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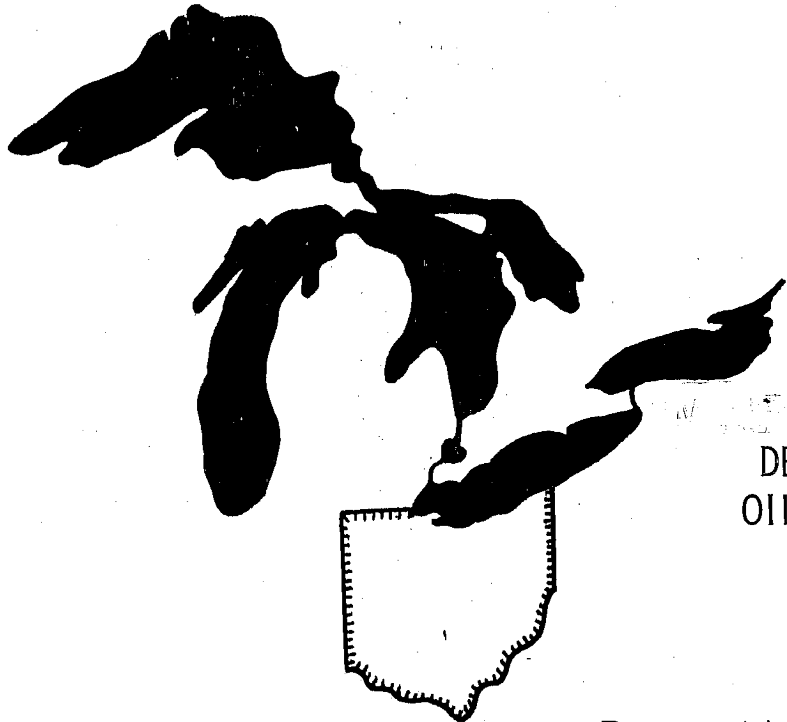

Final Report
ANTICIPATED ENVIRONMENTAL IMPACTS RELATED TO THE DEVELOPMENT OF NATURAL GAS AND OIL IN THE UNITED STATES WATERS OF LAKE ERIE

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Prepared for

Program for Energy Research, Education and Public Service
The Ohio State University
Grant No. PEREPS-0010
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COLUMBUS, OHIO

May 1980

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Abstract

The process of drilling for hydrocarbon reserves beneath U.S. Lake Erie is laden with potential environmental impacts in the form of discharges associated with the processes. The present work has reviewed many of the impacts anticipated. Increased salt loading from salt beds encountered in drilling for hydrocarbons may lead to increased lake stability, extended periods of anoxia and or death to plants and animals in the lake. Methane loading may lead to anoxic conditions in the lake due to methane oxidizing bacteria metabolising dissolved menthane. The possible impacts associated with sediment resuspension include toxic effects to fish due to damage or blockage of respiratory membranes. Although this paper does not dwell on all possible impacts, it does deal with many of the major impacts that will have adverse impacts on the biota present in Lake Erie.

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INTRODUCTION

With recent energy shortages, three of four U.S. states bordering Lake Erie are becoming interested in developing the recoverable natural gas from lands under Lake Erie. The growing scarcity of oil in this country will probably provide some incentive for removing any oil resource as technology provides safer means for doing so. The Canadians have been successful in drilling for natural gas since 1913, and 1,019 wells are in Canadian waters. As of 1978, 430 of these wells are currently producing or awaiting hook-ups to pipelines. Current production from Canadian wells annually yields $1.59 \times 10^8 m^3$ or 5.6 billion cubic feet per year. Similar levels of production can be anticipated for the Ohio waters of central Lake Erie. Ohio accounts for 66.6 percent of the U.S. Lake Erie total. If such production is permitted, adequate environmental safeguards must be provided.

This paper will analyze some of the possible adverse biological consequences of a drilling program beneath Lake Erie concentrating on the Ohio central basin waters. An attempt will be made to suggest relevant mitigating measures to deter any major environmental consequences. Due to the brevity of this effort, emphasis will be placed on those aspects thought by the author to be of greatest concern. It will become obvious to the reader that there is a lack of literature directly related to this problem, but an attempt will be made to extract pertinent information from the literature on each aspect discussed. It should be understood that the literature and findings discussed in this text may not coincide exactly with actual operations, but the contents of this report should point to vital areas deserving research within Lake Erie waters to either verify, elucidate or refute conclusions drawn.

In addition to extensive literature reviews, other activities that have led to the present effort included participation in a U.S. Army Corps of Engineers (COE) workshop on Lake Erie Natural Gas Development, and interviews with representatives of the Ohio Department of Natural Resources (DNR), and the Ohio Department of Energy (DOE). Discussions with members of local environmental groups and scientists with specialties in various associated fields were also of use in preparing this report.

A brief discussion of Lake Erie geology, sediment structure and physical limnology will be presented. Following this a discussion will be made of a typical drilling operation based on Canadian experiences with comments on stress factors associated with each phase of the operation under normal and accidental (worst case) conditions. Thereafter, each major stress factor will be treated individually based on the available literature and extrapolations to Lake Erie conditions will be made when possible.

Determination of the possible impact of developing natural gas and oil resources within the U.S. portion of Lake Erie is the subject of several other investigations (Argonne, 1978; Shafer, 1977; Cliford, 1974; Hurd, 1978). Ohio is one of three states bordering U.S. Lake Erie that is becoming interested in developing this resource. Based on the success of Canadian efforts and the recent lift on bans preventing exploration of natural gas, Argonne National Laboratory, Division of Environmental Impact Studies is presently involved in an impact study concerning natural gas development in the central and eastern basins of Lake Erie for the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency (the two agencies that are directly involved in permitting, navigation and discharge permits), so that if states should want to develop this resource the federal government would not slow up the development process. Argonne recently completed Phase I of their study (December 1978) identifying issues related to U.S. Lake Erie natural gas development. Frequent reference will be made to this work in the present treatment.

Production scenarios expected for Lake Erie natural gas resources in the United States have been predicted by Argonne based on Canadian experiences. The Argonne (1978) scenario calls for rapid development of the reserves in a 22-year period. Total estimated production over 22 years is about 533-833 billion cubic feet, which at 1978 consumption rates would supply five to nine years of natural gas to the 10-county region adjacent to the lake. These estimated resources represent between .4 and .2 percent of total U.S. proven reserves for 1976 and 1 percent of the reserves for the surrounding 13-state region. At the national and tri-state level, Lake Erie's natural gas would not be a significant new source of energy with the principal incentive being the potential for increased supplies to local industry in the basin (Argonne, 1978).

LAKE ERIE OVERVIEW

Lake Erie is the southernmost lake in the Laurentian Great Lake system located between 42° 45' and 42° 50' latitude with a total length of 386km. Total surface area has been calculated to be 25,300km^2 and total lake volume 470km^3. Ohio's total lake area is 913,630 hectares.

The excavation of Lake Erie began with glaciation of the Quaternary period and since that time has experienced four major glacial events. The outcome of all of these plus other geological stresses has caused the bedrock surface to lower the central and eastern basins relative to the westernmost region. Lake Erie can therefore be subdivided into three sub-basins; the western (maximum depth 11m), central (mean depth 25m), and the eastern (mean depth 64m). A combination of an island chain and an underwater ridge between Marblehead Ohio and Pt. Pelee Ontario forms the natural boundary of the western basin. A sandy ridge running from Presque Isle Pennsylvania to Long Point Ontario separates the central and eastern basins (Sly 1976; Argonne 1978; Rouse 1976).

Beneath Lake Erie Paleozoic sediments of considerable thickness underlie a thin veneer of recent unconsolidated sediments composed largely of sand, silt, and clay (Sly 1976). Rocks of the Paleozoic Era are sedimentary in their nature and range from about 450-375 million years old. Underlying these strata are basement rocks of the Pre-Cambrian Era composed of granite, gneiss and other igneous and metamorphic rocks. The main rocks found in the Paleozoic zone beneath the lake on the U.S. side consists of limestone, dolomite, sandstone, shale, salt (NaCl), and anhydrite. Their aggregate thickness ranges from 1740m off Ashtabula County Ohio to 1070m off Buffalo New York (Argonne 1978). It is from the lower Paleozoic rocks that oil and gas is currently being drilled on land in the United States, and from beneath Canada Lake Erie and on land in Canada (see Table 1). The Paleozoic rocks beneath Lake Erie will almost certainly contain recoverable reserves of natural gas and oil (Argonne 1978; Shafer 1977; Hurd 1978).

THE SILURIAN SYSTEM

Silurian rocks contain the only probable reserves of natural gas in Lake Erie (Argonne 1978). Probable reserves are those reserves that can be reasonably extrapolated from onshore areas to U.S. Lake Erie regions. Most of the natural gas will come from lower Silurian sandstone and dolomite which in Ohio is called the "Medina-Clinton Sandstone," which accounts for 90% of Ohio's natural gas production on land. Accounting for buffer zones around Ohio boundaries, about 526,110 hectares in the central basin of Ohio Lake Erie has these lower Silurian formations below it. The lower Silurian rocks are bound by Queenstone Shale below the Packer Shale (containing limestone and dolomite) above. Thickness of the gas producing section ranges from 43-60m (Argonne 1978; Hurd 1978).

In western Ohio waters, limestone and dolomite are found in place of sandstone, and west of a line extending from Lorain Ohio to Port Stanley Ontario, the gas bearing region is expected to be absent. Thickness and gas producing qualities in the "Medina-Clinton" formations are expected to vary significantly from well bore to well bore (Argonne 1978). Variations expected include thickness of a particular sandstone (or replacement by shale), grain size, proportions of siltstone and shale to sandstone, porosity and/or permeability and finally changes in the hydrocarbon content of the sandstone (Argonne 1978).

Other gas producing strata under U.S. Lake Erie waters include mound or reef structures which are either localized vertical mounds (patch reefs) or miles long (barrier reefs) located in the Lockport Dolomite of the middle Silurian system. These reefs represent the most likely gas reserve off Ashtabula County Ohio and reservoirs are expected to contain oil (Argonne 1978). Oil is also likely to occur in Cambrian rocks below the Silurian system.

Along the south shore of Lake Erie, a section of Lockport Dolomite known as Newburg Dolomite may contain salt (Argonne 1978). As well, upper Silurian rocks will consist of dolomite inter-bedded with salt, anhydrite and shale. The thickness of the upper Silurian system is the greatest off Ohio's border where the aggregate thickness of salt will reach its maximum of about 45m. The maximum thickness associated with a given salt bed will be about 20m. Figure 1 shows the extent of salt beds beneath Lake Erie (from Argonne 1978).

GEOLOGICAL CONSIDERATIONS

Tectonically, Lake Erie has been classified as a stable area with an inherently low degree of seismicity (Shafer 1977). The rocks into which surface casing will be placed (see discussion on drilling) is a minimum of 300 million years old and are thought to be hard enough to withstand any subsurface pressures that may be encountered upon hitting a productive region (Shafer 1977). In Ohio regions, a review of earthquake data in Ohio and the northeastern U.S. shows relatively frequent quake events around the city of Cleveland (see Table 2). A fault line exists in the western basin near Cleveland and another recently discovered off Presque Isle Pennsylvania (personal communication, Ohio League of Women Voters).

Reserves classified as possible are those reserves from formations that have produced hydrocarbons onshore, but whose geologic and producing conditions are not known to exist under U.S. Lake Erie with reasonable certainty (Argonne 1978). Reserves of this nature have been predicted to occur in the Devonian, Silurian, and Cambrian systems.

Considerable amounts of oil and some gas have been drilled from Cambrian rocks in Ohio, Ontario and Pennsylvania from the top sections of this system. Hydrocarbons were trapped here by stratigraphic and structurally controlled traps (Argonne 1978). Devonian reserves are located in the Oriskany Sandstone where onshore production in Ohio in the vicinity of Lake Erie has been successful, producing natural gas. Oil in the dolomite of the Silurian system has also been classified as a possible reserve (Argonne 1978; Shafer 1977; Bulmer and Bulmer 1972).

SEDIMENTS

The sediments beneath Lake Erie are a dynamic mixture of quartz, feldspars, carbonates and organic matter. The relative grain mixtures in the sediments are variable but average figures are 50-75% clay (<.004mm), 25-45% silt (.004-.062mm) and the remainder sand (>.062mm). Other constituents of the sediment include conservative, enriched and nutrient elements (Kemp et al. 1976; Argonne 1978).

Conservative elements in the sediment include Si, Al, K, Mg, and Na. For these elements there is a zero sediment enrichment factor (Kemp et al. 1976). Enriched elements include Hg, Pb, Zn, Cd, and Cn with associated positive enrichment factor values and higher surface concentrations due to anthropogenic loading. Nutrients elements include organic carbon, N, and P. Sediments act as a sink for these incoming materials with about 84% of the P and 58% of the N ending up in the sediments (Kemp et al. 1976). Nutrient loading increased in the 1900's and since that time we can see concomitant increases in sediment core concentrations (Argonne 1978).

Due to the high rates of sedimentation in Lake Erie, the lake is well suited for limnological historical interpretation based on sediment analysis (Kemp et al. 1976). Of considerable interest is the increased Hg concentrations related to the building of Chlor-Alkali plants in 1939 and 1954. Other metals increasing in concentrations are Cr, Cd, Zn, Ni, Sb, K, and Cu with the greatest concentrations located near Buffalo and Cleveland harbors. Many of these are considered to be enriched elements which are mostly toxic metals although these elements are the smallest group in the sediment contributing less than .1% (Kemp et al. 1976).

Western basin input of sediments from rivers is greater than output from the basin causing a net loading of sediment to occur. The western sediments are mostly fine grained in waters of less than 10m (Burns et al. 1976). This is in contrast to the central and eastern basins where the finer grained sediments are washed out of the areas of this depth and are redeposited in the deeper regions of these basins. This is due to the wind induced circulation on these basins. There is a large transport of sediments from the central to the eastern basin especially during storm events. The shallow regions are then left with coarser near shore sediments with most of the clay washed away into the center of the basin (Burns et al. 1976).

Erosion of shoreline bluffs constitutes the major source of natural fine grained sediments with an estimated input of 26 million metric tons/year input (Argonne 1978). River sources are of secondary importance but are not a minor input and are also carriers of anthropogenic material including heavy metals, pesticides and municipal organics with associated chlorides. The Detroit River is a major source of phosphates and chlorides in the lake. Large amounts of phosphates have been transported from the western basin to central basin by an unknown means (Burns et al. 1976).

Other inputs of sediments are the air, dredged spoils and allochthonous organics. There is an estimated total loading of 30 million metric tons/year with 15 million in the eastern basin, and 8 million in the central basin (Argonne 1978). Apparently the natural course of sediment movement is a series of depositions and resuspensions. This explains how sediments coming from the Detroit River can end up in the central basin. Anthropogenic heavy metals and nutrients are deposited in three ways: 1) association with clays, 2) incorporation in food chains thereby biologically recycled and transported, and 3) airborn particles such as heavy metals and pesticides (Kemp et al. 1976; Argonne 1978).

The major physiochemical mechanisms affecting the behavior of contaminants at the water-sediment interface are as follows. Redox potentials of the sediments at the water-surface interface can cause the release of chemicals into the water-column which are soluble in a reducing atmosphere. Manganese, Fe, and S seem to be related to Eh values with Mn concentrating in the normally oxidized zone of the interface, Fe becoming soluble in reduced regions and S increasing in concentration with reduced Eh values (Kemp et al. 1976). Along with these elements, associated nutrients such as P, organic carbon, N, etc. can be released to the water column (Argonne 1978; Wetzel 1975).

Biological mechanisms affecting the behavior of contaminants in Lake Erie are exemplified by bacteriological metabolism of Hg. Thomas and Jacquet (1976) measured concentrations of Hg in the top 3cm of 259 samples and found a range of 8-2929ppb with the highest concentrations near the Detroit River in the western basin. Bacteria transfer this sediment-bound Hg to soluble methyl Hg compounds which can then enter food webs. Biomagnification was thought to occur, resulting in levels in excess of .5ppm in fish which caused the fishery to close down in the western basin in June 1970.

The concentration of Hg in the sediments is affected by the turbidity of the water because Hg is scavenged by suspended particulates. Approximately 30-90% of the total Hg is slightly associated with particulates (Thomas et al. 1976). The central basin typically had 300-1000ppb Hg in the samples taken by Thomas et al. (1976). The distribution overall was related to the texture of lake sediments with higher concentrations in basin muds compared with coarser textured mixtures of inshore areas and crosslake moraines.

THE PROCESS OF DRILLING FOR NATURAL GAS IN LAKE ERIE BASED ON THE CANADIAN EXPERIENCES

The following treatment concerning the process for natural gas drilling is summarized below from Argonne's (1978) report.

Well Siting

Well-site selection is based on as much knowledge about the subsurface geology and seismicity that is available for a region. Air gun devices are used to generate shock waves which are analyzed aboard a seismically instrumented ship. The site is chosen and a buoy is dropped at the exact location. A drilling rig is floated on location and secured by either anchoring (drill ships) or using jack up bottom contact (jack-up rigs). Bottom sediment analysis should be conducted prior to jacking to prevent sitting on unstable bedrock, however the Canadian rig the "Mr. Neil" was observed stuck 5m into the sediment (personal communication J. Ferrante).

Stresses associated with this phase of the process include resuspension of sediments, increased turbidity, displacement and destruction of benthos and possible accidental incidents. Impact could occur when a jack-up rig with large pads is set up on soft unconsolidated material causing about 650m^2 of bottom material to be disturbed. Contaminants associated with the sediments would be resuspended allowing organisms to encounter this material at varying concentrations and depending on currents, increased reducing conditions, and anoxic regions could occur. Argonne (1978) is currently researching the plume characteristics to determine concentration gradients under Lake Erie conditions off Canadian drilling rigs. This information would help determine the impact associated with this process. In a review of offshore drilling data services (cited by Argonne), towing drilling rigs to site and jacking them up into position were two phases with a high frequency of accidents. The Canadians have experienced accidents related to the failure of the jacking mechanisms but have reported no environmental impact. A worst-case accident as predicted by Argonne involves the capsize of a rig with the loss of everything on board including diesel fuel, drilling muds, additives and lubricants on board.

Drilling

The process of drilling is split into two separate operational phases: surface drilling and drilling to depth. When surface drilling the Canadians usually use an open-cycle technique where the well bore is directly exposed to the lake with no casing (steel pipe) to transport drilling fluids, cutting or gases back aboard ship. Bentonite mud may be used as a drilling fluid, however the Canadians usually use lake water to cool and lubricate the bit. A plume of clay and cuttings with an associated increase in turbidity may be experienced depending on the bottom composition. The object of surface hole drilling is to drill down to competent bedrock so that a casing can be secured for drilling to depth in a closed-cycle process. When using a jack-up rig the hole is typically 11" in diameter and is drilled 50' into competent bedrock. When using a drill-ship the hole is 14 3/4" and is drilled 30' into competent bedrock.

On the U.S. side of the lake, there is an increased thickness of bottom sediments (Kemp et al. 1976) and an increased layer of shale to drill through (Sly 1976) which will cause a deeper surface hole to be drilled before hitting competent bedrock. There is a possibility of hitting a highly pressurized pocket of gas during the open-cycle process because such pockets have been shown to exist in the shale layers. The surface sediments on the U.S. side have higher concentrations of toxic materials and there is a risk of making this material more available to the biota by resuspending sediments. For these reasons and others, Argonne has recommended surface hole drilling on the U.S. side to be closed-cycle.

Closed-cycle drilling involves keeping the drilling fluids contained by the use of a circulating pump system. Cuttings are removed on board the rig using a shale shaker (vibration screen) and muds are reused by returning them to the mud tanks. Assuming rock cuttings are not returned to the lake, and spillage is minor, no significant amounts of material will be discharged into the lake. Well control is adequate, accomplished by cementing a steel casing into the surface hole, then installing blow-out preventer equipment on this casing. The hole is then drilled inside this casing in a closed-cycle. Minor releases of drilling fluids to the lake are anticipated in closed-cyle drilling when new lengths of drill pipe are added or removed from the drill string. This may present a potential problem depending on the constituents of this fluid. Total seasonal sediment input from drilling activity was calculated (Argonne 1978) to approximately 1245 MT or approximately .009% of the total yearly input from other sources. A worst case accident would involve a blow-out in open-cycle drilling causing loss of lives, rig destruction and capsizement, with a release of gas into the lake. This type of accident can be prevented using closed-cycle drilling.

After drilling the surface hole, a steel casing is placed into the well bore and secured with cement. Well casings are locked into place to prevent migration of fluids from one strata to another. Excess quantities of cement are used so there is some overflow which either goes into dissolution or could remain as a solid layer on the bottom of the lake. The anticipated impact is minor, with no toxic materials associated with the cement. In a worst case accident, the drill casing string could be dropped in the hole before the lowering of part of the drill string with cement hardened inside of it, with a period of possible inter-strata pollution. Once the casing placement and securement process is completed the hole is then drilled to depth of the gas producing layer using a closed-cycle technology.

Closed-cycle drilling as accomplished by the Canadians usually involves the once through use of lake waters for a coolant and a lubricant. Closed-cycle technology occasionally involves the use of drilling muds to clear the hole at the end of drilling. Muds are also available for accidents and well control. The drilling muds contain $CaCl_2$, bentonite, gels, additives and water. Muds returning from the well bore are filtered out with a shale shaker which removes large drill cuttings and recycles the rest of the mud. The drill cuttings which are removed along with adhering muds and contaminants are discharged at the surface of the lake. Many of these contaminants in sufficient quantities are toxic to aquatic life. Discharges associated with this process will have to be treated to lessen the potential of acute toxicity to the biota. Chlorides, sulfates, sulfides and phenols may be among the contaminants in the discharge. It is likely that a graded concentration plume will exist with toxicities decreasing quickly away from the source.

Every 9.1m a new drill pipe must be installed which allows about 4 liters of drilling fluids to be spilled on the platform which is then washed into the lake. If salt beds are hit in the process of drilling, the drilling may continue using a $CaCl_2$ or a Polybrine (pH 10-10.5) as a drilling mud. In either case, the material released under these conditions when adding new drill pipe sections will be of variable toxicity depending on concentrations released. The entire drilling process, if all goes well, should take approximately 4 days or 75 hours, thus it will be difficult to assess the biological impact related to this short term release. It is likely that acute impact will be negligible, but secondary impact although difficult to analyze, will be more serious. An example of this would involve the chronic exposure of chromium compounds used as drill fluid additives and/or the release of muds with a high pH into the water column.

The worst case accident during this phase of development would involve equipment failure with loss of well control. All drilling muds used as well as any gas encountered would be released into the lake. Property damage to the rig would be probable. Under normal operations, in addition to drilling muds and associated additives, large drill cuttings, clays, salts, and the release of gases and liquid hydrocarbons may occur. The water soluble fraction may present long term problems similar to those released from oil spills (see section in this text on oil spills). Lighter hydrocarbons may combine with the chloride forming possible carcinogens, however this is highly unlikely due to the rapid loss of these hydrocarbon fractions.

After the drilling processes are complete, it is usually necessary to stimulate gas flow via a fracturing technique. Depending on the lithologic conditions of the reservoir, one of two methods may be employed. If the strata is composed of limestone, HCl is forced down into the formation; if the strata is sandstone, a physical process involving pressurized pumping of acid, sand, surfactants, and CO_2 into the formation is used. The latter process is referred to as hydrofracturing. When the pumps are shut off, materials in the formation are brought back onto the barge and gas is vented to the atmosphere to prevent explosion. The captured fluids account for 40-50% of the introduced material with the remainder either lost to the formation or to the water column. A Canadian study by Borodczak (1968) indicated a potential for toxic conditions to occur during well stimulation. "The chemical and biological properties of fracturing effluent after it has been mixed and exposed to changes in pH and pressure remains unknown" (Argonne 1978). The various fracturing fluids available do vary considerably in their toxicities.

A worst case accident as described by Argonne (1978) would involve the stimulation barge capsizing and losing diesel fuel, HCl, and any other materials on board to the lake. More probable would be a break in one of the high pressure pipes with small amounts of materials being lost to the water column assuming safety valves work.

The Finished Well Heads, Pipelines and Onshore Facilities

After completion of the drilling and fracturing process, wells are capped and appropriate procedures for hooking the well into the pipeline system are followed. The underwater collection system will consist of a network of pipeline fabricated onshore. Fifty foot segments of pipe are welded together onshore, then towed into the lake supported by floatation devices using a tug boat. After the pipe is in its correct position, the pipe is submerged and connected by divers using dresser couplings.

Pipelines are typically buried a certain distance offshore to prevent ice scour which is a major problem associated with the Canadian program. Pennsylvania has included requirements for pipeline burial in its Lake Erie Draft Natural Gas Lease (1977) under shipping lanes and anchorages. Burial of lines adds considerably to the initial cost of laying a pipeline network and also places an additional stress on the system from sediment resuspension during the burial procedure. Main transmission line diameters will vary from 10.2-20.3cm and lateral lines that run from the main line to each individual well will be 5.1cm (Argonne 1978). Connections to the well head assembly are made using a 5.1cm neoprene hose. The entire system will be rated for 2000 psi, and manual and automatic check valves will be placed to allow shutting in of wells individually or in a group. Lines can be welded instead of fastened with a dresser coupling to reduce minor leaks and pipeline breaks.

In the event pipeline repair is needed, the quickest method involves raising the welded line above water using a barge mounted crane (Argonne 1978). Burial of pipelines would make repair more costly and difficult. Underwater repairs may also be performed by placing a band or coupling around the submerged pipe to stop any leakage occurring. Wells which are not buried will be covered by a dome, thus protecting the well head from ship anchors and fishing nets.

Development of gas or oil resources offshore requires onshore coastal area support facilities. Onshore facilities associated with natural gas development would involve construction of a number of landfalls equal to the number of main transmission lines. The number of collection lines is dependent on the geometric arrangement of well heads in the fields. Predictions by Argonne (1978) indicate that from 10-50 landfalls will be required, the lower value assuming a dense aggregation of well heads and the higher values indicating random locations for producing wells. Landfalls will most probably be underground, thereby protecting pipes from ice scour and lessening aesthic impacts. Stream valleys and uplands are considered to be more desirable areas for pipeline right-of-ways due to the fragile nature of wetland areas and the important commercial traffic in major rivers, the two alternative locales.

The initial construction of landfalls will involve temporary surface disturbance for pipeline burial. Anticipated disturbances will involve an area 10-20m wide at each landfall location. Siltation from this construction could be a serious problem to stream sites, so proper construction techniques should be employed with a sensitivity to these problems. Biological impacts associated with siltation of stream beds would vary depending on the stream substrate and current velocity and composition of the silt. A stream that is normally shale or rock bottom and which is then filled with muds would be significantly altered. Alteration of substrate type would cause a succession of benthos to ensue. One would expect to see a replacement of organisms adapted to rock habitats, where water can flow freely over delicate gill structures and thus provide oxygen needed for survival, by organisms adapted to burrowing in mud substrates. This shift in typical prey organisms would probably also be followed by a shift in predators, thus the fish adapted to eating benthos found in rock substrates would be replaced with other fish tolerant to the new habitat. Fish using the stream beds and associated wetlands as breeding sites may either avoid the altered habitat or attempt to use the area with the possibility of an unsuccessful breeding season, followed by a weak year class of the species involved.

Shore facilities would be necessary to scrub and compress gas brought to shore through the pipeline system. The facilities would occupy an estimated .2ha each including the actual facility and associated parking. Activities completed at shore facilities will include dewatering, condensate removal, scrubbing out H_2S, adding mercaptans and compressing the gas. Gas will leave the site under high pressures (500-800 psi) and would be fed through 20-40cm buried pipelines requiring a corridor 16m wide leading to the National Fuel Gas Distribution Systems. Pipelines are kept clear during construction and maintenance periods through the use of herbacides and other right-of-way maintenance procedures which enable quick and easy access to the pipeline trench (Argonne 1978). Since a broad target herbicide is used, problems associated with contamination of nearby lands and the lake via runoff and aerial drift should be anticipated and chemicals carefully chosen to reduce the impact associated with this process. Argonne (1978) states that a commitment of the estimated .2-.25 percent of the available land to developing natural gas will have little or no impact on land resources. This analysis may be a little misleading when one considers how much of the currently undisturbed shoreline would become committed to pipeline construction.

The problem of waste disposal should be addressed here because regardless of drilling location there are routinely generated waste materials including gas, liquid and solid residues. The closed-cycle technology can permit the retention of all materials on board which then necessitates an environmentally sound waste disposal method. Drilling fluids are reused as long as possible but eventually must be replaced and therefore end up as liquid residues. Liquid residues are also generated in large quantities during well fracturing. Solid residues will include anything from surface sediments and drill cuttings to H_2S which is removed when scrubbed onshore in treatment plants that bring the gas up to distribution line requirements. Waste disposal techniques available include: injection into approved wells, direct discharge into the lake, landfills, surface ponds, and other onshore waste disposal techniques. Waste disposal formations must meet a number of complex criteria so that contamination of freshwater aquifers will not occur (typically a site needs to be surrounded by two aquacludes) and to be sure there is enough void space to accomodate the waste material. It should be understood that deep well injection is the least preferred method for disposal of hazardous waste but is considered the best alternative for disposal of oil and brines (Frisbie 1978).

IMPACT ASSOCIATED WITH SALT LOADING

In trying to assess the impact of brines released either accidently as a result of a blowout, loss of well control, chronic leaks or during the normal process of drilling it is useful to review the literature pertaining to salt loading due to street deicing. Dickman et al. (1978) performed a series of experiments to assess the impact of NaCl on the rate and sequence of periphyton colonization using solid substrates in a small mountain stream which had never been exposed to road salt before. Species composition, relative abundance and diversity of colonizing periphyton were considered. At low concentrations (.3 ppm) it was found algae were stimulated by the salt which is actually needed for normal reactions such as ATP formation, FMN catalyzed phosphorylation and the Hill reaction. Absorption of phosphate by algae is stimulated by the presence of inorganic ions, thus the increased algal growth was expected. Inhibition of photosynthesis occurred with increased salinity levels. Lower algal diversity and increased auxospore formation was noted at the experimentally exposed site even though certain filamentous and budding bacteria species (e.g. Hyphomicrobium) were noted. The increase in bacteria was thought to be due to a decrease in grazer populations, thus a form of ecological release.

Judd (1970) worked on First Sister Lake, Michigan, a small lake receiving direct street runoff through a street sewer outfall, examining the influence of salt on lake stratification. Judd found that salt entering the lake in the form of street runoff caused an increased density of the hypolimnion causing an increased stability and a lowering of the center of gravity so that external wind action and eddy diffusion were insufficient to cause complete mixing. Differences in salinity can produce a stratified lake that is much more stable than the stratification associated with normal temperature-density relationships (Wetzel 1975). In Judd's study, it was found that during periods of extended stratification, oxygen depletion occurred rapidly in the spring but enough salt was lost to the sediments via ionic exchange as long as a negative gradient existed, that the lake was able to recirculate during the fall overturn.

Although it is difficult to compare the previously discussed work to a lake such as Lake Erie, one could assume that any significant salt loading would have an adverse impact on the biota. The benthos and other organisms in the hypolimnion would suffer greatly if oxygen depletion was prolonged. The massive mayfly die-off (Hexagenia) in Lake Erie in the 50's was associated with periods of anoxia in the Western Basin (Britt 1963). Redox changes associated with anoxia allow the resuspension of Fe and P which could add to the productivity of the lake, thus increasing BOD in an already eutrophic body of water. Increased osmotic pressures would cause freshwater organisms to experience dehydration and in many cases this could be lethal. It is obvious that the validity of these statements could be questioned, and the need for actual lake studies is clearly warranted. The fact remains, for a safe drilling operation installation of detection devices should be mandatory so that action could be taken if increased levels of salinity are detected.

OIL POLLUTION

Although current planning does not include the production of oil from beneath the lake, there is a possibility of striking oil when drilling for natural gas in Lake Erie. Current policy states that if any liquid hydrocarbons are found in the lake drilling program the hole should be plugged and abandoned by placing cement in the well bore. The number of plugs must be adequate to prevent any vertical flow of materials between geological formations with mud placed in between cement plugs (Argonne 1978). In 1969 a special committee of the IJC came out with a report on potential oil pollution incidents from oil and gas well activities in Lake Erie (IJC 1969). They reported two minor oil pollution incidents related to Canadian gas wells, consisting of a direct discharge of oil from two wells in 1959 and 1960. Flow lasted several minutes before control was established and the only estimate of discharge was 5 barrels. Other potential oil pollution sources include shipping, product transfer, watercraft, storage, pipelines, municipal and industrial sources and disposal of spent oils (IJC 1969; IJC 1970; Argonne 1978).

The fate and effect of petroleum hydrocarbons in aquatic systems whether from oil spills, wells or other sources is an area of increasing interest and study (Vandermeulen 1978; Argonne 1978; IJC 1969). Most of the work has been concerned with marine systems but an attempt will be made to correlate these studies with the Lake Erie situation. In general it can be stated that oil spilled in shallow coastal waters partially becomes incorporated with the sediments by one of several pathways including: absorption on precipitating sediments, direct precipitation resulting from increased specific gravity following weathering and microbial activity and ingestion and incorporation of dispersed oil into zooplankton fecal material (Percy 1977). When oil becomes emergent and is exposed to the sun and wind this promotes evaporation and photooxidation, but when submerged or washed by rain, dissolution occurs especially with more soluble oxidation products (Cretney et al. 1978). Increased amounts of sediment loading can cause most of an oil spill to be adsorbed and end up in the benthic habitat (Percy 1977).

Cretney et al. (1978) studied the long term fate of a heavy fuel oil spill in a British Columbia coastal bay, looking at both chemical changes and effects on biota. Oil is composed of various hydrocarbon fractions varying in molecular size and behavior in aquatic systems. Additionally crude oil often contains compounds of S, O, N, as well as metals such as Ni, and Va (Hutchinson et al. 1972). After the spill occurred, lighter molecules were lost first via evaporation and dissolution (Cretney et al. 1978). Biodegradation within the first year broke down n-alkanes and within 4 years pristane and phytane. Non-n-alkane components in the $n<28$-31 range seemed to resist degradation for longer periods of time. Summarizing their results, Cretney et al. found initially the spill had adverse effects on the biota but that recovery began after one year by which time the ecosystem had cleansed itself of most of the oil primarily by dissolution and evaporation.

Hutchinson et al. (1972) conducted some research on the effects of crude oil and some selected components on phytoplankton in both field and laboratory conditions. In field conditions species showed quite different responses to the crude oil. Algae such as *Dinobryon* and *Peridinium* were inhibited, *Tabellaria* and *Ankistrodesmus spiralis* stimulated (after 60 days following the spill) and *Fragillaria* and *Ankistrodesmus falcatus* unaffected. Laboratory analysis suggested that toxity of the crude oil may in fact be due to the decreased pH associated with the oiled media. In varying concentrations of oil, aqueous extracts had inhibitory effects that varied widely among different algae. By neutralizing the low pH they showed the oil extracts were still toxic. The water soluble fractions of crudes including benzene, toluene and xylene all showed algal toxicity and suppressed growth of algal populations.

Studies by Teal et al. (1978), Percy (1977), and Krebbs et al. (1977) have looked at the effect of oil on the benthic community. Percy (1977) pointed out the importance of looking at not only acute lethal effects, but also a complex of physiological, behavioral and biochemical factors as they influence both epi- and in-fauna of benthic systems. Normal behavioral sequences may be altered by either a direct attraction of aversion responses to the presence of oil. An example of this might be a reaction to swim instead of burrow, thereby increasing possible predation and thus decreasing the population of the organism. This may come about by indirect effects such as masking or mimicking natural chemical cues by some components of the oil. The two ways attraction-aversion responses can cause an impact on benthic communities or population structures include either the direct response to varying concentrations of the oil or the indirect interference of behavioral patterns.

To test these possibilities Percy (1977) looked at the effect of oil contaminations of bottom sediments on the normal habits of the amphipod Onisimus affinis, which showed consistent repulsion to oil and oil contaminated food. When offered a choice in-vitro between clean and contaminated sediment of varying concentrations, there was 90% or more avoidance of oiled sediments, but with increasing concentrations, selectivity actually decreased. This was probably due to decreased ability of the amphipod to distinguish between clean and polluted sediments because of either impairment by the loosely bound oil or possible destruction of neuronal dendrites on crustacean chemoreceptors. In addition, as the material weathered, a lower degree of selectivity was noted indicating loss of the substance responsible for the aversion. This substance is probably a more volatile component of the oil which was released in-vitro fairly quickly but may not leave the actual lake sediment as fast in arctic or winter conditions.

Little has been done in the way of scientific investigations concerning the effect of petroleum hydrocarbons on marine fishes. Ernst et al. (1977) looked at water soluble fractions of fuel oil and the effect on the development of Fundus grandis, an estuarine fish. Histological evaluation of embryos was accomplished and revealed that at relatively high concentrations (higher than one would expect to be associated with an oil spill) abnormal kidney and stomach epithelium development occurred, with a lower survival to hatchery. At low concentrations, embryos hatched earlier than usual. This type of study is important because in the early stages of development, animals are more sensitive to pollutant stresses and subtle changes can affect the ability of an animal to survive.

In trying to relate the above material in a discussion of Lake Erie oil pollution, one must consider the size differences between the lake and marine systems, the relative waveactivity, microbial abundance and diversity, lake stability and mixing and the differing nature of the sediments. It is clear that recovery of marine systems following an oil spill does occur and that recovery of a marine system can vary significantly depending on the amount of oil, the kind of oil and the physical, chemical, geological and biological processes that disperse and degrade the oil (Butler et al. 1978; Percy 1977; Cretney 1978). The single most important type of energy is provided by the wind and waves at the time of the spill causing the spill to disperse, spread out on the surface and into the water column (as droplets) and in general become diluted (Butler et al. 1978). Lake Erie, due to its location and rapid surface flow derived from prevailing westerly winds would probably allow a good dispersion of any oil, and therefore could contaminate shore areas, water intakes etc. but allow for evaporative and photooxidative processes to occur. Other processes such as biological degradation should be studied considering the populations of bacteria, fungi, algae, etc. found in the lake, so that an estimate of the importance of biological degradation in the lake could be made. One can clearly see that benthic organisms, algae, fish and plankton will all be affected to some degree, thus emphasis should be placed on determining the secondary effects on a community level. Since Lake Erie is a source of fresh water for millions of people (Argonne 1978), industry has not considered the oil under Lake Erie as a source of energy for the future. This does not mean that in the near future, with less and less energy in the form of oil becoming available, that development will never occur. Therefore, a detailed analysis should be attempted to deter and/or caution developers in this fragile ecosystem.

METHANE LOADING

One of the most obvious impacts associated with drilling for natural gas would be the release of methane (CH_4) which typically represents 89.9% of the gas found in Canadian wells (Argonne 1978). No clear knowledge is available concerning the influence of the methane cycle on whole lake metabolism (Rudd et al. 1978). Methane can be converted to CO_2 and particulates which can then serve primary and secondary trophic levels, but the overall impact of this process is yet to be discerned. It may be that the amount of O_2 consumed in oxidation of CH_4 will have a major impact on the O_2 budget of lakes, but this remains to be explored.

Rudd et al. (1978) attempted to discern how methane cycling affects the O_2 budget of an artificially eutrophic lake #227, a Precambrian Shield lake. The most important effect of CH_4 cycling was the consumption of dissolved O_2 by CH_4 oxidizing bacteria. Depending on yearly cycles of ice cover and spring overturns, this O_2 consumption could cause the hypolimnion of the lake to go anoxic. This occurred when there were still large concentrations of CH_4 in the dissolved state when ice formed. The methane oxidizers were not sensitive to low temperatures or O_2 concentrations and proceeded to oxidize the CH_4 during the winter ice-over causing anoxia to occur. The contribution of these bacteria to lake seston or production of CO_2 was minimal in terms of whole lake metabolism, but the use of O_2 during periods of little recharge was significant. Rudd et al. concluded that CH_4 carbon from anoxic sediments was important to the carbon cycle as well as the recycling of this carbon by the bacteria.

CH_4 is transported away from the anaerobic hypolimnia where it is formed from decompositional processes by two methods including diffusion and ebullution. Ebullution or bubble formation, occurs only if the critical concentrations for bubble formation are reached. The rest of the CH_4 dissolves and becomes available to the CH_4 oxidizing bacteria at the thermocline. Strayer et al. (1978) looked at in-situ methane production in Wintergreen Lake by separately measuring ebullution and vertical diffusion losses. They succeeded in bracketing a range of values which show the efflux of dissolved CH_4 from the sediments is at least equal to ebullution of CH_4.

In lakes deeper than Wintergreen Lake, the critical concentration at which bubbles form will depend on hydrostatic pressures, thus the loss of CH_4 via ebullution may be insignificant compared to the quantities of CH_4 lost by diffusion (Strayer et al. 1978). In addition, CH_4 production in winter months relative to organic matter production would be expected to be higher than in the summer. During fall turnover, 60% of the remaining dissolved CH_4 in Wintergreen Lake was converted by bacteria to cell material and CO_2 (in a 50:50 ratio) and 40% was lost to the atmosphere. Strayer et al. concluded the rate of CH_4 production appears to be a critical factor controlling the anaerobic carbon cycling in eutrophic lakes.

Considering the above discussion, one would think a CH_4 leak, especially during winter months, in Lake Erie would have an appreciable effect on the O_2 concentration in the lake. Although the critical concentrations are likely to be reached for ebullution to occur, the lake could be essentially saturated with CH_4 if a large scale leak occurred. As previously discussed, the lack of O_2 can have a dramatic effect on aquatic biota, which by and large require high concentrations of dissolved O_2 for survival.

PARTICULATE RESUSPENSION

During several phases of development, turbidity plumes are developed around drilling rigs (Argonne 1978). The question which arises is, what will be the direct and indirect effects of this turbidity? Argonne (1978) has suggested that direct effects include stress to fish respiratory systems (especially to larval fishes) and deposition of suspended particulates on benthos which may affect invertebrates and hatching of demersal-attached fish eggs. The majority of the literature available on this subject consists of studies related to the impact of dredging.

O'Connor et al. (1977) came out with a series of studies on acute and sub-lethal effects of suspended sediments on estuarine fishes. Suspension of particulate matter was found to affect estuarine fishes. Stress associated with suspension included changes in growth, survival and reproduction of fish. The effects were dependent on composition and concentration of particles and results were species specific. Physiological response to in-vitro tests included; increased microhematocrit, hemoglobin concentration, and RBC count, all of which act to raise the blood's oxygen exchange capacity to make up for interference of O_2-CO_2 exchanges at the gill by the suspended particulates. Increased mucus production and tissue disruption was noted in the gills; thus the respiratory surface was reduced. Most of the fish were able to avoid or temporarily leave hostile environments. Death, if it occurred, was due to anoxia resulting from blockage of small passages in the gills or abrasion of gill tissue.

Other factors to consider are sorbed toxic material, high BOD, and nutrient content of natural sediments. All of these exist in Lake Erie sediments, and the overall effect of sediment resuspension may be due largely to these factors. Increased turbidity will also reduce the amount of light transmittance, thus lessening the depth of the euphotic zone and thereby lowering the overall productivity. The actual extent to which any of the above factors will affect Lake Erie biota is unknown. Results from Argonne's Phase II study will help considerably in determination of impact from this source.

MITIGATING MEASURES

What follows is a list of suggested mitigating measures or operational requirements which could be employed, should a drilling program become a reality in Ohio Central Lake Erie. Many of these orders are presently in effect for OCS activities now ongoing in the Gulf of Mexico (U.S. Department of Interior 1977). The overall effect of instituting mitigating measures such as these would be to lessen or deter environmental degradation of Lake Erie resulting from a drilling program.

1. Site-specific Impact Assessment based on biota and substrate present, vicinity to water intakes, and other regions requiring good water quality.

2. Monitoring equipment at well heads to detect leakage of brines and other contaminants that could potentially be harmful.

3. Complete future plans for pipeline maze, to reduce excess pipelinage, thereby reducing environmental impacts associated with them.

4. Identify "sensitive" areas to avoid them in leasing agreements.

5. Plan land facilities to accommodate waste disposal sites, pipeline right-of-ways, compressor plants, etc. Set up a plan whereby equal or greater land is set aside for park land in the vicinity of the pipelines to provide refuge for wildlife that will be displaced by landfall activities. Special facilities for problem wastes such as brines should be established.

6. Plan a biological monitoring program using a before, during, and after approach to detect subtle changes that result from drilling activities.

7. Require sediment analysis of potential drilling sites to prevent placement of drilling rigs on unstable lake bottom and to detect presence of toxic materials associated with the sediment.

8. Determine how long it would take to respond to accident situations, to put into effect accident contingency plans.

9. Require frequent, on rig, surveillance to prevent operators from polluting Lake Erie.

10. Require inspection of all support vessels, docking facilities, and methodology of transporting potentially harmful materials.

11. Require closed cycle drilling for surface hole preparation and for drilling to depth.

12. All vessels, equipment, and wells should be well marked using conventional navigational markers.

13. Operators must file an application for drilling stating information on all equipment and programs, from drilling techniques to blowout control and personnel training. Equipment used for each phase of operations should be described.

14. Casing with cement should be required for support and prevention of intra-strata pollution. Pressure tests on casing strings should be performed to determine if there are any leaks or inadequate cementing.

15. Blowout protectors and other well-control equipment should be used, installed, and tested with dual controls for saftey reasons.

16. Failsafe valving should be installed to prevent leakage of excess material in the event of line breakage or other accidents.

17. Enough drilling muds should be present during drilling operations to control unexpected pressure pockets in wells.

18. Twenty-four hour supervision of drilling operations by a qualified experienced person trained in well-control should occur.

19. Weekly blowout prevention drill exercises should be required of all rig personnel.

20 Regulate all activities such as abandonment and plugging and require inspection of new wells to determine if the flow of gas will be great enough to warrant further completion of the well.

21. Require subsurface control devices on tubing installations that open into gas bearing zones below the lake bottom controlled either on the surface or subsurface. Regulate all phases of installing, testing, operating, or removing these devices.

22. Completed wells awaiting hook-up to the pipeline network should have subsurface safety devices installed within two days following well completion.

23. Recommend frequent testing of the subsurface safety devices and/or tubing plugs.

24. Waste disposal must be handled in the most appropriate way to ensure pollution prevention in Lake Erie. Disposal of wastes must not adversely affect public health, life, or property; aquatic life or wildlife; recreation; navigation; or other uses of the lake's resources.

25. Require notification of all materials used for drilling including detailed lists of drilling mud components, chemicals, and mud activities in the concentrations used for drilling the well.

26. Train all personnel in pollution prevention and handling techniques for the above materials.

27. Require the operators to report any spill, regardless of how serious and place severe fines on those companies or operators failing to do so. Comprehensive reports should be filed which include a statement on any unusual conditions encountered.

28. Pollution control equipment must be available in working-order to operators including booms, skimmers, clean-up materials, and chemical agents.

29. Formulate complete accident contingency plans including a list of all persons to be notified in the event of any accident. Financial liability should be clear.

30. All drilling rigs must be designed taking into consideration worst case 100-year storms on Lake Erie.

31. Monitor operation procedures including welding and installation of safety devices.

32. Outline approval procedures for gas or oil pipelines including: routing, capacity, pressure, water depth, size, and grade of pipe, burial depth, corrosion protection, protective coating, connecting and metering facilities, and pressure control facilities.

33. Monitor methods of welding and laying the pipelines.

34. Test pipelines for hydrostatic pressure greater than working pressures anticipated upon completion of the line.

35. Establish drilling techniques for encountering H_2S, oil, NaCl, or H_2O regions.

36. Prevent any waste of hydrocarbons and insure proper production of oil and gas placement of facilities to maximize production while minimizing environmental impact.

37. Make records and data concerning operations available to the public. Require accurate measurement of oil and gas production to ensure payment of royalties, etc.

38. Require operators to receive formal approval prior to commencing any work.

39. Require operators to submit a notice and detailed description of work they desire to perform to all government agencies involved, thereby preventing operations without planning for safety, conservation and protection of the environment, and to be sure all work will meet the present day standards of both state and federal governments.

40. Require on-site inspections for compliance with regulations using a combination of scheduled and unscheduled inspections to assure the achievement of safety and environmental objectives.

41. Require predrilling inspections as well as inspections during operations.

42. Review abandonment or suspension requests on a case-by-case basis to determine what procedures are applicable for the given location.

43. Be sure required regulations are followed to avoid potential hazards to personnel and to the environment.

44. Require warnings of non-compliance to be issued and date of correction recorded.

45. Visual and pressure tests on pipelines should be conducted daily.

46. Should detection of hazards or pollution occur during inspections, either written warnings will be issued allowing a certain time for correction to comply with regulations or a shut-in order will be issued for equipment or for entire drilling regions that are in non-compliance.

47. Additional penalties such as fines should be set for individuals guilty of knowingly not meeting regulations.

CONCLUSION

Ohio's state government will eventually have to decide whether or not to allow drilling for natural gas in Ohio's central Lake Erie waters. The process of drilling for hydrocarbon reserves beneath U.S. Lake Erie is laden with potential environmental impacts in the form of discharges associated with the drilling processes (see Table 3). The present study has reviewed many of the impacts anticipated, but is by no means a complete account of this complex problem. Some of the extrapolations to Lake Erie that were made may be a little far reaching, but the fact remains it will be difficult to decide if the benefits gained by instituting a drilling program at this time will outweigh the potential degradation of Lake Erie waters that are used as a resource by millions of people today.

Increased salt loading from salt beds encountered in drilling for hydrocarbons may lead to increased lake stability, extended periods of anoxia and/or death to plants and animals in the lake. Secondary effects, as yet unknown, could alter ecological balances necessary for a healthy food chain to exist. Methane loading, although possibly insignificant, may lead to anoxic conditions in the lake due to methane oxidizing bacteria metabolizing dissolved methane. The possible impacts associated with sediment resuspension include toxic effects to fish due to damage or blockage of respiratory membranes. Although the present treatment does not dwell on all possible impacts, it is the authors' hope that many of the major impacts that will have adverse impacts on the biota present in Lake Erie have been discussed.

REFERENCES

Argonne National Laboratory: Division of Environmental Impact Studies. 1978. An examination of issues related to U.S. Lake Erie Natural Gas Development. Prepared for the U.S.C.O.E. and EPA. Argonne, Illinois. 194 pp.

Bulmer, E.G. and W.E. Bulmer. 1972. Economic potential of offshore oil and gas exploration in the United States portion of Lake Erie. Presented at the First Annual Meeting, Eastern Section, American Association of Petroleum Geologists, Columbus, Ohio. 29 pp.

Burns, N.M., et al. 1976. Processes within Lake Erie. J. Fish Res. Board Canada. 33:639-645.

Butler, J.N., and E.M. Levy. 1978. Session I. Summary and Overview: Long-term fate of petroleum hydrocarbons after spills-compositional changes and microbial degradation. J. Fish Rev. Board Canada. 35(5):604-605.

Clifford, M.J. 1974. Reserves of hydrocarbons underlying Ohio portion of Lake Erie. Prepared for the Drilling Task Group of the Governor's Energy Coordinating Council. Ohio Division of Geological Survey. 21 pp.

Cretney, W.J., C.S. Wong, D.R. Green, and C.A. Bawden. 1978. Long-term fate of a heavy fuel oil in a spill-contaminated B.C. coastal bay. J. Fish Res. Board Canada 35(5): 521-527.

Dickman, M.D. and M.B. Gochnauer. 1978. Impact of Sodium Chloride on the microbiota of a small stream. Environ. Pollut. (17): 109-126

Ernst, V. and J. Neff. 1977. The effects of the water-soluble fractions of No. 2 fuel oil on the early development of the estuarine fish, _Fundulus grandis Baird_ and _Girard_. Environ. Pollut. 14:25-35.

Frisbie, L.H. 1978. Safe disposal practices for hazardous wastes. Mobay Chemical Corporation, Kansas City, Missouri.

Hudec, P.P. and P. Sonnefeld. 1974. Hot Brines on Los Roques, Venezuella. Science 185: 440-442.

Hurd, D.B. and D.J. Kingston. 1978. Clinton exploration and production on the Ontario side of Lake Erie. Petroleum Resources Section, Mineral Resources Branch, Ontario Ministry of Natural Resources. 26 pp. + App.

Hutchinson, T.C., P. Kauss and M. Griffiths. 1972. The phytotoxicity of crude oil spills in freshwater. Water Pollution Res. in Canada, Proceedings of the Seventh Canadian Symposium on Water Pollution Research.

International Joint Commission. 1969. Potential oil pollution incidents from oil and gas well activities in Lake Erie. A report of the international Lake Erie water pollution board to the IJC. 162 pp.

International Joint Commission. 1970. Special Report on: Potential oil pollution eutrophication and pollution from watercraft. Third interim report on pollution of Lake Erie, Lake Ontario and the International section of the St. Lawrence River.

Judd, J.H. 1970. Lake Stratification caused by runoff from street deicing. Water Res. 4:521-532.

Kemp, A.L.W., R.C. Thomas, G.I. Dell and J.M. Jaquet. 1976. Cultural impact on the geochemistry of sediments in Lake Erie. J. Fish Res Board Canada 33:440-462.

Newton, A.C. 1964. Offshore exploration of gas under the Canadian waters of the Great Lakes. Geological Circular No. 7 (reprint of 1951 edition). Ontario Department of Mines, Toronto. 31 pp.

Norling, D.L. 1970. Ohio: 110 years of oil and gas. Presented before Research Committee, Interstate Oil Compact Commission. Columbus, Ohio.

O'Connor, J.M., D.A. Neumann and J.A. Sherk. 1976. Lethal effects of suspended sediments on estuarine fish. TP 76-20, U.S. Army, COE, Coastal Engineering Research Center, Fort Belvoir, Virginia.

O'Connor, J.M., D.A. Neumann and J.A. Sherk. 1977. Sublethal effects of suspended sediments on estuarine fish.

Pennsylvania Department of Environmental Resources. 1977a. Natural Gas Lease for the lands beneath Lake Erie within the jurisdiction of the Commonwealth of Pennsylvania, and Stipulations for protection and conservation for lands beneath Lake Erie. Minerals section, Bureau of Forestry, Harrisburg, Pennsylvania (draft).

Percy, J.A. 1977. Responses of arctic marine benthic crustaceans to sediments contaminated with crude oil. Environ. Pollut. 13:1-10.

Rudd, J.W.M. and R.D. Hamilton. 1978. Methane cycling in a eutrophic shield lake and its effect on whole lake metabolism. Limnol. and Oceanogr. 23(2):337-348.

Shafer, T.J. 1977. Ohio-Lake Erie gas exploration and development feasibility study. Prepared for Ohio Energy and Resource Development Agency. Shafer Exploration Company, Columbus, Ohio 111 pp. + map.

Sly, P.G. 1976. Lake Erie and its basin. J. Fish Res Board Canada 33:355-370.

Strayer, R. and J. Tiedje. 1978. In situ methane production in a small, hypereutrophic, hard-water lake: Loss of methane by verticle diffusion and ebullution. Limnol. and Oceanogr. 23(6):1201-1206.

Teal, J.M., K. Burns and J. Farrington. 1978. Analysis of hydrocarbons in intertidal sediments resulting from two spills of No. 2 fuel oil in Buzzards Bay, Massachusetts. J. Fish Res Board Canada 35(5):510-520.

Thomas, R.L. and J.M. Jaquet. 1976. Mercury in the surficial sediments of Lake Erie. J. Fish Res Board Canada 33:404-412.

U.S. Department of the Interior, Draft Environmental Impact Statement Prepared by the Bureau of Land Management for Proposed 1977 Outer Continental Shelf Oil and Gas Lease Sale Gulf of Mexico. Vol. 1.

Wetzel, R.G. 1975. Limnology. Philadelphia, W.B. Saunders Co. 743 pp.

APPENDICES

TABLE 1

GEOLOGIC NOMENCLATURE FOR PALEOZOIC ROCKS UNDER LAKE ERIE WITH ESTIMATED RESERVES AND EXPECTED LOCATION OF PRODUCABLE HYDROCARBONS

Geological Structures USLE--Uniform SE Dip of Strata

System	Subdivisions	Named Formations	Main Rock Types	Comments		Estimated Reserves of Hydrocarbon Under LE: Probable	Estimated Reserves of Hydrocarbon Under LE: Possible
Devonian	upper		shale	youngest rocks under USLE--ran	Oriskany sandstone has produced 11 BCF in OH near LE and in Erie Co., PA		Oriskany sandstone 25 (BCF)
	middle	Onondaga, Bois, Blank	limestone	irregular distribution, produced gas near OH & PA with salt water.			
		Oriskany, Springvale	sandstone				
	lower	Helderberg	limestone	restricted to Lake County, OH, offshore			
Silurian	upper		dolomite, anhydrite salt, shale		Most probable gas reserve off Ashtabula County, OH; reservoirs expected to contain oil	excluded W. Basin & buffer zones; 1,231 (BCF) Lower Silurian sandstone	Lockport Dolomite 50-300 (BCF)
	middle	Lockport	dolomite	dolomite reefs producing sig. amts. nat. gas. in Ontario, even W. of Lorain-Pt. Stanley			
		Rochester	shale				
	lower	Medina-Clinton (Ohio)	sandstone, shale	most USLE nat. gas potential realized 43-60 m thick, W. of Lorain, Oh., Port Stanley sandstone expected absent			
Ordovician	upper	Cincinnation	shale		Trenton and Black River formations produced oil from reservoirs unlikely to be found under USLE		
	middle	Trenton, Black River	limestone				
	lower	Glenwood, Shadow Lake	dolomite				
Cambrian	upper		dolomite, sandstone	Porosity from Pre-Ordovician erosion; HC prod. in Cen. OH may prod. under LE	sig. amts. oil, some gas produced on OH, PA, & Ontario; most in OH has been oil, except 1 well in Medina Co., W & N of Cleve.; should be productive & possibly only gas; expensive to drill		Dolomite and Sandstone 25-100 (BCF)
	middle	Kerbel	sandstone	off Cleve. 15-30 m; proper trap cond., may have HC			
			dolomite, sandstone	175 m sandstone likely, may have HC			
	lower	Mt. Simon-Potsdam	sandstone	38 m			

TABLE 2

EARTHQUAKES IN OHIO AND NORTHEASTERN U.S.

DATE	HOUR	LOCATION	INTENSITY MM	AREA SQ. MILES	REMARKS
June 1 1638	3:00 PM	Mass.	-		
Jan. 26 1662	-	N.E.	7		
Feb. 5 1663	-	N.E. & Cleve.	11 - 12	750,000	Major
Nov. 8 1727	10:40 PM	Mass.	8		
Sep. 15 1732	11:00 AM	St. Lawr. Val.	8		
Dec. 7 1737	11:00 PM	N.Y.	6		
June 3 1744	10:15 AM	Mass.	-		
Nov. 18 1755	4:11 AM	Mass.	8	300,000	
May 16 1791	10:00 PM	Conn.	8		
Nov. 9 1810	9:15 PM	N.H.	6		
Oct. 5 1817	-	Mass.	7 - 8		
Oct. 17 1860	6:00 AM	Canada	8	700,000	
Oct. 22 1860	6:00 AM	Maine	8		
Oct. 20 1870	11:25 AM	N.E. & Cleve.	8	1,000,000	
Jan. 9 1872	7.54 PM	N.Y.	7		
Aug. 10 1884	2:00 PM	N.Y.	9		
Aug. 31 1886	9:30 PM	Cleve.	10		
May 27 1897	10:16 PM	N.Y. & Cleve.	6	150,000	
May 17 1901	1:00 AM	Ohio	5		
Mar. 21 1904	1:04 AM	Maine	7		
Feb. 10 1914	1:31 AM	Maine	7	200,000	
Aug. 21 1918	0:12 AM	Maine	7		
Feb. 28 1925	9:24 PM	N.H. & Cleve.	8	2,000,000	Severe
Sep. 9 1928	3:10 PM	Cleve.	5		
Aug. 12 1929	6:25 AM	N.Y. & Cleve.	8		
Apr. 20 1931	2:54 PM	N.Y.	7		
Nov. 1 1935	1:04 AM	Cleve. & Canada	6	1,000,000	
Mar. 9 1937	0:48 AM	N.Y. & Cleve.	7 - 8	150,000	
Mar. 8 1943	10:26 PM	Cleve.	4 - 5	40,000	
Sep. 5 1944	0:39 AM	N.Y.	8	175,000	
Aug. 9 1947	9:46 PM	Cleve.	6		Slight
Dec. 3 1951	2:00 AM	Cleve. & Wlby.			Press & P.D.
May 26 1955	12:09 PM	Cleve.	5		
June 28 1955	7:16 PM	Cleve.	5		
May 2 1958	6:42 PM	Cleve.			Press & P.D.
1963		Quebec			New York Times
Nov. 9 1968	12:05 PM	Cleve.			Press
Feb. 28 1973	3:21 AM	Phila. Pa.	3		N.Y. Times

M M = Modified Mercalli Intensity Scale of 1931 (Range from 1 to 12)

References: "Earthquake History of the U.S." (1956) U.S. Dept. of Commerce(41-1)
"Earthquake Investigations in the U.S. U.S.C. & G.S. (No. 282)
N.Y. Times - Cleve. Press - Plain Dealer - Cleve. Public Library
Seismology Lab. John Carroll University

TABLE 3

POTENTIAL INCIDENTS ASSOCIATED WITH
U.S. LAKE ERIE NATURAL GAS DEVELOPMENT

X - normal operations
0 - accidents

Operational Phase	Loss of well control or blow out	Loss of brines	Oil pollution	CH_4 loading	Resuspension of toxic sediments	Turbidity plumes	Release of drilling muds (fluids)	Loss of diesel fuel	Displacement of benthos	Loss of cement	Loss of drilling additives	Loss of lubricants	Loss of fracturing fluids (HCl)	Rig destruction	Loss of lives	Intra-strata pollution	Loss of drill cuttings	Loss of contaminants such as Phenols, Chlorides SOx	Change in pH	Shoreline dammage (alterations to accomodate system) (or onshore damages)
Siting of drilling vessel					X	X	0	0	X		0	0								
Surface hole drilling	0			0	X		X		X					0	0		X			
Casing placement and securement									X	X						0				
Drilling to depth	0	0	0	0	0	X	X				X			0	0	0	X	X		
Well stimulation and fracturing		?		?		?		0					XO			0			XO	
Transport of materials to and from site		0				0	0	0		0	0	0					0	0	0	
Plugging and abandonment										X						0				
Underwater collection system operation		0	0	0					X											
Landfall: processing, compressing																				X
Normal operation of system	0	0	0	0					X						0					
a) Ice scour																				
b) Line breaks																				
c) Fires																				
d) Valve failures																				
Waste Disposal		0	0		0	0	0		0		0	0	0			0	0	0	0	0
a) Shallow well injection		0	0	0	0	0	0				0	0	0			0	0	0	0	
b) Surface pond disposal		X	X	X							X	X	X				X	X		X
c) Land fill		X	X	X							X	X	X				X	X		X
d) Discharge to lake		X	X	X	X	X	X				X	X	X				X	X	X	X

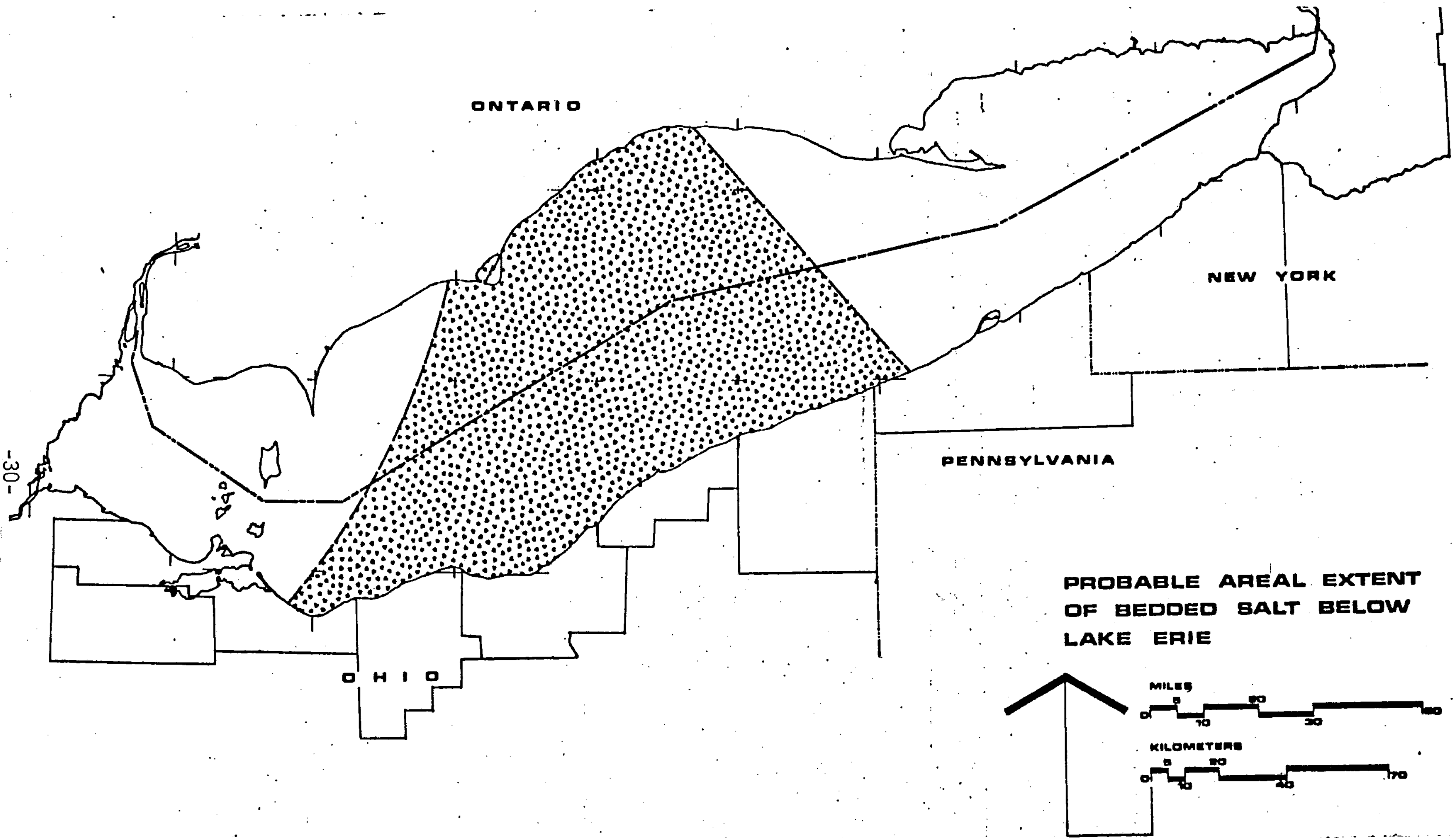

FIGURE 1. PROBABLE AREAL EXTENT OF SILURIAN BEDDED SALT BELOW LAKE ERIE.
from Argonne (1978)

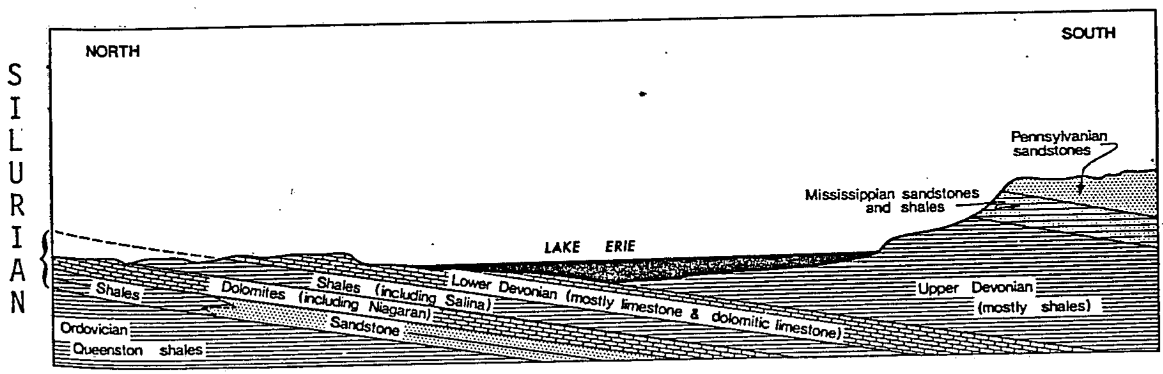

FIGURE 2. BEDROCK STRATIGRAPHY CROSS SECTION LAKE ERIE BASIN. (Modified from Hough 1958.)

from Sly (1976)