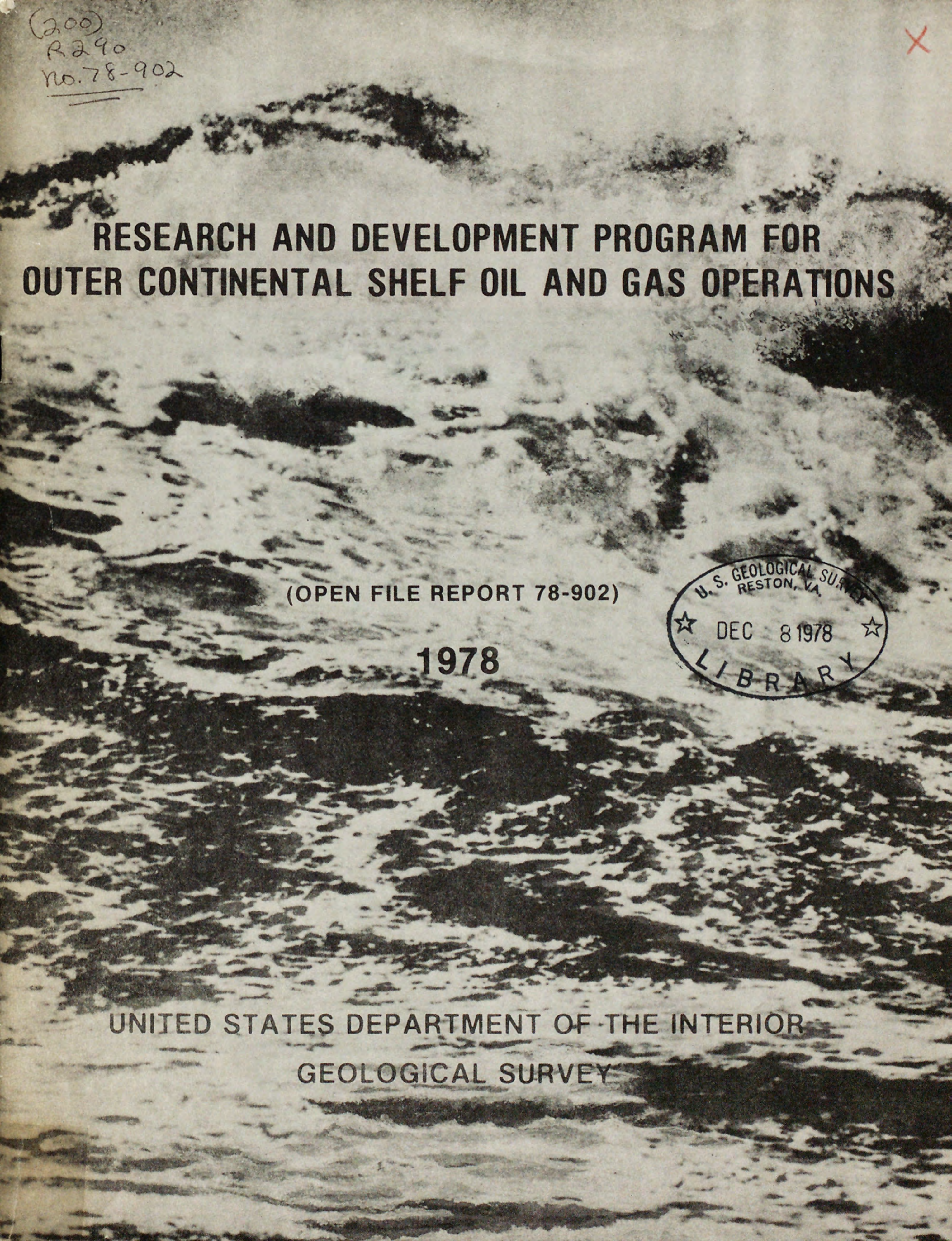

# RESEARCH AND DEVELOPMENT PROGRAM FOR OUTER CONTINENTAL SHELF OIL AND GAS OPERATIONS

(OPEN FILE REPORT 78-902)



1978

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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# RESEARCH AND DEVELOPMENT PROGRAM FOR OUTER CONTINENTAL SHELF OIL AND GAS OPERATIONS

REPORT FOR FISCAL YEAR 1978

COMPILED BY JOHN B. GREGORY

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OPEN FILE REPORT 78-902

# PREFACE

This report summarizes the contract research program in support of the Geological Survey's Outer Continental Shelf oil and gas operations. The program is technological, though certain environmental investigations are being conducted as a necessary adjunct. The program manager provides a focal point for communicating with the research community in both the university system and private industry as well as with Federal agencies. Interaction is needed not only with other Government agencies, such as the Bureau of Land Management and the Department of Energy, but within the Geological Survey itself. USGS engineers and scientists are in a unique position to contribute to the success of the program by their specialized knowledge and experience in the many aspects of offshore operations such as marine geology, seismology and petroleum engineering.

This document describes the program and reports on the research, development, and evaluation which are being undertaken.

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RESEARCH AND DEVELOPMENT PROGRAM FOR OUTER CONTINENTAL SHELF OIL AND GAS OPERATIONS--REPORT FOR FISCAL YEAR 1978
Compiled by John B. Gregory

## INTRODUCTION

The U.S. Geological Survey (USGS) has regulatory responsibility for activities which affect safety and pollution-prevention in marine oil and gas operations on the Outer Continental Shelf (OCS). In the course of these operations, USGS field personnel monitor industrial practices and identify technologies where research and development might reduce the likelihood of accidents and pollution. To this end, a contract research and development program was established as an integral part of the USGS marine oil and gas operations.

The guidelines followed are established by the Survey and specify a research effort which augments industry-sponsored programs and relevant research and development at academic and Government institutions. This augmentation results from a continuing assessment of OCS technology and an identification of aspects which require additional investigation.

The program involves both field and headquarters operations personnel who not only assist in performing technical assessments but review technical proposals and program accomplishments. At USGS Area offices, where OCS field operations are managed, Area

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1 U.S. Geological Survey, Policies, Practices, and Responsibilities for Safety and Environmental Protection in Oil and Gas Operations on the Outer Continental Shelf, page 10, June 1977.

Systems Review Committees are now being established to review safety and pollution-prevention matters on the oil and gas leases. Accidents, unusual conditions, equipment failures, inspections, the adequacy of USGS regulations, and research and development needs are deliberated and reported.

In the identification of technology gaps, assessments of new and anticipated problems in frontier areas, as well as in developed areas, must be taken into account. Deeper and rougher water, increased seismic risk, and even sea ice are a few of these projected problems. If participation in the solution of these identified problems is not forthcoming, USGS might undertake research.

Research is accomplished by contracts at universities, private industry, and through funding at Government laboratories. The Survey seeks to publicize the program in the scientific and technical communities and to locate people who have promising ideas for research. Notices in the Federal Register or Commerce Business Daily, attendance at conferences, and other means are employed in the search of sources of new technology.

Potential proposers are invited to write to the Research Program Manager for the information package Unsolicited Proposals for Research and Development in Support of OCS Oil and Gas Operations. The package describes the program and offers guidelines for preparing proposals.

The program consists of research, development and evaluation, basically in the field of technology. Though some projects involve the fabrication of hardware, such equipment is for purposes of modeling to prove-out the technology. The composition of the program depends upon the priorities established within the Survey and is limited by the research budget as well as potential project payoffs and costs.

The research program for Fiscal Year 1978 is summarized in this report. It is presented on a project-by-project basis with certain background information related so that the reader can see the context into which the work fits.

# DYNAMIC PROPERTIES OF OFFSHORE STRUCTURES

Principal Investigator: Dr. J. Kim Vandiver
Massachusetts Institute of Technology
Cambridge, Massachusetts

Objective: To determine dynamic design criteria for offshore structures.

Like most structures (ships, bridges, aircraft, etc.), offshore platform technology evolved from designs which neglected dynamic analyses. However, operational experience with these platforms, especially those in deeper water and therefore subject to more sway, eventually led designers to consider more than static loadings. Consideration had to be given not only to the ocean currents, winds, and the so-called "100-year storm" but also to the continuous cyclic forcing of the ocean waves which relegate the structures to the fatigue regime.

In 1975, Dr. Vandiver completed his Ph.D. thesis on the "Structural Evaluation of Fixed Offshore Platforms." The thesis compared computer simulations of structural damage with measured response data from an offshore platform. That same year Dr. Vandiver introduced the concept of structural monitoring to the offshore industry in a paper delivered to the Offshore Technology Conference entitled "Detection of Structural Failure on Fixed Platforms by Measurement of Dynamic Response." At that time it was recognized that numerous technical problems needed to be overcome before the technique could become generally useful for inspection of fixed platforms. By early 1977 considerable interest in the technique had developed, prompting several industry-sponsored projects.

Dr. Vandiver is continuing his investigations into the dynamics of ocean structures to provide technical insights which would be useful to designers as well as those involved in structural monitoring. Specifically, the objectives of his research are to (1) determine structural response properties (such as natural frequencies, damping and modal shapes) from field data and, (2) assess the importance of damping in the response of structures to wave excitation. The two subjects are closely related, and simultaneous studies are being conducted which use data from model tests and from ocean structures. The combined investigations involve the development of both sophisticated spectral analysis algorithms for studying dynamic response data, and predictive models for estimating the response level of a structure to a specific sea state.

To date Fast Fourier Transform (FFT) spectral analysis of ambient vibration records has proved inadequate in providing stable baseline determinations of structural natural frequencies above the fundamentals in bending and torsion.

In the MIT research two high-resolution spectral estimators are being applied to this problem: maximum entropy analysis and maximum likelihood spectral analysis. Although these methods have not been exploited in the study of ocean engineering structures, they are generally accepted in geophysics and acoustics. Maximum likelihood methods have been used to identify natural frequencies and damping of buildings to wind excitation. Both techniques probably will be quite accurate for identifying the spectral peaks associated with natural structural frequencies; furthermore, they use much shorter record lengths than those required for FFT analysis. The ability to utilize shorter records is especially useful for estimating damping, because the long record lengths required for FFT analysis (typically 1/2 to 1 hour) may often violate assumptions regarding the degree to which the excitation is stationary. Non-stationary excitation effects may result in erroneous damping measurements. A single-channel version of the maximum entropy algorithm is already operational and is being used to analyse platform response data. Figure 1 shows an acceleration response spectrum from a Navy platform which stands in 105 feet of water east of Cape Hatteras. The spectrum was computed from a single record 240 seconds in length, using the maximum entropy analysis. First and second order bending and torsional modes are easily differentiated.

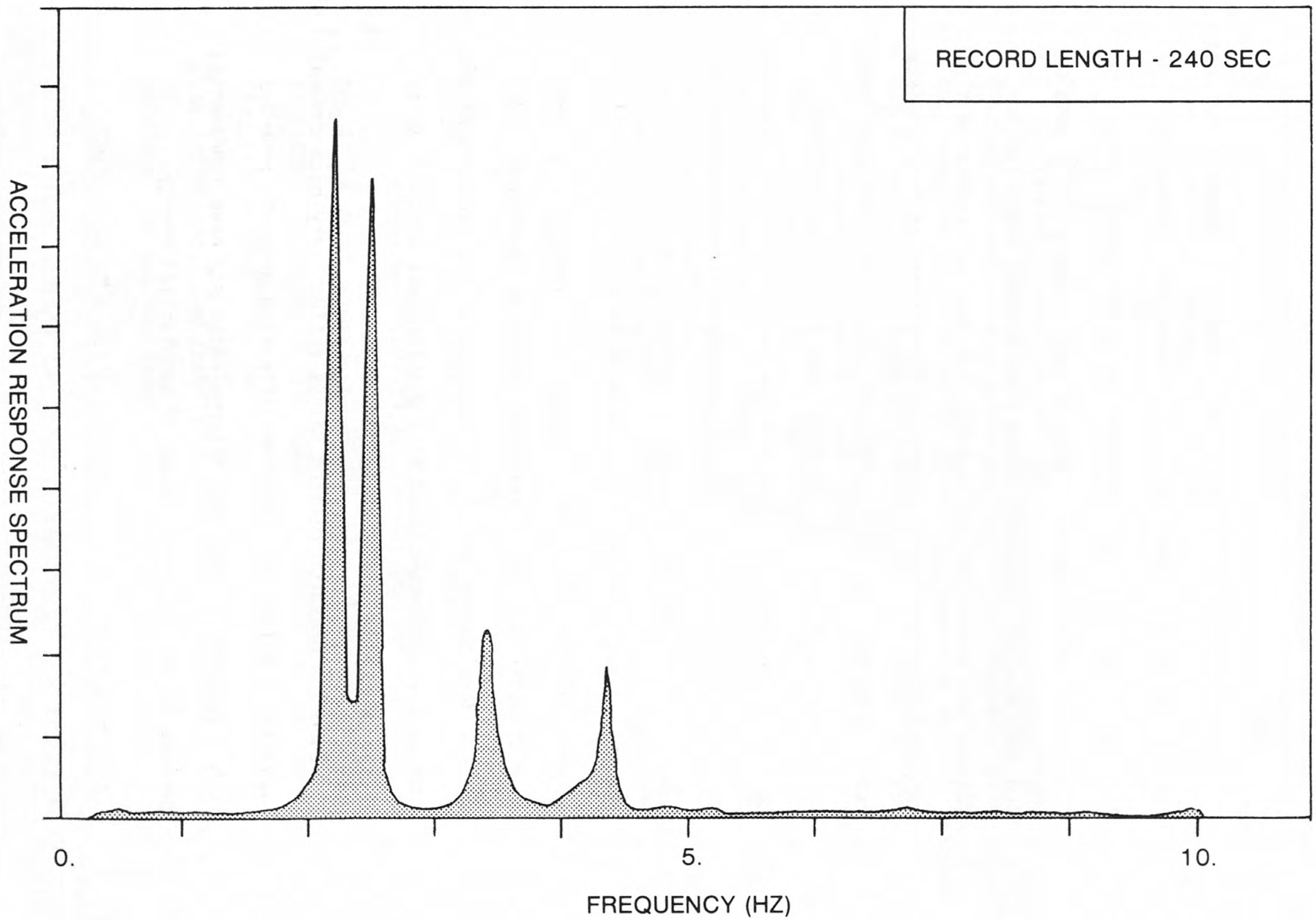



FIGURE 1 NAVY PLATFORM ACCELERATION RESPONSE SPECTRUM USING A MAXIMUM ENTROPY SPECTRAL ESTIMATE

Many deepwater structures have fundamental flexural natural periods exceeding 3 seconds. Calculating the fatigue life for such structures must consider the dynamic amplification of response which occurs at the natural frequencies in bending and torsion. It is widely known that dynamic amplification factors are controlled by damping; low damping results in high response. Unfortunately, reproducing measures of damping from response records has been difficult. Until reliable measurements from existing structures are obtained, it will be difficult to select appropriate values for the design of future platforms.

This research is intended to provide reliable measures of damping. Response records resulting from both ambient wave excitation and artificially forced vibration will be analyzed. Results to date indicate that damping values are substantially lower than commonly believed. For example, using techniques under current development at MIT, the damping of the fundamental bending mode of the above-mentioned Navy platform was computed to be 1.7 percent.

Such low measured damping values reflect very high dynamic amplification factors. High amplification presents problems to the designer of deeper platforms which may have fundamental periods corresponding to waves of substantial energy.

Recent research at MIT indicates that other response-limiting mechanisms will alleviate the problems posed by the apparent very high dynamic amplification factors.

It is widely believed that for a given sea state, as the damping decreases the response at the natural frequency must increase, reaching theoretically infinite response at zero damping. Recent results have shown that this is fundamentally not true for structures excited by predominantly linear wave forces (negligible drag exciting forces). In fact there exists an upper bound on the response which is independent of damping. This is a consequence of the often overlooked fact that linear wave forces and radiation (wave making) damping are directly related. That is, the wave force spectrum on a structure can be expressed in terms of the radiation damping.

Those results have been incorporated in a method for predicting dynamic response to linear wave forces, which puts the role of damping and dynamic amplification in proper perspective. The method is quite general and should apply to a wide range of problems. For example, the heave, pitch, and roll response of a tension leg platform are quite easily estimated by the new techniques. The results of this research have been recently submitted for publication.

Under some circumstances it may become advantageous to artificially suppress the dynamic response of a structure at a natural frequency. In the course of studying the influence of the motions of liquids in onboard storage tanks on the measured natural frequencies, a method was discovered for artificially suppressing structural dynamic response. The method is similar in concept to the use of antiroll tanks on ships, but utilizes tanks which are already required for other purposes. Additional tanks may not be required, only the optimum configuration of those which serve existing needs.

The principle is illustrated in figure 2. A water storage tank on board a U.S. Coast Guard light station was configured to suppress platform response at the fundamental flexural natural frequency. The natural mode was excited by two people shifting their weight in tune with the platform motion. Upon reaching the maximum response amplitude shown, the excitation was halted, and a transient decay was observed. Approximately 60 percent of the energy of vibration at the time the excitation ceased was eventually converted to sloshing waves in the tank (fig. 2).

Published reports: Vandiver, J.K., Detection of Structural Failure on Fixed Platforms by Measurement of Dynamic Response, Journal of Petroleum Technology, Volume XXIX, p. 305-310 March 1977.

Vandiver, J.K., The Effect of Liquid Storage Tanks on the Dynamic Response of Offshore Platforms, Proceedings: 1978 Offshore Technology Conference, Volume I, Paper No. 3162, May 1978.

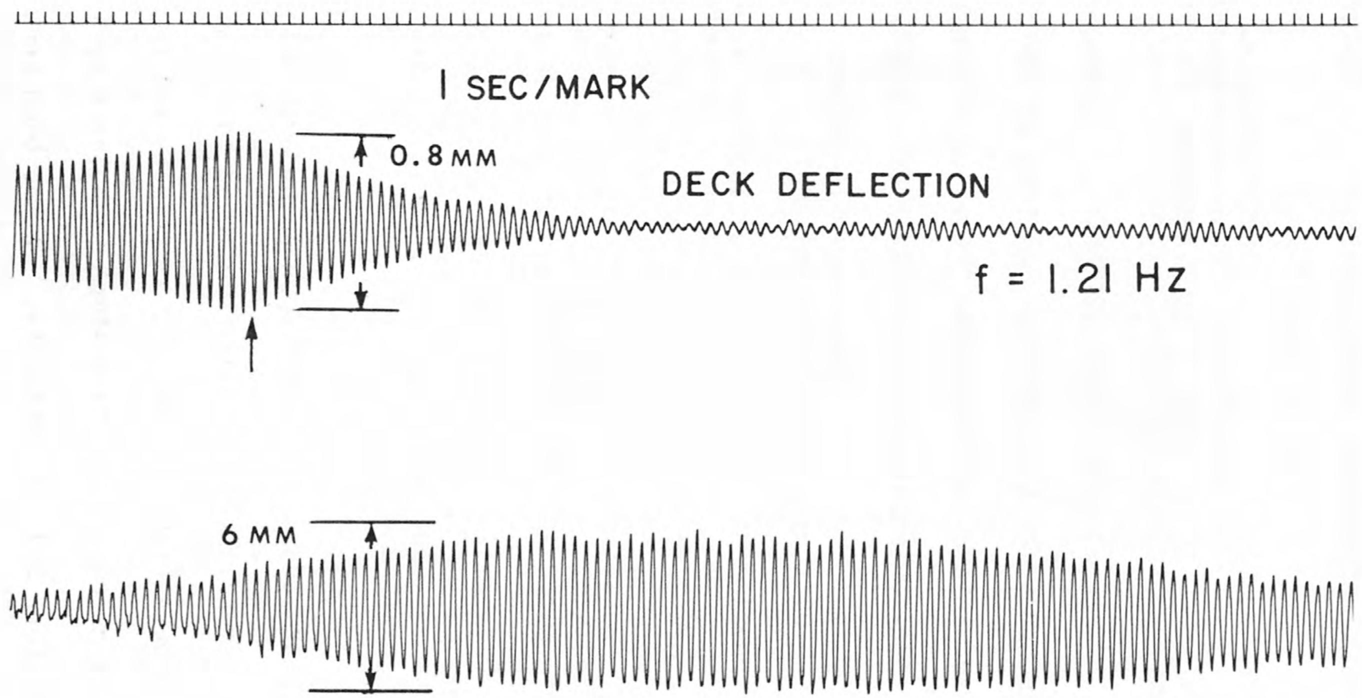



FIGURE 2. ARTIFICAL SUPPRESSION OF STRUCTURAL DYNAMIC RESPONSE BY MEANS OF A TUNED WATER STORAGE TANK .

DETECTING INCIPIENT CRACK FORMATION IN
OFFSHORE STRUCTURES BY INTERNAL-FRICTION MONITORING

Principal Investigator: Dr. Ambrose A. Hochrein, Jr.
Daedalean Associates, Inc.
Woodbine, Maryland

Objective: To determine the application of a technique which monitors internal friction for the detection of incipient cracking in structural joints, and to assess the value of a computerized system for monitoring progressive failure of a complex structure.

For his Ph.D. thesis at Catholic University, the principal investigator developed a nondestructive evaluation technique for detecting incipient failure from stress corrosion cracking in alloy metals. Subsequent experience with the procedure on structures, such as pressure vessels, submersible hulls, valves, and geothermal drill pipe, has led Dr. Hochrein to apply it as a technique for detecting incipient crack formation.

The test procedures are based upon an understanding of the behavior which metals manifest when subjected to stress. This behavior is a deviation from perfect elasticity and causes within a metal energy dissipation which is related to the granular structure and its integrity. It has been known for more than a century that metals do not exhibit perfect elastic behavior, even at very low levels of stress. Because of this anelasticity part of the mechanical energy input to a metal is converted to heat, and the various mechanisms by which this process occurs are collectively termed internal damping. Increases in internal damping during the service life of a metal indicate progressive fatigue, from which structural life can be predicted.

To measure internal damping a structure is subjected to a low stress pressure wave and the logarithmic decrement is measured. A simple beam can be excited by merely plucking it or a complex structure may be driven by means of a vibration shaker. The response of a simple beam may only contain the fundamental frequency and its overtones, but complex structures will exhibit many responses masked within a single response envelope (fig. 3). Further, whereas in the case of the beam, band-pass filtering of the logarithmic decrement will sort out the fundamental and harmonics, the decay envelope of the complex structure will most efficiently be scrutinized by means of a frequency spectrum analyzer.

In a complex structure, once degradation is detected, the incipient crack must be located. For a structure of welded columns, beams, braces, etc., accelerometers might be placed at various locations then, by means of triangulation, a failing joint could be identified. Or instruments could be placed at probable "hot spots" in structures and only those locations be monitored.

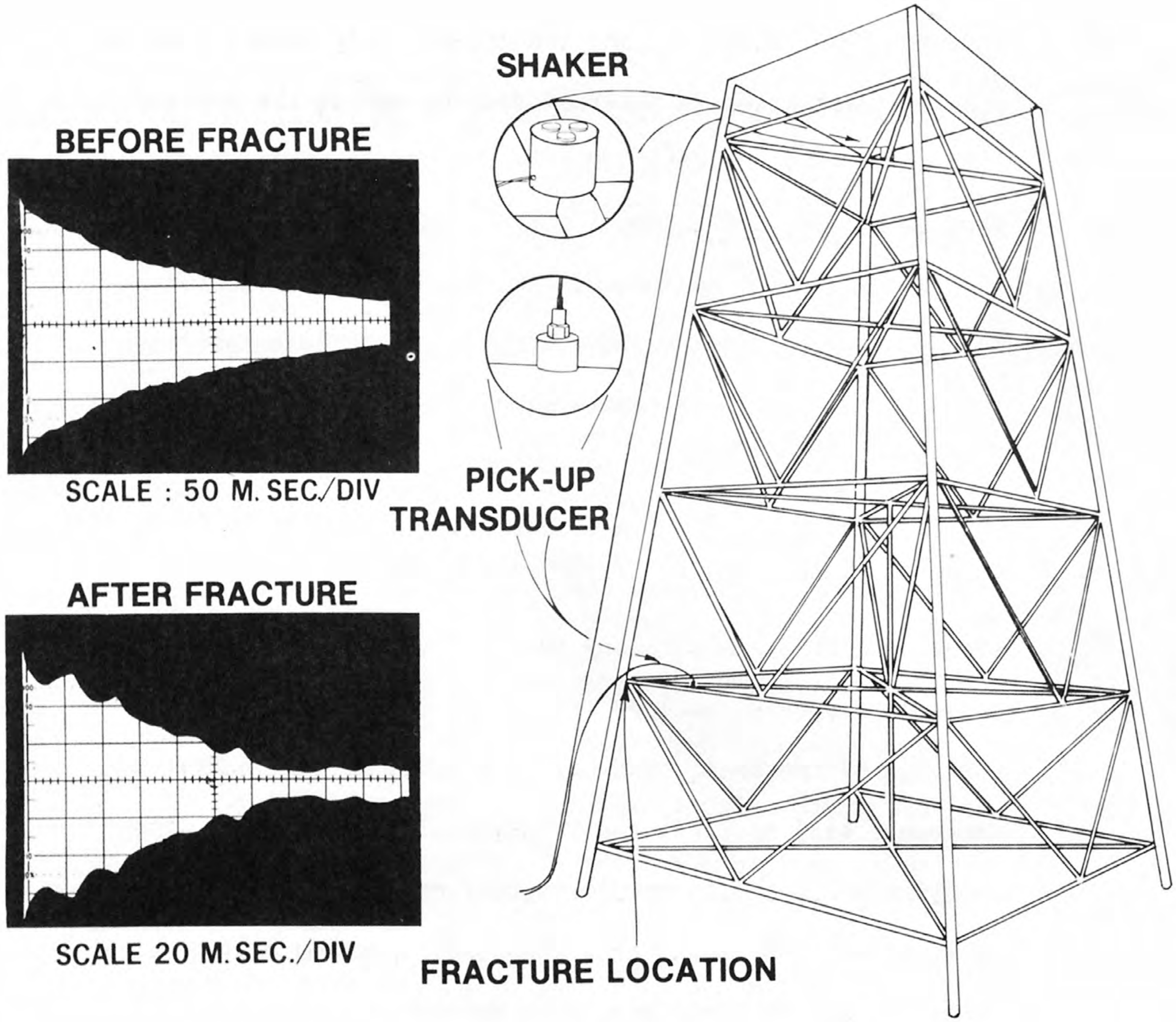



FIGURE 3 SCALE MODEL OF OFFSHORE PLATFORM SHOWING LOGARITHMIC DECREMENT ENVELOPES BEFORE AND AFTER FATIGUE FAILURE INCEPTION.

Still unanswered is the applicability of the technique to large structures, such as offshore platforms, which are subjected to complex fatigue regimes resulting from wind, wave, corrosion, ocean floor erosion, and changing deck loadings.

Daedalean Associates has constructed a one-fourteenth-scale model offshore platform (fig. 3). A platform-mounted small shaker excites the structure at various frequencies. At several locations on the legs and braces, small accelerometers record responses to input signals. During this process braces are fatigued in-place by means of a specially designed loading harness. Response signals are separated in a frequency spectrum analyzer and computed in a digital processor. By use of this computer-assisted digital processing system sensors can be placed at key locations in order to monitor structural integrity. Thus, in real time, the progressive failure of a complex structure can be observed. The company demonstrated the ability of the technique to measure progressive failure on the model in air and is determining an optimum software program to analyze complex systems and predict structural failure. After model evaluation, field experiments will be conducted.

This project is jointly funded by USGS and the Structural Mechanics Program of the Office of Naval Research.

DETECTION OF INCIPIENT STRUCTURAL FAILURE BY THE RANDOM DECREMENT METHOD

Principal Investigator: Dr. Jackson C. S. Yang
University of Maryland
College Park, Maryland

Objective: To evaluate the applicability of random decrement analysis for detecting flaws and predicting useful life in offshore structures.

A method of analysis known as the random decrement technique (RANDOMDEC) is well suited to determining the characteristics an inservice structure subjected to unknown random excitation. Analysis requires only the measurement of the dynamic response of a structure, not the excitation. On offshore platforms, such inputs result mostly from waves and wind.

The analysis of a time history of a response at some location on a structure produces a signature which reflects structural properties such as natural frequencies and damping. Having a signature which is sensitive to changes in structural properties allows the detection of changes in those properties. Hence, incipient failures are detected by monitoring changes in signature.

Because of inadequacies in methods for analyzing structural vibrations and changes in vibration characteristics (namely autocorrelation and power spectral density methods), the RANDOMDEC analysis was developed by Mr. Henry A. Cole about a decade ago.

In his work for NASA on flutter problems associated with the Saturn launch vehicle he found the autocorrelation function of random vibrations to change not only with the development of a fatigue crack in a structure but also with variations in the random environment, thus giving false indications of failure. Theoretically, the problem of changes in vibrations which results from changes in the input environment could be overcome by measuring both the input forces and the output vibrations and then calculating cross-spectra or cross-correlations. But this is extremely difficult to do in practice because the input forces occur at so many points that quantification is almost impossible. The problems with spectral and correlation methods are further complicated if, as often happens, a structure has damping which is nonlinear with amplitude.

The RANDOMDEC method analyzes the measured output of a system subjected to some ambient random input. After analysis a signal results which is the free vibration response or signature of the mechanical structure. This signal is independent of the input and represents the particular structure tested. The ability to obtain unique response signatures for different modes (usually accomplished by filtering the output) enables one to detect early damage before overall structural integrity is affected. Local flaws, such as cracks, too small to affect the overall integrity, have a significant effect on the signatures of the higher modes. As a flaw grows, progressively lower modes are affected until overall failure occurs. Damage is detected by studying and comparing the signatures of the higher structural modes. Figure 4 illustrates the acquisition of RANDOMDEC signatures.

When a fatigue crack develops, it introduces additional degrees of freedom which are then excited by random forces. Small cracks show up as small blips in the "hashy" high modal density region of the response spectral density, and as these cracks grow, the failure mode frequencies decrease and approach the fundamentals where failure becomes imminent. Flaws must be detected early enough--that is, at high enough frequencies--that corrective action can be taken. This procedure is accomplished by passing a random signal through a bandpass filter which is set at a high frequency. If a failure develops it will dramatically affect the signature because it will dynamically couple with structural modes within these bandpass frequencies.

The RANDOMDEC technique is applied to the filtered response data of the vibrating structure both numerically and on an analog computer specially designed by Mr. Cole to establish a set of signatures. From these signatures their sensitivity to fatigue cracks of various lengths can be shown.

A laboratory study was recently begun to establish the signatures and to determine their sensitivity to such variables as flaw size, distance, location, and frequency

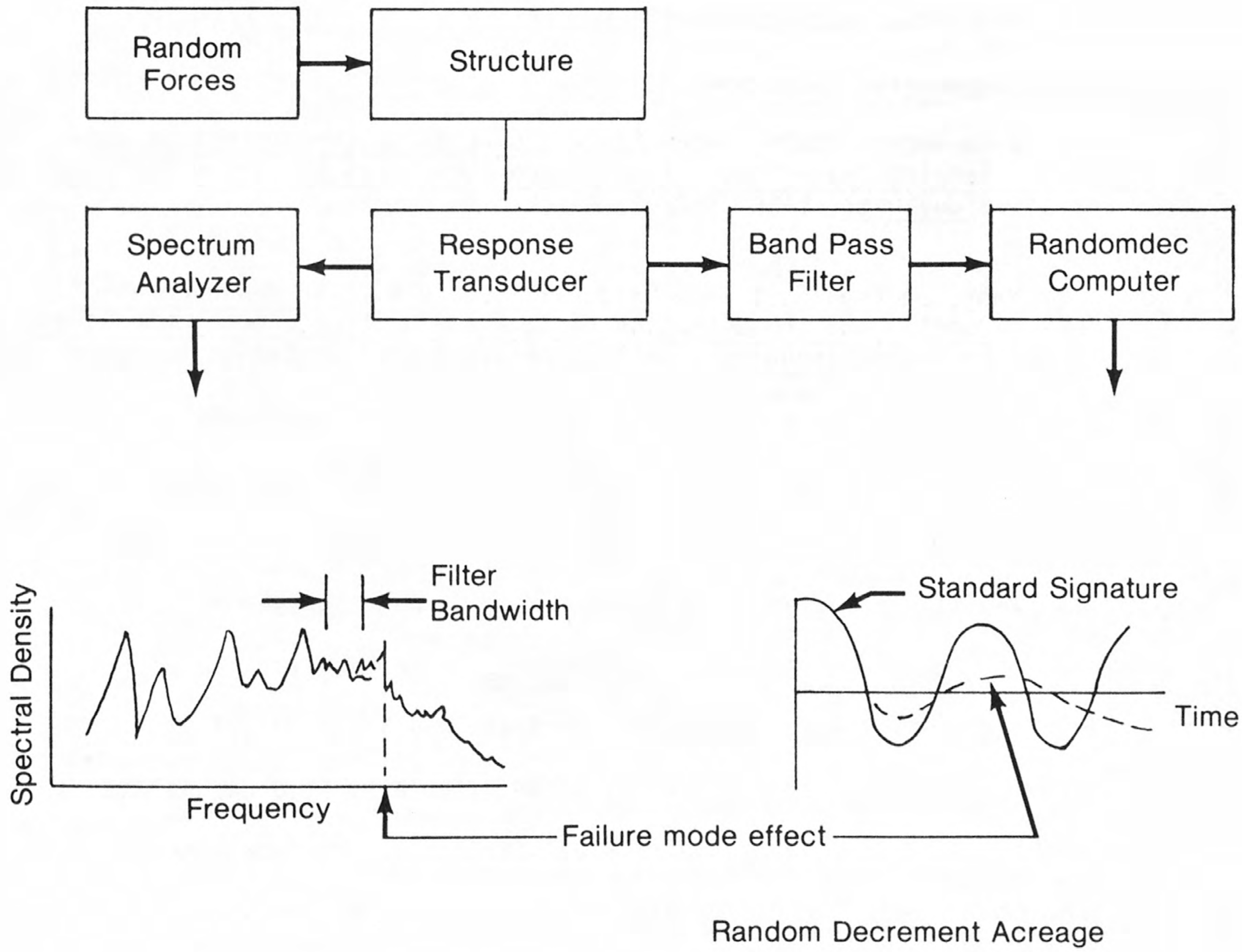



FIGURE 4. ACQUISITION OF RANDOM DECREMENT SIGNATURES

content. Future work includes studying the influences of corrosion, full-scale platform monitoring and the location of a flaw which has been detected.

References: Cole, Henry A. Jr., On-Line Failure Detection and Damping Measurement of Aerospace Structures by Random Decrement Signatures, NASA CR-2205, March 1973.

Yang, Jackson C. S. and Caldwell, Donald W., The Measurement of Damping and the Detection of Damages in Structures by the Random Decrement Technique, 46th Shock and Vibration Bulletin, August 1976, p. 29-36.

# CAVITATION EROSION TECHNOLOGY FOR CLEANING UNDERWATER STRUCTURAL JOINTS PRIOR TO INSPECTION

Principal Investigator: Dr. Alagu P. Thiruvengadam
Daedalean Associates
Woodbine, Maryland

Objective: To investigate the technology of controlled cavitation erosion to clean underwater structural joints for purposes of inspection.

During the past several years the Navy has evaluated the phenomenon of cavitating erosion for the purpose of harnessing its destructive forces to perform work underwater. The principal investigator, Dr. Thiruvengadam, has been studying both the physics of cavitating flow and its adaptation as a tool.

The basic effort has been to produce a cavitating water jet which can drill and cut steel underwater. Such a technological advance would provide Navy divers with a relatively safe, lightweight, and efficient tool. Other applications, including the cleaning of hard scale from boiler tubes, geothermal pipe and heat exchangers, as well as marine growth from ship hulls, are also being investigated at Daedalean. Any nozzle developed for hull cleaning would be quite similar to that required for blasting marine growth from the joints of the various underwater structural members on offshore towers to permit visual inspection for cracks. To this end, the USGS is participating in the development.

Experimentation at Daedalean has determined that the intensity of erosion of cavitating flow varies approximately with the twelfth power of nozzle velocity. The intensity is a quantitative measure of the energy flux to the cleaning surface and a critical design parameter. This velocity-power relationship results from the increased nucleation rate which occurs from the passing of high-pressure water through cavitation-inducing nozzles.

The relationship has held to the highest capacity of the laboratory pumping system, which is 12,000 psi. The nozzles being used are about 1/32-1/16 inch diameter and produce throat velocities of about 1500 feet per second. The exponential relationship is expected to decrease as the speed of sound in water is approached.

As the water flows through a specially configured cavitation nozzle, minute vapor bubbles rapidly form at the point of lowest pressure and are carried downstream and collapse outside the nozzle in a zone of higher pressure. When each bubble collapses and the vapor within it condenses, the resulting impact of opposing masses of water produces extremely high local pressure which is transmitted radially outward at the speed of sound. A negative pressure wave results and the vaporization-condensation cycle recurs.

Whenever the stress produced by the collapse of a single bubble exceeds the yield strength of a material, deformation is produced. If the associated collapse stress is less than the yield strength, but above the endurance limit, erosion may occur after many bubbles have impacted and collapsed at the surface of the material; erosion is then produced by fatigue failure.

The process of formation and collapse of bubbles is so nearly instantaneous that with the naked eye only a continuous opaque blur can be distinguished. This blur takes the shape of an envelope or plume (fig. 5). Variations in the flow of velocity beyond that required for incipient cavitation are made to adjust the size and shape of the cavitation envelope. Such adjustment is necessary to optimize the envelope for the particular task involved. In addition to erosion intensity, nozzle stand-off distance and projected erosion area are of utmost importance.

Thus far the project has demonstrated in the laboratory the feasibility of using cavitation errosion to remove marine growth and clean to bare metal. For a single nozzle, using twenty input horsepower, a cleaning rate of one-quarter square foot per minute has been obtained on laboratory samples. The project is currently optimizing the physical parameters of a system which is to be taken offshore and tested by a diver.

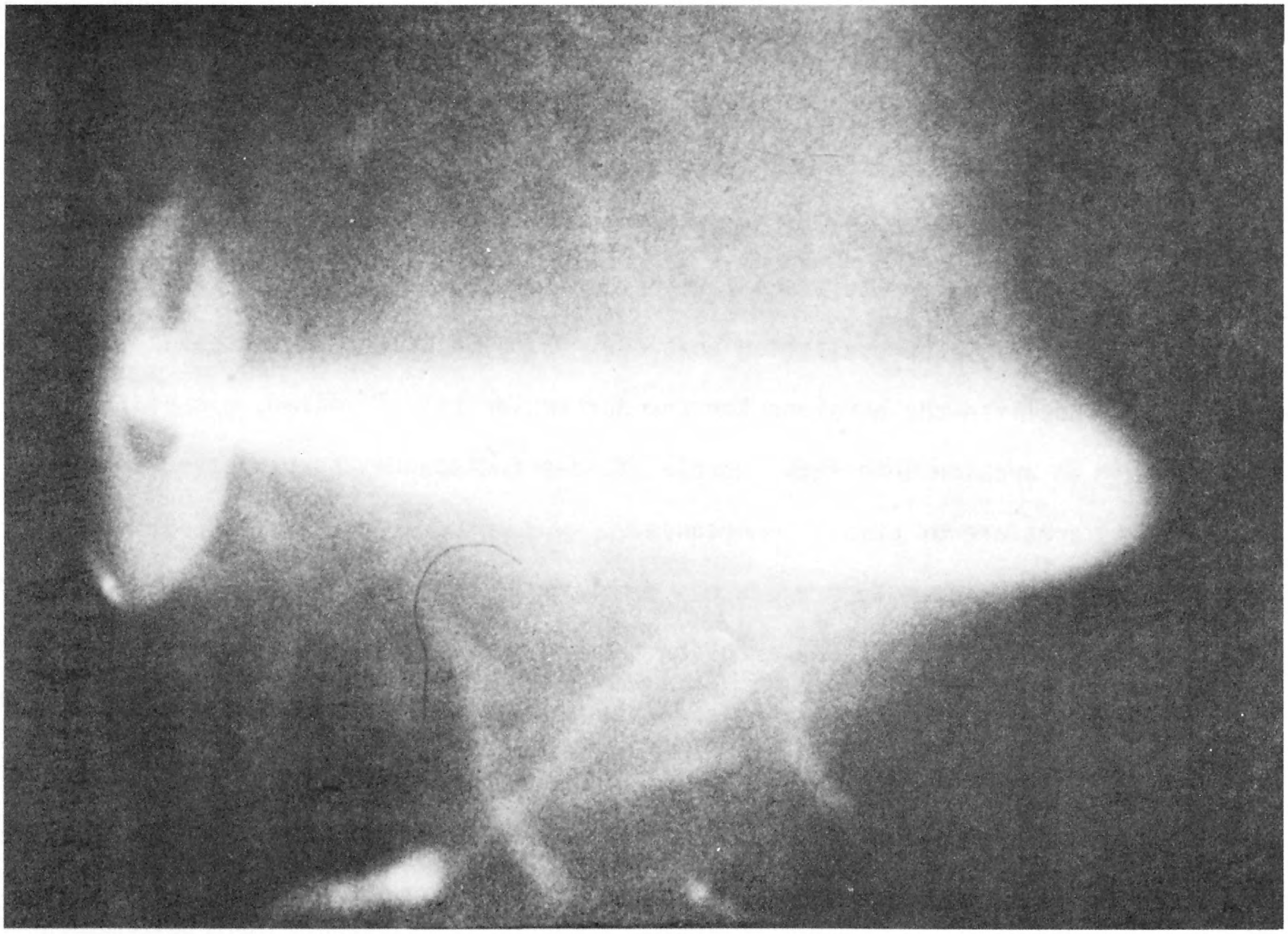


FIGURE 5 CAVITATION ENVELOPE OR PLUME. NOTE NOZZLE AT LEFT. (ENLARGEMENT 2X)

# UNMANNED, FREE-SWIMMING UNDERSEA INSPECTION VEHICLE TECHNOLOGY

Principal Investigators:

Paul Heckman
Naval Ocean Systems Center
San Diego, California

Dr. Robert Corell
University of New Hampshire
Durham, New Hampshire

Objective: To develop the technology for underwater inspections of pipelines and structures from unmanned freeswimming vehicles.

Two decades ago, underwater inspections were limited to the use of divers or sensors which were lowered or towed to obtain either a visual image or an acoustic or magnetic signature of the area being inspected. Sizable technological inroads have since been made in both manned and unmanned methods for accomplishing underwater inspections. These innovations reflect an overanticipation in the early 1960's of a large commercial and Navy demand for working and exploring in the undersea environment.

Manned submersibles were built for many applications but, except for commercial shallow-water inspection, their development has been hampered by lack of commercial market and limited Naval usage. Manned submersibles are expensive to build and operate, generally requiring a mother ship capable of taking them aboard and tending them at depth.

Tethered vehicles, too, require a properly outfitted mother ship. They must be controlled and manipulated so as to position them for inspection and, in some cases, for accomplishing useful underwater work such as grabbing objects.

In recent years, attempts have been made to develop unmanned vehicles which can swim and navigate freely underwater. Because of recent advances in electronics and computer microminiaturization, these vehicles now appear feasible and economical.

Several years ago, an acoustically controlled vehicle was developed and successfully tested by the Applied Physics Laboratory of the University of Washington for use under the Arctic ice. This vehicle, UARS (Underice Arctic Research System), was designed to sense and record the vertical profile of the underside of the ice.

Both the Naval Ocean Systems Center (NOSC), formerly known as the Naval Undersea Center (NUC), and the University of New Hampshire have begun to develop and test free-swimming vehicles. The NOSC vehicle, (fig. 6), is of torpedo shape and size and is designed for various underwater search and inspection missions of interest to the Navy. In the center of the NOSC vehicle's open frame are four canisters of batteries and electronics. Twin propellers are located aft and a vertical propeller is mounted amidships, between the canisters. Syntactic foam at the top of the frame provides neutral buoyancy. The frame is readily expandable in length so as to accommodate larger payloads.

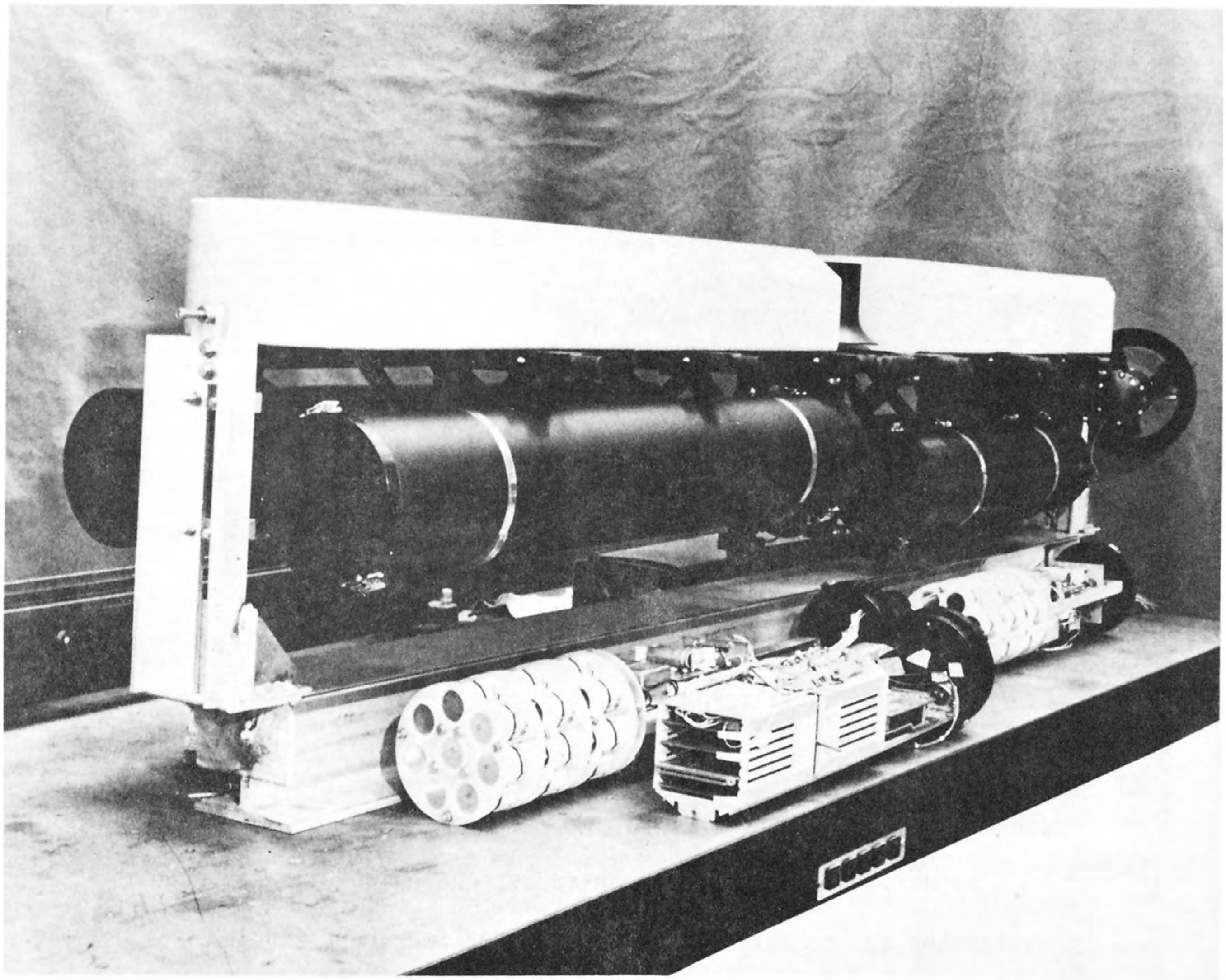


FIGURE 6 NAVAL OCEAN SYSTEMS CENTER FREE-SWIMMING TEST BED VEHICLE.

The University of New Hampshire, with financial aid from the Federal Sea Grant Program, had begun the development of a pipeline survey vehicle. This vehicle (fig. 7), has twin electrical thrusters on three axes so that it can navigate in any direction without preferred orientation. These thrusters are controlled by an onboard microcomputer which is programmed to interpret information from the vehicle's 12 acoustic sensors which are mounted on the ringlike structure at the base.

Subsystems for both test beds are being developed to meet the dual requirements of pipeline following and structure inspection. Basically, the long narrow NOSC vehicle will be faster but less maneuverable than the New Hampshire vehicle.

Under study at both institutions are navigation and control, and data storage and telemetry. Pending successful evaluation, the test beds are to be fitted with means for performing inspection and limited underwater work.

The University of New Hampshire is continuing with the acoustic navigation system development begun under Sea Grant funding and is beginning development of an acoustic communications link with the surface. The vehicle is being tested to determine its ability to follow a simulated underwater pipeline and is using an electrical umbilical for purposes of communication.

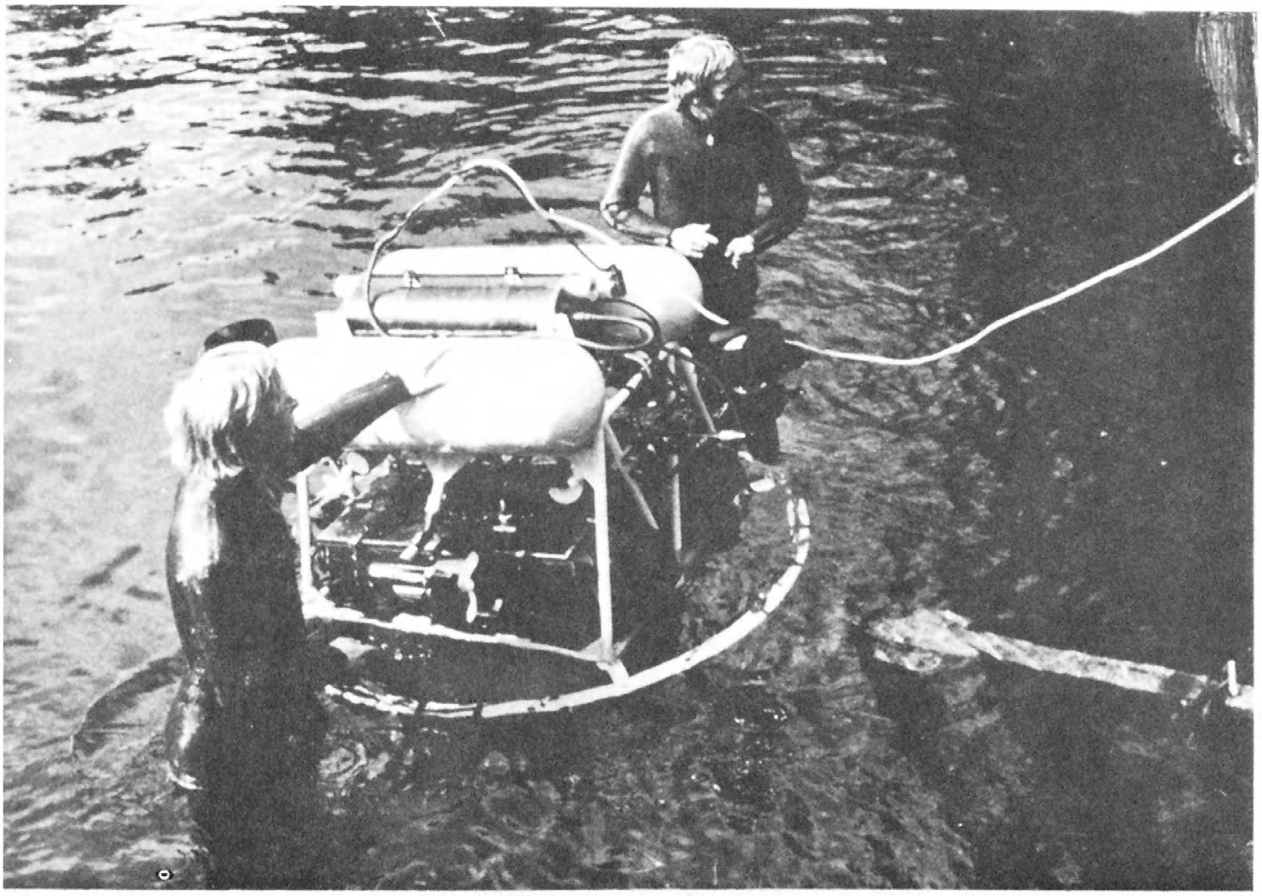


FIGURE 7 UNIVERSITY OF NEW HAMPSHIRE FREE SWIMMING TEST BED VEHICLE.

The NOSC vehicle will soon receive its first in-water test, during which it will be operated by means of preprogrammed commands. Upon successful completion of these tests, NOSC will investigate magnetic navigation sensing that will enable the vehicle to follow buried pipelines. Though acoustic telemetry (being developed by New Hampshire) may be fitted, NOSC is studying fiber optics technology under another program and will apply it to their vehicle. Whereas acoustic telemetry is apparently satisfactory for pipeline following, it may not suffice once a vehicle navigates underneath a structure; acoustic reverberation may require other means of communication. The fishline-sized fiber optics cable is to be paid out from the vehicle; this cable will present no drag and will allow the vehicle to maneuver at will around the braces of the structure as long as the vehicle does not run into the cable.

Published Report: Blidberg, D. R., Allmenglinger, E. F., and Sidiris, N., The Development of an Unmanned Self-Controlled, Free-Swimming Vehicle, Proceedings: 1978 Offshore Technology Conference, Volume III, paper No. 3235.

# ATTENUATION OF SURFACE WAVES OVER A LOCALIZED AREA OF OPEN WATER

Principal Investigator: Dr. Richard I. Hires
Davidson Laboratory
Stevens Institute of Technology
Hoboken, New Jersey

Objective: To investigate a method for achieving significant localized wave attenuation in the open ocean.

In the open ocean, when the wind rises above gentle to moderate breezes, it becomes increasingly difficult to launch buoyant objects such as small boats or submersibles. Furthermore, the transfer of personnel or equipment between boats or between a boat and a platform can be somewhat hazardous, depending upon the state of the sea. Even divers or submersibles operating under the surface can be encumbered by the cyclic effects of the wind-driven waves above. Much time and money could be saved if significant wave smoothing could be obtained in local areas so these normal sea operations could be carried out more safely and more rapidly.

Several years ago, at the Davidson Laboratory of Stevens Institute, very dramatic attenuation of regular waves was demonstrated in a study of the interaction of waves with turbulent wakes. The investigator, Dr. David Savitsky, used as a turbulence generator, a small vertical grid which was towed in the direction of a wave train but at slower speed. As successive waves rolled through the grid and its turbulent wake, the wave crests were refracted or bent away from the higher velocity regions of the current. This refraction of wave energy produced marked attentuation of wave amplitudes in the vicinity of the strongest current speeds.

Since wave energy was not significantly absorbed, there was wave reinforcement farther outward from the grid. Sailors have observed this reinforcement phenomenon on the edges of the Gulf Stream where the swiftly moving water is refracted outward from the stream.

The principal investigator, Dr. Richard Hires, has continued the study, focusing upon the physical parameters for wave smoothing by means of a towed grid type of turbulence generator. He experimented with regular waves to determine the empirical functional relationship between wave attenuation and the characteristics of both the laterally sheared current and the initial wave train. In addition, he determined the power necessary to generate a flow field sufficient to achieve a prescribed degree of wave attenuation under a given set of initial conditions.

The methodology used was to determine the dependence of attenuation on the dimensionless parameters of grid velocity to wave celerity, and grid length and draft to wave length. From these data the physical requirements were optimized for desired attenuation and minimum power expenditure. Previous theoretical studies though not strictly applicable, provided a framework for the study.

Figure 8 shows a grid being towed by means of an overhead carriage in the direction of regular waves and away from the camera. Three grids were employed which had widths of 2, 4, and 8 feet and drafts were varied to depths of 24 inches. Tow speeds ranged from 0.5 to 3.5 feet per second and the wavelengths ranged from 2 to 16 feet (1-3 inch initial wave heights).

Using hot-film anemometers to measure velocity distributions and a spring balance to measure drag, 700 test runs were made.

The velocity distribution in the wake of the grid was found to be approximately uniform along the wake centerline to the depth of the grid draft. This uniformity persisted 2-3 grid widths behind the grid. The centerline velocity was about one-half the grid speed.

Power required to achieve a specified attenuation ratio was shown to be independent of initial wave height; approximately three times the power was necessary to attenuate waves from 50 percent to 70 percent. For example to attenuate 6-second waves(wavelength 185 feet) to 50 percent of their initial height, required about 500 horsepower. Seventy percent attenuation required 1500 horsepower.

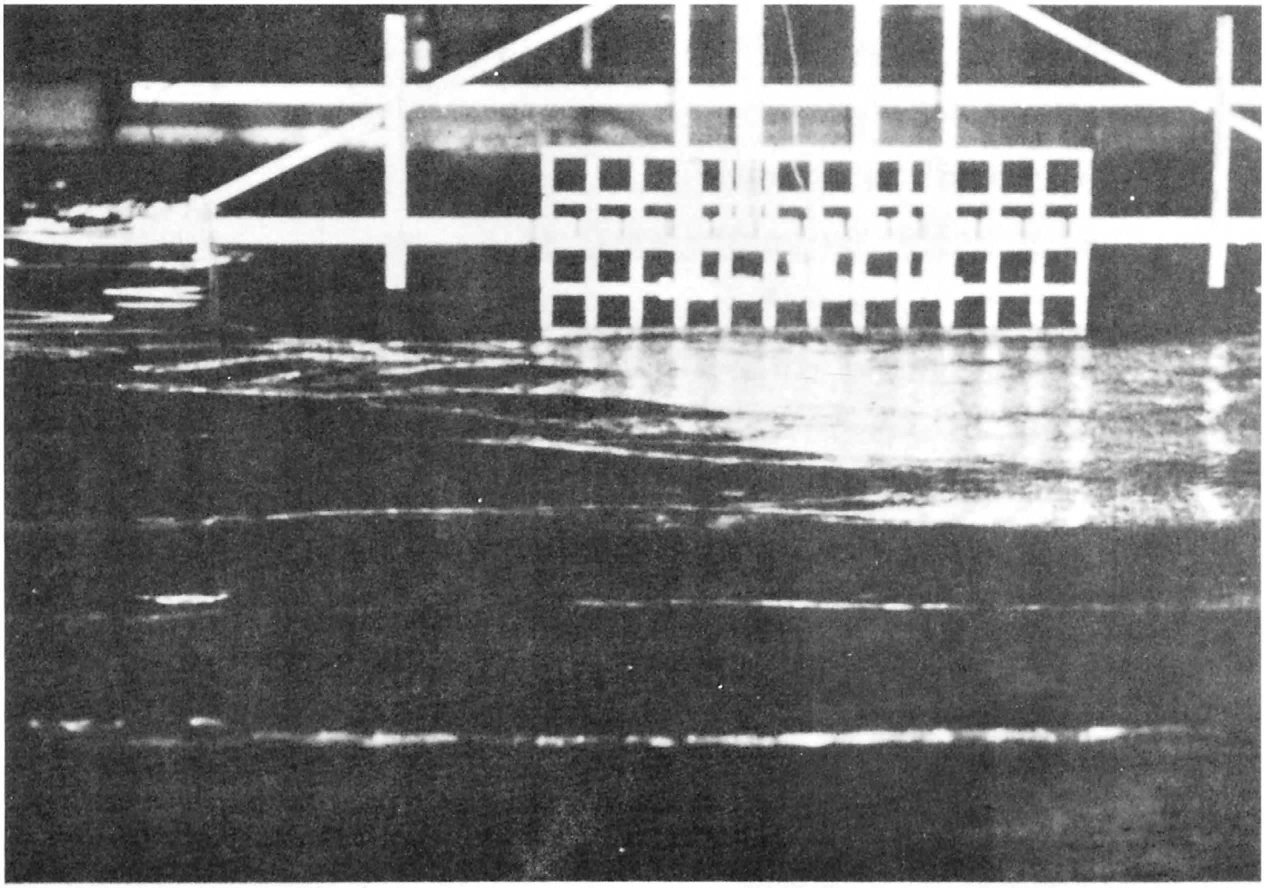


FIGURE 8 ATTENUATION OF REGULAR WAVES BY MEANS OF A TOWED GRID. WAVES AND GRID ARE MOVING AWAY FROM CAMERA.

Although difficult to measure precisely the duration of the attenuation apparently follows a Froude number scaling law. The 8-foot-wide grid produced 1 minute of attenuated waves, which relates to about 5 minutes for a 200 foot grid.

Additional model testing will focus on oblique and random waves, and further work will be conducted to reduce required power. The goal will be to determine the optimum grid shape and solidity ratio (that is, ratio of solid part to total area). Model experiments will be conducted to determine the most suitable towed bodies (nets for example) and testing methods.

Full-scale experiments will later be conducted in open water.

Project Reports: Hires, Richard I, An Experimental Study of a Method to Attentuate Surface Waves Over a Limited Region of Open Ocean, Davidson Laboratory, Stevens Institute of Technology, Hoboken, New Jersey, Report SIT-DL-78-2020. June 1978

# ACOUSTIC TRANSMISSION OF DIGITAL DATA FROM UNDERWATER SENSORS

Principal Investigator: Dr. Eric J. Softley
Ocean Electronic Applications, Inc.
245 Ridgewood Road
Key Biscayne, Florida 33149

Objective: To develop an adaptive acoustic link for underwater transmission of digital data.

As the exploration and development of the oceans continue, the need for data increases. These data may be environment information or may be used for the monitoring and control of underwater operations. Historically, ocean data were first obtained by observation (sailors observed the tides, winds, Gulf Stream, etc.) and then by sampling systems lowered from ships. Within recent years much information has been obtained by self-recording packages implanted and later retrieved by ship. More recently, depending upon the need for data timeliness, such as for military and oceanographic monitoring, electromechanical cables have been employed to transmit data directly to the surface. Cable systems are expensive to implant and are subject to the rigors of the sea which include wind, waves, currents, corrosion, and even fishbite. Cables and connectors are actually a major source of system failure.

Recent advances in electronics technology and power supplies, such as microcomputers and lithium batteries, herald greater improvements.

Obviously acoustic transmission of preprocessed underwater data would eliminate, in many instances, the need for electrical cables.

Acoustic signals travel well underwater. However, environmental conditions such as water depths and temperatures have a great effect on their attenuation and reverberation. At lower frequencies many acoustic paths are significant, and interference from multipath reception is a problem. At higher frequencies signals attenuate more rapidly but distinguishing such signals from many paths is simpler. In this latter case the data rate is proportionally higher, making high frequency systems more cost effective. Optimum choices exist both for acoustic frequency and modulation, depending on the variability of the environment.

The principal investigator is studying the use of acoustic telemetry for two USGS underwater data-gathering requirements: (1) Instruments placed at fixed locations by divers or submersibles and (2) instruments deployed by ship or aircraft.

In the first situation he will specifically study the retrieval of data from an instrument package placed on the leg of a platform to monitor structural integrity. The instrument package must sense, store and process the data, and acoustically transmit it to the surface.

In the second situation, the instrument package is placed by diver, ship, aircraft or other means depending on the application.

For example, a seismometer package may be flown out to a location and deployed to the ocean floor to record a seismic shock or aftershock. Use of an aircraft may be advisable because of time constraints or rough seas. Data are then retrieved by acoustic transmission to an expendable surface buoy (sonobuoy) which is also dropped by aircraft and which communicates with it by means of RF telemetry.

Another future application of the use of aircraft would be to fly over pipelines, where at various stations, these expendable sonobuoys would be dropped to relay data from cathodic protection devices.

For aircraft-dropped instruments, error may occur from navigation or shifting position of the sonobuoy during the transmission.

The basis of the transmission is frequency modulation of a central carrier. Pulse duration modulation is used, because this allows redundancy in bit detection and simultaneous evaluation of acoustic signals. This work continues a development program which was begun under U.S. Navy auspices. Results from that work indicate that, because of the acoustic variability of the ocean, a highly adaptive process in necessary if a single system is to be used for varying environmental conditions. Adaptability is achieved by allowing the receiver to evaluate the signal for optimum transmission and instruct the transmitter to adjust signal strength, acoustic frequency, and data rate. Special, low-power computers, now being developed by the principal investigator, will be used as a basis for the design.

The adaptive approach is a new development for data transmission. Present systems can transmit data under simple acoustic geometries (for example, a direct path from floor to surface with minimal horizontal displacement). However, these systems are not easily adapted to more complex acoustic paths where multipath interference and reverberation can occur. The acoustic frequency is not easily adjusted unless such capability is built into the original design.

## PATTERN RECOGNITION TECHNIQUES FOR UNDERWATER OPTICAL IMAGING

Principal Investigator: Harry Sadjian
General Sensors, Inc.
Fort Washington, Pennsylvania

Objective: To determine the applicability of pattern recognition techniques for underwater optical imaging in turbid coastal waters.

In "pattern recognition" observations are grouped so that only important data are retrieved for analysis. Such grouping hastens the retrieval of wanted data and avoids storing and analyzing unwanted data. The recognition of patterns of data could be applied to optical or acoustic imaging or even physical measurements.

In conjunction with the research program's untethered, unmanned underwater inspection vehicle study, pattern recognition technology is being investigated as an adjunct to an acoustic control and data link to the surface. Because simple messages require minutes of time to transmit by means of underwater digital acoustic telemetry, data should, ideally, be processed on board and only important information stored and transmitted to the surface.

In many respects optical imaging technology is much more advanced than acoustic technology.

At any rate the primary means of inspection used by present-day submersibles is optical viewing and photography.

Optical imaging is therefore an obvious starting point for pattern recognition studies. The U.S. Navy is studying optical imaging for the mid waters of the deep ocean, whereas turbidity is not significant; but offshore structures are located around the coastline of the United States in relatively shallow waters which have great turbidity variance. Thus, this situation must be analyzed to determine whether optical imaging will provide the necessary image quality for computer "recognition" of preprogrammed features.

It may ultimately be necessary to develop a system which incorporates both acoustic and optical imaging to provide a computer with the requisite information.

The principal investigator of this study is assessing the image quality obtainable from an optical viewing system as a prelude to developing a "recognition" computer system. Image quality depends upon viewing range and water turbidity, and these must be assessed for the coastal waters of interest. Having that information, he can then determine such variables as resolution, contrast and source illumination. Turbidity is expressable by means of characteristic attentuation and scattering coefficients of sea water.

Such analysis will provide the necessary information to determine the suitability of developing "characteristic algorithms" for an onboard pattern recognition computer.

DEVELOPMENT OF IMPROVED BLOWOUT PREVENTION PROCEDURES FOR DEEP-WATER DRILLING OPERATIONS

Principal Investigator: Dr. William R. Holden
Louisiana State University
Baton Rouge, Louisiana

Objective: To develop improved well control procedures for deep-water floating drilling operations.

An expensive and potentially dangerous problem associated with the production of petroleum is the control of high-pressure formation fluids encountered during drilling for hydrocarbon reservoirs. If not properly controlled the influx of these fluids can result in a blowout, with possible loss of life and property as well as attendant pollution.

A threatened blowout or "kick" in a well starts when the pressure exerted by the column of drilling fluid is less than the fluid pressure in a permeable formation which has been penetrated by the bit. Thereupon, formation fluid enters the well and displaces or "kicks" the drilling fluid from the wellbore annulus until the flow at the surface is stopped by closing the blowout preventers. Before normal drilling operations can be resumed, the formation fluids must be removed from the well and the density of the drilling fluid in the well increased sufficiently to prevent further influx of formation fluids. This is accomplished by circulating the well against a back-pressure provided by an emergency high-pressure flowline and an adjustable choke, using an appropriate well control procedure. These procedures have evolved over the years and numerous articles on them have been written by drilling experts for both drillpipe pressure control and casing pressure control. Drillpipe pressure control has been found to be the more practical and several variations of it are used in present-day operations.

In 1960 a better method of well control was proposed which specified the maintenance of a constant bottom hole pressure slightly exceeding the formation pressure. This could be accomplished by adjusting the surface choke, while maintaining a constant pump speed, so that the drillpipe pressure followed a predetermined schedule. This method allows a gas kick to expand as it rises, thereby reducing the pressure build-up in the annulus. Use of this method has decreased the frequency of underground blowouts.

Another technique for maintaining a constant bottom hole pressure during well control operations was introduced in 1962. It was the first method for calculating surface casing pressures required to maintain a constant bottom hole pressure. In this method the choke operation is based on the surface casing pressure rather than on the surface drillpipe pressure. Several variations of the drillpipe pressure method of well control are used in present-day operations. These variations are concerned mainly with the procedure used to increase the drilling fluid density in the well sufficiently to overcome the formation pore pressure. The three most common are (1) the drillers' method, (2) the wait and weight method, and (3) the circulate and weight method.

In, the drillers' method formation fluids are pumped from the well using the mud in the system at the time of the kick. A heavier mud, called "kill mud," which has a sufficient density to overcome the formation pressure, is then circulated into the well. The wait and weight method (sometimes called the Engineer's method or weight-up quickly method) involves pumping the formation fluids from the well while simultaneously introducing the kill mud. Well circulation is delayed until the mud density in the pump suction pit is high enough to overcome the formation pressure. The circulate and weight method involves a gradual increase in the mud density in the pump suction pit while the formation fluids are circulated to the surface. Several circulations may be necessary to obtain the requisite final mud density throughout the well. The relative merits of these three procedures depend somewhat upon the composition of the entering formation fluids and upon the available mud-mixing equipment.

In the absence of a sufficient length of protective casing, formation fracture can occur near the surface during well control operations. With insufficient sediment thickness and strength to confine the failure, the fracture will propagate to the surface and it may be necessary to drill or divert a well to protect the drilling equipment and rig personnel until the well can be controlled by pumping dense fluids down the drill string.

Industry people disagree as to the best procedure to follow when closing the blowout preventer and auxiliary well-control equipment during an impending blowout. Many operators prefer rapid shut-in, to minimize the influx of formation fluids. Others favor a soft shut-in procedure to minimize shock pressure loadings associated with the rapid deceleration of the fluid being ejected from the well.

The problem has been analyzed mathematically, but simplifying assumptions leave considerable doubt on optimum methodology. What is needed is an experimental program to evaluate theory. This experimentation must take into account the wide variety of equipment used in various offshore drilling operations.

In start-up procedures, the present-day method to initiate the circulation of formation fluids from the wellbore is to start pumping while simultaneously opening the choke so that the casing pressure is maintained constant at, or slightly above, its previous shut-in value. Because of the high frictional pressure drop in the long underwater flowlines associated with floating drilling operations, this procedure can produce an excessive annular back-pressure. This in turn could lead to formation fracture and a subsequent underground blowout. In addition, the subsea flowlines are sometimes intentionally filled with water to prevent them from becoming plugged when not in use. This complicates the annular pressure behavior during start-up because of the density difference between the water initially in the flowline and the drilling fluid which will ultimately displace this water.

Pump-out procedures are also questionable. When a gas influx (kick) is circulated from a well, an operational problem results as the gas bubble reaches the subsea preventer stack located on the ocean floor. The bubble rapidly elongates in the casing and proceeds upward through the small-diameter choke line which parallels the larger marine riser pipe. An operator may not have adequate time to respond properly to the rapidly changing pressure conditions associated with this event.

Many modern blowout control strategies are based upon mathematical analyses of the well drilling system during various phases of blowout control operations. These models are also being employed by some investigators to develop new procedures for floating drilling operations.

Preliminary research at LSU has already shown that the mathematical models used in blowout control simulations do not always predict actual well behavior. Two assumptions found to be at fault are (1) that gas influx enters the well bore as a continuous slug and remains in this configuration during subsequent control operations and (2) that the gas bubble does not migrate upward through the column of drilling mud but moves instead at the same velocity as the cirulating mud. Additional research is being undertaken to improve the knowledge of actual well behavior, especially for equipment used in floating drilling operations.

At the LSU well control training facility the investigators will construct a well for accurately modeling blowout control operations on floating drilling vessels in deep water. A survey will be conducted to determine the various control equipment and the procedures used for shut-in, start-up, and pump out. Using the various control configurations experimental studies will be conducted to determine optimum operational procedures.

# FLUIDIC MUD PULSE TELEMETRY

Principal Investigator: Allen B. Holmes
U.S. Army
Harry Diamond Laboratories
Adelphi, Maryland

Objective: To investigate the feasibility of applying fluidics technology to down-hole data telemetry without interruption of drilling operations.

For many years industry has recognized the desirability of developing a means of obtaining continuous data from the bottom of oil, gas and geothermal wells without interrupting normal drilling operations. Down-hole, real-time, data transmission systems would greatly increase the safety of drilling operations and permit more rapid development of energy resources. Except in specialized cases, previous attempts to provide real-time measurements while drilling have not been fully successful because of the harshness of the down-hole environment. Several data transmission methods have been considered, including hardwire, electromagnetics, and acoustics, but mud pulsing seems to be the most promising for general applications.

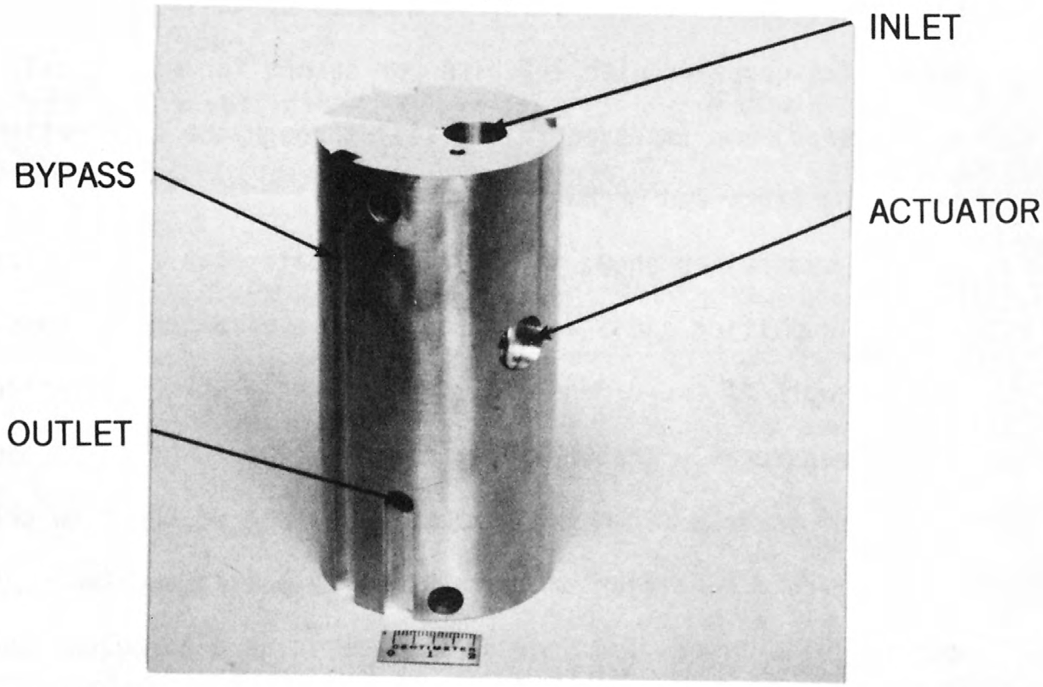
Fluidics--the technology of using various flow phenomena to perform control functions with no-moving part devices--is being investigated for use in mud pulse telemetry. A fluidic mud pulser has the potential of providing data rates up to 100 bits per second (as compared with 1-2 bits per second for mechanical mud pulsers) and improved reliability through the elimination of moving parts and mechanical seals.

The mud pulser shown in figure 9 contains two fluidic components: a fluid amplifier and a vortex valve. These components consist of a network of two-dimensional flow channels which are milled in a dimensionally stable base material. The function of each component is determined by the internal shape of the flow channels.

The fluid amplifier contains a supply nozzle and two control ports. Flow issues from the supply nozzle as a turbulent jet which attaches to a side wall because of a complex viscous interaction, known as the Coanda effect, between the wall and the jet. The jet remains attached to this wall until a pressure signal produced by an electrical actuator is applied to the control port on that side. The control signal raises the pressure in the boundary layer and overcomes the viscous interaction between the jet and the wall. The jet then deflects past the splitter plate toward the opposite wall and attaches to it.

The vortex valve contains two output ducts, a vortex chamber and a sink. The radial duct channels the amplifier flow directly to the sink with negligible pressure drop. The tangential duct

(a)




(b)

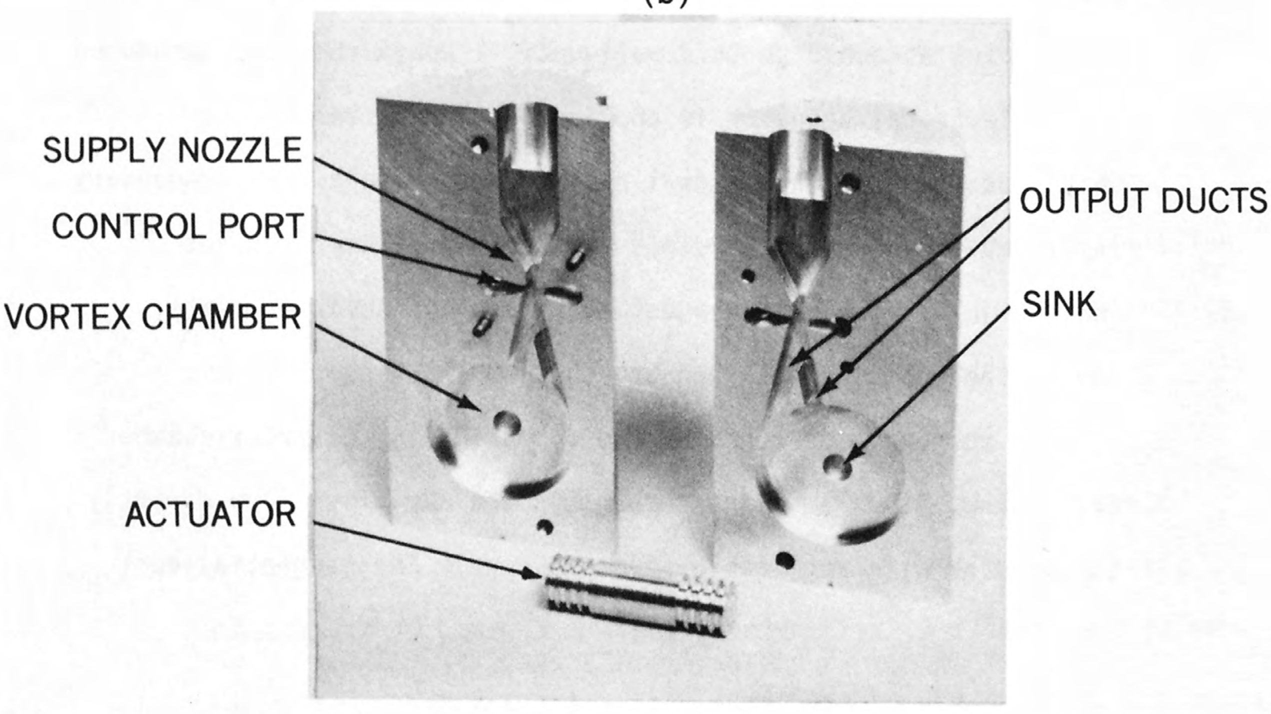



FIGURE 9. FLUIDIC MUD PULSER ASSEMBLY SHOWING (a) ASSEMBLED UNIT AND (b) PARTS AND FLOW CHANNEL GEOMETRY.

directs the amplifier flow tangentially through the chamber. A forced vortex is developed in the chamber which restricts the flow through the sink and produces a large pressure drop. The resulting flow reduction is called turndown.

Input pressure signals to the amplifier control ports are generated by an actuator which resembles a miniature loudspeaker voice coil. The actuator (fig. 9 b) is located above and between channels leading to the control ports. Acoustic waves are developed at the face of two opposing compliant diaphragms each time electrical energy is applied or removed from the coil. The waves exit through the control ports to switch the amplifier, and the duration of the output signals is determined by the time between turn on and turn off of the actuator. Frequency response characteristics of the pulser circuit are determined by response characteristics of the actuator.

Each time flow is diverted in the amplifier, the change in flow produces pressure waves which reflect back through the amplifier and up through the drill string. The amplitude of the pressure, commonly referred to as water-hammer pressure, is primarily a function of the change in the kinetic energy of the arrested mud column.

Laboratory tests are being conducted on sub-scale pulser circuits using both freshwater and drilling fluids to identify factors which might affect performance (amplifier switching characteristics, turndown ratios, and frequency responses) when non-Newtonian fluids are used.

Thus far, laboratory test results show that, for the drilling fluid compositions investigated, there occurs negligible change in amplifier performance and minimal variations in vortex valve performance when the pulser circuit is operated near atmospheric backpressure. Tests also show that the pulser circuit will operate up to the maximum pulse rate of the actuator used, which was 25 pulses/sec.

An analytical flow model was developed to estimate the performance of a full scale pulser (4.5 inches O.D., 3.75 inches I.D. drill string) under simulated circulating flow conditions using measured circuit turndown ratios and orifice geometries. Water-hammer pressures were computed from circulation pressures, pulser orifice areas, mud weight, drill-string diameter and nozzle areas at the bit.

Full-scale hardware will then be designed and evaluated by means of computer simulation of steady-state performance using empirical data from sub-scale tests. The downhole evaluation of hardware is also planned.

# ULTRASONIC FLOWMETER EXPERIMENT

Principal Investigator: Stacy Gehman
U.S. Army
Harry Diamond Laboratories
Adelphi, Maryland

Objective: To determine the feasibility and practicality of using ultrasonic flow-metering techniques to minimize oil spills from offshore oil lines.

Crude oil leakage from offshore pipelines can result in environmental pollution. Existing pipelines are aging, and current trends toward larger and longer offshore pipelines have increased the need for developing accurate methods for rapidly detecting leaks.

At present, highly accurate axial turbine flowmeters or positive displacement flowmeters are used in merchantable crude oil pipelines for custody transfer. Several such meter variance leak-detection systems have been successfully used. The accuracy of these meters, however, drops sharply when used with raw crude oils which may contain water, sand, and other sediment. Leak detection on raw crude lines is at present limited to the time-honored procedure of visual inspection from aircraft and low-pressure sensors at the pipeline origin.

The principal investigator assessed the capabilities of various new flow-metering techniques and concluded that acoustic metering offers promise for improved performance and cost effectiveness for raw crude oils found typically in offshore pipelines. He has designed an experiment to evaluate several production flowmeters over an extended period of time on both clean and raw crude . Whereas gas, sediment, and water have been removed from clean crude, these impurities are still present in raw crude, which complicates flow-measurement acoustics. Furthermore, the mixture of oil and impurities is not uniform but, depending upon the Reynolds Number, may be stratified. Also, flow between two widely separated points is not steady. Typically, crude oil is pumped intermittently through the lines on the way from a production platform to the pipeline which carries it to shore or in the pipeline itself. Thus, an accurate history of flow is necessary to determine leakage.

The meters which will be tested are of the pulsed acoustic traveltime type. Each meter consists of coaxially aligned upstream and downstream transducers, the angle between the transducer axis and pipe axis being about $45^{o}$. The transducers ensonify each other alternately such that the upstream transducer's pulsed signal ensonifies the downstream transducer and vice versa. The traveltime downstream is less than that upstream, and the difference is proportional to the flow velocity.

In cooperation with an oil company, five meter designs are being evaluated at a clean crude calibration facility. Calibration runs are being made to determine accuracy, linearity, and product sensitivity, using several types of merchantable crude oils.

Calibration is accomplished by comparing the ultrasonic meter performance with a meter prover. The prover consists of a straight section of pipe which contains a piston whose time of travel is the same as the flow velocity and is measured electronically between two points.

It is planned to evaluate on a raw crude test loop those designs which demonstrate adequate performance in the clean crude test series. Two meters of each selected design will be tested over a wide range of flow rates on crude containing about 40 percent water. The test meters will be compared with a calibrated positive displacement meter to determine accuracy and linearity. The ability of the test meters to track one another (an essential factor in a leak-detection system) will be determined by comparing outputs of meters of the same design over an extended period of time and widely varying flow rates. Meter factor stability and zero drift also will be determined.

# OVERPRESSURED MARINE SEDIMENTS

Principal Investigators: Dr. Lewis J. Thompson
Dr. William R. Bryant
Texas A & M University
College Station, Texas

Objective: To develop a consolidation theory for the progressive burial of marine sediments in order to explain the development of formations in which the pore fluid stress exceeds the hydrostatic or geostatic pressure.

Overpressured formations occur in zones of rapid sedimentation. They may be the major cause of submarine slope instabilities and of the low bearing strength for ocean bottom-founded structures. A theory is being formulated to explain how formations develop in which the fluid stress in the pores exceeds the geostatic pressure.

On the Gulf Coast diapirism and folding can be caused by the expansion of overpressured formations into low-strength overpressured shales and clays. Faulting can result when these expanded structures vent and collapse.

Subsidence occurs when the pressure decreases in a sand formation. Large hydraulic gradients are established in the adjacent clays causing new drainage into the sands. This drainage compresses the clay but not the incompressible sand.

The question of overpressurization will be answered when sediment porosity and temperature can be predicted as a function of depth and time, as the rate of deposition, heat flux and water level are varied. Principles of continuum mechanics show that the stresses, stress gradients, motions, velocities and material descriptors must be functions of strains, strain rates, temperatures and temperature gradients. In this one-dimensional study strains can only be described by porosity.

The approach to a solution is twofold: (1) The controlling differential equations are set up for the sediment and water individually, and then collectively, by use of the field equations for conservation of mass, linear momentum and energy. (2) Relationships are determined for sediment compressibility, permeability, heat conductivity and the coefficient of lateral earth pressure at rest as functions of porosity and temperature. These relationships must hold for very low porosities (10-15 percent) and high temperatures ($212^{o}$F).

The equations are coupled, nonlinear and multiorder and are not yet solved.

The investigators have shown that equilibrium does not require pore water pressure to be less than overburden pressure. It is the force in the water plus the force in the sediment which must be equal to the overburden weight. The area of the water must be multiplied by the water stress to find the water force. As shown by electron microscopy, the cross-sectional area of the water in clay sediments is the same as the porosity determined on a volumetric basis.

Application of the conservation of energy principle shows that the elastic strain energy stored in the water of the sands can provide the necessary power for blowouts.

Although the settlement rate can vary with depth, the principle of conservation of mass shows that the rate of settlement for every point is equal to the upward flow rate of the water. Where there is a nearly impermeable layer only localized flow can occur below it. In this case if one layer consolidates, the adjacent layer must expand and the consolidating layer must be at a higher pressure than the expanding one.

A simple pressure-density-temperature relationship has been developed for sea water and it has been found that the resistance to flow is proportional to the velocity and inversely proportional to the coefficient of permeability.

A high-pressure consolidometer has been constructed. In it, the ocean bottom sediment is compressed and heated to model the effect of both the overburden pressure and the thermal gradient. The maximum vertical stress is 10,000 psi and the maximum temperature is $200^{o}$ F. The rate of change of porosity is measured by the rate of height change, and this is checked against the rate of water flow from the sample.

After equilibrium is achieved the permeability and heat conductivity are measured. The coefficient of earth stress at rest is also measured continuously during the consolidation process. The sample is confined by a PVC cylinder which is strain gauged. The PVC cylinder is confined by water inside the thick stainless steel outside cylinder. As the strain gauges register, water is forced in to null strains. The measured water pressure is the lateral earth stress.

Permeability is measured directly by forcing sea water through the sample at various huydraulic gradients.

The heat conductivity is measured using the transient method. A tiny heating element and a thermistor is embedded in the center of the sample. A computer program has been written to calculate the conductivity by iteration methods. The mineralogy of each sample is determined before and after each test.

The experiments have shown that the total stress minus the pore water pressure times the porosity can be described by a power law function of porosity. Direct measurements of permeability show that Darcy's law describes the steady-state flow in clays. The permeability data can be described by a power law function of porosity. These functions show that the permeability decreases many orders of magnitude faster than the porosity decreases.

Sand was found to be very incompressible, although the very high stresses did cause some grain breakage and degradation.

Inasmuch as the governing differential equations have been formulated, the major analytical effort now will be to reduce these equations by transform methods to the uncoupled linear form. The thermal equations will be combined with the mechanical equations so that thermal convection as well as thermal conduction can be considered.

# ATMOSPHERIC GAS CONCENTRATION SENSOR

Principal Investigator: Maurice Funke
TRITEK, Inc.
Columbia, Maryland

Objective: To determine the feasibility of a fluidic gas volume-concentration sensing system for offshore use.

The threat of gas leaks around offshore drilling and production platforms is always present. For this reason, combustible-gas (and sometimes toxic-gas) sensing systems are located at various points on the platforms. These systems must operate reliably under a variety of environmental conditions, while being able to discriminate between, for example, $H_2S$ in concentrations of a few parts per million and unanticipated background gases of higher concentrations.

Fluidic gas concentration sensing techniques are being investigated to determine whether they can detect toxic and/or combustible gases in an offshore environment. These techniques use devices that have no moving parts or sophisticated electronics, and thus appear to offer very high reliability.

The basic technique (fig. 10), is to (1) draw a sample of gas, (2) split the sample into two identical parts, (3) use one half the sample as a reference gas, (4) pass the other half through a chemical processor which produces a reaction with the concentration of the gas of interest and (5) measure the

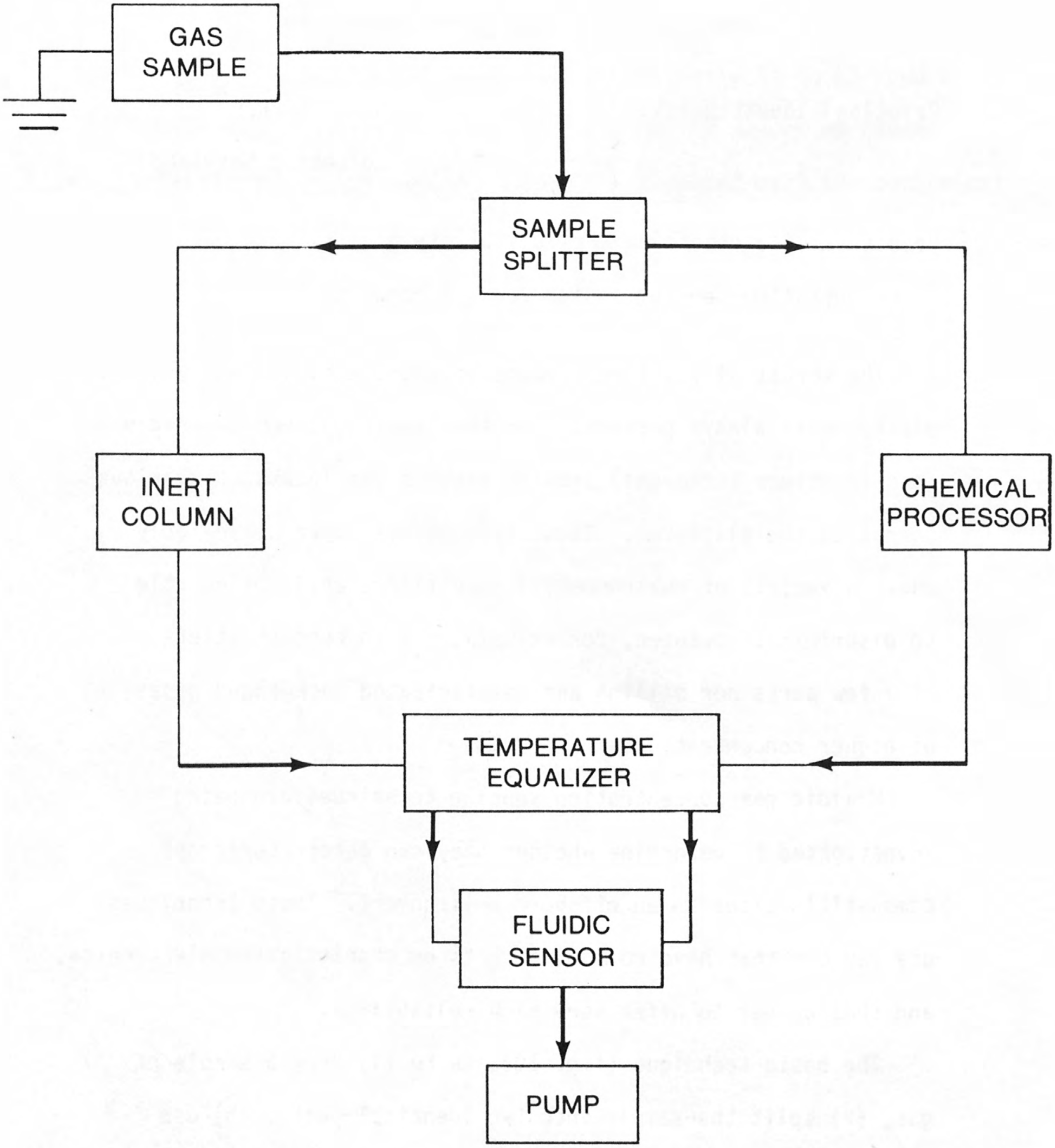



FIGURE 10 DIAGRAM OF FLUIDIC GAS SENSING SYSTEM

resultant change of bulk gas properties with an appropriate sensor. Three candidate sensors are under investigation: jet edge resonator oscillator, vortex sensor, and resistance bridge sensor.

The jet edge resonator oscillator relies on the change in the ratio of specific heat and density between the sample gas produced by the chemical processor and the reference gas. This change, in turn, produces a linear change in the frequency of the oscillator which contains the sample gas. The resulting signal is compared to a reference signal produced by a second oscillator containing the reference gas. The two frequency signals are either processed fluidically or monitored by electronic transducers.

In a vortex sensor both a chemically processed sample gas and a reference gas are fed into a vortex chamber aligned with the gravity field. A density difference between the gases causes them to swirl toward a drain where they encounter an airfoil. The pressure difference across the airfoil is proportional to vorticity and hence the difference in density of the gases. The pressure differential is amplified fluidically and measured with a pressure transducer.

The resistance bridge sensor consists of both linear (viscosity-dependent) and nonlinear (density-dependent) fluid resistors connected in a bridge circuit. The sample gas is passed through one side of the bridge while the reference gas is passed through the other. The resultant differential pressure signal caused by the change in viscosity and density between reference and sample gases is proportional to the unknown concentration of the gas of interest in the gas sample.

An analysis of the theoretical behavior of these fluidic devices under representative environmental conditions shows that any of the three could be used to detect the required hydrocarbon levels (0.1 percent). While current studies of hydrogen sulfide properties indicate that parts per million thresholds are feasible with present designs, there is little documentation on the effects of pressure, temperature, and humidity on functional performance.

The objective of the fluidic gas concentration sensor project is to design, fabricate and test laboratory models of both the chemical processor and candidate sensors. The sensor processor and peripheral equipment will be operated under simulated environmental conditions. The results of this project will be used to establish the applicability of the sensors, and peripheral equipment in monitoring hydrogen sulfide or hydrocarbon gases in offshore operations.

# TOXICITY OF DRILLING MUDS ON CORALS

Principal Investigator: Eugene A. Shinn
U.S. Geological Survey
Fisher Island Station
Miami Beach, Florida

Objective: To determine the toxcity of a variety of well drilling muds on common reef-building corals.

The question of the effects of drilling near coral reefs arose in the early 1970's, when an oil company leased offshore tracts near the Flower Gardens bank, a thriving coral reef 110 miles off Galveston, Texas. The reef is a salt dome. Although there was no knowledge of possible deleterious effects of drill mud on corals at the time of the sale, Government concern was sufficient to stipulate that a lessee should drill no closer than 1 mile from the reef and that drilling muds and cuttings should be discharged near the bottom, rather than near the surface, as is usual.

Later, in 1973, at the time of the MAFLA (Mississippi, Alabama and Florida) offshore sale, concern developed for corals growing on the Florida Middle Grounds. Baseline studies of the area had been made but did not include experiments to determine direct effects on corals. Since then, the Environmental Protection Agency has sponsored relevant laboratory studies at Texas A & M University. In anticipation of continuing concerns as drilling progresses into other areas of coral growth (northeast Florida shelf, Georgia Embayment and southwest Florida) the research program on OCS Oil and Gas operations is sponsoring studies at the USGS Fisher Island Station off Miami Beach, Florida, where living corals and clean salt water are readily accessible.

Working under the principal investigator, Eugene Shinn, Texas A & M graduate student Jack Thompson is combining laboratory and field studies, using whole used drilling muds from Gulf Coast wells. Muds tested to date are from wells where drilling depths at the time of collection were 5,436 feet and 13,800 feet. These muds are being used as follows: clearing-rate experiments are conducted in which corals are covered with varing amounts of mud. The time required for the coral to purge the mud is compared with a control mud treated with natural common calcium carbonate mud which occurs in coral areas. Modified 96-hour bioassay tests are also conducted. In these tests corals are placed in aquaria containing muds in suspension (at concentrations of 0, 100, 316, and 1,000 ppm whole mud). The suspensions are maintained by small plastic circulating pumps. In all experiments, results are recorded by means of time-lapse photography. Individual movie frames are exposed using strobe lights once every 24 seconds. When projected, the activity of slow-moving coral polyps appears accelerated, and their behavior in response to the muds is observed and compared with control specimens.

One and one-half inch diameter cores (fig. 11) taken from a single living Montastrea annularis, a common massive reef-building coral, were used in laboratory clearing-rate studies. The use of cores instead of entire coral heads yields several benefits: (1) They provide a more uniform surface upon which to apply test materials. (2) All cores for a given experiment are taken from a single parent colony and, therefore, can be expected to react similarly under given conditions. (3) A minimal amount of living coral must be harvested.

Undiluted mud from the 13,800-foot well was applied to the living surface to produce a viscous layer about one-quarter inch thick. This layer, compared to untreated controls and a control treated with calcium carbonate mud, interfered with normal cleaning behavior and caused some mortality. After dilution to a thin slurry (1:10 dilution with sea water), the same mud was removed almost immediately. It was also found that the same diluted mud applied to the surface of a dead test specimen quickly ran off the surface, indicating that this mud was removed more by mechanical processes than by the action of the coral polyps.

Mud from the 5,436-foot well was applied both full strength and diluted, and in both cases it was rapidly removed (90 percent removed within 1 minute). Natural sediment was removed more slowly (in 4 hours). These experiments indicate that (1) mud from the 13,800 foot well was either more toxic or more adhesive than the mud from the 5,436-foot well; (2) diluted mud from both

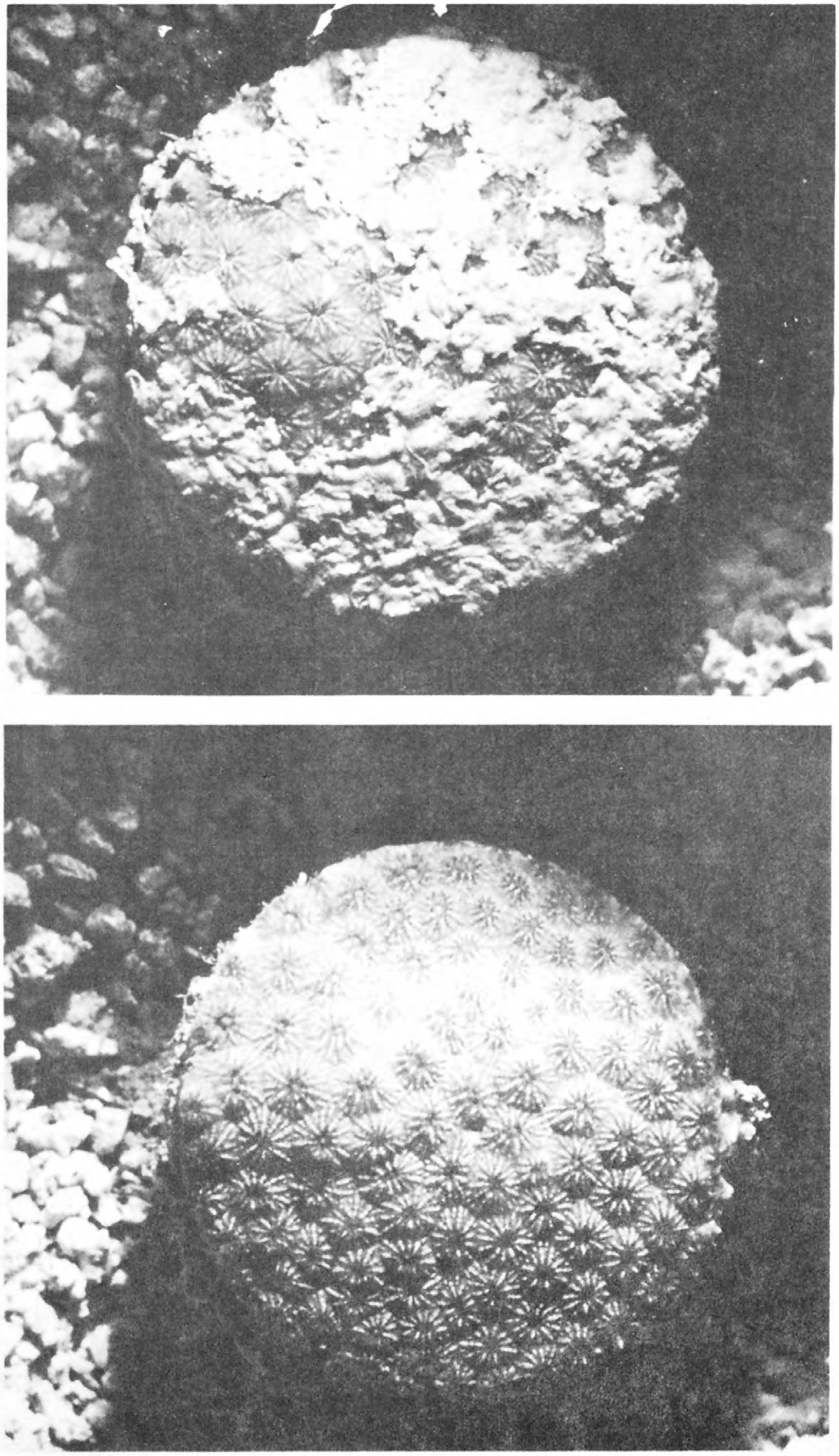


FIGURE 11 VERTICAL VIEW OF CORE OF LIVE CORAL USED IN CLEARING-RATE EXPERIMENT. NOTE MUD PARTIALLY CLEARED FROM CORAL, AT TOP, AND SAME SPECIMEN AFTER CLEARING, AT BOTTOM.

wells (deep and shallow) tended to run off the coral mainly by physical rather than biological activity; and (3) for unknown reasons, natural carbonate mud was more slowly removed from the coral than dilute drilling mud, but was more easily removed than the deep full-strength mud.

Modified 96-hour bioassays were performed on a common branching species of reef coral, Porites sp. Suspension of whole mud from 13,800 feet were prepared in aquaria containing sea water and maintained in suspension by circulation.

Except in the control tank (0 ppm), a uniform sheath of mud mantled all the coral branches, and the rate and amount of accumulation on the coral surface was roughly proportional to the concentration of mud in suspension. After 96 hours, each treatment chamber was flushed of all suspended mud without disturbing the test specimens. Three days after terminating exposure to the mud suspensions, corals in the 100 ppm treatment chamber began slowly removing the mud sheath. Most of the mud was removed after 1 week of recovery time.

In the 316 ppm and 1,000 ppm treatment chambers, only partial removal had occurred after 24 days of recovery time. At that time, all branches were cleaned by the investigator and transferred to a holding tank for further observation. Tissue which had remained covered with mud the longest exhibited distress, but no major areas of mortality were detected. A duplicate experiment using mud from the 5,436 foot well is in progress.

Additional tests will be performed on a living reef near Carysfort lighthouse in the Florida Keys. Corals will be exposed to various muds *in situ* in an attempt to relate effects of muds to actual conditions which may exist near a drilling platform. This relationship of laboratory experimentation to actual situations remains the most difficult aspect of the work, the solution of which is made more complex by the following:

1. It is nearly impossible to know the exact chemical composition of a typical drilling mud, especially after it has been used and contaminated by formation waters and sediment and rock cuttings from the well.

2. The composition of muds varies from well to well and with time and depth for a particular well.

3. Dilution rates downstream from actual drilling operations are poorly known and generally still theoretical.

4. It is very difficult to predict changes in hydrographic conditions, which in turn determine the fate of a plume from drilling operations.

5. Exposing an entire coral reef community to test substances is neither feasible nor is it desirable because of the possibilities of damage from pollution.



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