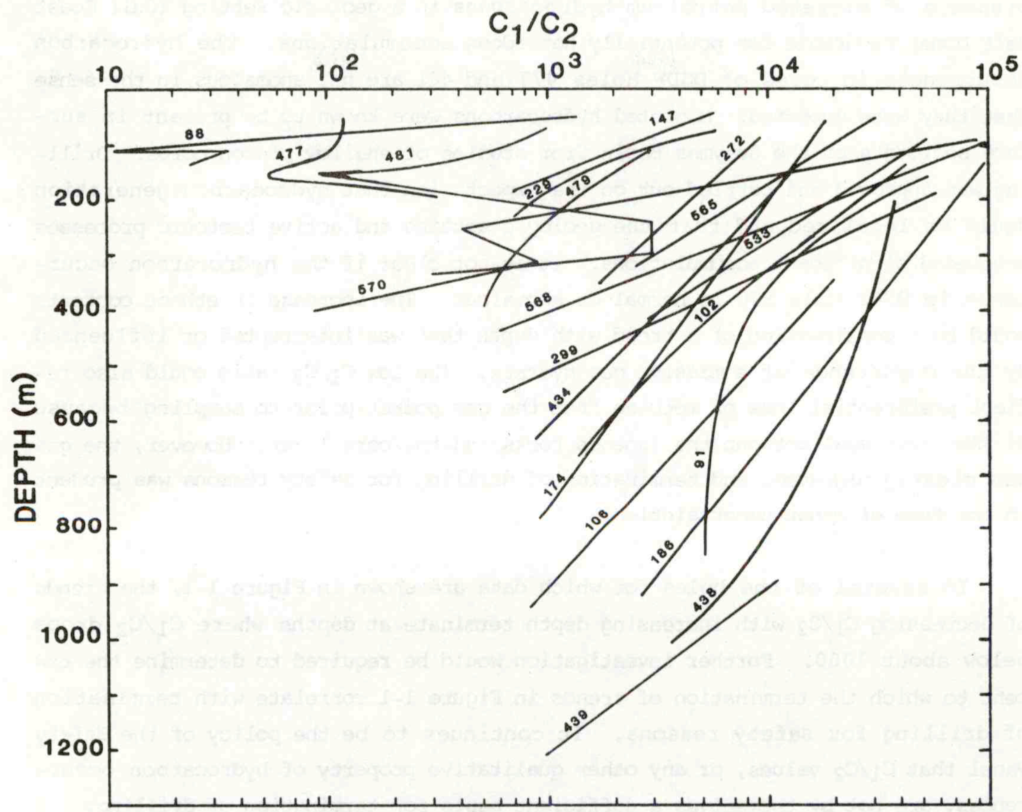

Figure 1-1: Methane to ethane ratios (C_1/C_2) of gas pocket (vacutainer) samples with depth of burial for selected DSDP sites. [Constructed from Init. Rpts. DSDP series, 1973-1985, vols. 10-85: Washington (U.S. Govt. Printing Office).]

presence of migrated petroleum hydrocarbons. Holes 477 and 481 in the Guaymas Basin rift were drilled through Quaternary sediments intruded by dolerite sills. The C_1/C_2 trends in cores from these holes reflect localized hydrocarbon generation associated with igneous and hydrothermal alteration of organic matter in the sediments. DSDP Hole 570, in the upper slope sediment of the Middle-America Trench, penetrated 374 m of sediment and 27 m of basement composed of serpentinized peridotites. Low C_1/C_2 ratios in the serpentinite caused abandonment of the hole for safety reasons. It was speculated that the hydrocarbons migrated from sediments beneath an overthurst ophiolite. Alternatively, the gas in the serpentinite could have been related to gas hydrate in the overlying sediment in Hole 570.

The hydrocarbon shows in Pleistocene sediments of DSDP Hole 88 are clearly anomalous and demonstrate the capability of the gas pocket samples to reveal the presence of migrated petroleum hydrocarbons in a geologic setting (Gulf Coast Salt Dome) favorable for potentially hazardous accumulations. The hydrocarbon occurrences in cores of DSDP Holes 477 and 481 are not anomalous in the sense that they were expected. Migrated hydrocarbons were known to be present in surface sediments of the Guaymas Basin from studies of shallow piston cores. Drilling was approved and carried out on the expectation that hydrocarbon generation would be localized and that the geologic setting and active tectonic processes precluded significant accumulations. It is not clear if the hydrocarbon occurrence in DSDP Hole 570 is normal or anomalous. The increase in ethane contents could be a continuation of a trend with depth that was interrupted or influenced by the occurrence of a massive gas hydrate. The low C_1/C_2 ratio could also reflect preferential loss of methane from the gas pocket prior to sampling because of the poor seal between the igneous rocks and the core liner. However, the gas was clearly migrated, and termination of drilling for safety reasons was prudent in the face of other uncertainties.

In several of the holes for which data are shown in Figure 1-1, the trends of decreasing C_1/C_2 with increasing depth terminate at depths where C_1/C_2 drops below about 1000. Further investigation would be required to determine the extent to which the termination of trends in Figure 1-1 correlate with termination of drilling for safety reasons. It continues to be the policy of the Safety Panel that C_1/C_2 values, or any other qualitative property of hydrocarbon occurrences, are not by themselves a sufficient basis for termination of drilling.

The usefulness of other hydrocarbon monitoring techniques such as headspace gas analysis and pyrolysis assay will be enhanced to the extent that data are systematically collected in a variety of deep sea sedimentary environments. Headspace gas analyses also provide some information on the quantity of gas present in the sediments. As indicated in the Safety Guidelines, it is the quantity of gas encountered in drilling that is of primary concern; understanding of the composition and the possible origin of hydrocarbon gas is important in order to help avoid gas in hazardous quantities. The headspace gas technique provides an estimate of the amount of gas dissolved in the pore water of the sediments. However, the amount of gas that can be retained in solution under surface conditions is much less than the amount that can be dissolved in the pore waters at depth. Therefore, in gassy sediments the quantity of gas measured by the headspace technique will be a minimum because the gas in excess of solubility at surface condition will have escaped from the cores (unless the gas is retained in the metastable solid hydrate form).

In the absence of a functioning pressure core barrel and shipboard systems for degassing confined core samples, there is no method for accurately estimating the quantity of gas associated with a given quantity of sediment. A qualitative scale for rating the amount of gas in cores, called Gas Quantity Factor (GQF), has been developed by Glen Foss (Supervisor, Drilling Operations, ODP/TAMU). The GQF scale is useful as a guide based on past observations.

GQF 0 - No noticeable degassing or detectable hydrocarbons in core tube (vacutainer) samples.

GQF 1 - Detectable hydrocarbon gas but insufficient for reliable analysis. No notable pressure, separations, or bubbling.

GQF 2 - Sufficient hydrocarbon gas for analysis of core tube samples. Widely scattered bubbling and/or separations.

GQF 3 - "Frying" or "chirping" sounds of gas bleeding from indurated cores. Slight bulging of end caps in storage rack. Minor checking and cracking in softer cores.

GQF 4 - Pronounced bubbling of gas from core on retrieval. Numerous small separations in soft cores. Strong bulging of end caps.

GQF 5 - Numerous large separations in soft cores. End caps blown off. Small amounts of soft core extruded from sections on rack.

GQF 6 - Indications of pressure before opening core barrel--water forced out through check valve at top of barrel. Pronounced expansion of soft core on removal from barrel.

GQF 7 - Core catcher forcibly blown off. Very large gas-filled voids in core liner.

These GQF guidelines do not necessarily indicate safe operational limits. However, the GQF can be used to estimate trends of relative gas content with depth. The last two stages (GQF 6 and 7) may indicate presence of gas hydrates in the cores.

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for the quantity of gas associated with a given quantity of sediment. A qualitative [illegible] for judging the amount of gas in cores, called the Gas Quantity Index (GQI), has been developed by [illegible] (personal communication, [illegible]). The GQI scale is listed [illegible] based on [illegible] observations.

GQI 0 - [illegible] of gas [illegible] core [illegible] samples.

GQI 1 - Essentially no reaction and has the fluidity for reliable analysis. No evidence of pressure, separations, or bubbling.

GQI 2 - Sufficient gas [illegible] for analysis of core [illegible] samples. Widely scattered bubbling and/or separations.

GQI 3 - Escape of [illegible] sounds of gas bleeding from [illegible]. Light [illegible] bubbling [illegible] to storage [illegible]. Minor cracking and [illegible] in softer [illegible].

GQI 4 - [illegible] bubbling of gas from core on [illegible]. Noticeable small separations in soft core. Strong smell of bad eggs.

GQI 5 - Numerous large separations in soft cores. End caps blown off. Small amounts of soft core extruded from sections on deck.

GQI 6 - Indications of pressure before opening core barrel--water forced out through check valve at top of barrel. Extensive expansion of soft core on removal from barrel.

GQI 7 - Core catcher forcibly blown off. Very large gas-filled voids in core liner.

These GQI guidelines do not necessarily indicate the occurrence of hydrates. However, the GQI can be used to estimate trends of relative gas contents with depth. The last two stages (GQI 6 and 7) may indicate presence of gas hydrates in the cores.

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APPENDIX 2
ESTIMATING THE DEPTH OF THE GAS-HYDRATE STABILITY ZONE

At the high pressures and low temperatures characteristic of deep-sea environments, methane and water combine to form the solid, non-stoichiometric inclusion compound or clathrate, methane hydrate (CH_4:$6H_2O$). At high latitudes, with bottom-water temperatures of 1°C or less, the pressure requirement for methane-hydrate stability in surface sediments is provided by water depths as shallow as 300 m. At lower latitudes the minimum water depth and pressure required for methane-hydrate stability in surface sediments depends on the vertical temperature structure of the water column, but typically water depth of 500 m is sufficient. A third requirement for methane-hydrate stability (in addition to an appropriate combination of temperature and pressure) is a dissolved methane content such that the pore water is saturated with respect to methane hydrate. Except in areas of active gas seepage from depth (i.e., below 1 km), methane is not present in surface (0 to 10 m) sediments at concentrations sufficient to stabilize methane hydrate. Under open ocean conditions, burial depths of 20 m to 80 m usually are required to create the anoxic, sulfate-deficient conditions that permit microbial methane to accumulate in the sediments.

The pressure-temperature relationship for the pure methane:pure water:gas-hydrate equilibrium is shown in Figure 2-1. In estimating the depth of gas-hydrate stability using this phase diagram, pressure and temperature at the sediment-water interface and at various depths sub-bottom are plotted and extrapolated to the intersection with the gas-hydrate:gas:water equilibrium line. The theoretical depth to the base of gas-hydrate stability is equal to the difference between the pressure at the sediment-water interface and the pressure at the intersection of the pressure-temperature gradient through the sediments with the equilibrium line, divided by the pressure gradient. For example, a site in 2500 m of water has a pressure at the sediment-water interface of 250 bars (using hydrostatic pressure gradient of 0.1 bar/m) and a measured mudline temperature of 2.5°C. This pressure-temperature combination is plotted as point A in Figure 2-1. Temperature measurements in the hole at 200 m and 600 m give points B (P = 270 bars, T = 7.5°C) and C (P = 310 bars, T = 12.5°C), respectively, on Figure 2-1. Extrapolation of the line through points ABC intersects with the equilibrium line at point D. The pressure at point D is 330 bars, so the depth at point D would be:

(330 bars - 250 bars)/(0.1 bar/m) = 800 m.

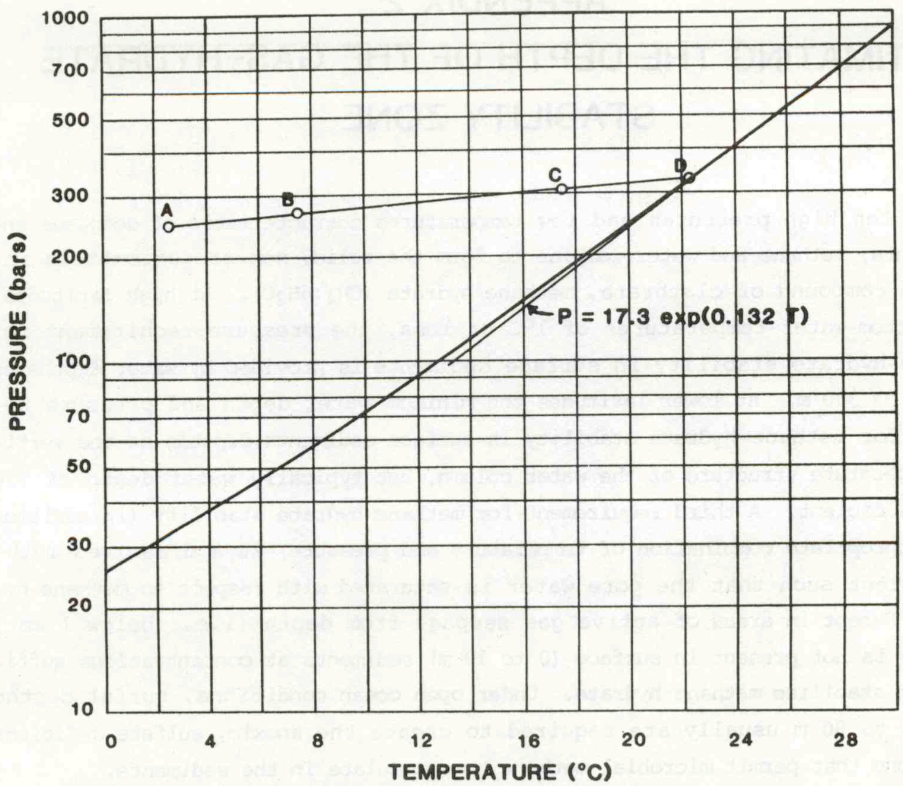

Figure 2-1: Line ABCD is an example of using the diagram for the equilibrium of pure water:pure methane:gas-hydrate to estimate the depth of gas-hydrate stability (see text). In numerical calculations, Equation 1 [P = 17.3 exp (0.132T)] is used. The deviation of this equation from the equilibrium line is also shown. (The equilibrium line is taken from the <u>Handbook of Natural Gas Engineering</u>, D.L. Katz, et al., 1959, New York: McGraw-Hill.)

A more direct way to estimate the depth to the base of the gas-hydrate stability zone is by use of Figure 2-2, which incorporates the assumptions of hydrostatic pressure, bottom-water temperatures based on high latitude water column, and gas-hydrate pressure-temperature equilibrium conditions for pure methane and seawater. Figure 2-2 requires only water depth and geothermal gradient to graphically estimate the depth of gas-hydrate stability. Figure 2-2 is used by projecting horizontally from the water depth (on the vertical axis) to the point of intersection with the curve representing the appropriate geothermal gradient, and then vertically to the depth at the base of the hydrate (on the horizontal axis). The data from the example given above (2500 m water depth, 25°C/km geothermal gradient) yield a depth to base of hydrate of about 817 m, when used with Figure 2-2.

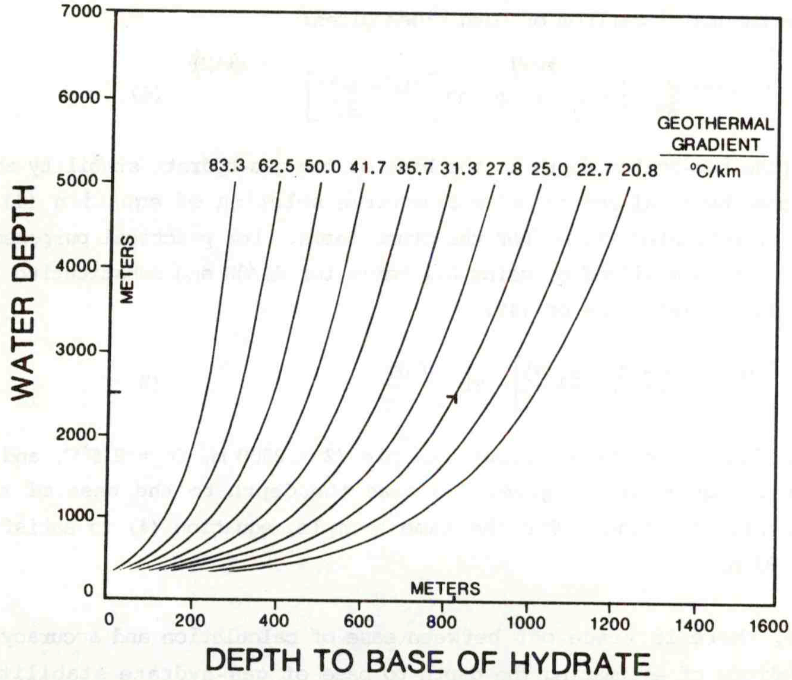

Figure 2-2: Hydrate stability curves for methane in Arctic seawater at hydrostatic pressure. (After MacLeod, M.K., 1982. Amer. Assoc. Petrol. Geol. Bull., 66, 2649-2662.)

A third method for estimating depth to the base of the gas-hydrate stability zone is by numerical calculation. For water depths greater than 2000 m (hydrostatic pressure in excess of 200 bars), the univariant equilibrium for methane:water:methane hydrate is well approximated by the equation:

$$P = 17.3 \exp(0.132\ T) \quad (1)$$

In marine sediments, hydrostatic pressure is given by

$$P = (Z + z)\ dP/dZ \quad (2)$$

and temperature by

$$T = Tb + (z\ dT/dz) \quad (3)$$

where Z is water depth in m, z is sub-bottom depth in m, Tb is bottom-water temperature in °C, dP/dZ is pressure gradient in bar/m, and dT/dz is geothermal gradient in °C/m. Substituting equations (2) and (3) in (1), rearranging, and taking the natural logarithm of both sides gives:

$$\ln\left[(Z+z)\frac{dP}{dZ}\Big/17.3\right] = 0.132\left[Tb + \frac{zdT}{dz}\right] \qquad (4)$$

Depth z (the sub-bottom depth to the base of the gas-hydrate stability zone) can be calculated by trial-and-error or iterative solution of equation (4), using measured or estimated values for the other terms. For practical purposes, equation (4) can be simplified by using 0.1 bar/m for dP/dZ and substituting Z + 600 for Z + z in the left side of (4):

$$z = \left[\frac{\ln(0.0058\ Z + 3.47)}{0.132}\right] - Tb \Big/ \frac{dT}{dz} \qquad (5)$$

Using the data from the previous example (Z = 2500 m, Tb = 2.5°C, and dT/dz = .025°C/m) in equation (5) gives 775 m as the depth to the base of the gas-hydrate stability zone. For the same example, equation (4) is satisfied by a value of 793 m.

Thus, there is trade-off between ease of calculation and accuracy for the various methods of estimating the depth to base of gas-hydrate stability. Use of the P-T equilibrium diagram (Figure 2-1) requires that pressures and temperatures be estimated at a series of depths in a hole. The graphical method (Figure 2-2) may contain assumptions that are inappropriate for a specific site, although a series of diagrams for different salinity and bottom water temperatures would solve this problem. Equation (4) is accurate only over a limited range of pressure and temperature and is difficult to work with. Equation (5) uses a simplifying assumption that introduces error which increases in proportion to the deviation of the depth to base of hydrate from 600 m. Both Figure 2-2 and the equations (4) and (5) assume hydrostatic pressure gradient within the sediments. Gas hydrates are most common in areas of convergent tectonics where significant overpressuring has been observed at shallow depths (e.g., DSDP Sites 542, 565, 567). Availability of accurate subsurface pressure measurements would favor the use of Figure 2-1 for estimating depth to base of gas-hydrate stability.

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APPENDIX 3
MANDATE AND MEMBERSHIP OF THE JOIDES POLLUTION PREVENTION & SAFETY PANEL

The general purpose of the JOIDES Pollution Prevention and Safety Panel is to provide independent advice to the JOIDES Planning Committee and to the Ocean Drilling Program with regard to safety and pollution hazards that may exist because of general and specific geologic circumstances of proposed drill sites.

The Panel's mandate is:

All drilling operations involve the chance of accident or pollution. The principal geologic safety and pollution hazard in ocean drilling is the possible release of substantial quantities of hydrocarbons from subsurface reservoir strata. In most deep sea regions, the risk of hydrocarbon release can be reduced or eliminated by careful planning and proper site surveys. Additionally, safety problems may arise in drilling hot hydrothermal systems for lithosphere targets. Those who plan each Ocean Drilling Program cruise and select its drilling sites are initially responsible to propose only sites that are considered reasonably safe. The JOIDES Pollution Prevention and Safety Panel independently reviews each site to determine if drilling operations can be conducted safely.

The preliminary site survey information and the operational plan are reviewed for each site. Advice is communicated in the form of site approval, lack of approval, or approval on condition of minor site relocation or amendment of the operational plan. Approval is based on the judgment of the Panel that a proposed site can be safely drilled in light of the available information and planning.

Membership of the JOIDES Pollution Prevention and Safety Panel

(as at 1 January 1986)

Dr. George Claypool (Chairman)
U.S. Geological Survey, Denver, Colorado

Dr. Mahlon M. Ball
U.S. Geological Survey, Woods Hole, Massachusetts

Dr. Rustum Byramjee
Total Compagnie Francaise des Petroles, Paris, France

Dr. Graham Campbell
Canadian Oil & Gas Lands Administration, Ottawa, Canada

Dr. Arthur R. Green
EXXON Basin Exploration Division, Houston, Texas

Dr. David B. Mackenzie
presently at Marathon International Petroleum (G.B.) Ltd., London, U.K.

Dr. Gunter Stober
Deminex, Essen, Federal Republic of Germany

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Special Issue No. 1: Manual on Pollution Prevention and Safety, 1976 (Volume II)

Special Issue No. 2: Initial Site Prospectus, Supplement One, April 1978 (Volume III)

Special Issue No. 3: Initial Site Prospectus, Supplement Two, June 1980 (Volume VI)

Special Issue No. 4: Guide to the Ocean Drilling Program, September 1985 (Volume XI)

Special Issue No. 5: Guidelines for Pollution Prevention and Safety, March 1986 (Volume XII)