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APPLICATIONS OF AEROSPACE TECHNOLOGY TO PETROLEUM EXPLORATION

Study Report

Volume 1: Efforts and Results

Sponsored by
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Office of Energy Programs

Prepared by
JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, California

September 30, 1976



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Authors

Leonard D. Jaffe

Hosea Alexander
Wayne E. Arens
Lloyd H. Back
Ara Chutjian
Michael Diethelm
Warren L. Dowler
Glenn W. Garrison
Paul G. Gordon
William R. Gulizia
George R. Hansen
Lewis Leibowitz

Jack S. Margolis
Stephen R. McReynolds
Asok K. Mukhopadhyay
Yukio Nakamura
Robert Nathan
Peter R. Paluzzi
Paul L. Parsons
Shakkottai P. Parthasarathy
Gerald S. Perkins
Peter T. Poon
Virendra Sarohia

Melvin I. Smokler
Don. S. Sparks
John R. Stagner
Donald J. Starkey
Bert M. Steece
Donald L. Vairin
Giulio Varsi
Lien C. Yang
George Yankura
G. Michael Ziman

Donald R. Baker (Rice University)
Frank C. Catterfeld (Rockwell International)
Jerome A. Eyer (University of Missouri)
K. Y. Narasimhan (Consultant)

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PREFACE

This document is Volume 1 of two volumes which report the work carried out in a study of petroleum exploration problems and their solutions through possible applications of aerospace technology. This volume includes an executive summary, findings and recommendations and a description of the work done in the study. It presents and discusses a number of concepts that may help solve certain identified problems. Volume 2 contains appendixes which go into greater depth on various aspects of the study. This work was performed under contract to the National Aeronautics and Space Administration (Contract NAS7-100).

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We would like to express our appreciation to the many individuals in industry, universities, and government who contributed information, advice, and time. Their names are given in Appendix A. Without their cooperation and help, this study could not have been carried out.

Special thanks are due to C. Hewitt Dix and Patrick J. Fazio for their extraordinary efforts to educate, rapidly, a group of novices in the elements of petroleum exploration. That most of us are still relatively naive in the subject is not their fault; we would have been even more so without their aid.

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ABSTRACT

The purpose of this study was to determine whether aerospace techniques can help solve significant problems in petroleum exploration. Through contacts with petroleum industry and petroleum service industry, important petroleum exploration problems were identified. For each problem, areas of aerospace technology that might aid in its solution were also identified where possible. Six topics within the field of exploration were selected for further consideration. Work on these topics led to the formulation of twenty-one specific concepts as candidates for development. Each concept is addressed to the solution of specific exploration problems and makes use of specific areas of aerospace technology. The topics and concepts are shown below.

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EXECUTIVE SUMMARY

Most people in the petroleum industry are convinced that there is still a great deal of oil and gas to be found within the U.S. and off its coasts. The discovery of these sources, however, is becoming increasingly more expensive and more difficult. Policy, financial, and environmental factors undoubtedly play a major part. Nevertheless, it is a truism that the fields easiest to find have already been found. The technical problems of finding new fields at reasonable expense are becoming increasingly significant.

Some of the techniques used to find petroleum are highly developed and technically sophisticated. Improved methods continue to be developed, and the payoff for a successful one can be high.

More or less independently of the petroleum industry, a large amount of effort and technical skill has been devoted to the U.S. space program. This has led to the development of a number of areas of technical knowledge and skill related to aerospace. In recent years, Congress and the National Aeronautics and Space Administration (NASA) have increasingly emphasized the desirability of utilizing this technical knowledge and ability "back on Earth."

Some interchange of technology between aerospace and petroleum exploration has already occurred. There has been considerable interest, for example, in the possibility of using remote sensing from earth satellites to help find oil and gas. Realizing that other possibilities might still be unrecognized, the NASA Office of Energy Programs initiated a study aimed at determining which additional problems in petroleum exploration, if any, could be aided by utilizing aerospace techniques. NASA asked the Jet Propulsion Laboratory (JPL) in Pasadena, California, to conduct this study.

JPL is part of the California Institute of Technology. Under contract with NASA, it has grown into a leading research and development center and was recently named the center for all U.S. planetary missions. Though most of JPL's effort continues to be oriented toward space missions, it is not limited to this area or to NASA sponsorship. JPL activities in energy-related areas are growing in importance. They include activities related to geothermal energy; remote sensing, including its use in petroleum, mineral, and geothermal exploration; coal extraction; improved automotive engines; improved burners for power stations; low-cost solar cells; and a variety of other techniques for utilizing solar energy. The Laboratory also works in planetology, geology, geophysics, and geochemistry.

METHODS USED IN THE STUDY

Work on this 1-year study began at JPL in October 1975. The first step was identification of the significant problems facing petroleum explorationists. A number of management and technical individuals in petroleum companies and petroleum service companies were contacted by the JPL study team and asked to identify significant problems. Based on these contacts, a list of problems was prepared, and a preliminary attempt was made to match each problem with areas of aerospace technology that might aid in its solution.

These problems were then evaluated on the basis of their pertinence to petroleum exploration, the appropriateness of matching areas of aerospace

technology, the likelihood of reaching a solution within 5 years, and the scale of required development effort. On the basis of this evaluation, six topics were chosen for more detailed study:

- Seismic-reflection systems.
- Down-hole acoustic techniques.
- Identification of geological analogies.
- Drilling methods.
- Remote Geochemical Sensing.
- Sea-floor imaging and mapping.

These topics were then carefully examined by the JPL study team. Available literature on each topic was studied, discussions were held with knowledgeable people in industry, at universities, and at government agencies, and in a few instances, laboratory experiments were conducted. As a result of this effort, a number of concepts evolved (21 in all). Each of these concepts applies aerospace technology in one form or another toward the solution of exploration problems. These concepts are summarized here under the appropriate topic. The originality of these concepts has not been fully checked as yet. The subject has been discussed with individuals in the petroleum industry and petroleum service industry, and some of these discussions are reflected in the report.

SEISMIC-REFLECTION SYSTEMS

Many of the identified problems dealt with seismic-reflection prospecting, the principal geophysical method used in petroleum exploration. Correspondingly, many of the concepts arising from the study also deal with seismic methods.

Systems Approach to Seismic Prospecting (Concept 1)

Seismic-prospecting systems have evolved over the years, incorporating improved sources, geophones, data processing, field procedures, logistics, and other elements as they have become available. For the most part, there was no deliberate overall design of a whole system to meet specific objectives.

Aerospace systems, in contrast, are typically designed as a whole, starting with the performance and cost requirements to be met, exploring alternatives, then defining the subsystems, and then repeating the process for the subsystem and at successively more detailed levels. Interfaces between subsystems are given particular attention.

This orderly, step-by-step systems approach has been successful in assuring successful development and operation of aerospace systems and avoiding unnecessary costs. When applied to nonaerospace systems, it has proven most useful with those in which the organization paying for the services receives the benefit (unlike some government operations). The systems approach has been especially successful with these nonaerospace systems whose product is information. Seismic prospecting shares both these characteristics. Accordingly, the use of the systems approach in designing future seismic-prospecting systems with specific systems objectives could be worthwhile.

SEISMIC SOURCES

A wide variety of sources are used to provide the seismic signals needed for prospecting. They include explosive, chemical, pneumatic, hydropneumatic, steam, electrical, and electromagnetic sources. Some provide a single impulse, others an extended "chirp": a signal of definite pitch (frequency) which is changed ("swept") during the chirp.

Each type of source has certain advantages and disadvantages. For example, for land use, a charge of dynamite provides high energy and high portability and is operable below the water table, which helps in providing a "clean" signal. Other sources transmit energy efficiently from source to ground and permit spreading the energy over a chirp to reduce environmental effects. None combines all of these advantages.

Swept-Frequency Explosive Seismic Source (Concept 2)

This concept utilizes a string of many small explosive charges with time-delay pyrotechnic elements between them. The time delays provide a swept frequency. The assembly is inserted in a small-diameter drilled shot-hole for operation.

The concept provides high energy, high portability, and operation below the water table. Moreover, because the explosive energy is released in many small increments rather than a single large one, less of it is wasted in deforming and fracturing the walls of the shot-hole, and the peak shock and noise (undesirable environmentally) are much reduced.

The aerospace contribution to the concept includes much experience with pyrotechnic devices and especially with the design of mechanical assemblies to absorb the shock of detonation. The latter will be needed to insure that the shock from the explosion of each charge does not initiate explosion of the other charges close by in the hole.

Swept-Frequency Solid-Propellant Seismic Source (Concept 3)

In this concept, a solid-propellant charge is placed in a shot-hole and capped with a pressure-relief valve that opens and closes to provide a swept frequency. This would provide the advantages mentioned for the preceding concept plus reduced hazard and environmental effects since the propellant burns but cannot explode. Also, this concept can be adapted to marine work.

The aerospace contribution to the concept includes the technology of solid propellants themselves and of solid-propellant rocket engines plus expertise in combustion and fluid flow.

Oscillation-Free Bubble Seismic Source (Concept 4)

Many marine seismic sources transmit their energy to the water by producing a bubble. However, the pressure of the water causes the bubble to collapse,

producing oscillations that generate seismic noise which tends to obscure the desired signal.

A variety of methods are in use to reduce the undesirable effects of bubble oscillation. None of them are entirely satisfactory. This concept consists of releasing the air or gas produced by the source into a collapsed bag rather than into the water. The bag has sufficient strength to prevent the air from expanding to a pressure lower than that of the surrounding water. This prevents the bubble from collapsing and setting up oscillations. The air is then slowly released above the water surface.

The aerospace contributions include experience with the design of collapsible-deployable structures and with fluid flow.

Oscillation-Free Implosion Seismic Source (Concept 5)

This concept also provides an oscillation-free source but is intended for use in fairly deep water or when a source to operate in a borehole is needed. The output of bubble sources decrease when they are operated at increased depths in water because more of their energy is used in overcoming water pressure. Also, at increased pressures, bubble oscillations become faster and more detrimental.

This concept utilizes a hollow glass or plastic sphere which is attached to a miniature linear shaped explosive charge. The sphere is pulled down by a weight. At the desired depth, the shaped charge is ignited and cuts the sphere cleanly and reproducibly. As the sphere breaks, the surrounding water which is under high pressure collapses inward, providing an oscillation-free signal. The signal energy increases with depth because the water pressure increases.

The aerospace contribution includes extensive experience with the use of small shaped charges to provide a variety of mechanical functions.

SEISMIC OPERATIONS AND TELEMETRY

Aerial Seismic Survey (Concept 6)

Seismic surveys in land areas are made by ground parties. In some kinds of terrain, it may be difficult or expensive for ground parties to move their equipment or to avoid damaging the environment.

This concept envisages carrying out a land seismic survey from an aircraft in flight. The procedure involves first dropping, from a low altitude, strings of geophones with a telemetry transmitter attached to each string. Aerodynamic cases would keep the geophones vertical during descent. Their input velocity would drive a spike into the ground to provide good seismic contact. The phones can be gimballed or provided with a tilt switch to disconnect ones that tip over.

Next, the aircraft drops seismic sources with attached radio receivers. It records positions and elevations of the layout by stereophotography and navigation data. The aircraft fires the sources by radio command. Geophone data are telemetered to the plane and recorded. Finally, the aircraft, without landing, retrieves the geophones by a pickup technique which is widely used by the U. S. Coast Guard and military services.

The difficulty of emplacing large or complex arrays by this method and the effort of moving them would probably constrain the method to reconnaissance rather than detailed surveys. The aerospace contribution includes the aircraft and aerial operations themselves plus aerodynamic design for the elements dropped and telemetry.

Telemetry of Seismic Data from Ship to Computing Center (Concept 7)

Seismic data are recorded on magnetic tapes. Hundreds of tapes may be produced in a single marine survey. They are brought back by ship, air, and land transport to a computer center for processing. This requires a number of days, occasionally even weeks. This delays the time when the data are available for interpretation and check. The delay may be costly. If the interpretation or check indicates that repeat or additional work in the survey area is desirable, the ship may have left the area and additional cost and time may be needed to bring it back.

No adequate method exists for returning marine seismic data by radio, and only very limited facilities for this purpose are planned. This concept is to provide a satellite communications system specifically designed to return seismic data, as rapidly as it is obtained, to computing centers from many survey ships simultaneously. The data would be coded to prevent possible use by competitors.

The aerospace contribution includes the communications satellite system itself and experience in coding of radio signals to prevent unauthorized use.

SEISMIC DATA PROCESSING

Data processing is a major part of a seismic-prospecting system. Three concepts for improved data processing are outlined in the following paragraphs.

Low-Cost Seismic Data Processing (Concept 8)

At present, seismic data are recorded on magnetic tape in a form that requires very large numbers of magnetic tapes to be bought, transported, handled, and stored.

In the computer, except for some special purpose auxiliary equipment, information is expressed and manipulated in the form of individual "bits." Only a small number of bits are processed at a time. Because a seismic survey involves many millions of bits of information, a digital computer, despite its speed, requires considerable time and expense to process seismic data.

Since computers capable of a full range of seismic processing at reasonable speed tend to be large, complex, and expensive, they are usually located at fixed land sites. Only limited processing is usually done aboard ship or in a field van.

This concept consists of three parts. First, introducing high-density tape recording of seismic data to reduce the number and expense of tapes by 50% or more. Second, introducing charge-coupled devices into fixed-site computing. In these devices, information is expressed not as bits but as "words" equivalent to 10 or more bits. Moreover, charge-coupled devices can process hundreds of words simultaneously. Use of these devices could significantly reduce the cost and time of fixed-site computing. Third, introducing charge-coupled devices into field processing. They should reduce the processing cost and time of shipboard and van computers to permit immediate availability of high-quality processed data both for on-site analysis and for transfer to off-site interpreters.

The aerospace contribution to this concept includes experience with field use of high-density tape recording and with data processing by charge-coupled devices.

High-Resolution Seismic System (Concept 9)

Beds 10 or 15 feet thick often contain commercial quantities of petroleum. Present seismic-reflection methods, however, do not resolve beds thinner than about 50 feet except at shallow depths. Thus, systems providing higher resolution at moderate depths are needed.

This concept would provide such a system. It would differ from present systems in several respects. Seismic sources that provide high energy at high frequencies would be used since resolution improves as the frequency increases. The size of individual phone groups within the seismic array would be reduced and the number of groups increased. Data sampling rates would be increased and, in marine work, signals generated at closer time intervals. Seismic velocities would be very carefully determined.

The data processing would convert the signal to "zero-phase" as is done now when high resolution is needed. It would avoid the use of some approximations that reduce cost at the expense of quality. Mathematical models of the geologic situation would be constructed in the computer and automatically iterated with the rest of the data processing to reduce errors. Also, processing would be based on analysis of the data as coming from 3 dimensions rather than 2 dimensions as is now customary for routine processing. Three-dimensional processing will also necessitate some change in the phone array.

The required data processing, in particular, is expected to be considerably more extensive and costly than with conventional systems. To bring the cost down to a practical level, it will probably be necessary to take advantage of the cost-saving possibilities of charge-coupled devices, discussed above.

The aerospace contribution includes experience in data processing, particularly image processing, with special attention to the conversion of signals to zero-phase. Another aerospace contribution would be experience

in the design and integration of large systems and possible improvement of seismic sources.

Time Delay Spectrometry in Seismic-Reflection Surveys (Concept 10)

The limited ability of current seismic systems to find thin layers has been mentioned. Another limitation is that even for thicker layers they provide only limited information about the nature of each layer and such important quantities as the fluid content.

One reason for this limitation is that present data-processing methods do not utilize all of the information contained in the data. For example, the received seismic signal contains a range of frequencies. These frequencies are combined in processing. In so doing, information is lost.

This concept involves the use of time-delay spectrometry, a method now employed in biomedical work. The signal strength (amplitude) and the precise time information (complex phase, in mathematical terms) are preserved separately for each frequency. With the complex phase, it is possible to resolve beds much thinner than the limit of conventional processing (half the shortest wavelength of the received seismic signal). Also, the added information will permit better estimates of the nature and fluid content of each layer.

The aerospace contribution includes expertise of NASA laboratories on time-delay spectroscopy and data processing.

DOWN-HOLE ACOUSTIC TECHNIQUES

Down-Hole Seismic Tomography (Concept 11)

When one or more holes, dry or productive, have been drilled, well-logs and cores can provide information on the rock sequence (stratigraphy) and structure at the holes. Information on stratigraphy and structure away from the hole may still be needed to determine whether and where to drill additional holes. Similar information may also be needed in planning secondary recovery operations.

Seismic-reflection measurements over the areas of interest can be made from the surface in such cases or may already be available. They have, however, some important limitations: highly attenuating or reflecting layers overlying those of interest may prevent adequate signal transmission; steeply dipping layers may reflect little energy back to the seismic array; in some land areas, it may be difficult to determine the corrections required for the near-surface layers. Thus, if a borehole is available, it may be worthwhile to use it in obtaining seismic data.

This concept involves placing seismic sources in a borehole to transmit signals to phone arrays placed along the surface and in another borehole if one is available. A key feature of the concept is that tomographic methods would be used iteratively in the data processing together with methods of refraction seismography.

Tomography is a technique, used particularly in biomedical work, for reconstructing an object from a set of its projection. Refraction seismography is a well-known technique used in seismic prospecting from the surface.

The outlined concept would avoid the limitations of reflection seismography from the surface as mentioned above. The output of the processing would be a cross-sectional diagram of seismic velocity and attenuation for each geologic layer.

The aerospace contribution would include experience of NASA laboratories in tomography and data processing.

Acoustic Backscatter Log for Fracture Patterns (Concept 12)

The possible rate and amount of recovery of petroleum often depends on the nature of the fracture patterns in the petroleum-bearing formations. If well-stimulation or secondary/tertiary recovery methods are contemplated, the fracture patterns are again critical.

Some useful information about fracture patterns can be obtained from cores and from some existing acoustic well logs. Fracture patterns in cores and in the walls of a borehole may not be representative of those deeper into the wall because drilling the hole changes the local stress and fracture patterns. Available logs that detect fractures deeper into the wall tend to be limited to detecting fractures at specific orientations.

This concept involves the sending out of high-frequency acoustic pulses from a transducer in a borehole and the observing of the signal scattered back. From these observations, an indication can be obtained of the frequency, spacing, and orientation of fractures several yards out into the wall.

The aerospace contribution includes expertise in acoustics and instrumentation.

IDENTIFICATION OF GEOLOGIC ANALOGIES

Improved Computer Aid in Recognizing Geologic Analogies (Concept 13)

In evaluating a new prospect or basin, geologists commonly reason by analogy with other prospects or basins that are more fully characterized. The other prospects or basins are generally those that the geologist remembers or finds by manually searching through the files. The closeness of the analogy is determined by mental comparison of the known characteristics of the new prospect or basin with those of the others remembered or found in the files.

Limitations of this method are those of human memory, the difficulty of finding things on thousands of sheets of paper files and the difficulty of properly assessing which of the known areas is most closely analogous to the new prospect.

The proposed concept would provide computer assistance to the geologist in processing the large quantities of relevant data. A computerized data base would be utilized that contains basin, pool, and digitized well-log data obtained from company records plus commercial vendors (if desired). Company data would not be disclosed to others. The computer programs (software) would emphasize pattern recognition methods to detect analogies, and direct, iterative, interaction between the geologist and the computer.

The output would include lists and characteristics of areas most closely resembling the new area on the basis of parameters selected by the geologist. Optionally, it would also include estimates of the prospect ranking or success probability, obtained by analogy with the matching known areas, for use in risk analysis.

The aerospace contribution would include experience in the use of pattern recognition methods and in establishing and using of large computerized data bases combining various types of data.

DRILLING METHODS

The conventional rotary drill of the petroleum industry uses a mechanical rotary bit driven by a rotary table at the surface. A long string of drill pipe connects the rotary table to the bit and transmits the torque needed to turn the bit. Special "mud" is pumped down the inside of the drill pipe and up the outside to cool the bit, remove the rock chips, and balance the high-fluid pressures encountered at depth. The load and speed of rotation and the bit life are limited by the capabilities of the bearings in the bit mechanism.

Rotary bits are well developed, and great improvements in their performance are not very likely. When the bearings on a bit wear out, the entire drill string must be removed from the hole and uncoupled to replace the drill. The deeper the hole, the more withdrawals are needed per well and the more time required per withdrawal.

The time and expense of these "round trips" are major contributors to the overall cost of drilling. Thus, drilling costs increase very rapidly as well depths increase. Costs are especially high for drilling off shore and in remote areas. The following concepts are aimed at reducing drilling costs.

Automated Drilling Rig (Concept 14)

This concept is to equip a drill rig to automatically monitor and control drilling parameters; to automatically withdraw, decouple, and rack the drill pipe and reverse these operations; and to automatically handle the steel casing that must usually be set along the length of the hole to prevent caving and inflow of undesired fluids.

Savings would come from increasing rig efficiency and safety from decreasing shutdown time and drilling accidents. The aerospace contribution includes equipment reliability and automatic control of operations under severe conditions where maintenance must be minimized.

High-Pressure Drilling (Concept 15)

Field tests have shown that the rate of drilling and the footage drilled between bit changes can be increased by a factor of 3 by drilling at very high-mud pressures. The operating cost would be decreased roughly in proportion. A bit is used that, in addition to its normal functions, directs high-pressure mud jets against the bottom of the hole. The pressure must be greater than a "critical pressure" characteristic of the rock.

Unfortunately, pump valves and seals in the surface equipment tend to wear out very rapidly under the high pressure, wiping out the cost benefit. The aerospace contribution would include expertise in mechanical engineering, fluid flow, and materials, and especially in design of pumps, valves, and seals for reliable operation under severe conditions. This expertise should permit increasing the lifetime of valves and seals so as to make the method economical.

Resonant-Vibration Drilling (Concept 16)

This concept utilizes a resonant-vibration element that is placed in the drill string just above the drill. By vibrating in torsion, this element, driven by a mud motor, drives the bit through a ratchet on the forward stroke. The string is rotated in the normal manner, but the bit moves forward intermittently instead of continuously. Apparently, the device induces coupled vibrations in the rock which help to fracture it. Limited tests of a prototype showed that the rate of penetration in granite was increased ten times.

The aerospace contribution includes expertise in vibrations and mechanical design and in vibration testing which will be needed to provide adequate life and reliability.

Improved Down-Hole Drill Motor (Concept 17)

An alternative to driving the drill bit by rotating the whole drill string is to provide a hydraulically driven motor near the bottom of the hole. Energy for the motor comes from the mud stream pumped through the drill string.

This technique would save energy lost in the friction of the rotating drill string against the wall of the hole. Also, it would simplify running an electrical cable up the string to transmit data from down-hole sensors; this is difficult to do if the drill string rotates.

Mud-driven drilling motors are commonly used when the direction of the hole is to be changed. For straight drilling, they have not been able to compete in cost with equipment rotated from the surface because of lower reliability and higher maintenance.

This concept is to utilize aerospace expertise in mechanical design, vibrations, fluid flow, and materials needed to provide an improved design that will have adequate reliability and low maintenance.

Combustion Fracture Drilling (Concept 18)

This concept allows the drilling of a hole without a rotating bit. The hole is drilled by using a modified liquid-propellant rocket engine down-hole. The rock is not melted but is chipped away by thermal and mechanical shocks. The shocks are provided either by pulsing the rocket engine on and off or by a controlled violent oscillation set up in the exhaust gas system. Fuel and oxidizer would be piped down the string, and mud would be used in the usual way.

The aerospace contribution would include rocket-engine technology and expertise in supporting areas such as thermodynamics, combustion, subsonic and supersonic fluid flow, vibration, etc.

REMOTE GEOCHEMICAL SENSING

Remote Optical Spectroscopy of Airborne Iodine and Other Petroleum Indicators (Concept 19)

Present surface techniques of exploration do not indicate the presence of subsurface oil but only the occurrence of geologic conditions or physical properties that may be associated with oil. There is, therefore, much interest in the possibility of surface geochemical techniques that would directly indicate the presence of petroleum at depth. Even better would be airborne or satellite geochemical techniques since they could provide coverage of large areas.

Most U.S. companies feel that surface geochemical techniques for finding petroleum have not been satisfactory. Some preliminary tests of a sensitive optical spectrometer did detect a plume of iodine molecules over and downwind of a producing oil field. More recent work suggests that enhanced concentrations of iodine molecules and other chemical elements correlatable with petroleum could be detected in air over an undrilled prospect which was later found to contain oil.

Iodine concentrations are believed to originate from deposits containing the remains of marine plants. Such plants concentrate iodine very efficiently. The same organic remains may be buried by later deposits and sometimes develop into petroleum. Presumably iodine and other indicators in the formation waters very slowly leak up to the surface and are transferred into the air.

This concept is to obtain an indication of subsurface petroleum by remote observations of localized concentrations of iodine and other indicators in the air over the petroleum deposits. Very small concentrations could be detected by specialized optical spectrometers carried by aircraft or possibly satellites. The aerospace contributions would include background in the spectroscopy of iodine and in remote sensing of trace quantities of atmospheric constituents.

SEA FLOOR IMAGING AND MAPPING

Acoustic Imaging of Large Areas of the Sea Floor (Concept 20)

To permit geologic interpretation of the topography of the sea floor, a need has been expressed for pictures equivalent to those provided for the land surface by the Landsat spacecraft and covering large areas.

This concept encompasses an integrated system, including a high-powered side-looking sonar carried by a "fish" towed at some depth. The data are recorded in digital (numerical) form on magnetic tape and transferred to a computing center. They are then computer processed to provide high quality images on photographic paper or film and with resolution similar to or better than Landsat pictures.

The aerospace contribution includes technology for digitally processing and enhancing imagery and for transforming this imagery into high-quality photographic and mosaic products. It also includes systems engineering and instrumentation technology.

Detailed Bathymetric Charting (Concept 21)

The available charts of the continental shelf are not adequate for petroleum needs. In particular, the horizontal and vertical spacing of the data they present (soundings and contours) are too great to permit adequate planning of drilling equipment and, subsequently, of production equipment.

This concept is for an integrated system which would use conventional echo-sounding equipment along closely spaced tracks. The sounding data and precision navigation data are recorded digitally on the same magnetic tape. The data are processed to provide computer-drawn bathymetric charts and shaded relief maps.

The aerospace contribution includes technology for digitally processing and enhancing imagery and for transferring this imagery into computer-produced shaded relief maps. It also includes systems engineering and instrumentation technology.

STATUS

This report concludes the NASA sponsored study effort at JPL. Any further development of the concepts mentioned will depend on the interest of government or private organizations in supporting further work.

The concepts have been developed only to the extent detailed in the study report with its appendixes. They are believed to be technically feasible. Some of the concepts could now be taken up by the petroleum exploration industry and service industry for further development. Others would probably require further participation by their designers. All would need development

and demonstration, as indicated in the report, before they could enter exploration service.

NASA's ultimate goal in initiating this study was to attain routine use of aerospace technology in petroleum exploration; this study was pursued to that end. NASA and JPL will therefore actively encourage those interested in further development and utilization of the concepts which emerged from this study.

SECTION I

INTRODUCTION

To aid in attaining energy independence for the United States, the National Aeronautics and Space Administration (NASA) Office of Energy Programs initiated a study at the Jet Propulsion Laboratory (JPL) to determine whether aerospace techniques can help solve significant problems in petroleum exploration. The ultimate goal of the effort is to increase discovery rates, reduce exploration costs, and reduce uncertainty in identifying potential petroleum reserves. The study was started because of NASA's interest in applying technology developed in the space program to problems on earth, especially to energy problems, and because of interest shown by some petroleum companies in learning about and possibly utilizing NASA's developments.

Aerospace technology includes design, manufacture, production, operation, and utilization of spacecraft and aircraft; scientific measurements of properties of the earth, its atmosphere, and other planets; instrumentation for these measurements; associated data handling, storage, transmission, processing analysis and display; systems analysis and engineering; and a wide variety of specialties in the fields of mechanical, electrical, and chemical engineering. The NASA Office of Energy Programs is primarily interested in application of these capabilities to energy problems on earth.

JPL has recently been active in a number of energy-related areas. Among them are activities related to: geothermal energy; remote sensing, including its use in petroleum, mineral, and geothermal exploration; coal extraction; improved automotive engines; improved burners for power stations; low-cost solar cells; and a variety of other techniques for utilizing solar energy. The Laboratory has also been actively involved for a number of years in space research and technology, particularly in carrying out satellite, lunar, and planetary missions, including planetology, geology, geophysics, and geochemistry.

A. NATURE AND PURPOSE OF THIS REPORT

This report describes the work done in the study and the obtained results. It outlines a number of concepts for improving petroleum exploration, namely, an identification of new technological approaches to problems in petroleum exploration and related fields, each based in part upon aerospace technology.

It is hoped that this report will stimulate thought within the petroleum industry and petroleum-service industry and within appropriate governmental agencies at the technical, managerial, and policy-planning levels as to better ways to approach problems in petroleum exploration and related fields and as to which of the presented concepts they may wish to pursue. It should also help NASA in assessing the potential benefits of aerospace research within the covered area particularly as applied to the energy needs of the United States.

JPL is seeking to expand its efforts related to energy, and this report suggests some ways in which this could be done. JPL would be interested in follow-up work toward development of selected individual concepts or groups of concepts that organizations may be interested in supporting.

B. OBJECTIVES AND SCOPE OF THE STUDY

The specific objectives of this study were as follows:

- 1) For the Fiscal Year 1976 (through June 1976): To evaluate if there are major problems of technology or management methods in petroleum exploration that may benefit from application of aerospace techniques. If so, to identify some possible matches between problems and techniques and the possible benefits that may result.
- 2) For the Fiscal Transition Period (July-September 1976): To evaluate whether solution of one or more of the identified petroleum exploration problems will be substantially aided by application of the matching aerospace technique. To quantify benefits of the solution in terms of increased discovery rate, reduced exploration costs, and reduced uncertainty in identifying reserves and potential reserves.

The study included such areas as the geology, geochemistry, and geophysics of petroleum exploration; associated measurement techniques and instrumentation; data acquisition, handling, processing, analysis and display; exploration operations; economic factors; system considerations; decision making; and management techniques. Exploration in the United States and adjoining waters was of primary interest.

In the course of the study, problems were found that pertain primarily to related fields such as foreign petroleum exploration, petroleum development and production, or exploration for other energy resources or minerals. Such problems were noted but, in general, not addressed.

The application of aerospace technology to petroleum exploration that is usually thought of first is remote sensing from spacecraft. Significant efforts on such use of remote sensing are already underway; remote sensing therefore was not especially emphasized in this study.

The study was limited to assessment of problems and of possible approaches to their solution. It did not incorporate the development work required to solve the problems. That would be decided upon and undertaken subsequently on the basis of the results of this study.

C. STUDY PLAN

The overall study effort was divided into two phases. Phase I consisted of an assessment of petroleum exploration and an attempt to match important problems with areas of aerospace techniques that may aid in their solution. Phase I was divided into three tasks:

- 1) Task 1 was a general assessment of current technology and problems in petroleum exploration. The primary technique selected for this task is direct contact with knowledgeable persons in the petroleum exploration industry and the petroleum service industry. Also included in this task was preliminary identification of areas of aerospace technology that might match the problems found.

- 2) Task 2 consisted of a series of specific study efforts to evaluate probable success and impact of solving individual problems, using the matching technology identified in task 1.
- 3) Task 3 consisted of integration and focussing of the results of tasks 1 and 2 together with preparation of a report covering all of Phase I.

Phase II was to be conducted if appropriate and would consist of second-generation or additional study efforts identified too late for completion in Phase I or requiring additional resources.

The work was to be done in close cooperation with the petroleum exploration industry and its supporting service industries.

Work on the study began in October 1975. A first interim report, JPL Document 5030-10, March 31, 1976, (Ref. 1) covered effort on Task 1. This report summarizes Phase I (Tasks 1, 2, and 3.)

Phase II extension of the study is not now planned.

SECTION II

TASK 1*

A. METHOD AND PROCEDURE

In accordance with the plan, the JPL study team members contacted a number of petroleum companies and petroleum service companies for information on techniques and problems in exploration and exploration management. Personal interviews and visits were carried out with various managers and experts concerned with exploration and exploration techniques in these companies. Though only a small percentage of the companies in the field were consulted, they probably provide a fairly representative sample. To obtain additional point-of-views, discussions were held with members of university faculties and consultants and with representatives of professional and industry associations and of federal agencies as well as numerous JPL colleagues. Contacted organizations are included in the listing of Table 1; Appendix A gives the names of contacted individuals. The technical literature provided additional information.

JPL sought to include, among those contacted, individuals sufficiently high in company management to insure a broad view of the problems and of their importance to the company (in oil companies, for example, a vice-president for exploration). To emphasize problems of concern to management and with identified importance, an effort was made to contact persons whose responsibilities included exploration management and operations.

In this data-gathering effort, identification of the current problems was emphasized. Information on current technology was sought primarily as a basis for understanding the problems; no attempt was made to assess the technology in detail. Appendix B illustrates the kinds of questions used as a basis for discussions.

Problems obtained from various companies were similar in many cases. Further, many of the problems clearly represent long pursued goals for petroleum exploration and could be described as representing a "wish list." Others may represent problems to some companies but have already been solved by their competitors. It should be emphasized, however, that all the problems were suggested by industry and not by JPL. Many of them have been addressed by industry for years. Over 100 problems were suggested by various industry sources.

The information and particularly the problems obtained from contacts were circulated to all members of the JPL study team. Individuals were asked to evaluate each problem, to obtain more information if necessary, and to identify, if they could, matching aerospace technology areas and possible approaches that are beyond those recognized in the petroleum industry and that could

*This section and accompanying Appendixes B-D are slightly revised from the account given in JPL Document 5030-10 (Ref. 1) to reflect Task 1 activity continuing after preparation of that document.

Table 1. Organizations Contacted*

Oil Companies

Amoco Production Co., Tulsa, Oklahoma, and Denver, Colorado.
Atlantic Richfield Corp., Los Angeles, California, and Dallas, Texas.
Berry Holding Co., Taft, California.
Carlsberg Petroleum Corp., Los Angeles, California.
Cities Service Corp., Tulsa, Oklahoma, and Denver, Colorado.
Continental Oil Corp., Houston, Texas, and Ponca City, Oklahoma.
Exxon Production Research Co., Houston, Texas.
EHK Co., Oklahoma City, Oklahoma.
Forest Oil Corp., Denver, Colorado, and Jackson, Mississippi.
General Crude Oil Co., Houston, Texas.
General Exploration Co., Dallas, Texas.
Great Basins Petroleum Corp., Los Angeles, California.
Gulf Oil Corp., Pittsburg, Pennsylvania, and Houston, Texas.
Kerr-McGee Corp., Oklahoma City, Oklahoma.
Louisiana Land and Exploration Co., New Orleans, Louisiana.
McCulloch Oil Corp., Los Angeles, California.
Natomos of the Netherlands, Inc., Houston, Texas.
Occidental Petroleum Corp., Los Angeles and La Verne, California.
Oil Development Co. of Texas, Houston, Texas.
Pauley Petroleum, Inc., Santa Barbara, California.
Reserve Oil and Gas Co., Denver, Colorado.
Shell Oil Company, Houston and Belaire, Texas.
Standard Oil Co. of California, San Francisco and La Habra, California,
and Denver, Colorado.
Tenneco Oil Co., Houston, Texas.
Texaco, Inc., New York and Beacon, New York.
Union Oil Co., Los Angeles and Brea, California.

Petroleum Service Companies

Barringer Research, Ltd., Rexdale, Ontario, Canada.
Bechtold Satellite Technology Corp., Industry, California.
Benthos, Inc., North Falmouth, Massachusetts.
Century Geophysical Corp., Tulsa, Oklahoma.
Dawson Geophysical Co., Midland, Texas.
Digital Resources Corp., Houston, Texas.
Dresser Industries, Houston, Texas.
E. I. DuPont de Nemours & Co., Wilmington, Delaware.
Fluor Drilling Services, Santa Ana, California.
General Geothermal Inc., Denver, Colorado.
Geophysical Systems Corp., Pasadena, California.
Geosource, Inc., Houston, Texas.
Halliburton Services, Duncan, Oklahoma.

*Nature of contacts vary widely from short telephone calls or attendance at briefing to repeated visits with extensive discussion.

Table 1. Organizations Contacted (contd)

Petroleum Service Companies (contd)

International Business Machines, Houston, Texas.
Intercomp, Inc., Houston, Texas.
Kansas Seismic Exchange, Wichita, Kansas.
Kapadia & Associates, Inc., Houston, Texas.
La Coste-Romberg Corp., Austin, Texas.
NL Industries, Baroid Division, Houston, Texas.
Petroleum Information Corp., Denver, Colorado.
Schlumberger Well Services, Houston, Texas.
Scientific Software Corp., Denver, Colorado.
Scintrex, Ltd., Concord, Ontario, Canada.
Scope International, Camay Drilling Division, Los Angeles, California.
Seiscom Delta Corp., Houston, Texas.
Seismograph Service Co., Tulsa, Oklahoma.
SIE, Inc., Fort Worth, Texas.
Smith International, Newport Beach, Long Beach and Irvine, California.
Sonatech Corp., Goleta, California.
Teknica Resource Development, Ltd., Calgary, Alberta, Canada.
Teledyne Exploration, Houston, Texas.
Texas Instrument Co., Dallas, Texas.
United Geophysical Corp., Pasadena, California.
Varco International, Orange, California.
Western Geophysical Co., Houston, Texas.
Whitehall Corp., Dallas, Texas.

Other Companies

Aerospace Corporation, El Segundo, California.
Bionetics, Inc., Pasadena, California.
Comsat General Corp., Washington, D. C.
The Futures Group, Glastonbury, Connecticut.
General Dynamics Corp., Convair Div., San Diego, California.
General Electric Co., Rockville, Maryland, and Los Angeles, California.
Hyperdynamics, Inc., Santa Fe, New Mexico.
Lockheed Aircraft Corp., Burbank, California.
Rockwell International, Canoga Park, California.
United Shoe Machinery Co., Woburn, Massachusetts.
Xerox Corp., El Segundo, California.

Associations

American Association of Petroleum Geologists.
American Petroleum Institute.
Independent Petroleum Association of America.
Society of Exploration Geophysicists.
Western Oil & Gas Association.

Table 1. Organizations Contacted (contd)

Government Agencies

City of Long Beach, California
Dept. of Oil Properties, Long Beach, California.
Energy Research and Development Administration, Washington, D. C. and
Oakland, California
Brookhaven National Laboratory, Upton, New York.
Sandia Laboratories, Albuquerque, New Mexico.
Interior Department:
U.S. Geological Survey, Denver, Colorado, Flagstaff, Arizona, and
Menlo Park, California.
Bureau of Mines
Mining Research Center, Denver, Colorado.
Kansas Geological Survey, Lawrence, Kansas.
National Aeronautics and Space Administration, Washington, D.C.
Goddard Space Flight Center, Greenbelt, Maryland.
Johnson Space Flight Center, Houston, Texas.
Wallops Station, Wallops Island, Virginia.
National Oceanic and Atmospheric Administration:
Environmental Research Lab., Boulder, Colorado.
National Science Foundation, Washington, D. C.
Navy Department:
Naval Electronics Laboratory, San Diego, California.
Naval Weapons Laboratory, Dahlgren, Virginia.
Office of Naval Research, Chicago, Illinois.
Research Council of Alberta, Edmonton, Alberta, Canada.

Universities

California Institute of Technology, Pasadena, California.
University of California, Livermore, California.
Colorado School of Mines, Golden, Colorado.
Massachusetts Institute of Technology, Cambridge, Massachusetts.
University of Missouri, Rolla, Missouri.
University of Oklahoma, Norman, Oklahoma.
University of Ottawa, Ottawa, Ontario, Canada.
University of Pennsylvania, Wharton School, Philadelphia, Pennsylvania.
University of Puget Sound, Tacoma, Washington.
Rice University, Houston, Texas.
Southeastern Massachusetts University, North Dartmouth, Massachusetts.
University of Southern California, Los Angeles, California.
Stanford University, Palo Alto, California.
University of Texas, Dallas, Texas.

help solve each problem. These evaluations and identifications were reviewed by the entire group representing a variety of backgrounds and specialties. Compared to the long-term industry efforts on some problems, the JPL evaluation has necessarily been shallow. However, it has been relatively broad, and comparative across various approaches and among many problems, and from a somewhat different perspective.

Various problems were combined whenever several inputs reflected similar problems or aspects of a common problem. Titles of the problems so derived are given in Table 2; statements of the problems in Appendix D.

The criteria used in comparing, assessing, and selecting from among these problems are as follows:

- 1) Problems considered not pertinent to petroleum exploration were not considered for Task 2 activity. These include, for example, problems relating only to petroleum production.
- 2) Importance of the problem toward increasing petroleum discovery rates, reducing exploration costs, and reducing uncertainty in identifying potential reserves was weighed. Problems were rated as to estimated relative importance to petroleum exploration as a whole, rather than to any petroleum service specialty.
- 3) Appropriateness of identified areas of matching aerospace technology or approaches was evaluated. Problems for which matching aerospace technology was not identified or for which aerospace technology seemed to offer little not encompassed in present petroleum technology were excluded from consideration for Task 2. (In some cases, work using aerospace technology is underway under NASA, Department of Interior or other governmental or private sponsorship.)
- 4) Judgment was made on the likelihood of a successful solution within 5 years if a development program were to be undertaken. The study was interpreted as aimed primarily at fairly short-time solutions based on fairly straightforward development and engineering rather than long-time solutions that might involve research or a number of developments in series. Five years was chosen rather arbitrarily to provide a guide. Problems judged likely to require more than 5 years to attain proof of technical feasibility of a solution based on the identified technology were downrated in the selection process.
- 5) Scale of the effort required was considered on the basis of information at hand. No formal ratings were assigned for scale-of-effort, and problems thought to require large effort were not excluded, but this evaluation was weighed against the importance of the problem in judging the desirability of choosing it for Task 2.

Additional details concerning these evaluation criteria and a numerical scheme for summarizing the evaluations are presented in Appendix C.

Table 2. Problems Suggested by Industry

	<u>Reference</u>	
<u>Geological Exploration</u>		
<u>Topography</u>		
1. Topographic mapping of large areas of sea bottom.	(All of the problems listed in this table are discussed in detail in Appendix D, under the Problem Number.)	
<u>Stratigraphy</u>		
2. Determining why a shale layer is a good source rock in one area and not in another area close by.		
3. Mapping stratigraphy with occasional holes for control.		
<u>Structure</u>		
4. Computer programs to recognize lineaments on images.		
5. Detecting surface geological expression of possible traps.		
<u>Location</u>		
6. Geographic location at sea.		
7. Geographic positioning on land.		
<u>Geophysical Exploration</u>		
<u>Reflection Seismology</u>		
<u>Systems</u>		
8. Finding and identifying thin beds.		
9. Improved detection of stratigraphic traps.		
<u>Equipment</u>		
10. Improved seismic sources.		
11. Seismic prospecting through highly attenuating or highly reflecting layers.		
<u>Data Transmission, Handling, and Processing</u>		
12. Seismic data transmission from sensors to recorder.		
13. Seismic data transmission from survey ship to home office.		
14. Marine seismic cable jackets.		
15. Faster seismic-processing turnaround.		
16. Weathered-layer effects on seismic-reflection data.		
17. Multiple reflections from sea bottom and surface.		
18. Improved displays of processed seismic data.		
19. Porosity and permeability determinations from seismic data.		
20. Recognizing subsurface petroleum from surface measurements.		

Table 2. Problems Suggested by Industry (contd)

	<u>Reference</u>
<u>Field Operations</u>	
21. Seismic surveys from moving vehicle on land.	(All of the problems listed in this table are discussed in detail in Appendix D, under the Problem Number.)
22. Comfort at sea.	
23. Base-camp logistics for remote land locations.	
24. Storing magnetic and gravity data.	
25. Estimation of temperature at depth.	
26. Gravimetry from a moving ship.	
27. Revival of old geophysical methods and development of new ones.	
<u>Well Logging</u>	
28. Improved logging method for detection of fractures.	
29. Digital logging.	
30. Correcting well logs for drilling-mud properties.	
31. Measurements from bottom of hole during drilling.	
32. Determining stratigraphy far out from borehole.	
33. Down-hole permeability measurement.	
34. Distinguishing oil from water by borehole measurements.	
<u>Geochemical Exploration</u>	
35. Improved surface geochemical techniques.	
36. Landsat sensors attuned to geologic needs.	
<u>Drilling</u>	
37. Better drilling methods.	
38. Drilling stratigraphic test holes.	
39. Light-weight drilling equipment.	
40. High-temperature rubber for down-hole drill motors.	
41. Alternatives to drilling muds.	
42. Rock implosion into borehole.	
43. Maintaining drill-ship position.	
<u>Administrative and Business</u>	
44. Technical support to independents.	
45. Revised methods of federal leasing.	
<u>Exploration Synthesis and Multiple Methods</u>	
46. Comparison of drilling experience with predictions.	
47. Cheaper offshore reconnaissance methods.	
48. Field detection of source rock.	
49. Assessment of offshore potential reserves.	

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Table 2. Problems Suggested by Industry (contd)

	<u>Reference</u>
<u>Production and Development</u>	
50. Extraction of oil from siltstone and other fine grained reservoirs.	(All of the problems listed in this table are discussed in detail in Appendix D, under the Problem Number.)
52. Petroleum production from wells in deep water.	
52. Better secondary/tertiary recovery techniques.	
53. Perforating casing and deep into formation.	
54. Material resistant to hydrogen sulfide.	
55. Steel quality control.	
56. Sea ice prediction.	
57. Iceberg control.	
58. Earthquake prediction.	
<u>Miscellaneous</u>	
59. Time-scale for replacement of petroleum by other energy sources.	

The individual problems are briefly discussed one by one in Appendix D. This Appendix also gives, for each problem, the evaluation of the problem and identification of matching technology made by JPL.

The problems, assessments, and recommendations developed in Task 1 were reviewed by an advisory panel of experts from the petroleum industry and petroleum service industry and from universities. Their comments were utilized in finalizing the results of the task.

B. ASSESSMENT OF MOST SIGNIFICANT AND PROMISING PROBLEMS

As evaluation and assessment continued, it became clear that many of the problems could well be grouped into larger topics. Among the topics judged best in meeting the criteria stated in the preceding section were

- Seismic-reflection systems: how to get better, cheaper, and faster seismic-reflection results (Topic A).
- Down-hole acoustic techniques: mapping of stratigraphy and fracture patterns with the aid of boreholes (Topic B).
- Identification of geological analogies: identification of known areas most closely resembling an area being explored (Topic C).
- Drilling methods: better drilling techniques (Topic D).
- Remote geochemical sensing: remote sensing of chemical indicators of subsurface petroleum (Topic E).

- Sea-floor imaging and mapping: low-cost imaging and charting of the sea floor (Topic F).

Topic A - Seismic-Reflection Systems

This category includes many problems, including several clusters of problems, which in the following listing are ranked loosely in order of significance and are identified by the numbers used in Table 2 and Appendix D.

- Finding and identifying thin beds (Problem 8).
- Improved detection of stratigraphic traps (Problem 9).
- Porosity and permeability determinations from seismic data (Problem 18).
- Recognizing subsurface petroleum from surface measurements (Problem 19).
- Improved seismic sources (Problem 10).
- Seismic prospecting through highly attenuating or reflecting layers (Problem 11).
- Weathered-layer effects on seismic-reflection data (Problem 16).
- Multiple reflections from sea-bottom and surface (Problem 17).
- Seismic data transmission from sensors to recorder (Problem 12).
- Seismic data transmission from survey ship to home office (Problem 13).
- Marine seismic cable jackets (Problem 14).
- Faster seismic-processing turnaround (Problem 15).
- Improved displays of processed seismic data (Problem 18).
- Seismic surveys from moving vehicle on land (Problem 21).
- Comfort at sea (Problem 22).
- Base-camp logistics for remote land locations (Problem 23).

Problems in the above list were reported as important by the majority of contacted companies. Seismic reflection is the primary technique used in petroleum exploration; improvements in the technique could clearly and significantly increase discovery rates and reduce exploration costs.

An applicable approach to this range of problems appeared to be a systems approach, attempting to optimize the entire system of seismic-reflection measurements and interpretation. Hardware, software, data transmission, field operations, and logistics would be considered as major elements of the overall system. Trade-offs would be considered, emphasizing relative advantages and disadvantages of alternative designs including present methods. This approach is basic to most aerospace projects. Flexibility would be emphasized.

Besides this overall approach, there are several areas of technology that might be applicable to individual elements. Solid-propellant and thrust-engine techniques might lead to powerful seismic sources with selected frequency spectra. Adaptions of some aerospace data-processing techniques might aid in improving sensitivity, signal/noise ratio, and spatial localization. Aerospace telemetry and signal-transmission techniques might reduce cable problems

and return data more promptly. Increased use of aircraft and ground-effect vehicles might reduce costs and improve logistics and comfort in field operations.

The study team considered that the likelihood of significant improvements being reduced to practice within 5 years was good. A moderate-to-substantial effort would be required because of the wide range of technical disciplines to be used.

Topic B - Down-Hole Acoustic Techniques

Problems grouped under this topic include

- Determining stratigraphy far out from borehole (Problem 32).
- Mapping stratigraphy with occasional holes for control (Problem 3).
- Improved logging method for detection of fractures (Problem 28).

Stratigraphic mapping from boreholes, according to industry sources, would very useful in determining whether and where to try again under the following circumstances: (1) if a dry hole is encountered, (2) in assessing potential reserves, and (3) in planning continued development of a field. A solution to this problem should provide a moderate decrease in exploration cost. An appropriate technique appeared to be acoustic imaging by transmission, using paths between boreholes or perhaps between a borehole and the surface. Acoustic tomography might be particularly appropriate. The technique is used in medicine for observations of soft tissues in the human body. In that application, a source and receiver outside the body are moved to a number of positions in a plane intercepting the body. The method provides a map of the distribution of acoustic properties over the cross section. There is a possibility that the method could provide some stratigraphic data at depths greater than the borehole.

Fracture patterns around boreholes are, in certain beds, important in estimating the flow to be expected and perhaps more important in evaluating and planning stimulation techniques. Examinations of well walls and of cores often do not give reliable information because drilling a hole and taking a core to the surface alter the stress patterns and therefore may alter the fractures already present or introduce new ones. To obtain fracture patterns some yards out from the borehole, acoustic-reflection techniques with source(s) and receivers in the hole were considered a possibility. Directional sources providing relatively high frequencies and probably scanned in direction warranted consideration. Some industry effort may be in progress on these techniques. The nearby-fracture problem is probably of more concern in recovery than in exploration.

The suggested technique for subsurface stratigraphic mapping uses transmission, and the technique for determining fracture patterns uses reflection. There is appreciable commonality between the approaches, suggesting a broad look at the possibilities of down-hole acoustic techniques. Clearly, there is also some relation to seismic-reflection systems, Topic A. Emphasis on Topic B would be on acoustic imaging rather than on velocity measurements within the scope of existing sonic logging.

The probability of proving technical feasibility of at least one method within 5 years was considered good. A moderate effort would probably be adequate.

Topic C - Identification of Geological Analogies

This topic includes Problem 46, comparison of exploratory drilling experience with discovery predictions. It was also intended to aid specifically in finding and clarifying analogies between new areas and areas previously explored; a method that appears to be extensively used in evaluating new prospects. Individuals at several companies suggested that effort in this area could aid such evaluation. It seemed probable that a moderate increase in discovery rates and reduction in costs due to dry holes could result.

An approach that could be considered is computer-based data storage and retrieval with the capability of combining a variety of data, both map- (or contour-) type data and that pertaining to specific points and of comparing sets of such data for various sites. Service and petroleum companies are apparently doing some work along these lines. Perhaps the MILUS (Multiple Input Land Use System) technique (Ref. 2) might provide another starting point.

The chance of developing a practical method within 5 years was considered fairly good. Whether the method would provide useful information would then have to be determined. A relatively small effort would probably suffice.

Topic D - Drilling Methods

This topic includes two problems:

- Better drilling methods (Problem 37).
- Drilling stratigraphic test holes (Problem 38).

Drilling costs constitute a large fraction of the overall exploration cost (as well as of development cost). Better drilling methods could produce a major reduction in exploration costs. By permitting more exploratory holes to be drilled for the same budget, these methods could lead to a major increase in petroleum discovered.

Pertinent areas of aerospace technology included design for shock, vibration, and other hostile environments; resonant mechanical mode analysis; thrust-engine design, combustion transients and instabilities, and combustion aerodynamics. Among the possible approaches were

- 1) Better down-hole motors and turbines (being worked on by an aerospace company).
- 2) Using mechanically resonant drives (proposed by a private company).
- 3) Drilling with shocks from a rocket engine operating in pulsed or unstable mode.
- 4) Automated drill rig.
- 5) High-pressure drilling (previously worked on by several companies).

Although the Energy Research and Development Administration (ERDA) is supporting work on better drilling methods, it is apparently not covering the above approaches. ERDA's efforts at Sandia and Los Alamos Laboratories include:

- 1) "Subterrene," melting the rock by electrical heating.
- 2) Spark drilling.
- 3) Systems for replacing worn cutters without pulling the drill string from the hole.
- 4) "Terra-Drilling," projectiles which are carried by mud through the center of a bit and which crack the rock ahead of the drill.

The probability of proving technical feasibility of one technique within 5 years was considered good. A moderate effort would be needed.

Topic E - Remote Sensing of Geochemistry

This topic includes Problem 35, improved surface geochemical techniques. Information from petroleum companies suggested that better geochemical methods could lead to at least a moderate increase in petroleum found. More reliable methods would save significant cost by reducing the number of dry holes.

The most pertinent area of aerospace technology appeared to be remote sensing. For geochemical indicators at the present state-of-the-art, remote sensing is probably limited to exploration on land. Instrument development was another possibly applicable area of aerospace technology.

Somewhat discouraging was the opinion generally gathered from U.S. oil companies that geochemical techniques based on analyses of surface soils or near-surface water have not been reliable indicators of oil below. A remote-sensing approach already under investigation by U. S. Geological Survey is remote detection of surface bleaching which may arise through reduction (probably microbiological) of Fe^{+++} to Fe^{++} by hydrocarbons reaching the surface from underlying petroleum. Another method that has been proposed in the course of earlier NASA sponsored work is spectroscopic detection of I_2 in the air, arising from iodine compounds in the soil; the high iodine is presumed to have reached the surface from marine organic deposits that led to petroleum (Ref. 3). If a correlation of I_2 in air with undrilled or unproduced petroleum reservoirs could be confirmed, the probability of proving technical feasibility within 5 years was considered fairly good. A relatively low effort should be adequate.

Topic F - Sea-Floor Imaging and Mapping

This topic includes

- Topographic mapping of large areas of sea bottom (Problem 1).
- Detecting surface geological expression of possible traps (Problem 5).
- Cheaper off-shore reconnaissance methods (Problem 47).

Several petroleum companies pointed out that images of the ocean bottom at resolution and with quality comparable to those provided by Landsat imagery

of land areas would be of significant aid in offshore exploration, reducing cost and reducing the number of dry holes. They would provide an inexpensive reconnaissance method by enabling recognition of the surface geological expression of possible traps.

A potential approach appeared to be side-looking sonar (long-range if possible) combined with digital-recording and image-processing techniques. Bathymetry could provide control. Many characteristics of the sonar resemble those of side-looking radar, an aerospace technique. Many aerospace data-processing and recording methods used for radar and for optical imagery appeared applicable.

A prime limitation of the usual side-looking sonar technique is the recording technique: analog recording on heat-sensitive paper. The resulting images have very few shades of gray; the quality and possible resolution is poor compared to that of good photographic images. Also it is very difficult to recover data recorded in this matter for subsequent digital processing.

The probability of proving technical feasibility within 5 years was considered good. A moderate effort would probably be needed.

(Note: This topic was not included in the original selection of topics recorded in JPL Document 5030-10, Ref. 1, but was added subsequently).

C. TASK 1 RECOMMENDATIONS

1. Task 2 Study Effort

On the basis of the criteria given in Section II-A and of the evaluation of the topics outlined in Section II-B and Appendix D, it was recommended that the more detailed Task 2 study effort include

- Seismic-reflection systems (Topic A).
- Down-hole acoustic techniques (Topic B).

Further examination of the following was also recommended

- Identification of geological analogies (Topic C).
- Drilling methods (Topic D).
- Remote sensing of geochemistry (Topic E).
- Sea-bottom topography (Topic F).

with the possibility of including one or more of these topics in Task 2.

2. Recommendations on Other Problems

The hundred or so problems suggested by petroleum and petroleum service companies were reduced, by eliminating duplicates and combining similar items, to the 59 listed in Table 2. Of these, 25 were included in the 6 broader topics discussed in Section II-B and recommended above for possible Task 2 effort. The remaining 34 problems appeared less appropriate for continued attention in this study and were not covered in Task 2.

Recommendations as to these latter problems or comments regarding their disposition are as follows:

- 1) Worth considering aerospace technology application - some work underway using aerospace techniques:
 - Computer programs to recognize lineaments on images (Problem 4).
 - Gravimetry from a moving ship (Problem 26).
 - Light-weight drilling equipment (Problem 39).
- 2) Worth considering aerospace technology application - no known aerospace-related effort underway:
 - Digital logging (Problem 29).
 - High-temperature rubber (Problem 40).
 - Cheaper offshore reconnaissance methods (Problem 47).
- 3) Improvements in Landsat sensors already under consideration:
 - Detecting surface expression of possible traps (Problem 5).
 - Landsat sensors attuned to geologic needs (Problem 36).
- 4) Likely to be helped indirectly by effort on other problems:
 - Detecting surface expression of possible reservoirs (Problem 5 (for offshore areas, helped by effort on Topic F, Topographic mapping of sea bottom)).
- 5) Should probably be handled commercially:
 - Geographic location at sea (Problem 6).
 - Geographic positioning on land (Problem 7).
 - Storing magnetic and gravity data (Problem 24).
 - Digital logging (Problem 29).
 - Measurements from bottom of hole during drilling (Problem 31).
 - Distinguishing oil from water by borehole measurements (Problem 34).
 - High-temperature rubber (Problem 40).
 - Cheaper offshore reconnaissance methods (Problem 47).
 - Time-scale for replacement of petroleum (Problem 59).
- 6) Production problem, rather than exploration - worth considering aerospace technology application:
 - Extraction of oil from siltstone and other fine-grain reservoirs (Problem 50).
 - Better secondary/tertiary recovery techniques (Problem 52).
 - Steel quality control (Problem 55).
 - Sea-ice prediction (Problem 56).
 - Earthquake prediction (Problem 58).
- 7) Production problem - should probably be handled commercially:
 - Perforating casing deep into formation (Problem 53).

8) No matching aerospace technology identified:

- Determining why a shale layer is a good source rock in one area and not in another area close by. (Problem 2).
- Estimation of temperature at depth (Problem 25).
- Revival of old geophysical methods and development of new ones (Problem 27).
- Correcting well logs for drilling-mud properties (Problem 30).
- Downhole permeability measurement (Problem 33).
- Alternatives to drilling muds (Problem 41).
- Maintaining drill-ship position (Problem 43).
- Technical support to independents (Problem 44).
- Revised methods of federal leasing (Problem 45).
- Field detection of source rock (Problem 48).
- Assessment of offshore potential reserves (Problem 49).

9) Production problem, rather than exploration - no matching aerospace technology identified:

- Rock implosion into borehole (Problem 42).
- Petroleum production from wells in deep water (Problem 51).
- Material resistant to hydrogen sulfide (Problem 54).
- Iceberg control (Problem 57).

D. GENERAL TASK 1 FINDINGS

On the basis of the gathered information, a few general findings not specifically related to any individual problem mentioned were made. These include

- 1) According to statements from a number of oil companies and to some published literature (Refs. 4-6), a large fraction of the petroleum resources within the land area of the 48 contiguous states have already been discovered, and most of what remains to be discovered will be recoverable only at very high cost. Thus, problems and techniques applicable only to onshore exploration may be less significant than those applicable to marine exploration.
- 2) Most on-land exploration in the 48 states is done by or for the smaller petroleum companies; most offshore exploration is done by the larger companies. If it is intended to find more of the economically extractable oil in the 48 states or to lower the cost of finding it, some of the effort should be applicable to land exploration and addressed to problems of the smaller companies.
- 3) Techniques used in petroleum exploration are, on the whole, technically excellent and near or at the state-of-the art.* Many petroleum and service companies are aware, in general, of pertinent technical

*The techniques recognized as best are not always utilized, however, because of the cost, the industry pricing practices, and the usual lag in applying new methods.

developments occurring in other fields, and considerable cross-fertilization occurs. The areas of prime technical attention in petroleum exploration are, however, different from those receiving prime attention in aerospace. Thus, there may be significant areas in which use of aerospace technology could help advance petroleum exploration technology. These areas probably include combustion, power supplies, phased arrays, telecommunications, telemetry, and certain types of data processing; aerospace remote-sensing techniques are already being used in petroleum exploration. Likewise, there are significant areas in which petroleum exploration technology could help advance aerospace; some petroleum exploration techniques are already being so applied.

- 4) There are a number of difficulties in petroleum exploration for which greater expertise in materials selection, mechanical engineering, failure analysis and quality assurance would be useful. The need seems to lie in a multiplicity of small applications rather than a few major ones. It would probably be worthwhile to establish some means whereby the needed skills which are available in the aerospace field could be made available as needed, especially to petroleum service companies and the smaller petroleum companies.
- 5) The payoff for improvements in petroleum extraction appears greater than that for improvements in petroleum exploration. For example, only 30% of the petroleum in a reservoir is, on the average, recovered by conventional extraction methods. It would probably be worth investigating the possibilities of applying aerospace or other new techniques to petroleum extraction.
- 6) Likewise, it probably will be worth investigating the possibilities of applying aerospace techniques to reservoir assessment.
- 7) Many of the aerospace techniques that may be applicable to petroleum exploration appear as easily or more readily applicable to minerals exploration. It would probably be worth investigating this also.

SECTION III

TASKS 2 AND 3

In carrying out Task 2, all 6 of the topics listed in Section II-B were addressed. A separate group of specialists in appropriate technical areas of JPL considered each topic to the depth allowed by the funds and time available. During the course of the study, each topic was discussed with members of the petroleum industry or petroleum service industry. Consultants, experts in petroleum exploration, supplied valuable advice. A small amount of laboratory testing and mathematical analysis was carried out in selected areas.

The pages that follow present the work on the 6 selected topics. The results of Task 2 and Task 3 have been combined in these discussions. In the course of the Task 2 effort, 21 concepts were identified that, after examination, appeared worth presenting in this report (see Table 3). Each is discussed under the appropriate topic and is identified by the concept number shown in Table 3.

It should be noted that a search has not yet been made to determine whether some of these concepts have been brought forth and patented by others. Some of the ideas are not original with the study participants; if recognized, this has been noted in the account which follows.

The individual JPL groups provided technical analysis of their topics and estimates of the costs that would be incurred in developing and applying them. Results of the group efforts were integrated and presented to an advisory panel of experts from the petroleum and petroleum service industries, universities, and government agencies. Their comments were utilized in preparing updated written and oral accounts.

A briefing and a series of workshops were then held; at which time the results were presented and discussed and draft copies of this report were available. The briefing and workshops, arranged in cooperation with the Industrial Associates Office of Caltech, were open to anyone interested. Invitations were sent to individuals from a large number of companies listed in published indices as engaged in petroleum exploration or offering pertinent types of petroleum exploration services as well as to individuals from other companies, universities, and government agencies. Persons who had provided information earlier in the study were specifically invited. Approximately 100 persons, mostly from industry, participated in the briefing and workshops at which considerable interchange of ideas took place. Registrants are listed in Appendix W.

Comments made during the workshops were in turn used in preparing this report, together with comments obtained in other contacts, such as the "benefits" interviews described below (in Section III-G).

Table 3. Selected Topics and Proposed Concepts

	<u>Concept No.</u>
<u>Topic A: Seismic-Reflection Systems</u>	
Systems approach to seismic prospecting	1
Seismic sources:	
Swept-frequency explosive source	2
Swept-frequency solid-propellant source	3
Oscillation-free bubble source	4
Oscillation-free implosion source	5
Aerial seismic survey	6
Telemetry of data from ship to computing center	7
Data processing	
Low-cost data-processing system	8
High-resolution seismic system	9
Time-delay spectrometry.	10
<u>Topic B: Down-hole Acoustic Techniques</u>	
Down-hole seismic tomography	11
Acoustic backscatter log for fracture patterns	12
<u>Topic C: Identification of Geological Analogies</u>	
Improved computer aid in recognizing geological analogies	13
<u>Topic D: Drilling Methods</u>	
Automated drilling rig	14
Improved high-pressure drilling	15
Resonant-vibration drilling	16
Improved down-hole drill motor	17
Combustion-fracture drilling	18
<u>Topic E: Remote Geochemical Sensing</u>	
Remote optical spectroscopy of airborne iodine and other petroleum indicators	19
<u>Topic F: Sea-Floor Imaging and Mapping</u>	
Acoustic imaging of large areas of the sea-floor	20
Detailed bathymetric charting	21

A. TOPIC A - SEISMIC-REFLECTION SYSTEMS

Seismic prospecting is such an important technique that it absorbs about 90% of the geophysical prospecting budget of the petroleum industry. In the U.S. alone, it results in expenditure of hundreds of millions of dollars per year. This expenditure in operations has been supported by a research and development program which has resulted in incorporation of sophisticated technology. Despite this effort, the Task 1 part of this study revealed that there is substantive room for improvement in seismic-prospecting technology and that there is pertinent aerospace technology which has apparently not received consideration. Therefore the seismic-reflection system was designated as one of the topics to be studied as part of Task 2.

1. Technical Method and Procedure

The outcome of Task 1 was a list of problems uncovered and a judgment that some aerospace technology has relevance to seismic prospecting. Task 2 was conducted by the following process:

- 1) Organization of the problems to define basic objectives for new concepts.
- 2) Review of the state-of-the-art by literature search and by meetings with organizations at the forefront of the technology.
- 3) Delineation of each proposed concept including:
 - a) Description.
 - b) Expected performance.
 - c) Feasibility of demonstration within 5 years.
 - d) Development cost and schedule.
- 4) Evaluation of benefits of each proposed concept in terms of
 - a) Technical impact on exploration.
 - b) Capital and operations cost.
 - c) Expected value of successful application of the concept.

Regarding the first step, the 16 seismic-prospecting problems identified in Task I were

	<u>Problem Identification Number*</u>
Finding and identifying thin beds.	8
Improved detection of stratigraphic traps.	9
Porosity and permeability determinations from seismic data.	19
Recognizing subsurface petroleum from surface measurements (perhaps).	20
Improved seismic sources.	10

	<u>Problem Identification Number*</u>
Seismic prospecting through highly attenuating or reflecting layers.	11
Weathered-layer effects on seismic-reflection data.	16
Multiple reflections from sea bottom and surface.	17
Seismic data transmission from sensors to recorder.	12
Seismic data transmission from survey ship to home office.	13
Marine seismic cable jackets.	14
Faster seismic-processing turnaround.	15
Improved displays of processed seismic data.	18
Seismic surveys from moving vehicles on land.	21
Comfort at sea.	22
Base-camp logistics for remote land sites.	23

These problems can be grouped and redefined in general terms as the desired objectives of new seismic system concepts. These objectives are

- 1) To measure physical properties of the subsurface.
- 2) To extend the capability of differentiating subsurface lithography.
- 3) To reduce operations costs.

2. Industry Needs for More Information

The study team visited several oil companies and service companies to seek the opinions of those directly involved in petroleum exploration as to the primary geophysical problems faced by industry.

The categories of exploration geophysics that might likely benefit from application of aerospace techniques include data acquisition, data transfer, and data processing. Within these categories, more specific subjects were identified as those which were of most interest to industry, would, potentially, significantly improve exploration techniques and would provide some new parameters for the explorationist. Comments from industry often included the hope of gaining added direct or indirect information on physical characteristics of subsurface stratigraphic units.

The primary parts of the seismic data presently used are the amplitude information of the vertical or pressure component seismic signal and the interpreted velocity information for first arrival along each path. Efforts

*The problem identification numbers correspond to those in Table 2 and Appendix D; the problems are discussed individually in Appendix D.

have been made to use other parts of the seismic signal, but for various reasons, these have not become standard in the industry at this time. A listing of correlatable data is tabulated below:

Geologic Factors

Gross lithology
Fluid filled reservoirs
Depth to unit of interest
Dip of stratigraphic unit
Tectonic relationship/events
Depositional environment
Pressure environment

Geophysical Data

Seismic velocity
Reflection amplitude
Arrival times
Arrival times (from geophone spread)
Angular relationship of events
Pattern of events on seismic record
Velocity differences

Resolution is a primary problem that has been considered at length by geophysicists. The "quarter wavelength" and "half wavelength" resolving power has been widely discussed. Velocity increases with depth; detected frequency decreases with depth, and therefore resolution deteriorates with depth. Deep stratigraphic units (10000-15000 feet) must be 150-250 feet thick to detect. Resolution can be improved in recording and processing and by having sufficient power so that the higher frequencies are not completely attenuated at shallow depths.

Physical information that would be of high value includes

- 1) Thin (<50 feet) bed definition.
- 2) Porosity.
- 3) Fluid saturation.
- 4) Sediment compaction.

Use of additional characteristics of the received seismic signal may provide some of this information.

3. Concept 1: Systems Approach to Seismic-Reflection Prospecting

Statement of Concept: Use of a systems approach to the design of seismic-reflection systems should insure that the various elements of the system fit together well, improve the overall performance, and reduce cost.

a. Problems Addressed

All 16 seismic-prospecting problems listed above (Section III-A-1) are addressed by this concept.

b. Background and Approach

The seismic-reflection systems now in use consist of a number of elements - seismic sources, receivers, signal handling, data storage, data transmission, data processing and display - all of which originated more or less independently and have been combined in an evolutionary way. For the most part, these systems grew and were not designed as a whole. It is possible that a more orderly and systematic approach could provide seismic systems with better overall performance, faster turnaround, and/or lower cost.

The approach to seismic-reflection prospecting that best fits aerospace methods is the systems approach. This methodology developed in aerospace work offers an orderly step-by-step process by which overall objectives and requirements are first explored, and functional and performance requirements of the various elements of the system can then be determined.

The systems approach facilitates optimization efforts directed at improving the end-to-end system performance because it affords a better visibility over the functions and the performance needed from each element as well as the interactions between elements and the effect on other elements of changing the functions or performance of one element. It is felt that this approach has potential in improving the overall performance of seismic-prospecting systems. A brief description of such an approach is included as Appendix E. Despite the cursory nature of Appendix E, it identifies some of the areas in which further work is needed and discusses some of the management tools furnished by a properly executed systems approach.

The systems approach is considered especially applicable to seismic-prospecting systems since such systems are purely information-producing systems, and the customer can be easily identified. Past efforts to apply this approach to such systems have usually been successful; whereas, they have been relatively unsuccessful when the systems approach was applied to other areas such as urban problems, local transportation planning, or, generally, projects in which one entity pays for the services and another gets the benefits.

For these reasons, it is believed that a possible future effort to apply the systems approach to seismic prospecting in much greater depth, particularly if it were applied to a number of specifically delineated systems objectives, could be of significant value.

One difficulty recognized in implementing any new seismic-prospecting system is that responsibility for implementation is likely to be divided among equipment manufacturers, seismic-survey companies, data-processing companies, and the petroleum companies.

c. Aerospace Contribution

The aerospace contribution to this concept is the systems approach itself.

d. Recommendation

If there is sufficient industry interest, initiate a much more thorough systems study and preliminary design effort for a seismic-reflection system intended to achieve specific stated objectives.

4. Data Acquisition and Transmission Improvements

Present methodology in seismic-reflection prospecting varies, but one of the methods most widely used on shore (Vibroseis, a hydropneumatic vibrator) employs a frequency sweep up to about 80 Hz over a 16- to 20-second time period. The power (energy per unit time) transmitted into the ground is relatively low, but the received energy for each path can be summed over the time period. Dynamite or other explosives placed in a drilled hole are often used and provide high-power pulses. In offshore seismic work, most surveys are presently conducted using some sort of air or gas gun. The energy output is relatively low, and high frequencies (above 200 Hz) are not acquired. With the low-energy sources, higher frequencies would probably not be received or recorded from strata at depths of more than a few thousand feet because of attenuation in the earth. Attenuation of the higher frequencies is greatest in the near-surface.

Better seismic sources could help in obtaining more of the desired information including information with better resolution and that concerning physical characteristics. Four concepts arising from aerospace techniques are outlined on the following pages:

Swept-frequency explosive seismic source (Concept 2).

Swept-frequency solid-propellant source (Concept 3).

Oscillation-free bubble source (Concept 4).

Oscillation-free implosion source (Concept 5).

Use of aircraft in seismic-field operations is considered next, and then the use of radio and communication satellites to convey data from the field to the computing center.

a. Concept 2: Swept-Frequency Explosive Source

Statement of Concept: For a seismic source, use a string of many small explosive charges with time-delay pyrotechnic elements between them. Each charge provides 1 cycle of pressure, and the time-delay elements provide a swept frequency.

(1) Problems Addressed.* The following problems are addressed by this concept:

Finding and identifying thin beds (Problem 8).
Improved detection of stratigraphic traps (Problem 9).
Improved seismic sources (Problem 10).
Seismic prospecting through highly attenuating or reflecting layers (Problem 11).

(2) Approach. The major objective of this concept is to improve the explosive seismic sources for land petroleum exploration. By sequentially setting off a number of explosive charges of different mass at programmed times, frequency sweep and amplitude modulation can be achieved in the seismic wave. Both parameters can be tailored in wide ranges as needed by the application. The time separation between the explosions will be the dominant controlling factor of the source-frequency spectrum. The concept would also improve the energy coupling to the earth by reducing the peak-shock amplitude and by using impedance matching between the explosive container and the ground. The device can be used in marine exploration. However, in water, bubble oscillation would be a problem just as it is for a single-shot explosive source application.

(3) Background. The advantages of using a single-explosion (detonation) seismic source as compared to a surface hydropneumatic vibrator are

- 1) High-energy density and amplitude.
- 2) Smaller system weight and high portability.
- 3) Source operable below the water table.

The disadvantages of single-shot explosive sources are

- 1) Need to drill a hole in the ground.
- 2) Single shot, no frequency sweep capability.

*The problem numbers correspond to those in Appendix D where each problem is discussed.

- 3) The detonation front causes undesirable damage to the hole walls and, therefore, wastes energy and causes signal distortion.
- 4) Handling hazard.
- 5) Environmental impact.

Hole drilling and handling hazard can be improved or overcome with modern techniques and precautions. It is the objective of this concept to eliminate disadvantages 2) and 3) and reduce disadvantage 5) while retaining the advantages of explosives.

(4) Single-Explosion Characteristics. Past experience has quantitatively defined these characteristics for common high-density nonporous insensitive high explosives such as Detasheet, picryl sulfane, RDX, HNS, TACOT, TNT, etc.

Detonation velocity	4 - 7 km/sec
Detonation pressure	100 - 300 kbars
Blasting-wave peak pressure	100 kbars
Blasting-wave equation of state	Jones-Wilkins-Lee Eq. of State
Energy density	4 - 8 kJ/g
Blasting-wave propagation speed	0.1 - 1 km/sec over a range of a few meters
Blasting-wave duration	depends upon the size of the explosive - the larger the mass the longer the duration. For a typical <0.5 lb of mass, the effective duration is about $10^2 \mu\text{s}$.
Shock initiation sensitivity	20 - 40 kbars

The advantage of using a detonable high explosive as a seismic source over nondetonable explosives such as pyrotechnics and propellants is that the detonation, once initiated by a detonator (blasting cap), is independent of the surrounding confinement. The reaction of the latter is dominated by the confinement because the burning rates vary with the pressure.

(5) Problems Involved in a Multi-Explosion Package.

(a) Prevention of Sympathetic Initiation. For simplicity of transportation and installation, the charges for the programmed multi-explosion in a time sequence have to be located reasonably close and integrated together to be installed in a ground hole. Therefore, the insulation of the charges from each other's shock is a crucial problem.

It is well known that soft plastic or porous materials, such rubber and foamed plastics, have high attenuation for high-amplitude stress waves. Orders of magnitude attenuation have been observed in a thickness of a few centimeters in these materials. Therefore, they can be used to contain the

the high explosives so that the detonation wave or the high-amplitude blasting wave can be attenuated below the shock initiation sensitivity of the high explosives thereby avoiding sympathetic initiation. This also reduces the undesirable damage to the hole wall by the detonation.

(b) Sequential Initiation. Theoretically, one can achieve sequential initiation by using different detonators for different explosive packages. The timing can be programmed by a small electronic package. However, the system cost and complexity may not be tolerable for this design. Hot-wire initiated detonators with sub-millisecond response and response variation are available but very costly. A detonator system initiated by an exploding wire has microseconds response but costs about \$300 per detonator, plus cables. Installation of the detonators and the placing of the assembly into the hole are difficult.

The system should therefore use initiation by a single detonator with the subsequent initiations achieved by a delay and relay technique. Common pyrotechnic delay lines have difficulties of installation and are subject to destruction by the detonation. A flexible detonation cord does not have these problems but its propagation speed is too high to achieve the desirable explosion frequency in the range of 10 to 10^2 Hz.

The proposed explosive delay mechanism utilizes sensitive pyrotechnic columns inserted between the high-explosive charge columns. Conventional delay-pyrotechnic mixtures such as $BaCrO_4$ mix have too slow a propagation rate, of the order of 0.01 - 0.1 inch/sec. Sensitive pyrotechnics, such as $Zr/KClO_4$, Zr/NH_4ClO_4 mixes (pyrotechnics used for spacecraft applications), have a rate of 1.0 inch/ms and less sensitive pyrotechnics, such as B/KNO_3 , $B/KClO_3$, and black powder, have rates of the order of 0.1 inch/ms. By using these materials, time delay of the order of 1 - 10 ms (10^3 to 10^2 Hz) can be achieved in a column height of the order of 1.0 inch.

(6) Design of the Swept-Frequency Explosive Source. Figure 3-A-1 shows the conceptual design of the system. It includes a stack of plastic high-explosive containers held together by a locking mechanism (threads as an example). This provides easy assembly. The amount of the high explosive controls the amplitude of the explosion pulse. The minor dependence of the pulse width on the charge mass is insignificant because it is much smaller than the time separation between pulses.

The interface between the containers is a plastic plug containing highly pressed pyrotechnics. Its length and burning rate control the time delay and, therefore, the separation of the explosion pulses. The pyrotechnic column acts as a shock attenuator as does the rest of the plastic diaphragm. The tapered shape provides a tight seal of the interface during the high-compression transient period to restrict surface burning of the pyrotechnic and prevent by-pass burning along the pyro-plastic interface. At the end of the pyrotechnic device is a small amount of lead azide to insure reliable initiation. The entire pyrotechnic device is assembled in the plastic container by a screw mechanism so that it can be fabricated separately and, subsequently, easily assembled in the container.

For frequency sweeping, both the amplitude envelope and the pulse separation can be predesigned. The explosion is initiated at the top of the assembly

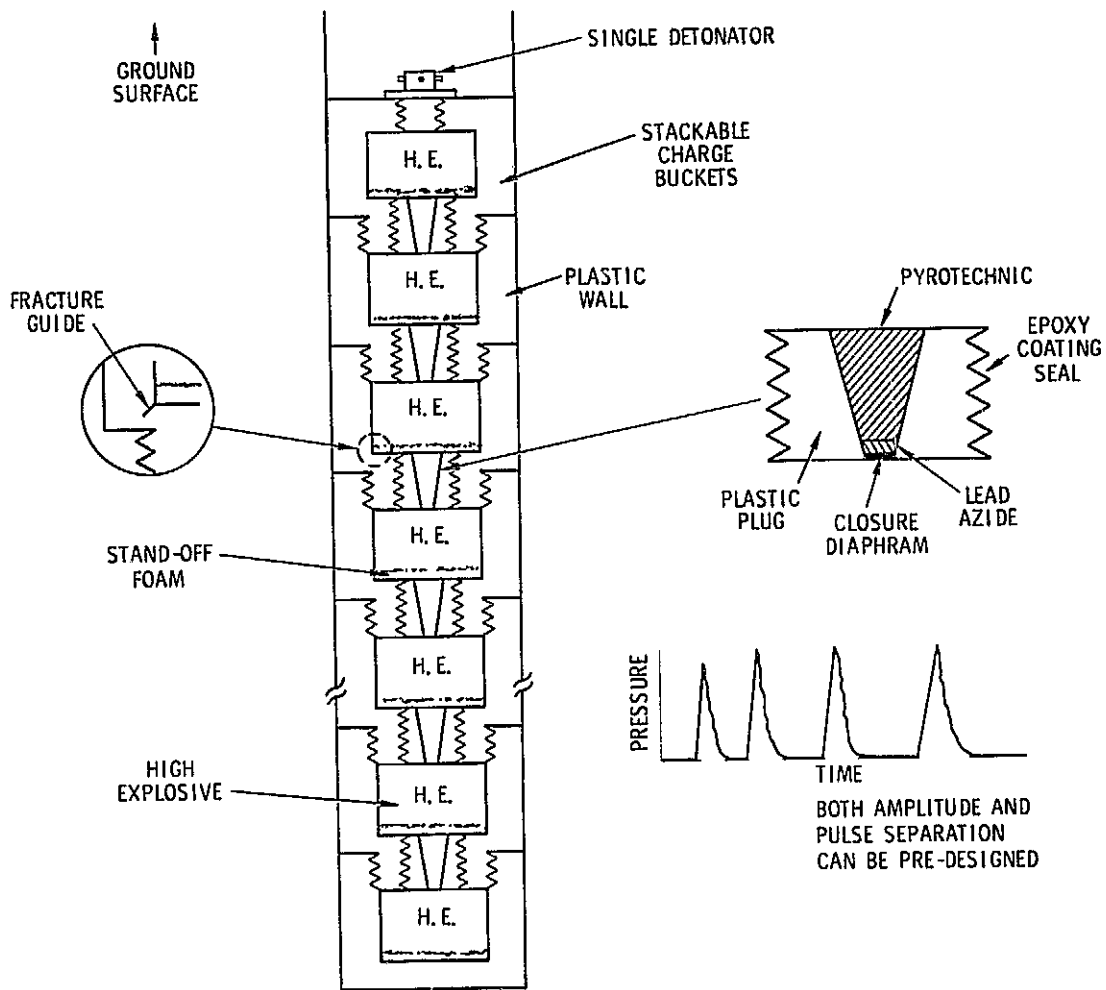


Figure 3-A-1. Conceptual Design of Swept-Frequency Explosive Seismic Source

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so successive detonation-produced blast waves are vented to the atmosphere through the hole and produce less disturbance to the uninitiated explosive containers. If the time separations between the pulses are made shorter than the blasting-wave duration, the pulses can be piled up on top of each other and still be identified. Good source coupling efficiency can be obtained by adding an external shell surrounding the assembly to achieve acoustic impedance matching between the ground and the plastic container of the assembly. A geophone near the device is needed to record the reference signal for digital processing.

(7) Expected Source Characteristics. The expected characteristics are

High-energy density	4-8 kj/g of explosive
High amplitude	>10 kbars near the source
Frequency sweep	up to 200 Hz or more
Number of pulses	adjustable by no. of charges
Amplitude modulation	by size of charge
Simplicity	one detonator/charge assembly
Operates in a drilled shot hole	hole diameter 2 inches
Diameter of the assembly	1.5 inch
Length of the assembly	<5 feet
Weight of the assembly	<20 lb
Cost	< \$40.00 per hole on mass production basis

(8) Advantages and Disadvantages in Exploration.

(a) Advantages. The advantages in exploration are

- 1) High-energy density and amplitude. Good for deep prospecting.
- 2) Good coupling of energy to ground.
- 3) Low-weight and high portability.
- 4) High frequency generation (say 200 Hz), providing resolving power for thin (25-foot thick) stratigraphic units.
- 5) Can operate below water table, thus reducing weathered-layer effects.

(b) Disadvantages. The disadvantages in exploration are

- 1) Need to drill a shot-hole.
- 2) Explosive handling hazard.
- 3) Environmental impact (but should be less than single-shot explosive).

(c) Points Needing Further Attention. These points are

- 1) Minimizing contribution of individual pulses to frequencies within sweep.
- 2) Can enough changes be incorporated to provide 15- to 20-second sweep?
- 3) If assembly is placed in rock with very low-seismic velocity, will seismic transmission time from top

- to bottom of assembly be so long that signal cannot be taken to come from a point source?
- 4) Possible prior invention.*

(d) Economic Impact and Relative Value to Industry. The impacts and values are

- 1) Should be less expensive than a "Dinoseis" or "Vibroiseis" operation and slightly more expensive than a regular explosive-source operation.
- 2) Would require added capabilities for processing and storing data if the higher frequencies are to be utilized.
- 3) Permit and damage costs would probably be equal to other explosive-source operations.
- 4) Would not require significant changes in field crew operations.
- 5) Environmental problems in sensitive areas would exist and actual damage characteristics would need to be tested and well documented.

(e) Effect on Prospect Generation and Discovery Rate. If thin-bed discrimination and additional lithologic information can be obtained, the method would greatly enhance stratigraphic trap exploration. As an example, assume that this methodology would permit mapping of thin sands, such as barrier bars, within shales. If barrier bars of the type that produce at Bell Creek, Kitty, Hilight, Recluse, etc. in the Powder River Basin could be detected and seismically mapped, this would greatly enhance the industry's capability to find analogous stratigraphic traps. (These were not seen seismically.) The producing Muddy sandstone varies from about 0-feet to 40-feet thick and is about 4400-feet deep at Bell Creek. It has recoverable estimated at about 200-million bbl oil. A conservative estimate of new oil in other undiscovered fields of this size is 2-billion dollars.

*Multiple explosive charges, rather widely spaced along a shot-hole, have been used to build up a signal directed downward. The topmost charge is detonated first and then successively lower charges at such intervals that each goes off when the seismic signal from the top charge, transmitted downward in the surrounding rock, is passing by. That concept, if ideally executed, leads to a single pulse transmitted downward, not to a swept-frequency signal. Other differences from the suggested concept are that all the charges are detonated within a fraction of a second, and their timing needs to be tailored to the seismic velocity of the rocks in which they are emplaced. In the suggested concept, the explosions are spread over the sweep time of perhaps 15 seconds, and their timing can be fixed independent of the properties of the surrounding rock.

(9) Aerospace Contribution. The aerospace contribution to this concept includes

- 1) Use of sensitive pyrotechnics as delay elements. These pyrotechnics are characteristically used in spacecraft for a variety of engineering functions.
- 2) Use of soft materials to produce very high attenuation of explosive shocks in engineering assemblies. This is characteristically done in spacecraft to protect delicate components from shocks. In the proposed concept, this is essential to prevent the shock from one charge detonating the next.

(10) Recommendation. If there is sufficient industry interest in the concept and it is confirmed to be new, initiate a development program.

b. Concept 3: Swept-Frequency Solid-Propellant Source

Statement of Concept: For a land seismic source, solid propellant is placed in a shot-hole which is capped. The propellant is ignited. As it burns, a pressure-relief valve in the cap opens and closes to provide a swept-frequency pressure signal. For a marine source, a modification embodying a re-useable case and a vent could be employed.

(1) Problems Addressed.* The problems addressed by this concept are

Finding and identifying thin beds (Problem 8).
Improved detection of stratigraphic traps (Problem 9).
Improved seismic sources (Problem 10).
Seismic prospecting through highly attenuating or reflecting layers (Problem 11).
Porosity and permeability determinations from seismic data (Problem 19).

(2) Introduction. This concept (see Figure 3-A-2) covers another seismic source for land use. It utilizes solid propellant to provide an energetic swept-frequency signal. It retains most of the advantages of an explosive source (listed a few pages earlier) and reduces most of the disadvantages.

(3) Energy Efficiency. Solid propellants have high-energy density (about 8 kJ/g), and this approach seeks to use it with high efficiency.

(4) Coupling Method. A solid-propellant rocket motor of conventional design generates high thrust. However, coupling of its energy into the ground is difficult. Using a push-plate on the ground requires a large amount of propellant and is not energetically efficient, and the cost of the propellant and motor case is high. The combustion products of a large quantity of propellant can affect the environment.

A better approach is to drill a hole in the ground and utilize the hole as the pressure vessel. In this way, the pressure generated by the combustion is directly and fully coupled to the ground. Solid-propellant pellets contained in a steel wire basket are placed in the hole and initiated by a small electrical igniter cartridge. They are not tamped.

(5) Frequency Generation. An objective is to provide a swept-frequency output. A depressurization mechanism using a variable thrust sonic nozzle

*The problem numbers correspond to those in Appendix D where each problem is discussed.

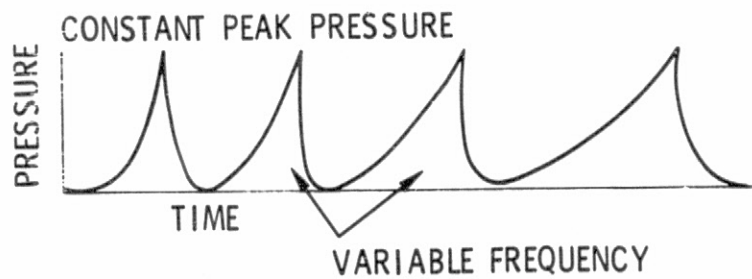
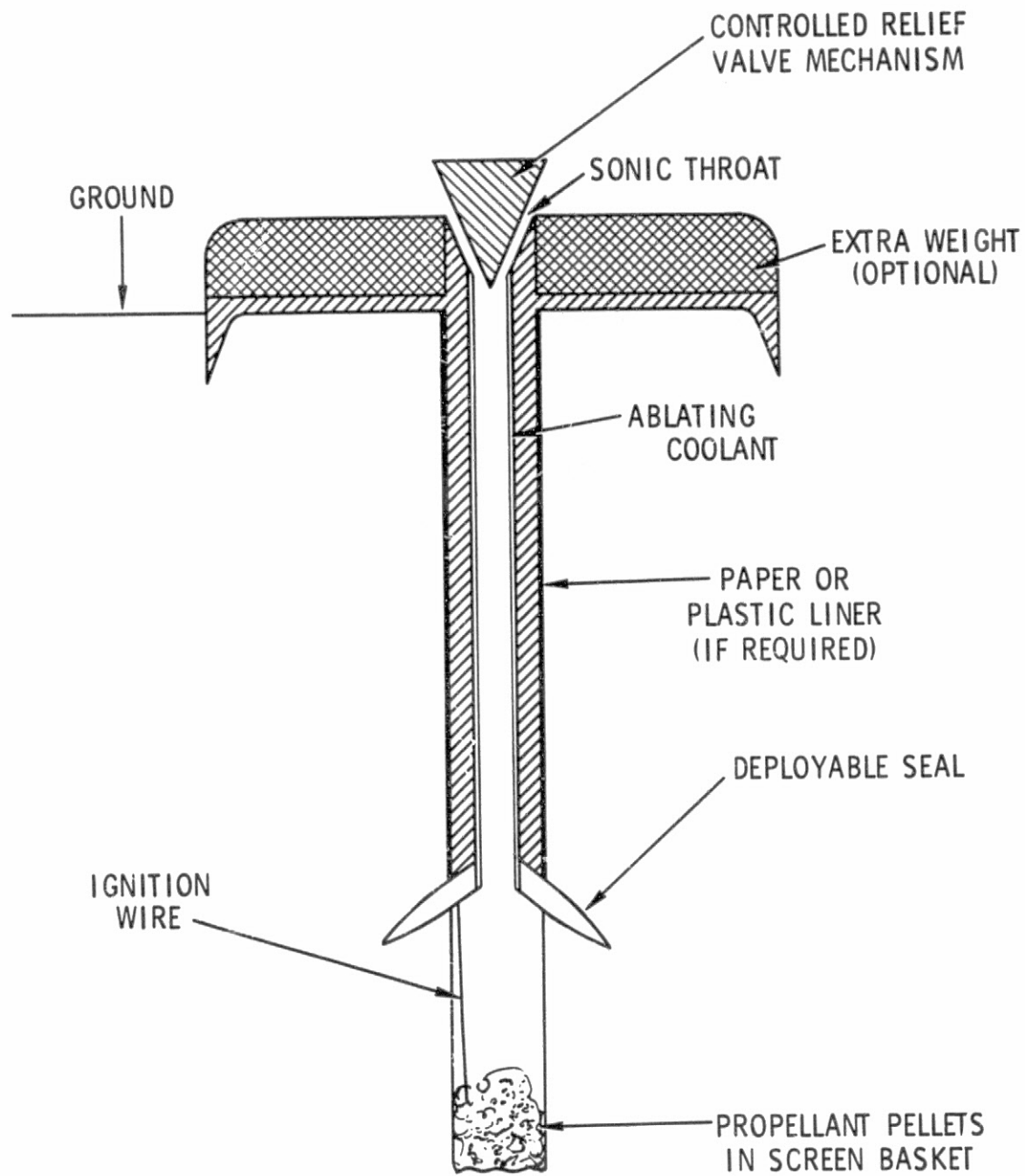


Figure 3-A-2. Concept of Variable Frequency Solid-Propellant Seismic Source

(a pressure-relief valve) is proposed.* Such devices are available for pressures up to 1000 or 2000 psi for moderate temperature gases. In principle, if the cavity volume is controlled, a valve opening at a fixed pressure could provide the desired frequency sweep (as described below).

(6) Cavity Sealing. Two methods can be used to seal and retain, within the hole, the propellant gases and the gas-relief mechanism. The first one is a self-sealing conical device which can be pointed upward or downward to lock and seal around the wall of the hole upon pressurization by the combustion. The depth of the coupling point and the area and direction of the cone depend upon the maximum pressure design for the cavity as well as the strength and density of the adjacent soil. A second method for small (approximately 1-inch diameter) holes is to use a metallic rod of the same diameter as that of the hole. The rod is supported by a heavy flat plate in contact with the ground. For reliability, these two methods can be combined as shown in Figure 3-A-2. For some holes in weak or wet soils, the hole walls may have to be sealed. A low-modulus high-elongation material such as plastic pipe may be used for these situations.

(7) Frequency Control. The pressure buildup in a closed cavity by propellant combustion depends upon the void space and the rate of generation of combustion products. The latter in turn depends upon the burning rate of the propellant and the surface area of the propellants. If the surface area is relatively constant and the burning rate is linearly dependent upon the pressure, the buildup is exponential in time. To provide frequency sweep, the pressure is varied by the changing propellant surface area. As the pellet during combustion, the surface area rapidly decreases (r^2 dependence).** This leads to a corresponding decrease in the rate of buildup of the chamber pressure, which also depends on the amount of gas venting through the relief valve. The pressure pulse fall time depends upon the reset relief pressure and the detail design of the valve. This time will be smaller than the rise time.*** Frequencies of 200 Hz appear attainable.

If frequency and amplitude are both to be controlled, then hole void volume and propellant gas generation rate are critical and need to be controlled. However, if one parameter, such as amplitude, is allowed to vary, then the

*Another approach is to utilize self-induced dynamic oscillations which sometimes occur in conventional rocket motors due either to the motor cavity resonance or flow instability. They appear, however, to be unreliable and difficult to control for seismic applications. Also, efficiency for the alternating component is low (approximately 20% of the chamber pressure at high pressures).

**Change of the pressure rise time through change of cavity dimension by regression of the propellant does not appear to be feasible because, in order to achieve the 1000 to 2000 psi pressure, a volume ratio between the void space and the propellant volume on the order of 50 is needed.

***Additional control of the timing and the degree of depressurization can be obtained by valve design by using a pressure feedback control technique.

frequency can be controlled by the valve timing, and the hole volume can have wide limits.

If one aims on a moderate cavity pressure of 2000 psi, the average burning rate is on the order of 0.3 in./second. Therefore, for a few seconds operation of the valve, the propellant pellet size is of the order of 0.5 in. thick.

(8) Interaction with the Earth. The peak pressure is low compared to explosives, and little or no energy is expended in deforming and fracturing the soil. This will decrease deformation of the cavity walls and reduce energy loss. The hole should be deep enough to ensure wall strength and static head to retain the pressure.

(9) Some Quantitative Aspects. These aspects are

Total energy	900 kJ
Peak pressure	adjustable up to 2000 psi
Frequency	adjustable up to 200 Hz
Propellant weight	~0.5 lb.
Propellant volume	~10 in. ³
Pellet diameter	0.5 in.
Hole depth	10 ft (or more as desired)
Hole diameter	≤2.0 in.
Cost of propellant	\$3.00
Cost of igniter	\$2.00
Assembly weight	100 lb
Environmental impact	small
Synchronization of multiple sources	difficult
Source signature record	provided by a nearby geophone

(10) Modification for Marine Use. Modifications of the concept that make it applicable for marine work can be envisaged. The charge could be contained in a reusable (semipermanent) case. Coupling to the water could be provided, for example, by incorporating an expandable volume in the case. A vent pipe to the surface could also be provided.

(11) Advantages and Disadvantages in Exploration.

(a) Advantages. The advantages compared to hydropneumatic vibrators are

- 1) Higher energy and amplitude (900 kJ and 2000 psi vs 400 J and 10 psi). Good for deep prospecting.
- 2) Good coupling of energy to ground.
- 3) More power at higher frequencies provides potential of discriminating thin (25-foot thick) stratigraphic units.
- 4) Low power to operate.
- 5) Lighter weight.

(b) Disadvantages. The disadvantages are

- 1) For land use, need to drill a shot-hole.

- 2) Amplitude modulation appears to be difficult.
- 3) Synchronization of several sources appears difficult.

(c) Point needing further attention.

- 1) Gas venting may cause surface seismic noise.

(d) Economic Impact and Relative Value to Industry. These factors include

- 1) Method should be less expensive for land seismic surveys than present nonexplosive sources and about the same cost or cheaper than other explosive source seismic surveys.
- 2) Capital equipment costs should be less than for present nonexplosive sources.
- 3) Data processing and storage will require modification if higher frequency data are to be utilized.
- 4) Mobility of land seismic operation should be somewhat better than for present nonexplosive seismic surveys.
- 5) Permit and damage costs probably will not be changed from explosive source operation.
- 6) Environmental problems probably less than an explosive source.
- 7) For land use will require drilling a hole which will exclude many urban areas.

(e) Effect on Prospect Generation and Discovery Rate. These effects are

- 1) If higher frequencies are attained and thin-bed definition possible, the impact will be much the same as with the swept-frequency explosive source. Several types of potential reservoirs will be possible to detect that are not identifiable with presently acquired seismic data.
- 2) Because of the added data, there is a greater probability of obtaining information on 1) sand vs/shale vs/carbonate (lithologies) 2) porosity, and 3) fluid content.
- 3) If thin (<50-feet thick) sandstone or carbonate reservoirs can be detected, it will give industry a tool to explore for barrier bar sandstones of the type found in Rocky Mountains basins, distributary channel sands and bar finger sands as found in all major deltas of the world, and fluvial sandstones such as point bar sands and channel sands as found in the Springer production in Oklahoma. Sands of this type are often very valuable but are not detectable by present seismic methods. Known oil accumulations in these types of fields in the U.S. produce 500×10^6 bbl oil or equivalent gas.

Many of these types of fields produce 20 to 50×10^6 bbl oil. At current prices for new oil, a conservative estimate of value of a 20×10^6 bbl oil

field is \$200 million, and for a 500×10^6 bbl oil field, the value is \$5 billion.

The probability of finding oil accumulations in stratigraphic traps of the 20 to 80×10^6 bbl size in the U.S. is high. At least eight Rocky Mountain area basins are highly prospective for barrier bar stratigraphic traps that are too thin to be detected with present seismic data. At least four Mid-Continent basins are prospective for fluvial sand reservoir production. Other nonstructural accumulations are certainly present in the Mississippi delta complex and the Mississippi embayment.

(12) Aerospace Contribution. The aerospace contribution to the concept includes the solid-propellant and rocket-engine technology.

(13) Recommendation. If there is sufficient industry interest, initiate a development program.

c. Concept 4: Oscillation-Free Bubble Source

Statement of Concept: Use a deployable bag to contain the gas bubble used as an underwater seismic source. The fixed maximum bag volume confines the gas at a residual pressure higher than that of the water. This eliminates rapid collapse of the bag. Therefore, the device is oscillation free. The bag is vented above the waterline over a period of several seconds between shots.

(1) Problems Addressed.* The problems addressed by this concept are

Finding and identifying thin beds (Problem 8).
Improved seismic sources (Problem 10).

(2) Background. Bubble oscillation which causes serious deterioration of seismic signals occurs for most marine impulsive seismic sources, such as dynamite, air guns, gas guns, and sparkers. The oscillation follows the Rayleigh-Willis relation in which the period has a $1/3$ power dependence on the total potential energy of the source. Also, there are minor problems due to the after-flow effect in which underpressures are induced immediately after the main pulse caused by the tangential expansion of the water surrounding the bubble.

Various damping techniques are used to remedy the bubble oscillation problem. They have partial success at the cost of adding system complexity or reducing signal strength. Examples are the air gun array, second pulse technique (Seismojet), perforated enclosure (Flexotir), and waveshape kit (WSK) to throttle the bubble. Injection into the sea of steam, which condenses without leaving a bubble, is also used (Vaporchoc), as are implosion and displacement sources but not as commonly as other sources mentioned.

(3) Energy and Amplitude Considerations. The pressure in a gas bubble is a very rapidly decreasing function of the bubble dimension due to the volume expansion and the energy dissipation to generate the seismic pulse. For a typical source such as 300 in.³ compressed air at 2000 psi, the pressure after a diameter expansion ratio of 3 is about $1/30$ of the initial pressure. The pressure pulse generated after this point is insignificant for seismic mapping and can be cut off by the bag envelope.

The residual pressure on the order of 10^2 to 10^3 psi can be used to resist the collapse of the bag. From simple stress calculation, a metal

*The problem numbers correspond to those in Appendix D where each problem is discussed.

cloth bag with a plastic inner liner can be used to contain this pressure. For high-strength metal, a thickness of about 0.1 inch is needed to contain 2000 psi with a diameter of a few feet.*

(4) Heat Transfer Estimation. The change of the residual pressure in a fully deployed bag is solely dependent upon the heat transfer. For a gas-explosion actuated bag, the gas is warmer than the ambient water; therefore, the residual pressure decreases due to the cooling. The time constant can be estimated as

$$t \approx \frac{r^2}{k}$$

where r is the radius of the bag and k is the diffusivity of the gas; typically, $k \approx 0.2$ cgs units. Therefore, the relaxation time constant is on the order of 10 seconds and the corresponding frequency about 0.1 Hz which is much lower than those used in seismic mapping.

For sources operated by compressed gas, the final gas temperature is lower than that of the water due to the expansion. The residual pressure will increase with the time, resisting collapse.

(5) The Design of a Gas-Driven Bag Source. Almost every gas- or air-driven seismic source for marine exploration can be converted to this design. Instead of directly releasing the high-pressure gas into the water, the gas is utilized to deploy a metal-cloth bag. To increase the pulse amplitude, a pressurized reservoir volume as large or larger than the bag should be provided.** A gas-relief mechanism is needed to permit throttled venting of the gas to the atmosphere over a period of a few seconds to depressurize and refold the bag.

(6) Characteristics of Gas-Driven Bag Source. These characteristics are

Single pulse, no oscillations	4000 to 8000 kJ
Internal energy	>50%
Energy coupling efficiency	2000 psi
Initial gas reservoir pressure	200 to 1000 psi depending upon the gas reservoir volume
Final pressure	3 ms
Pressure pulse rise time	< 0.1 ms
Pressure pulse fall time	< 1%
Ripple at full deployment	

*The ability of the bag to constrain the expansion at substantial pressures distinguishes this concept from the sleeve exploder (Aquapulse).

**It may be possible to increase the amount of gas per bubble and hence the energy. Design of the gas release mechanism which involves movement of large mechanical parts tends to limit the amount of gas released into an unconstrained bubble. The bag may make it possible to simplify the release mechanism.

Repetition rate	Can reach a rate of 1 shot every 6 seconds
Bag diameter	3 to 4 feet
Bag volume displacement	400 to 950 liters
Life of the bag	(depends upon the design) Expected to be >10,000 operations
Cost of the system	Comparable to an air-gun (the cost of a reusable bag is small as compared to the gun)

(7) Advantages in Exploration.

(a) Advantage. The advantage is elimination of bubble-oscillation problems in acquisition of marine seismic data.

(b) Effect on Prospect Generation and Discovery Rate. The effect is uncertain at this time. The difficulty lies in assessing how many structures have been overlooked or misinterpreted as a result of bubble oscillation.

(c) Economic Impact and Relative Value to Industry. These factors are

- 1) Impact uncertain at this time.
- 2) Method will be better than others that are being used to filter or damp bubble oscillations.
- 3) Would require extensive demonstration.

(8) Aerospace Contribution. The aerospace contribution to the concept includes technology in handling high pressure, flowing, hot and cold gases, and in deployable structures, and a background expertise in fluid and solid mechanics.

d) Concept 5: Oscillation-Free Implosion Source

Statement of Concept: For a seismic source in deep water or in a borehole, a hollow glass ball is released with an attached weight. At the desired depth, a small explosive shaped charge attached to the ball is detonated. As the ball breaks, the resulting implosion produces the seismic signal.

(1) Problems Addressed.* The problems addressed by this concept are

Finding and identifying thin beds (Problem 8).
Improved seismic sources (Problem 10).
Multiple reflections from sea bottom and surface (Problem 17).

(2) Background and Approach. The desirability of an oscillation-source for marine work was covered a few pages earlier. This subsection describes another approach to the problem, applicable when the water is deep. In deep water, there may be an advantage in having the source at some depth below the surface. Also, a seismic source operating in a borehole may sometimes be needed; see Topic B (Section III-B).

There are two severe problems in using conventional marine seismic sources for below the water surface:

- 1) The period of bubble oscillation becomes shorter, the deeper the source.** Interference from the bubble oscillation at a depth of 500 m can completely cover the initial pulse signature.
- 2) The amplitude of the initial pulse decreases as the source depth increases because the internal energy depends upon the pressure difference between the gas bubble prior to the expansion and the ambient pressure.

*The problem numbers correspond to those in Appendix D where each problem is discussed.

**According to the Rayleigh-Willis formula, the period

$$T = \frac{0.000209(\kappa Q)^{1/3}}{(d + 33)^{5/6}}$$

where Q is the total internal energy

d is the depth in feet

K is a proportional constant $\approx 10^{10}$ when Q is expressed in kilojoules

The suggested concept uses the implosion of an empty vessel in deep water to produce the pressure signal. Unlike the explosion case, the pressure signal is oscillation free; also the peak pressure amplitude increases with the depth because the internal energy in this case depends solely on the magnitude of the external pressure supplied by the water.

Previous work (Ref. 7) has demonstrated that an implosive source consisting of a 1 atm gas-filled 3-inch diameter glass ball produces a good signature from a depth of 6000 feet. However, reproducibility is poor due to the inefficient means of initiating the implosion. A mechanical pin crushing technique was used. It is proposed to use, instead, a miniature linear shaped charge initiated by an electrical detonator. This technique has been widely used as a separation and cutting mechanism in aerospace applications.

(3) Proposed Characteristics. These characteristics are

Gas pressure in the sphere	1 atm
Container material	glass on synthetic polymer
Thickness of the glass wall	0.200 in.
Diameter of the sphere	1 ft*
Implosion technique	miniature linear shaped charge
Initiation	electrical detonator
Initiation signal	via wire or acoustic signal from ship or by pressure actuated switch
Initiation power	via wire from ship or by expendable battery
Energy	1300 kJ at 500-m depth* (varies linearly with depth)
Energy coupling efficiency	>80%
Pulse amplitude	= pressure of the water
Pulse duration	≤ 1 ms
Descent technique	weighted net around the sphere
Data on implosion position	from hydrophones
Cost	less than \$15 apiece

The spheres (Figure 3-A-3) could either be prefabricated or, to save storage space, assembled from halves aboard ship. With ship-board assembly, an O-ring would provide a seal between the halves.

(4) Advantages in Exploration.

(a) Advantages. The advantages include

- 1) Provides a good deep source to acquire reliable seismic data for the subsurface in deep (>500 feet) water areas of future interest.
- 2) Provides a good borehole seismic source, useable in cased or uncased holes without hazard to hole or casing.

*Less for use in borehole

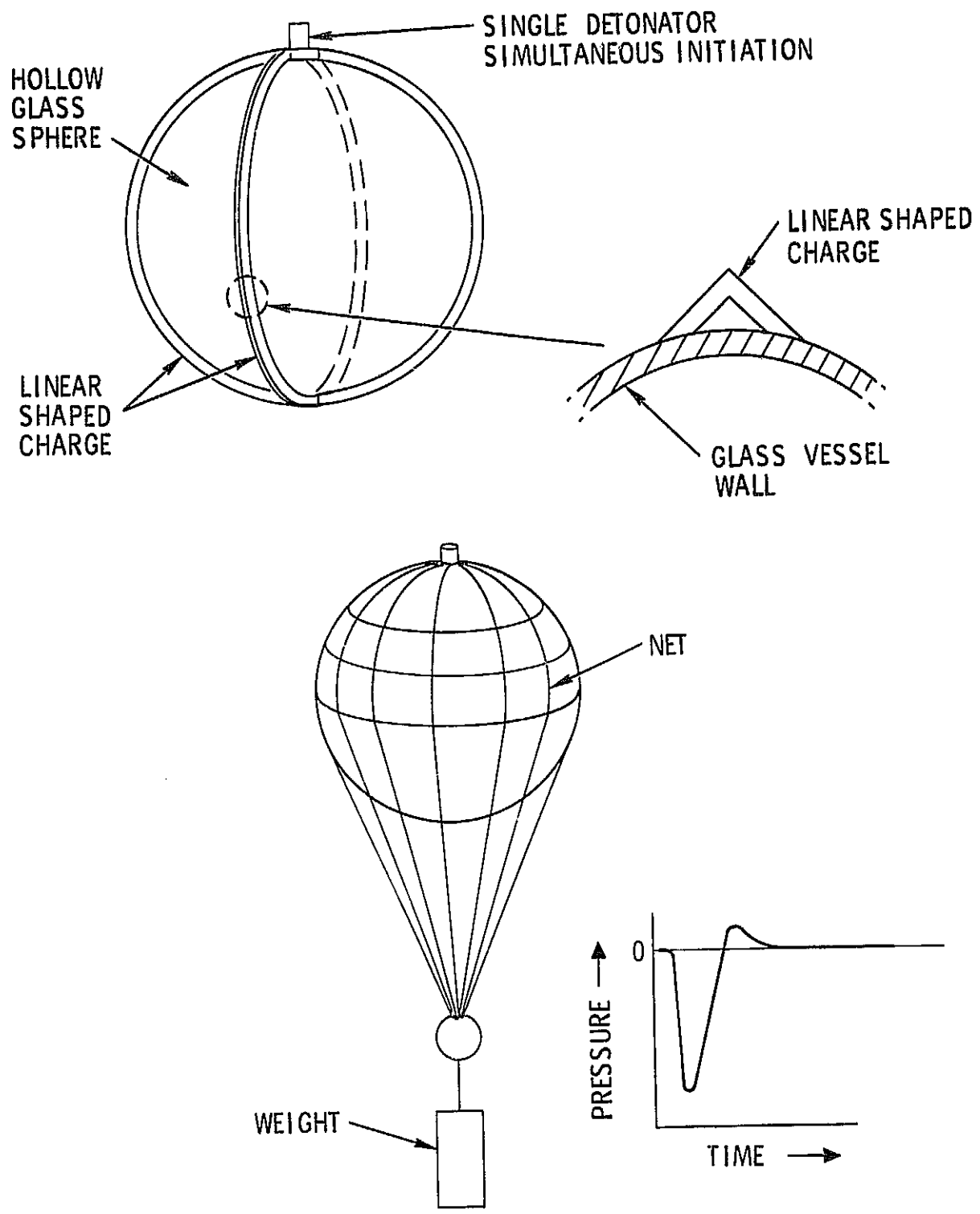


Figure 3-A-3. Oscillation-Free Implosion Source for Deep-Water or Borehole Use

(b) Points Needing Further Attention.

- 1) Adequacy of control and knowledge of position and depth at time of implosion.
- 2) Getting sphere down quickly enough.
- 3) Possible prior invention. One company at least, is offering pre-weakened glass spheres (up to 17 inches in diameter) for use as seismic sources. Their method of initiating the implosion appears to be different and may not give as reproducible results.

(c) Economic Impact and Relative Value to Industry.

These factors include

- 1) May decrease the risk of deep-water prospecting where exploration costs are very high.
- 2) Temperature variations in deep water pose problems in sound-wave propagation and signal return when near-surface sources are used. There is considerable disagreement however, as to the value of a deep source for seismic prospecting in deep water.
- 3) Perhaps of use under arctic sea-ice.
- 4) Cost appears too high for extensive use.

(d) Effect on Prospect Generation and Discovery Rate.

Interest in deep-water exploration has diminished over the past 2 to 3 years. Reasons include lower returns on investments, lack of capital worldwide, lack of technology required for operational drilling in deep water, and the relatively high risks that must be assumed in exploration in these areas. Industry has little definitive information on (1) reliability of seismic data (reverberations) and (2) presence of source rocks. This recent lack of interest will not be permanent. Technical improvements in the areas of seismic data acquisition will lower the risks and stimulate interest for industry exploration activity. If, as an example, we assume that the same basin types extend off shore in southern California as are present on shore, then there is high potential that major oil accumulations are present in basins covered by >500 feet of water. Accumulations of the 100 to 500 x 10⁶ bbl size could be expected. If one 200 x 10⁶ bbl field is found, its worth is >\$2 billion and can add valuable reserves to the U.S. total reserve status. Equal sized accumulations may also be anticipated in the Gulf of Mexico, east coast offshore U.S., and arctic sea offshore Alaska.

(5) Aerospace Contribution. Background in use of shaped charges for mechanical applications and in fluid mechanics, solid mechanics, acoustics, and materials.

(6) Recommendation. If industry interest is sufficient and the idea is new, initiate a development and demonstration program.

e. Concept 6: Aerial Seismic Survey

Statement of Concept: Land seismic survey from an aircraft with no ground crews in area. Aircraft deploys geophone strings and sources, surveys their positions, fires sources, records data telemetered via radio, then retrieves geophones and telemetry packages for reuse.

(1) Problem Addressed.* The problem addressed by this concept is:

Seismic surveys from moving vehicle on land (Problem 21).

(2) Background. Seismic surveys are expensive and time consuming. This is especially true in adverse conditions such as swamps and arctic regions. A reduction in cost and time without compromising the quality of the obtained data, can allow more area to be explored for each dollar allocated to exploration thus increasing the probability of locating oil.

(3) Approach. The approach used was to find a method of placing and retrieving a standard or near-standard seismic system that would be able to operate in difficult areas and operate more rapidly. A literature review provided data on seismic systems and on the Foster recovery system used by the Air Force and Coast Guard for various pickup operations.** The following is the result of examination of these techniques.

(4) Findings. An airborne system for conducting seismic surveys appears technically feasible. Linear geophone arrays with a limited number of channels would be air-dropped. Limited 2-dimensional arrays could be placed by multiple passes.

*Problem number corresponds to that in Appendix D where the problem is discussed.

**The Foster Skyhook is a system for making aerial pickups of packages up to 500 pounds from the earth's surface or from the air. The system uses a clamp that is mounted on the nose of a recovery aircraft which grabs and holds a cable attached to the recovery package. Large tines on each side of the clamp guide the cable to the clamp as the plane flies into it. The cable is wound on a drum on the recovery package and unreels when it is lifted by a balloon that is inflated prior to recovery. The balloon lifts the cable to the plane's altitude, the plane flies into the cable, locking it in the clamp, and the package is pulled up behind the plane. Crew members in the rear of the plane hook the cable and pull the package aboard.

An aerodynamic housing would be built around each geophone to assure proper orientation at landing. Spikes attached to each geophone would stick in soft ground thus providing proper coupling, and flat plates would be provided for hard ground. To avoid obtaining signals from nonvertical geophones (those that may have tipped over because of hitting rocks), a switch could be incorporated to permit signals only from properly aligned geophones to be incorporated in the data stream. Alternatively, gimballed geophones could be used. Sources (probably either shaped explosive charges or a specially designed packet of solid propellant) would be dropped separately with radio receivers attached for the firing signal. A data package attached to the geophone cable would telemeter data to the aircraft (see Figure 3-A-4). Stereo photographs from the plane would locate phones and sources for data reduction. After use, geophones, cables, data package, and perhaps receivers would be picked up by the plane using proven techniques.

Obtaining the quality needed for detailed surveys would be difficult. Operations are feasible over most types of terrain except jungles and heavily forested terrain. Marine operations would probably be more costly with the proposed method than with current techniques. The technique appears to have most promise for a preliminary reconnaissance in remote and difficult terrain to ascertain whether the structure warrants the more detailed mapping that can be provided by a ground crew. More details are provided in Appendix F.

It is very difficult to estimate the time that would be required to deploy and retrieve the packages. The time is a strong function of the skill and experience of the crew. If three* geophone packages are used per mile, an experienced crew should be able to deploy the entire array in one pass. The sources would be dropped on the second pass and detonated on the third. A single pass would be needed to pick up each package. Deployment, firing and recording should take no more than 30 minutes per mile. Recovery should take between 1/2 and 2 hours. Allowing an hour overhead time (orientation, etc.) and 45 minutes transit time gives an estimated maximum of 5 hours for 1 mile and 7-1/2 hours for 2 miles. This equates to about \$4500 and \$3375 mile with a fixed-wing aircraft. It is possible that a heavy-lift helicopter could be used in place of a fixed-wing aircraft.

The environmental impact should be less than that of ground parties since the equipment will be placed and recovered without trucks running over the scenery. The danger of dropping a package on a structure or animal is negligible at the low altitude the plane will be flying.

(5) Advantages and Disadvantages to Exploration

(a) Advantages. This concept may provide reduction of cost and time for reconnaissance seismic survey in remote land areas and those where ground operations are very difficult.

*Assumes 150-foot spacing between geophone groups, 12 groups per package. A more practical design may be 6 groups per package, 6 packages per mile.

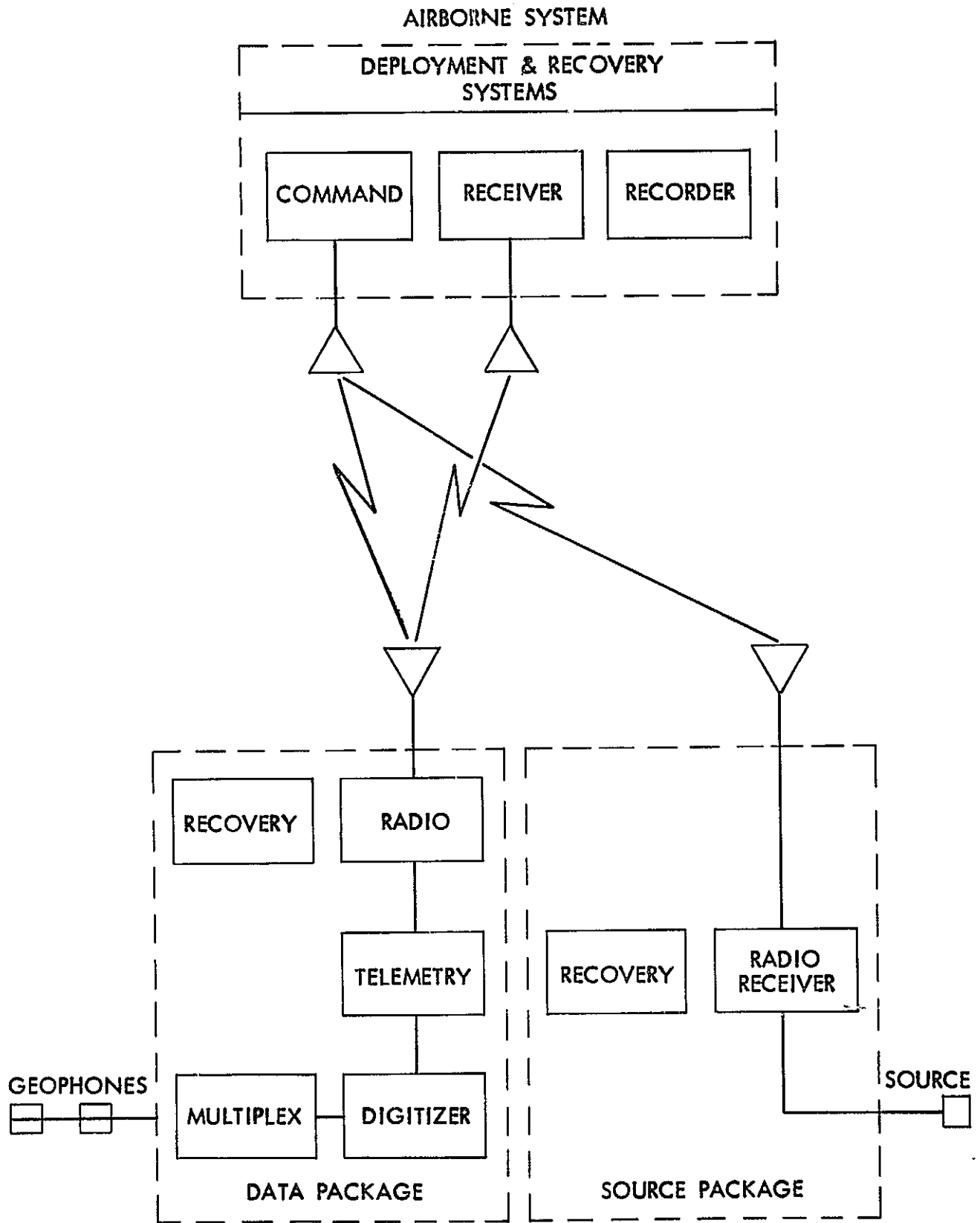


Figure 3-A-4. Aerial Seismic-Survey System

(b) Disadvantages. The disadvantages include

- 1) Assuming all components worked as proposed, there are few areas that may prove to be applicable. The arctic tundra is one such area. Others that would be of lowest risk are outside the U.S. - Chad, Niger, Libya, Egypt. These are desert areas without any appreciable vegetation.
- 2) Probably not practical to provide detailed high-quality survey with large arrays by this method.

(c) Points Needing Further Attention. These points include:

- 1) Ability to deploy and retrieve equipment over 2 to 5 miles of a seismic line in a controlled manner.
- 2) Ability to emplace geophones with proper coupling to the ground.
- 3) Minimum fly-off distance for the plane to avoid pickup of its acoustic noise by the geophones.

(d) Economic Impact and Relative Value to Industry. The high cost of the aircraft and relatively limited use negates the a major economic impact can be realized from the proposed system. The special conditions necessary for usage also negate any great value as an exploration tool.

(e) Effect on Prospect Generation and Discovery Rate. At present, there are too many variables concerning the utility of the system to give definitive answers to the usefulness of the system.

(f) Alternative concepts. One suggested alternative is to retrieve the data package but not the geophones or to not retrieve either. This is said to have been tried. The trade-off is the cost of the equipment not retrieved vs. development and use of retrievable equipment.

Another alternative is to transport a crew with equipment by helicopter. The crew would then deploy and recover the equipment. The trade-offs are on cost, on the difficulty of getting around on the ground, on crew safety, and on environmental damage from ground operations.

(6) Aerospace Contribution. Aerospace contributions to the concept include the technology of aircraft themselves, techniques of deployment and retrieval by aircraft, aerodynamic background to control orientation and spacing of geophones as they descend, and telemetry technology.

(7) Recommendation. If industry interest is sufficient, initiate a test program to verify the emplacement concepts.

f. Concept 7: Telemetry of Seismic Data from Ship to Computing Center

Statement of Concept: Provide a satellite communications system specifically for transmission of geophysical data from survey ships or vans to their respective computing centers.

- (1) Problems Addressed.* The problems addressed by this concept are Seismic data transmission from survey ship to home office (Problem 13).
Faster seismic-processing turnaround (Problem 15).

(2) Background. Seismic data, from marine or land exploration, are now digitized and recorded on magnetic tape at the point of data acquisition. Tapes may be picked up daily or weekly or in some cases dropped off in a port after a week or two of survey, then transported to data-processing centers for analysis. Data-processing turnaround (time from data acquisition to completion of analysis) runs from a few days to a month. This long turnaround is often costly due to data-acquisition equipment problems not immediately identified or promising results requiring more detailed survey work, necessitating a return to the area by the ship or land party, and even in some cases, the survey party waiting for analysis results, prior to moving to other survey areas.

The data-turnaround problem is apparently most critical for marine surveys but identification of cost-effective methods of real-time data transmission to data analysis centers for land surveys is also desired for the same reasons.

In summation, the problem to be addressed is to identify and detail techniques for real-time data transmission from data acquisition sites on land or water on or near North America to data analysis centers within the continental United States.

- (3) Approach. The basic approach was to look at requirements, existing systems, and potential state-of-the-art systems and obtain rough estimates of their capabilities and costs.

The only existing operational satellite system for supporting mobile operations is the Maritime Communications Satellite, Marisat, owned by Comsat General Corp.

*Problem numbers correspond to those in Appendix D where each problem is discussed.

(4) Results. A more detailed analysis is given in Appendix G. Briefly, direct ship-to-shore data links will be short range and provide only low-data rates. Marisat will provide 2 channels somewhat limited in bandwidth (240 kb/s) from areas east of the U.S. and 2 from areas west. Cost will be \$300-500/hour for short time use; less if a channel is permanently leased.

A communication satellite system dedicated to seismic data transmission could be established for \$100 million or less. This would provide 400 kb/s transmission links for 16 ships at a time east and 16 ships west of the U.S. Assuming continuous transmission the cost for each ship would be \$180/hour, paying off the investment in 2 years.

A similar system could be developed for land use if a satellite land-mobile frequency allocation were obtained. Land seismic work is, however, amenable to data storage during firings with subsequent playback at low-data rates.

Absolute security of the data against a determined competitor is difficult to assure. However, the system could be designed so that obtaining and decoding the data illegitimately would cost more than to repeat the survey.

(5) Advantages and Disadvantages in Exploration

(a) Advantages. Advantages include

- 1) Provides immediate return of data to processing center as fast as it is acquired, thus decreasing turnaround.
- 2) Eliminates massive storage of tapes aboard ship.
- 3) Permits elimination of tape recording aboard ship, if desired.

(b) Disadvantage. This concept would probably increase cost of returning data.

(c) Point Needing Further Attention. Potential customers will want a high degree of assurance that competitors cannot intercept and decode their data at reasonable expense.

(6) Aerospace Contribution. Aerospace contributions to this concept include the satellite and satellite-communications technology, telemetry technology, and a familiarity with coding technology. Considerable work on coding technology has been done by aerospace organizations, and it is applied in providing security for radio commands to spacecraft.

(7) Recommendations. If a dedicated satellite system appears attractive to the potential users, a more thorough examination of it should be made. The current Marisat system could be used to demonstrate concepts. A new satellite system could easily be designed, fabricated and put into operation within 5 years.

g. Evaluation of Data Acquisition and Transmission Concepts

The primary items that appear to have the greatest potential of the proposals considered under this category include

- 1) Higher energy seismic sources that have the potential of generating higher frequency signals with greater depth of penetration on shore.

This has the advantage of making feasible the detection of reservoir beds <50-feet thick which can contain large amounts of petroleum and are presently are not detectable. Also with the same sources, there is a high probability that other physical parameters can be determined.

- 2) Transmission of marine seismic data to data-processing centers by dedicated communication satellites.
- 3) Seismic data acquisition in marine areas without the problems associated with bubble oscillations.

5. Data-Processing Improvements

Industry personnel are aware that certain portions of the seismic information is lost during processing and cannot be retrieved at a later time for examination. The focus in the past has been on utilizing information to determine the structural and stratigraphic aspects of the subsurface and, more recently, on attempts to better detect fluids by better use of the amplitude information. Recent computer hardware developments will greatly improve processing capabilities. These capabilities should provide incentives to utilize other data that will enable explorationists to determine physical parameters of the sediments. Other identified needs include resolution of thinner beds and faster turnaround. Low costs are always desired.

a. Concept 8: Low-Cost Seismic Data Processing

Statement of Concept: Seismic-processing system embodying:
(1) High-density tape recording to reduce tape volume,
(2) use of charge-coupled devices in central processing to provide more extensive parallel processing, (3) use of charge-coupled devices in field system to permit rapid and extensive field processing at low cost, and (4) preservation of quadrature as well as real components of signal.

(1) Problems Addressed.* The problems addressed by this concept are

Finding and identifying thin beds (Problem 8).
Improved detection of stratigraphic traps (Problem 9).
Seismic data transmission from survey ship to home office (Problem 13).
Faster seismic-processing turnaround (Problem 15).
Porosity and permeability determinations from seismic data (Problem 19).

(2) Background. Current seismic data-processing techniques and practices reflect a potential need for improvement. Although an extremely sophisticated processing capability has been demonstrated by industry using advanced digital computing technology, the results are limited by cost and data content considerations. It is frequently impractical from a cost standpoint to process the majority of seismic data to the level desired by analysts. Also, many seismic arrays receive a signal for which important information is either lost or destroyed during processing. Cost effectivity is influenced by such factors as processing turnaround time, data volume, and processor complexity. Data content is influenced by such factors as energy source signature and ability to effect corrections.

Significant problems of current data processing include

a) Processing Turnaround Time - Only limited processing is normally accomplished in the field. Tests are usually completed and equipment removed from the field before the data are processed and analyzed. Therefore, it is often not possible to use results in near-real time to change system parameters to execute a testing sequence.

*The problem numbers correspond to those in Appendix D where each problem is discussed.

b) Data Volume - Since raw seismic data is being gathered in increasingly greater quantities, the cost of tape including the handling thereof is rapidly becoming prohibitive. Data are generally stored on computer compatible tapes and transferred to central-processing facilities for processing and analysis.

c) Processing Cost - The complexity associated with present processing techniques and practices make cost-effective processing increasingly more difficult. Processing now represents a major part of the total cost of seismic exploration.

d) Energy Source Signature - Many seismic systems do not provide a signal of known phase characteristics or signature. Moreover, it is difficult to correct the source signature for selective attenuation of high frequencies before using it for correlation.

e) Loss of Phase Information - It is generally assumed that all reflection coefficients are real rather than complex. Therefore, phase information which could be a valuable tool for data analysis and interpretation is frequently lost.

(3) Design Approach. To help reduce the noted problems, an approach including the following elements was considered:

- 1) The raw seismic data should be stored on high-density magnetic tape so that the number of reels of tape can be greatly reduced while still retaining all data for subsequent processing and analysis as required.
- 2) Some near-real time processing of data should be accomplished in the field to a level that the data volume required for subsequent processing at a central facility is significantly reduced.
- 3) The source signature should be known or measured so that compression techniques may be employed to achieve an impulse response function.
- 4) Cross-correlation, using both real and quadrature components, should be performed to achieve the maximum signal/noise ratio and information preservation possible.

- 5) Charge-Coupled Device (CCD) processing technology* should be applied so that the required processor complexity and cost can be significantly reduced, and desired processing functions and corrections can be effected in a much faster turnaround time.

A possible design is discussed in Appendix H.

(4) Results. The potential operational benefits to be realized from a successful development of the seismic data-processing system considered are listed below and shown in Table 3-A-1:

- 1) 90% reduction in the required computer-compatible tapes to be generated for processing at a central-processing facility.
- 2) 50% reduction in required processing operations and time at a central-processing facility.
- 3) Immediate availability of high-quality processed data in the field for both on-site analysis and transfer to off-site interpreters for analysis.

(5) Costs. Rugged high-density instrumentation-type digital tape recorders (over 250,000 bit/inch²), intended for field use, are commercially available and need not be developed. There would be a cost, estimated as not over \$80,000, for developing a tape formatter to condition the geophone signals for high-density digital recording and integrating the recording system.

The cost of developing the field data-processing system is estimated to be \$2,000,000. Once development is completed, field-processing equipment capable of mounting in a small van for land applications or on board a ship for marine applications could be procured for a unit cost of approximately \$200,000.

The cost of developing a new central-processing system will depend on the capability desired.

Note that the high-density recording, the field-processing system, and the central-processing system could each be developed and used without the

*A charge-coupled device (contained in a single silicon chip) stores many packets of electrons or charge, each proportional to an analog voltage. By controlling voltages applied to transfer electrodes in the device, these packets of charge can be transferred virtually intact from potential-well to potential-well (Figure 3-A-4). The charge packets can also be read, summed, multiplied, weighted, correlated, and manipulated in other ways. As compared to a typical digital device, a CCD has the advantages that (1) Each packet of charge represents a whole word, perhaps 10 bits, rather than a single bit; i.e., words rather than bits are stored and manipulated and (2) many packets can be transferred and manipulated simultaneously. A typical CCD handles hundreds of packets at once.

Table 3-A-1. Seismic Data-Processing Benefit Summary

Processing Mode	Current Capabilities	Capabilities of Suggested Concept
Recording	<p>1 mile/reel</p> <p>12,000 bpi x 8 tracks 10,000 bpi</p> <p>$10 \times 10^3 \times 2200 \times 12$ $\approx 3 \times 10^8$ bits/reel.</p>	<p>100 miles/reel</p> <p>25,000 bpi x 10 tracks $\approx 250,000$ bpi</p> <p>$250 \times 10^3 \times 9200 \times 12$ $\approx 3 \times 10^{10}$ bits/reel.</p> <p>(Reduces tape reels required by 2 orders of magnitude. Tapes with present format are not required to process data in field or at station.)</p>
Field Processing	<p>100% of all raw data stored.</p> <p>0-10% of data corrected for statics, NMO, and migration and CDP stacked in the field.</p>	<p>100% of all raw data stored.</p> <p>50-100% of data corrected for statics, NMO, and migration (optional) and CDP stacked in the field. (Provides near real-time turnaround of higher quality data in the field for quick look analysis.)</p>
Central-Facility Processing	<p>100% processing of all raw data to high quality possible but not usually cost effective.</p>	<p>100% processing of all raw data to high quality in a cost-effective manner. (50% reduction in cost for same quantity and quality of processed data. 50% reduction in processing time for same data quality and cost.</p>

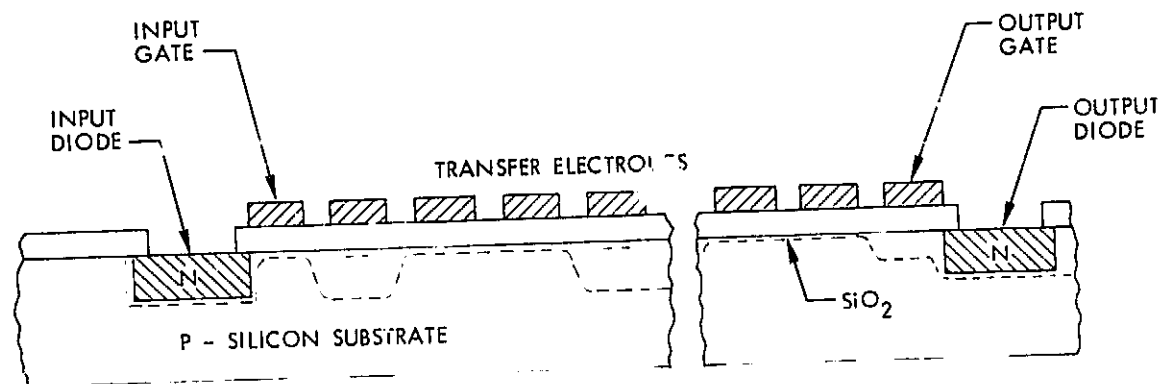


Fig. 3-A-4. Cross Section of Charge-Coupled Device

other two (except that with high-density recording, compatible high-density playback equipment must be used.)

Operating costs for data processing should be less than 50% of present costs.

(6) Advantage to Exploration

(a) Advantages. Some of the advantages are

- 1) Reduced tape usage, transport, and storage.
- 2) Near-real time processing capability in the field.
- 3) Reduced turnaround time at central-processing facilities.
- 4) Possibility of utilizing data that are not presently used because of present limitations of processing capability.

(b) Points Needing Further Attention

- 1) Demonstration of added capability must be made.
- 2) Technology is apparently not widely known. A few petroleum service companies are, however, beginning to offer high-density recording* and at least one is working on a computer system utilizing CCD's.
- 3) If one company (say a survey company) does the field recording and another company (say a data processing company or a petroleum company) processes the data, one of them cannot change the recording method unless the other changes the playback method.
- 4) Industry may be slow to accept concept without convincing documentation of the added capability in order to make a commitment to change.
- 5) A direct comparison of costs is needed.

c. Economic Impact and Relative Value to Industry. Values include

- 1) Following development, the cost of processing will be significantly lowered.
- 2) Added data use may improve ability to find petroleum.
- 3) Will require significant change in strategy and processing arrangements by companies, including the central-processing centers, but benefits should overshadow these required changes.

(7) Findings. Significant improvements in current seismic data-processing capability from both a performance and cost standpoint could be realized within the next 3 years. These improvements would allow achievement of the following benefits:

- 1) Ability to handle larger volumes of seismic data cost-effectively.
- 2) Ability to process more high-quality seismic data in near-real time in the field for the same cost.
- 3) Ability to extract more information from seismic data both in the field and at central-processing facilities for the same cost.

*One of these uses rotating-head video recording equipment (Ref. 8). Fixed-head instrumentation recorders are suggested as being more rugged, more reliable, and requiring less adjustment and maintenance than rotating-head recorders.

- 4) Ability to conduct seismic surveys for a lower overall data-processing cost with comparable data return.
- 5) Likely ability to achieve a higher drilling success ratio for a given cost investment.

A seismic data-processing architecture potentially capable of providing all of these benefits simultaneously appears to be realizable with a modest development effort using state-of-the-art CCD and tape recorder technology.

(8) Aerospace contribution. Aerospace contributions include experience with the technology of field computing equipment using CCDs and high-density tape recording and with handling and recording data at very high rates.

(9) Recommendation. Further evaluation, emphasizing industry views, is recommended. If favorable, requirements should be established and development effort should begin. A 3-year development time is estimated for a field processing system (see Appendix H).

b. Concept 9: High-Resolution Seismic System

Statement of Concept: A 3-dimensional seismic-reflection system providing 15-foot resolution to depths of 10,000 feet. The system includes sources, arrays, and data processing somewhat different from those now generally used.

- (1) Problems Addressed.* The problems addressed by this concept are
Finding and identifying thin beds (Problem 8).
Improved detection of stratigraphic traps (Problem 9).

(2) Background. Discovery of a great deal of oil should be possible if resolution in structural reconstruction by computer is increased to detect bed thicknesses as small as 10-25 feet. Common Depth Point (CDP) section processing as performed today can, at its best, resolve 50-foot structures. Computer-processing methods are in a state of rapid change as the sophistication continues to increase and the volume of data processed also increases. Two summary articles indicate the progressive evolution of the seismic data service industry in the period 1968-74 (Refs. 9 and 10).

(3) Technical Discussion. Aerospace experience in image enhancement has a general transferability to the oil industry. Noise removal, spatial frequency enhancement, geometric and contrast manipulation, pattern extraction algorithms, etc., are all relevant to improving the required data analysis.

Where do present petroleum seismic methods limit resolution? Information concerning depths from 5000 to 30,000 feet is presently considered by the industry to come from seismic signals that contain frequencies which, at best, go up to about 80 Hertz. For sound velocities of, say, 10,000 ft/sec, resolution (at about half a wavelength) would come to

$$R = \frac{1}{2} \left(\frac{10000}{80} \right) \approx 60 \text{ ft.}$$

Though there is severe attenuation of high frequencies by earth absorption (attenuation approximately proportional to frequency), these frequencies are effectively obliterated in CDP processing. This superposition of adjacent seismic records is performed after corrections are made for time differences estimated from velocity calculations. Any errors in velocity cause high-frequency phase interference and signal cancellation.

*The problem numbers correspond to those in Appendix D where each problem is discussed.

In marine surveys, coupling high-frequency sources to water appears feasible with the use of sparker arc sources with frequencies up to 1000 Hertz with low energy for shallow depths and with air guns up to about 100 Hertz at higher amplitude. Multiple small but carefully phased sources would also appear to provide high-frequency sources. Because these are not quite pulse sources, frequencies above 100 Hertz are present but at much lower amplitude (see Figures 3-A-5 and 3-A-6).

WASSP (WIRE ARC SEISMIC SECTION PROFILER) SYSTEM

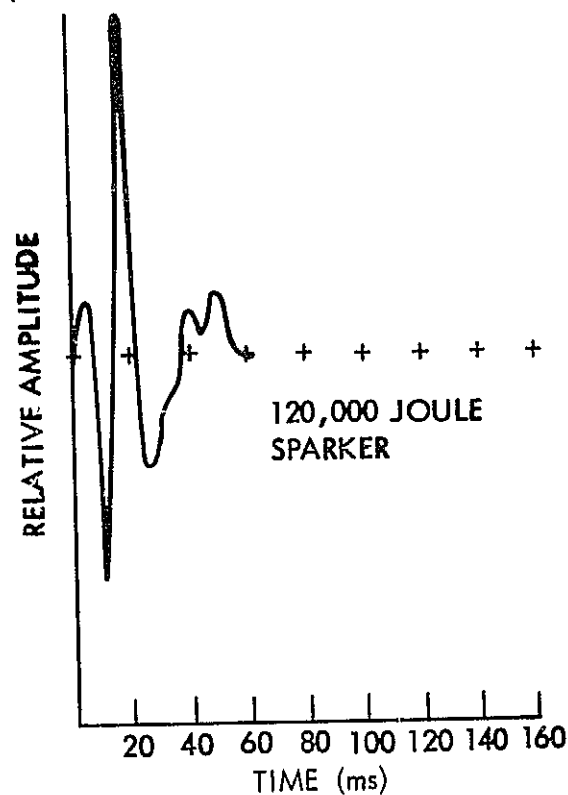


Figure 3-A-5. Signature from a 120,000 Joule Sparker System, (from Ref. 11)

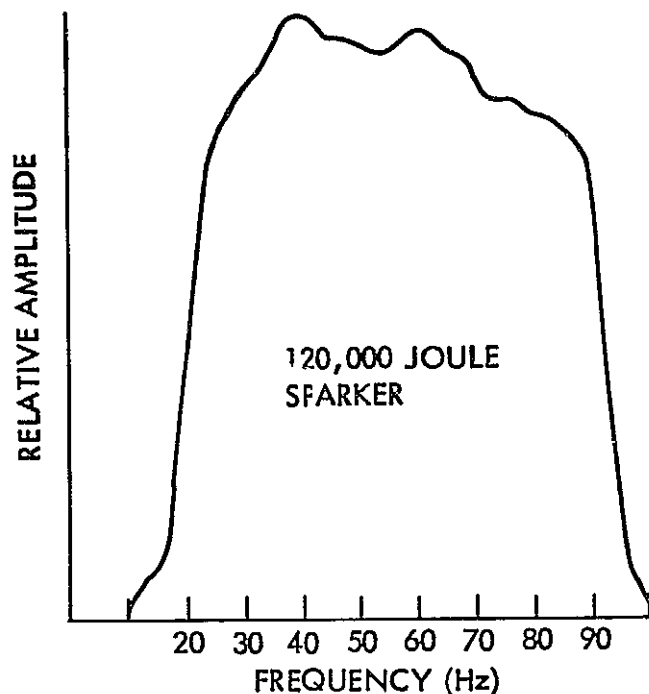


Figure 3-A-6. Amplitude Spectrum of the Signature Shown in Figure 3-A-5, (from Ref. 11)

(4) Characteristics of Proposed Concept

1) Three-dimensional reconstruction to a resolution of about 15 feet at depths of about 10,000 feet (at velocities of about 10,000 ft/s) appears to be a practical goal.

- a) High frequencies must be recovered: $F = \frac{1}{2} \left(\frac{10000}{15} \right) = 300 \text{ Hz}$
- b) Improved sources must be used to supply these frequencies with adequate amplitude.
- c) Velocities must be very carefully measured to avoid phase interference during signal superposition.
- d) CDP stacking prior to migration causes destructive phase interference for tilted surfaces (which are

of interest). Therefore one might consider that migration summation should only be performed on individual traces even though the expense would be greater.

- 2) Utilize related aerospace experience in computer-image processing to convert the real signal to a zero-phase wide-band pulse. (For state of the seismic art, see Ref. 11.)
- 3) Present day configurations for data collection are optimized for 2-D section reconstruction at low (80 Hertz) resolution. The receiver group size should be decreased from its present configuration by at least a factor of 4-5 to avoid high-frequency phase interference.
- 4) Data sampling rates will have to be increased from 2 msec to about 0.6-0.8 msec. Signals should be repeated at more frequent intervals (implying a slow-down of the recording vessel from 6 knots at present to about 2-3 knots).
- 5) Velocity determination and multiple reflection are very closely associated with model comparison so that an automated iteration between model improvement and error reduction would appear justified.

(5) Expected Performance. A resolution of 15 feet at 10,000 ft depth appears to be attainable but only with significant increase in data volume and computer processing.* Among the critical requirements are higher frequency sources. If these can be obtained only with weak amplitude (as is implicit with present use of arcs and air guns), then repeated measurements become necessary.

(6) Cost

Present costs for seismic exploration are divided approximately as follows:

- 1) Data Collection
 - Land \$2000/mi
 - Arctic \$5000/mi
 - Marine \$500/mi
- 2) Data Processing
 - CDP Stacking \$150/mi
 - Migration \$250/mi
 - 3-D Reconstruction 3 x 5 mi \$300,000

*15-foot resolution is now available at shallow depths only, say, to 1500 ft depth. Several companies are working toward this resolution at greater depths. Some of the "high-resolution processing" now offered is limited to 80 or 100 Hz with corresponding resolution limited to 50-60 ft for high-velocity beds.

New costs would include (1) marine cables would have to be rewired to increase the number of channels and (2) small source arrays would have to be synchronized. These costs are minimal, relative to the continuous high data volume and computer time and occur only once per equipment set. The major cost increase arises from handling a data volume jump by a factor of 10 to 100 times the present rates. If computation costs in real time could be cut, then the problem becomes manageable. CCD logic would appear to be a major key in bringing down such computation costs.

Cost for algorithm development and testing with data gathered to this specification is estimated at \$120,000 algorithm development and \$100,000 for new data collection.

(7) Advantage in Exploration. The advantage of this concept is higher resolution (to 15-foot beds).

(8) Disadvantage. The disadvantage of this concept is higher cost.

(9) Points Needing Further Attention. These points include the following:

- 1) Distinguishing gradual transitions from thin layers.
- 2) Handling irregular interfaces.
- 3) Handling scattering.
- 4) Obtaining coupling adequate for high frequencies between source and ground and between geophones and ground.
- 5) Correcting reference signals for selective attenuation of high frequencies.
- 6) Attaining adequately high processing accuracy.
- 7) Methods of best displaying the output.

(10) Economic Impact and Relative Value to Industry. These factors include

- 1) Greater data rates (by 10 to 100 times).
- 2) Higher processing costs (at least 5 times present cost).
- 3) Offshore example:

	<u>Present cost</u>	<u>Predicted cost (excluding added cost of acquisition equipment)</u>
Marine Acquisition	\$500/mile	\$1000/mile (minimum)
Stacking and Migration	\$400/mile	\$4000/mile (minimum) using present computers
Total	<u>\$900/mile</u>	<u>\$5000/mile</u>

- 4) CCD systems would probably be prerequisite to lower costs for an operational system.
- 5) May be useful primarily as a follow-up method in difficult but promising areas.

(11) Effect on Prospect Generation and Discovery Rate. Assuming thin beds can be resolved, the system would have a large effect, but the cost may not warrant the effort.

(12) Aerospace contributions: Aerospace contributions to the concept include possible improved seismic sources (above), experience in computer image enhancement, experience with CCDs in computing applications, and experience in overall design and integration of large systems.

(13) Recommendations. Evaluate the possibility of reducing cost using CCD technology. If industrial interest is sufficient, determine if available elements can meet the criteria and conduct a computer simulation. It should be possible to test the concept with a real system in 3 years.

c. Concept 10: Time-Delay Spectrometry in Seismic-Reflection Surveys

Statement of Concept: Using a swept-frequency source, isolate several recorded frequencies and process each separately. Determine true complex phase shift and amplitude at each frequency.

(1) Problems Addressed.* The problems addressed by this concept are

Finding and identifying thin beds (Problem 8).
Improving detection of stratigraphic traps (Problem 9).
Porosity and permeability determination from seismic data (Problem 19).
Recognizing subsurface petroleum from surface measurements (perhaps) (Problem 20).

(2) Approach. Seismic-reflection data obtained from a chirp (swept frequency) or other modulated signal can be processed utilizing time-delay spectrometry (TDS) (Ref. 12). Basically, TDS preserves phase as well as amplitude data for each frequency separately. The TDS processing is to be done on each signal from a group of geophones, and the "time section" is obtained for a representative frequency. The frequency chosen depends on the signal, the depth of primary interest, and the required thickness resolution. Any "stacking" similar to common depth point stacking can be done after the "time sections" are obtained for the given frequency. Appendix I describes the TDS method.

With conventional processing, it is difficult to identify a bed thinner than a wavelength and to determine its thickness because reflections from the top and bottom of the bed interfere destructively. With TDS, a phase shift is displayed proportional to the bed thickness and detectable even for beds much thinner than the wavelength (see Appendix I).

(3) Results. Time-delay processing can be applied to seismic data from a chirp signal. The generated waveform and of all phase-shifts in the generating, receiving, and data-handling equipment must be known accurately; this may require some improvements over present hardware. The data are processed to yield the phase change of each frequency at reflecting boundaries. It is believed that phase changes are sensitive indicators of multiple reflections from thin beds which are not brought out in conventional processing.

*The problem numbers correspond to those in Appendix D where each problem is discussed.

(4) Cost. TDS will be somewhat more expensive than conventional seismic processing, perhaps twice as expensive. (A typical figure for present data processing is \$150/mile if migration is not done.)

(5) Advantages to Exploration.

a) Advantages. The advantages are

- 1) Potential to discriminate thin beds.
- 2) Potential to determine lithology.
- 3) Possibility of determining density.
- 4) Possibility of determining porosity.
- 5) Possibility of determining fluid saturation.

b) Points Needing Further Attention

- 1) Effects of noise.
- 2) Correcting reference signals for selective attenuation of high frequencies.
- 3) Methods of best displaying the output.

c) Economic Impact and Relative Value to Industry. These factors are

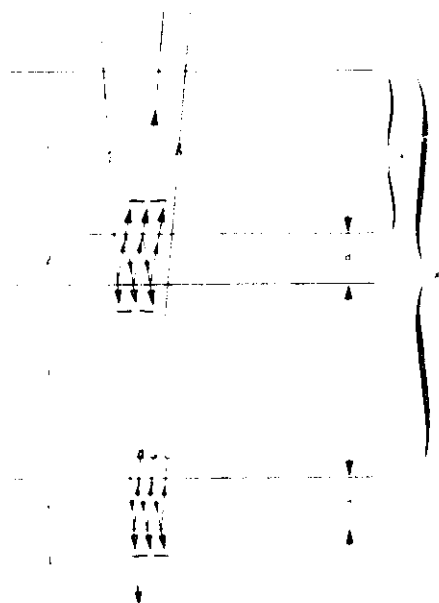
- 1) Will require added software development.
- 2) Will probably not require added or special hardware.
- 3) Will utilize seismic data that are presently lost during initial processing such as phase data.
- 4) Will require added processing time on present computer systems, perhaps as much as twice present usage.
- 5) Demonstration will be needed to convince most potential users of worth.
- 6) May be useful primarily as a follow-up method in difficult but promising areas.
- 7) Benefits should greatly exceed the costs of added processing if the quantities mentioned above can be determined.

(7) Effect on Prospect Generation and Discovery Rate. Could have very significant impact to exploration if items listed under "Advantages" can be determined. If these quantities could be correctly identified 50% of the time in the subsurface from seismic data, the benefits would be very

significant to exploration. The elimination of one dry hole off shore will save from \$1 to \$5 million. The lowering of the present discovery-to-dry-hole ratio from one discovery for six dry holes of wildcat drilling (Ref. 13) to one discovery for every five dry holes of wildcat drilling would significantly reduce the exploration costs by industry. Most of the cost of exploration is in drilling. The data utilization that time-delay spectrometry can potentially offer should increase the discovery-to-dry-hole rate.

(8) Aerospace contribution. The aerospace contribution to the concept includes experience with the technology of utilizing CCDs in data processing.

(9) Recommendations. Analyze the following problem as a computer model by conventional and TDS methods to compare the two.



Two layers of medium (2), each of thickness d , occur at depths x_1 and x_2 as shown. A chirp signal is reflected at the top and bottom surfaces of each layer. The reflected signal is constructed taking into account multiple reflections in (2) but ignoring the interferences in (1) between the layers at $x_1 + d$ and x_2 . This signal is now processed by the conventional cross-correlation method and also by TDS to plot the recovered signal indicating the reflection coefficient. Noise should be added to the reflected signal to see how it affects the comparison and how the thickness information is recovered. If result is promising, further development should be considered.

d. Evaluation of Data-Processing Concepts

The primary items that appear to have the greatest potential among the data-processing concepts include

- 1) The potential capability to discriminate lithology and determine physical parameters including porosity, fluid contact, and compaction and to resolve thinner beds is of utmost importance to exploration. This should be a very high priority.

- 2) Processing capability that will greatly reduce tape usage allows the explorationist to have data available to interpret very soon (<24 hours) after acquisition and significantly reduce costs. This should be evaluated by industry as soon as practical.
- 3) Three-dimensional processing and display is presently available at high cost to most of industry. If it can be coupled with better resolution at a more reasonable cost, it may be of additional interest to explorationists. Changing the seismic spread configuration to acquire higher density and subsequent processing of the data will add significantly to cost and may not be practical unless high-frequency data can be obtained from greater depth and processing costs can be reduced by the use of CCDs.

6. Summary and Conclusions on Seismic-Reflection Systems

When the concepts suggested for improving reflection seismography are considered together as parts of the same system, it is clear that there is an excellent potential for making an impact technically and economically on petroleum exploration.

Listed in summary form, these advantages include

- 1) Potential seismic sources capable of frequency sweep to at least 200 Hz with penetration to 1.75 km.
- 2) Great reduction in tape usage.
- 3) Potential processing capability to process the data within <24-hour period on an operational basis and to reduce costs for a given processing job.
- 4) Potential capability of detecting stratigraphic units 15- to 25-foot thick, differentiating and determining lithology and possibly obtaining information on porosity and fluid content. Higher data rates will need to be considered in the processing, but the potential of the combined added computer ability and added information make the method attractive.

Perhaps the development efforts most justified in each category are

- 1) Seismic Sources development:
 - a) Swept-frequency solid-propellant source testing.
- 2) Data-Processing Development:
 - a) Charge-coupled device (CCD) development.
 - b) Time-delay spectrometry development.

B. TOPIC B: DOWN-HOLE ACOUSTIC TECHNIQUES

1. Introduction

Several problems identified in Task 1 appeared amenable to down-hole acoustic (seismic) techniques.

One of these was the problem of determining stratigraphy and structure in an area where one or more boreholes exist. Though conventional seismic techniques operating from the surface can be used, they have significant limitations. It appeared worth considering possible advantages of placing seismic receivers, sources, or both down-hole and transmitting between two holes or between a hole and points on the surface some horizontal distance away. Related to this is the problem of mapping stratigraphy with occasional holes for control.

Another problem is that of determining fracture patterns around a borehole. Some present techniques (cores and borehole cameras) are limited to the borehole itself. The fracture pattern in cores and borehole walls may not be representative of that away from the hole because drilling the hole changes the local stress pattern and therefore the local fracture pattern. Some logs penetrate further into the rock, but methods presently used are limited in detecting tight fractures. The possibility of developing logs and interpretation methods specifically to find tight fractures, therefore, seemed worth some thought.

Possible approaches utilizing down-hole acoustic methods for these two problems are discussed in the following paragraphs.

2. Concept 11. Down-hole Seismic Tomography

Statement of Concept: Seismic sources in a borehole transmit signals to phone arrays along the surface and in another hole if one is available. Timing and amplitude of the first arrival for each source-phone combination are measured. A key feature is that data are reduced iteratively by techniques of tomography and refraction seismography to give cross-sectional diagrams of velocity and attenuation distribution.

- a. Problem Addressed.* The problem directly addressed by this concept is
Determining stratigraphy far out from borehole (Problem 32).

Addressed indirectly is

Mapping stratigraphy with occasional holes for a control (Problem 3).

b. Background

When a hole (or holes) has been drilled, logs and cores will provide information on stratigraphy and structure at the holes. Information on stratigraphy and structure away from the holes may still be needed. If a hole is dry, where (if anywhere) should another attempt be made? If the hole is producible, where should step-out or development wells be placed? Are there buried stream beds, sandbars, or reefs whose location is critical to further efforts?

Seismic-reflection measurements at the surface can provide useful information in such cases. Important limitations, however, include difficulty in determining proper static corrections in some land areas; highly attenuating, reflecting, or scattering layers overlying those of interest; steeply dipping horizons that reflect little energy back to the seismic array; and loss of high frequencies and therefore of resolution for deep features. Accordingly, if a borehole is available, it may be worthwhile to take advantage of it, placing seismic sources or phones in the hole.

It is not unusual to place a seismic source in a hole with phones at the surface near the top of the hole or vice versa. This is usually done to obtain seismic velocity data to use in seismic surveys from the surface or for lithologic information and does not provide information on stratigraphy or structure away from the hole. It may also be advantageous when seeking

*The problem numbers corresponds to those in Appendix D where each problem is discussed.

detail on deep features to place a source in a hole with the receiving array on the surface to reduce the overall path and hence the attenuation of high frequencies.

c. Method Used for This Study

Information for this portion of the study was gathered primarily through examination of the literature on seismic methods, logging acoustics, and tomography (discussed below), and through contacts with individuals knowledgeable in these fields.

d. Technical Method and Procedure

The down-hole technique on which attention has centered in this study is that of acoustic tomography, aided by seismic refraction methods. Tomography is the reconstruction of an object from a set of its projections. The considered technique involves placing seismic sources in one borehole and phones in another borehole and/or on the surface (see Figure 3-B-1). If only one hole is available, sources may be placed in the hole and phones at various points on the surface or vice versa. Data are processed by summing the time-delays and amplitudes associated with several different seismic paths that intercept a small region (element) of interest (see Figure 3-B-2). The output is the velocity and attenuation characteristic of that element. Appendix J describes the method in more detail.

e. Costs

The estimated operating cost, after development, is \$10,000 - \$15,000 per borehole.

f. Findings

Hole-to-hole and surface-to-hole acoustic (seismic) methods should, be useful for obtaining subsurface information when one or more boreholes exist. The technique of acoustic tomography in combination with seismic refraction methods should indicate velocity and attenuation distribution over the cross-sections examined.*

g. Advantages to Exploration

(1) Advantages. The advantages of this concept are

- 1) Reduces effects of weathered and poorly transmitting layers.

*Downhole seismic receivers and sources have been used in the past but without tomography or with only an elementary form of this technique.

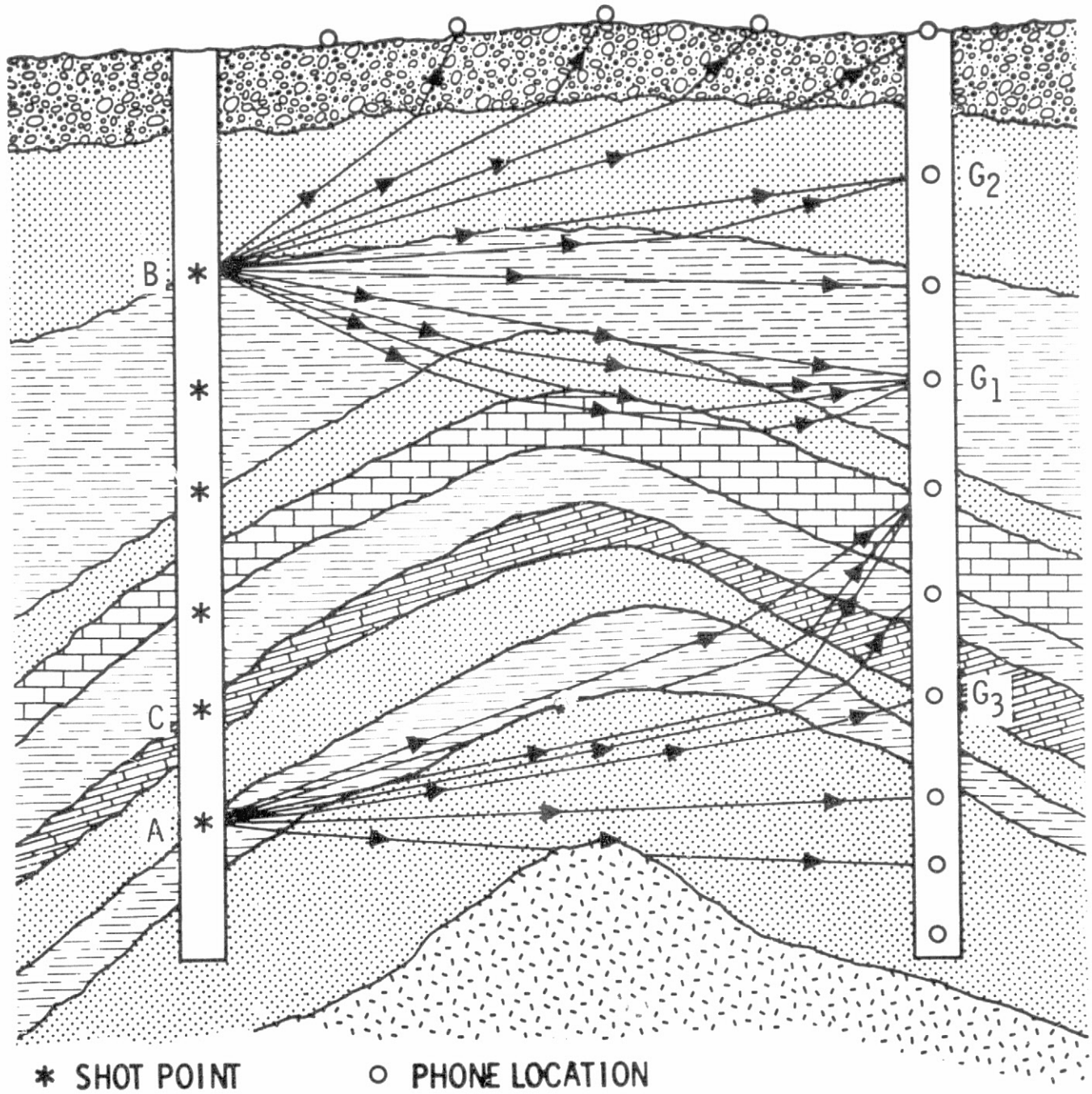


Figure 3-B-1. Application of Down-Hole Acoustic Technique and Tomography for Mapping Geology Between Two Boreholes

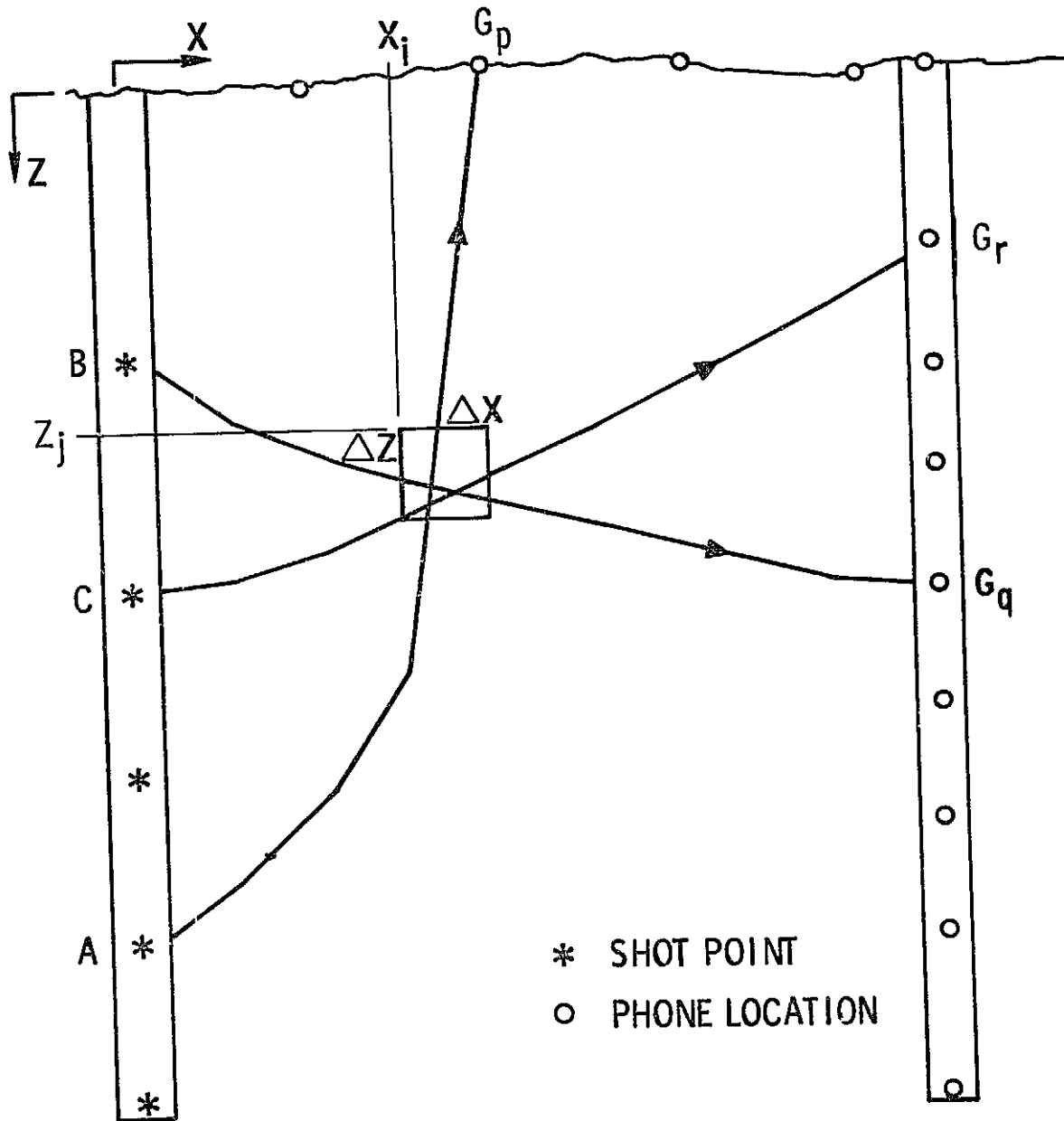


Figure 3-B-2. Processing Diagram for Tomographic Reconstruction

- 2) Reduces total path length and, therefore, total attenuation.
- 3) Provides information on attenuation and velocity of each layer, permitting estimation of physical properties.
- 4) For flooding or other secondary recovery techniques, could provide information on large fractures between boreholes.*

(2) Disadvantages. A disadvantage of this concept is that it requires availability of one or more boreholes.

(3) Points Needing Further Attention. These points are

- 1) Ability of technique to identify reflections including compression-shear interconversions, and to separate reflection coefficients from attenuation within the layers.
- 2) Ability to handle diffraction and scattering.
- 3) Ability to operate in cased holes.

h. Aerospace Contribution

NASA laboratories are familiar with the technology of acoustic tomography and are actively engaged in other applications of it.

i. Recommendation

If industry interest is sufficient, development of the technique should be initiated. A development sequence is outlined in Appendix J.

*This would also be valuable in efforts to recover geothermal energy from hot dry rock by pumping water through fractures between borehole.

3. Concept 12. Acoustic Back Scatter Logging for Fractures

Statement of concept: Send high-frequency acoustic pulses from a transducer in a borehole out into the well. Observe the signal scattered back into the hole to obtain an indication of the frequency, spacing, and orientation of fractures a few meters out into the wall.

a. Problem Addressed*

Improved logging method for detection of fractures (Problem 28).

b. Background

The productivity of a formation is greatly affected by its permeability to fluid flow. Porosity can be determined by radioactivity, acoustic velocity and resistivity logs and by core measurements. To determine the permeability, however, is difficult. The porosity does not uniquely indicate the permeability. For example, in a low-porosity formation, fractures may provide local short-range drainage for the matrix and effective flow paths to the borehole. Even relatively small fractures can increase the total permeability greatly. For example, fractures 1/100-mm wide spaced about 3 cm apart can increase the total permeability from 0.3 md to 3 md. The fractures greatly increase the permeability without contributing much to the porosity of the formation.

Permeability can be measured on core samples. The results do not necessarily represent the permeability of the rock around the borehole, unfortunately. Drilling the hole changes the local stress pattern and hence may change the fracture pattern. Fractures may not intersect the core. Coring is rather expensive. Permeability may also be measured by flow testing the well. This is expensive and time consuming.

Besides their effect on permeability, fractures are also important in evaluating possible well-stimulation methods. Fracture orientation and spacing can be important. Fractures at the wall of the borehole can be found by the televiwer log, provided they are not too "tight." As mentioned above, these fractures may not represent conditions further into the wall. The acoustic amplitude microseismograph can indicate horizontal fractures some distance into the wall. It does not indicate vertical fractures and has other significant limitations (see Appendix K).

*Problem number corresponds to that in Appendix D where the problem is discussed.

c. Method of This Study

This part of the study utilized literature on acoustics, ultrasonic testing of materials, well-logging, and seismic surveying as well as contacts with individuals knowledgeable in these fields.

d. Technical Method and Procedure

The method considered for this application is that of ultrasonic pulse-echo. An electrically driven source in the borehole generates an acoustic pulse. The echo is received in the same borehole. The echo "reverberation" indicates the spacing of inhomogeneities such as fractures and the fracture widths. Also, major fractures within range of the signal give individual discrete echoes. Simple analog data processing would be used. Appendix K describes the method and analyzes it in some detail.

e. Cost Estimate

The cost of operation of the Back Scatter Log (BSL) is estimated by comparing it with the existing sonic logging devices. The Borehole Televiewer costs \$1600 for 500 feet and the Cement Bond Log costs \$650 to \$850 for 2000 feet. The sonic log costs \$1080 per 2000 feet plus additional charges for amplitude logs, integration of transit time, and oscilloscope traces. The Cement Bond Log is similar to BSL, and it may be expected that Back Scatter Logging would cost from \$650 to \$850 per 2000 feet.

f. Findings

Development of a well-log utilizing acoustic backscattering gives promise of providing information on the frequency distribution of fracture spacings and their number density. It should also provide data indicative of permeability. Effective depth of penetration into the wall of the borehole should be of the order of 1 - 10 meters.

g. Advantages to Exploration

(1) Advantages. The advantages are

- 1) Should provide information on spacing and orientation of fractures.
- 2) May provide data indicative of permeability.

(2) Disadvantages. Not absolute. Interpretation primarily by comparison with tests on samples.

(3) Points Needing Further Attention. Determination of whether this concept is new.

h. Aerospace contribution. The aerospace contribution includes experience with the technologies of acoustics and of nondestructive testing of materials.

i. Recommendations. If industry interest is sufficient, initiate laboratory tests and development. Development steps are suggested in Appendix K.

4. Comparison of Proposed Down-Hole Acoustic Techniques

The two concepts outlined above address different problems, use different hardware, different data processing, and different methods of interpretation. They are not alternative approaches to the same problem, and each should be considered independently. In their development stages, they could probably share one laboratory model. Recommendations on each are given above.

C. TOPIC C - IDENTIFICATION OF GEOLOGICAL ANALOGIES

1. Introduction

Despite continued improvements in oil exploration methods, such as seismic techniques and data processing, the risks in the exploration for oil remain high. The decision to drill an exploratory well is based in part on the interpretations of available data which can vary widely. These interpretations are the result of the skills and experience of veteran explorationists. It is from their wealth of past experience that prospects are evaluated. From past success and failure, each individual develops an outlook for the key clues which determine his interpretation. This study considers development of a tool to aid the exploration staff in making its interpretations and decisions.

Discussions with members of the oil exploration industry during this project indicate that improvements in the exploration evaluation process would be valuable. A need was identified to correlate geologic data with drilling results on a more systematic basis. Analysis of past drilling reports in order to correlate discoveries with initial estimates may not be performed consistently. The final report and experience of unsuccessful drilling programs may be confined to a few individuals.

Frequently the decision to develop a new exploration prospect is based on an analogy of the new area to a geologically similar productive oil field. Comparisons are made between the known factors of the producing field, such as source rock, reservoir rock, trap configuration, reservoir size, etc., and the inferred properties of the prospective reservoir based on the available geophysical data. However, the number of analogous fields that can be compared are limited by the data handling and assimilation ability of the exploration staff and management.

Heavy demands are placed on the exploration manager and staff. Large reservoirs are increasingly difficult to find in the heavily surveyed U.S., and the search for large oil pools on the outer continental shelf (OCS) requires the risk of hundreds of millions of dollars for leases and drilling platforms. In some cases, company exploration districts have been expanded, or the exploration staff has been reduced. This reduces the manpower available for each play evaluation, and it reduces the number of staff members with detailed knowledge of the basins within the region. Thus exploration decisions may be made by staff without long-term experience within a region, and exploration managers must make difficult planning and scheduling decisions.

The exploration staff is always able to provide more promising prospects than the budget will permit. The exploration manager must constantly screen and prioritize the new projects available to him. New prospects are developed frequently, one play at a time. The optimistic staff may be viewed as promising "a middle east" with each new prospect. These claims must be evaluated against each other and against the past experience of exploration in the prospect basin or analogous basins. Managers are seeking guidance in looking for new areas. For corporate planning purposes, means of evaluating future plans and determining future budget requirements, manpower, and expected production potential are needed. If a prospect appears favorable in the light of past experience, the decision to drill is made easier.

Risk analysis for oil and gas exploration has become increasingly popular among oil industry management. It provides a quantifiable methodology for evaluating the level of risk presented by each new prospect. However, the exploration staff is required to produce numerical probability estimates for each possible outcome. There is currently a need for more systematic techniques to provide these probabilities.

The recent advent of computer data banks has made large quantities of data easily available to the exploration group. No longer is data limited to company proprietary files and broker logs and maps. While this increase in information brings the advantage of increased knowledge, it does result in increased time and manpower spent in data handling and sorting. Computer assistance in sorting and analysis would allow better use of the data that is available.

2. Concept 13: Improved Computer Aid in Recognizing Geologic Analogies

Statement of Concept: A system to aid the geologist in recognizing known areas that most closely resemble a new prospect or basin of interest. It includes a computerized data base containing basin, pool, and digitized well-log data, plus software emphasizing pattern recognition methods and direct interaction between geologist and computer. Output are lists and characteristics of areas most closely resembling the new area, on the basis of parameters selected by the geologist, and (optionally), by analogy with known areas, estimates of prospect ranking or success probability for use in risk analysis.

a. Problem Addressed*

Comparison of drilling experience with predictions (Problem 45).

b. Objective

The objective of this topic was to identify a geologic analogies system which would maximize the use of prior experience in making exploration decisions.

c. Method of This Study

The approach consisted of several steps. First, information on the current status of and on problem areas in geologic analogies was obtained from the petroleum industry, research institutions, and universities. Then aerospace capabilities relevant to petroleum exploration were investigated in the areas of image processing, pattern recognition, systems analysis, data management, telecommunications, statistical analysis, and artificial intelligence. The system requirements pertaining to the scope and techniques for geologic analogies were determined through discussions with industry exploration staffs, petroleum exploration consultants, and university faculties. The synthesis of aerospace capabilities with the system requirements resulted in the evolution of new ideas. The final step was the evaluation of the geologic analogies system concept in terms of its relevance to the needs of the petroleum industry and importance in reducing the uncertainty in identifying potential reserves.

*Problem number corresponds to that in Appendix D where the problem is discussed.

3. Technical Method

The geologic analogies system is envisioned as a means of processing large quantities of relevant previous data and of bringing appropriate portions to the attention of the exploration staff. It would also serve as a tool to aid in making management decisions and planning.

An interactive geologic analogies system which uses well and field data banks is considered. It would utilize an interactive pattern recognition system to produce outputs which would assist the geologist and exploration manager in new prospect evaluation. Two types of output could be produced by the system: analogous prospect identification and prospect ranking or success probability. The output of analogous prospect identification would be a description of the most similar previous prospects. This data would then be available for geologic evaluation and comparison with the new prospect. It would be useful in pointing out key considerations and would perhaps indicate the need for further data acquisition, such as more geophysical surveys, for the new prospects.

Prospect probability estimates represent a further use of the geologic analogies capabilities. Estimates of commercial potential and probable risk are calculated based on the past experience of geologically similar prospects. These data are used to evaluate the prospect relative to other prospects available for exploration.

The geologic analogies system should provide a methodical frame work for exploration program evaluation and may be useful for making drilling decisions and for planning future program requirements. A key use would be to provide a consistent inputs from each prospect for risk analysis and economic analysis programs (see, for example, Appendix T). The usefulness of risk analysis methods is increased by availability of more reliable probability values.

The geologic analogies system may be characterized by a large computerized data bank, an interactive pattern recognition system, and high-speed input/output capabilities. The system consists of

- 1) A data base containing well-log data, pool data, and basin data; relevant geologic geophysical and production data are included.*
- 2) A comprehensive software system that manages selectable pattern recognition subprograms and allows a high degree of man-machine interaction.
- 3) A computing/hardware complement which has cathode ray tube (CRT) and keyboard input/output with hardcopy plotting (for contour maps).

*The data base for each user consists of either data provided by that user, or commercially available data he may rent or purchase, or both. Data provided by one user is not available to other users except under sharing agreements.

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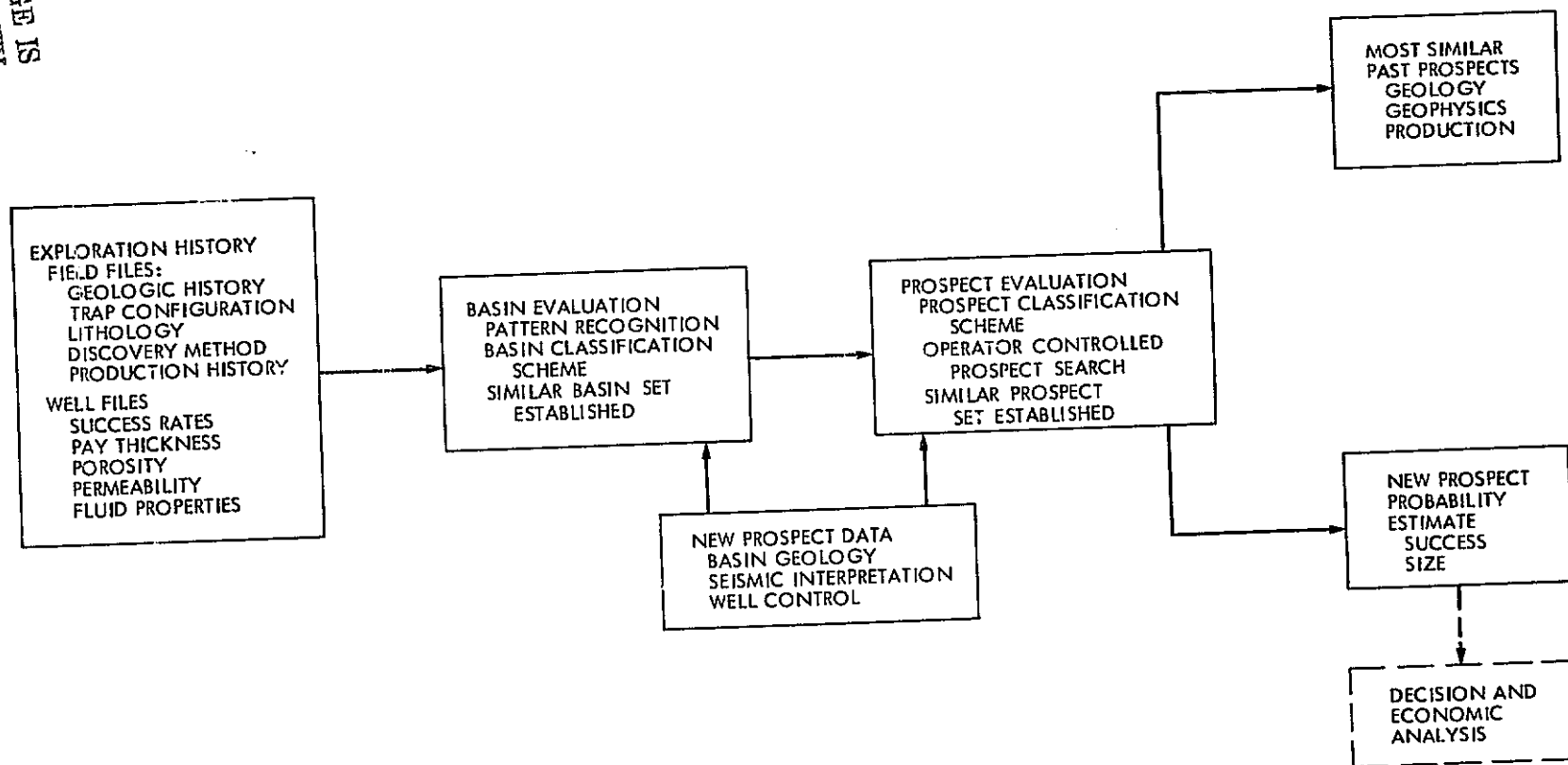


Figure 3-C-1. Geologic Analogies System Schematic Diagram

A schematic diagram of the system is shown in Figure 3-C-1. Existing methods and data and details of the proposed technique are described in Appendix M.

4. Estimated Costs

Costs associated with the development and use of the geologic analogies system have been roughly estimated. Cost can be considered in three categories: development, implementation, and operation costs. Development cost include manpower and computer time necessary for system definition and development. Implementation costs for a specific user can be minimized by developing portable software which can be used on many systems. Use at those sites not having in-house computer capability would be provided by service bureau organization offering time-sharing services. Operating costs are difficult to estimate at this time, as they are dependent both on system development and data requirements. Estimates are given below:

Development Cost	\$1,000,000
Implementation Cost (at user site)	\$2,000*
Operating Costs	
Data	\$50 to \$100 (each area)**
Operation	\$50 to \$200 (each area)

5. Findings and Aerospace Contribution

The application of aerospace experience with large operational pattern recognition systems combined with the experience and knowledge of exploration departments will permit development of a flexible and useable system to aid the explorationist in identifying geological analogies and evaluating prospects. Development of a system that allows the user to have minimum computer equipment will permit use by most of the exploration industry.

No commercially available computer-based system on identification of geologic analogies has been identified that evaluates prospects using data from more than a single basin. Services are available to locate new prospects using a computer analysis of digitized well logs (see Appendix M), in basins already extensively drilled. This evaluation may be integrated with available seismic and gravity data and sold as a package.

6. Recommendation

If there is sufficient industry interest, it is recommended that a development program be initiated to develop the geologic analogies system. Full integration of the system into the exploration program would follow. Appendix M contains a recommended sequence for the development.

*Cost of purchase and installation of software, assuming user has all required hardware.

**Includes charges for use of commercial data banks.

D. TOPIC D - DRILLING METHODS

1. Introduction

There has been a continuing effort since the beginning of the petroleum industry to improve drilling techniques. The physical process of drilling involves fracture failure of the formation being drilled by mechanically inducing stresses. Early drilling was accomplished by simply lifting and dropping the bit on the end of a cable in the hole bottom. The chips and other debris would then be removed from the hole by a bailer. The introduction of the rotary drill bit with circulating mud to remove cuttings was a dramatic improvement which resulted in the drilling at a much faster rate (about 10 times faster), drilling deeper holes, and the capability of directional drilling.

The conventional mechanical rotary bit is driven by a rotary table located at ground level. The bit is loaded against the formation by the weight of thick-walled pipes called drill collars which in turn are connected to a thin-walled pipe called a drill pipe. The drill pipe extends the length of the hole being drilled and delivers the torque from the rotary table to the drill bit. The load and speed of rotation and bit life are limited by the capabilities of the bearings in the bit mechanism. The bearing size and associated load bearing capability are limited by the hole size. In effect, the power which can be delivered to the well bottom and converted into the work of fracturing rock is limited by the bit itself and not by the availability of on-site power. Any significant further improvement in this limit for the conventional rotary bit is not likely. Furthermore, the finite operating lifetime of the bearings and bit cutting surfaces requires periodic withdrawal of the entire drill string for replacement of the bit. The deeper the well, the more time is required to pull the drill string to replace bits.

2. Study Approach

The approach was to first conduct a literature survey to assess the current state-of-the-art and to identify the underlying problems that have impeded the development or introduction of new technologies into the petroleum industry. Next, discussions were held with users, equipment manufacturers, and organizations active in research and development on petroleum drilling to gain further insight into the technological and non-technological problem areas faced by the drilling industry and to assess the probable match between industry's needs and aerospace technology. For those areas where potential matchups were identified, initial inquiries were followed by site visits and detailed discussions to further the understanding of the basic problems and the reasons for failure of previous unsuccessful approaches. A few laboratory tests were made of an advanced drilling concept. The concepts were then compared and a relative ranking of their applicability was formulated along with the potential role that aerospace technology could play in bringing these concepts to fruition.

Five advanced drilling concepts were evaluated: (1) automated drilling rig, (2) high-pressure drilling, (3) resonant-vibration drilling, (4) down-hole motors, and (5) combustion-fracture drilling. In the discussion that follows each of these concepts is described.

3. Concept 14: Automated Drilling Rig

Statement of concept: Combine capabilities for computer control and monitoring of down-hole parameters, mud handling, and drill pipe, including "round-tripping."

a. Problem Addressed*

The problem addressed by this concept is

Better drilling methods (Problem 37).

b. Background

The present petroleum industry drilling rig has evolved over the years and provides a reliable and efficient method of drilling the majority of wells for petroleum exploration and production. Wells drilled for petroleum are in sedimentary rocks, and current drill bits are capable of drilling considerable distances before they are worn out and require replacing. Since the bits need not ordinarily be replaced too often during the drilling petroleum wells of average depth, the methods of changing the bit have not been the subject of a great deal of research or development. However, as the depth of the wells increases, as more expensive offshore facilities are required, and as drilling is conducted in more inaccessible locations with adverse climatic conditions, improved methods of changing bits as well as of other drilling operations should be considered.

Each time the bit is changed, a round trip time of approximately 1 hour is required per 1000 feet of depth. This normally represents only a small portion of the total rig time for shallow holes, but the trip time becomes significant in deeper wells. Recent tests with automatic pipe handling equipment has shown that trip time can be reduced by 20%. This increased efficiency plus safety considerations and the lack of trained drilling crews in some areas emphasize the need for development of automatic drilling equipment.

Although there will no doubt be continued improvements in conventional drill bit in which will result in increased life while drilling, the inherent difficulties in deep-well drilling will still require the utmost attention and control of drilling parameters, mud weights, etc. which reliable automatic controls could provide.

*Problem number corresponds to that in Appendix D where the problem is discussed.

Since an estimated 2000 to 2500 rigs are used in the U.S. and Canada, it is important to analyze the impact that an automated rig would have on costs and drilling efficiencies.

c. Automatic Drilling Rig Method and Procedure

The automated drilling rig would perform several vital functions in the drilling operation including "round tripping" to change bits, handling casing, mixing mud, controlling drilling parameters such as rotary table speed, weight on bit, torque applied to drill string, and mud pump pressure and flow rate. Equipments to sense these parameters are presently available, and several separate devices are in existence which could perform the necessary functions. What remains to be accomplished is to integrate these various parts into a reliable complete system which could either be added to existing rigs or built into new rigs.

d. Economic Evaluation

The cost of adding automated rig equipment to a conventional rig is estimated to be \$500,000. The overall increase in rig efficiency is not known at this time but could be determined by analysis and a demonstration rig. Such factors as cost for maintenance, improved drilling rates, rig and personnel safety would all need to be determined.

e. Findings

Automatic control of drilling rig operations would result in cost savings by increased rig efficiency, reduced safety hazard to crews, reduction in periods of rig shutdown because of crew shortage, and a reduction in drilling accidents such as twist-off of drill pipe, lost mud circulations, blowouts, etc.

The information gathered from the drilling industry indicated that there would be initial resistance by the drilling contractors to using unknown and untried equipment. However, a good demonstration project which included some of these contractors would go a long way toward improving the negative attitudes. The contractor that can drill a given well for the least cost will get jobs, especially during periods when drilling effort is slow and rigs are available. This cyclic situation provides incentive to competitive contractors to update their present equipment or replace worn out rigs with automated equipment.

f. Aerospace contribution

The aerospace contribution includes experience in equipment reliability and in automating complex systems while retaining the capability of efficient supervision and intervention by humans.

g. Recommendations

A prototype automated drilling rig should be produced and tested in active drilling situations. The testing would compare the efficiency, reliability and cost effectiveness of the automated rig against a modern conventional rig. The results of these demonstration tests would be published and presented to the drilling contractors and oil companies for evaluation.

The project should be divided into phases to reduce the risk. Equipment to perform the various tasks could be designed, built, and tested in modular units. After these units are developed, the entire system would be assembled and operated.

4. Concept 15: High-Pressure Drilling

Statement of Concept: Pumps and mud-handling equipment are used that provide a pressure inside the drill bit perhaps 15000 psi higher than outside the bit. A rotary bit is used with extended nozzle tubes that direct high-pressure jets of mud against the bottom of the hole.

a. Problem addressed*

The problem addressed by this concept is Better drilling methods (Problem 37).

b. Background

The rotary drill bit on the bottom end of the drill pipe is driven by a motor at the top through torsion in the drill pipe. A mud-water mixture is pumped down through the drill pipe, exiting through orifices in the drill bit. The mud impinges on the hole bottom where it loosens the chips, cleans the drill cone teeth, and hydraulically floods the debris out. Viscosity and mass density of the drill mud are varied to maintain control of the hole characteristics. The mud is pumped at the rate of 200 to 300 gallons per minute at pressures between 2000 and 3000 psi. The mud pressure is regulated by exit restriction and/or pump speed (volume flow). The pump is typically a positive displacement type using spring-loaded poppet valves.

c. High-Pressure Drilling Procedure

The high-pressure drilling concept is a process that simply increases the drilling-fluid pressure and impinges high-pressure mud through nozzles onto the hole bottom to fracture the formation being drilled. Previous experiments have shown that the needed pressure depends on the formation and is called the critical pressure required to break the rock. Pressures in excess of the critical pressure will rapidly increase the rate of drilling. When the pressure is increased above the critical pressure, the specific energy (see Figure 3-D-1) will decrease to a minimum. Continued pressure increase will increase the specific energy required. Figure 3-D-1 illustrates this condition for Berea sandstone. Each formation being drilled will react in a similar manner. The lowest specific energy demand will yield the highest rate of drilling per unit of hydraulic horsepower (Ref. 14).

*Problem number corresponds to that in Appendix D where the problem is discussed.

After a series of laboratory experiments, high-pressure drilling equipment was taken to the field for full-scale tests, and several experimental wells were drilled. High-pressure drilling was found to be most effective when using a combination rotary-jet drill bit. The extended-nozzletube drill bit was best. The nozzle tubes, holding the nozzles, protrude between the drill tooth cones to within 1/2 inch of the hole bottom. Drilling at this pressure is limited by hardware capability and reliability (Ref. 14).

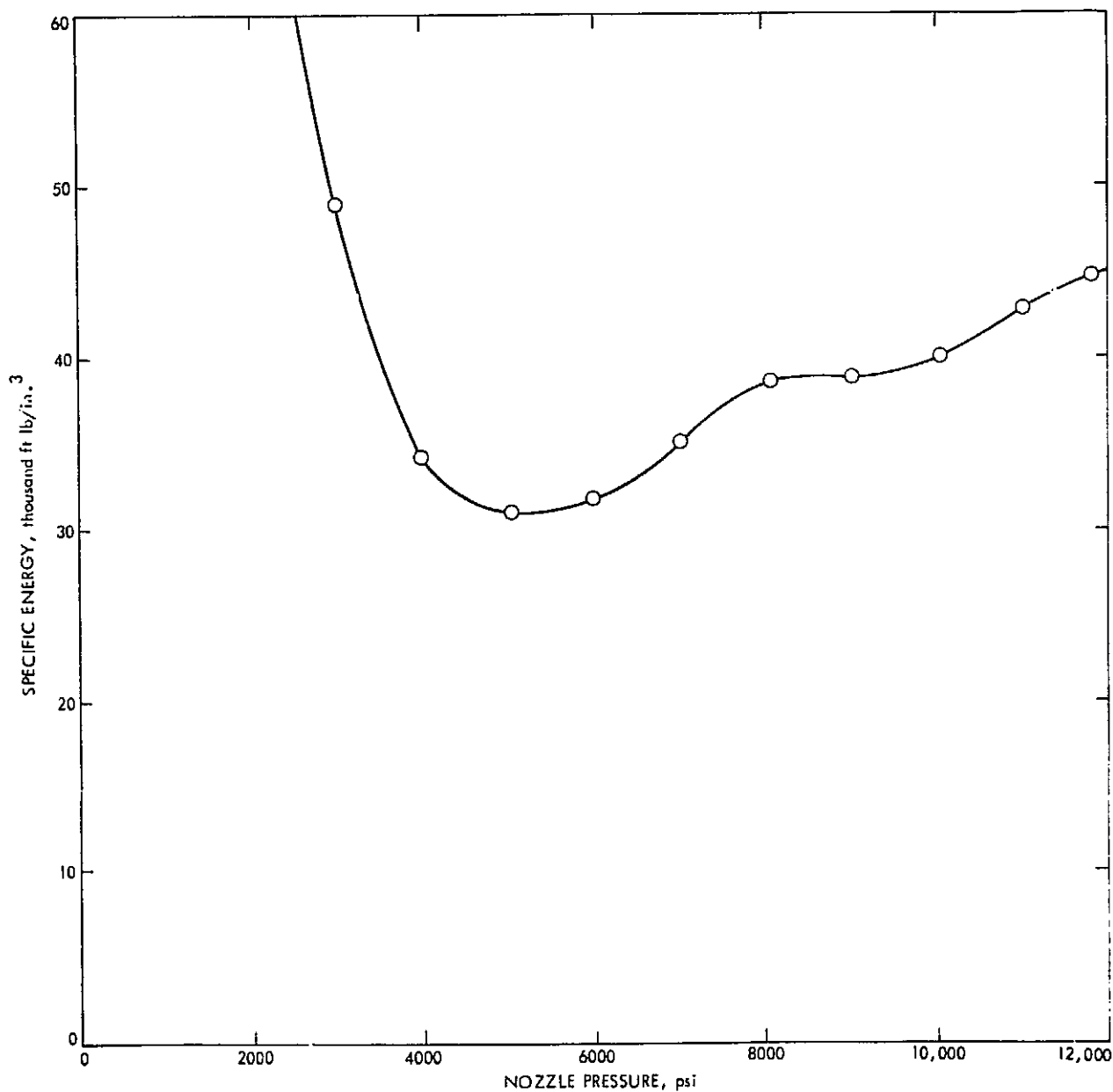


Figure 3-D-1. Specific Energy Required to Drill Berea Sandstone with a High-Pressure Drill (Ref. 14)

d. Results of Early Studies

The results of field tests by previous investigators yielded the following conclusions:

- 1) High-pressure drilling rates are up to three times the rates of conventional rotary drilling (Ref. 14).
- 2) Rotary bits last proportionally. They typically drill three times as far as the standard pressure-fed rotary bit (Ref. 14).
- 3) Hole trips can be one third the usual number per well because of the above two conditions.
- 4) One important advantage of high-pressure drilling is that, aside from some special surface equipment, little is changed in the drilling process. No changes are necessary in the mud. Circulation flow rates are essentially the same as for conventional drilling and annular velocities are similar. High-pressure drilling operations look similar to conventional procedures.
- 5) Conventional surface pressure capabilities have limited the drilling horsepower (hp) used to 1000. High-pressure drilling is not limited in this way; it could conceivably use 4000 to 10,000 hp if available. Two to threefold drill rate increases can be expected with 3000-4000 hp. Considerably faster rates can be achieved with 5000-10,000 hp. Equipment reliability must be achieved in order to make this possible (see Appendix O).

e. Economic Evaluation

Although the pressure-jet drilling concept has demonstrated increased drilling rates from two to three times that of conventional rotary drilling, the increased cost of operation caused by equipment breakdowns has eliminated jet drilling as an economic option. The problems discussed under "Findings" below, are the reasons for this unfavorable economic picture. Solutions to these problems will reduce the operational costs, and the increased drilling rate will permit some increase in operating cost over the present methods. For example, if a present drilling rig costing \$250 per hour to operate was converted to jet drilling, the resulting three times increase in drilling rate would produce a 50% overall cost saving if the operating costs did not exceed \$325 per hour (see Appendix U).

Work on high-pressure drilling to date has cost about \$5,000,000. The additional costs to develop an economically viable drilling system could be equal to that amount. When developed, the increased cost over commercial equipment should not be greater than 15 to 20% of conventional equipment costs. Present drilling activity is approximately 40,000 holes per year, and the number of holes and associated cost will probably increase. The cost of a jet-drilling development program, though high, would be amortized in a short period of time.

f. Findings and Aerospace Contribution

The problems encountered in high-pressure drilling are mainly in equipment life. The concept is effective and provides a major increase in drilling rate. The problems of equipment reliability must be solved to make high-pressure drilling a commercial process. Appendix O contains a more detailed discussion of these problems.

Most of the problems encountered in high-pressure drilling seem to be in mechanical design and materials. Extensive aerospace experience in both these areas, as well as in fluid flow and specifically in design of pumps, valves, and seals, can hasten the solutions of the problems. High-pressure drilling is an extremely important advance in drilling technology. Equipment reliability will make high-pressure drilling an economic process. Drilling costs will be reduced.

g. Recommendations

Low-cost field tests should be arranged to verify the design solutions to the problem mentioned above. Following the test phase, a demonstration drilling rig should be built and operated over a period of time to evaluate drilling efficiency in various rock formations as well as safety and reliability.

5. Concept 16: Resonant-Vibration Drilling

Statement of Concept: A resonant-vibration element is placed in the drill string just above the drill. This element vibrates in torsion and is driven by a mud motor. It drives the bit on the forward stroke by means of a ratchet. The string is rotated by the Kelly in the usual way, but the bit moves forward intermittently instead of continuously.

a. Problem Addressed*

The problem addressed by this concept is

Better drilling methods (Problem 37).

b. Background

The resonant-vibration technique uses vibrational energy to produce work. A resonant-beam structure or member provides a highly efficient energy transfer function at its resonant frequency because of low internal losses and its energy-storage capability. A mechanical oscillator/resonator driven by a prime mover produces the force or vibrational energy. This energy is stored and transmitted to a working face or tool as required, through the resonant member.

Using resonant-vibrational energy to do work is not new. The concept has been fully protected by the inventor, A. G. Bodine (Ref. 15) through a host of patents. A few of the commercial applications used by industry to date are pile driving, oil-well casing removal, rock crushing, tunneling, earth removal, tree cutting, paint removal, and earth plowing or ripping (Refs. 16 and 17). Almost a decade ago, Shell Oil and Borg-Warner tried to apply this technique to oil-well drilling. A mechanical oscillator was combined with a longitudinal resonant member. This configuration was used for near-surface drilling during the development phase. Eventually, the development was abandoned due to extensive mechanical problems with the 80-foot long resonant member.

No resolution is in sight for the mechanical problems associated with an 80-foot long resonant member under these vibration loads. With this in mind, a new design approach is being considered by the inventor using a torsional resonant member in place of the longitudinal unit. Preliminary indications are that the torsional resonant member will be in the 20-foot range and will

*Problem number corresponds to that in Appendix D where the problem is discussed.

have fewer parts. The oscillator and drive unit will have their axes parallel to the long axis of the resonant member instead of transverse as in the longitudinal design. This will provide for better mechanical mounting of larger and more efficient drive and oscillator units within the drill system.

Preliminary bench tests by Bodine (Ref. 15), using a 2-inch diameter resonant member, a torsional mechanical rectifier, and drive by an external mechanical oscillator/resonator, have provided significant drilling rate increases through such materials as limestone and other sedimentary materials. Admittedly, this bench testing provides only a slight indication of the feasibility of the concept.

Further information about the concept is provided in Appendix P.

c. Technical Method and Procedure

The procedure to be followed in applying resonant-vibration energy to an oil well drilling system is as follows: A hollow cylindrical tube should be sized so that it has a first harmonic natural frequency of 200 Hertz in torsion. The tube should have an outside diameter less than 6 inches and be about 20 feet long. Just above the working end of the resonant tube, a torsional mechanical rectifier should be installed so that the cutting tool will not be pulled backwards during the negative-motion phase of the resonant-vibration cycle. The cutting tool should be placed at the tip of the resonant member. The mechanical oscillator/resonator should be placed at the opposite or upper end of the resonant member with its rotational axis parallel to the long axis of the resonant member.

d. Costs

The cost for further development of the concept is estimated as \$1,000,000. Once it is fully developed, the added cost is estimated as \$10,000 per month per rig.

e. Findings and Aerospace Contribution

The technical basis for the resonant-vibration method of drilling appears sound, and it gives promise of considerable increase in drilling rate. However, extensive development will be required to bring the concept into operation. Mechanical design of the device is critical: Special attention should be devoted to keeping the component vibrational loads low so that parts will not suffer premature structural or fatigue failures. Aerospace experience in vibration technology and mechanical design should be especially helpful. Considerable effort will also be needed to design a system that will fit within a 6-inch drill hole. If it can be made sufficiently small, it should be very useful for drilling shot-holes.

f. Recommendations

Testing of the resonant-vibration drilling method, utilizing torsional resonance, is recommended. The suggested steps are

- 1) Develop a prototype drill and carry out bench tests.
- 2) Conduct near-surface testing to evaluate and demonstrate drilling-rate capabilities. Down-hole drilling and monitoring instrumentation has a history of being very unreliable under normal drilling conditions. Rather than submit this instrumentation equipment to the additional vibrational loads inherent in the resonant-vibration drilling technique, the proposed demonstration/evaluation testing will be done near the earth's surface, so sensitive instrumentation will not be required. This testing concept will also provide easy access to the resonant drilling system in the event of a mechanical problem. At this stage, the oscillator should be driven by a hydraulic motor.
- 3) Conduct operational design and development. Once the concept has been shown to work and to provide significant drilling rate increases, the hydraulic motor should be replaced by one of the several commercially available mud-driven turbines and further down-hole tests performed. Then design and development of an operational version could begin.

6. Concept 17: Improved Down-Hole Drill Motor

Statement of Concept: An improved down-hole mud motor that will provide up to 150 hp at 50 rpm at the bottom of a drill hole together with good motor reliability and life. The motor would be used to drive a bit down-hole for straight drilling

a. Problem Addressed*

The problem addressed by this concept is

Better drilling methods (Problem 37).

b. Background

Conventional oilwell drilling apparatus utilizes long pipe shafts called drill strings to deliver rotating power from the surface of the ground to the drill bit down the hole. These drill strings are subject to whipping and attendant wear and friction between shaft and hole; this, coupled with viscous fluid drag on the drill string (increasing as the hole gets deeper) can result in power losses up to 90% along the hole.

The use of a hydraulic (mud-driven) turbine that produces rotary power down the hole at the drill bit can significantly reduce drilling energy requirements by utilizing available mud-pump power. In addition and perhaps more important, this technique will facilitate drilling to much greater depths since more power can be applied at the bit.

A number of down-hole mud-powered devices have been tried in the past, but in the U.S.A. all failed to compete economically with the present surface-driven rotary drilling system.** One device is presently in limited use for directional drilling. This device is not economical for vertical-hole drilling but is very useful for accurately drilling a deviated hole.

In general, the problems of the drilling environment (drill mud hydraulics, abrasive particles, temperature, shock forces, etc.) result in uneconomic short lives of the devices. However, the down-hole motor concept is promising and if these problems could be eliminated, the new drilling system would provide much needed advances over the conventional system. The following

*Problem number corresponds to that in Appendix D where the problem is discussed.

**This is also true of a Soviet turbine design which has been tried in the U.S.A.

discussion outlines one promising device which has been proposed by the Rocketdyne Division of Rockwell International.

c. Technical Description

The components that comprise the system are shown in Figure 3-D-2. The design utilizes a multi-stage hydraulic turbine as the prime mover. Two hydraulic turbines have been studied: a multistage radial inflow and a four-stage axial-flow rotor. The system is self-propelled by means of a cylindrical clamshell system. The shell sections are spread apart and locked against the surrounding wall by means of hydraulic cylinders. A hydraulic motor drives the turbine and drill assembly downward by means of a threaded shaft until fully extended. The clamshell is then retracted, and by reversing the hydraulic motor, follows the turbine unit downward until the start position is reached and the cycle repeated.

Additional details regarding the hydraulic turbine, speed reduction gearbox, bearing housing with drill bit, and the drill propelling unit are presented in Appendix F.

d. Results

The results of this study indicate that the down-hole motor concept is a viable advanced drilling option to explore.

e. Advantages and Disadvantages

(1) Advantages. The advantages are

- 1) Elimination of drill pipe with related power losses, torque transmission problems, and deep-hole weight problems.
- 2) Accurate real-time control of bit drilling parameters, brought about by the ability to transmit down-hole data to the surface through a cable. (This is not presently possible because of the rotating drill string.)

(2) Disadvantages. The disadvantages are

- 1) Power losses in the mud flow.
- 2) More down-hole equipment requiring maintenance.

(3) Economic Evaluation. An important aspect is economic feasibility, and one element is the cost comparison between the conventional rock-bit drilling technique and that using an improved down-hole motor.

It is assumed that a new drilling method will drill the same size hole as a conventional rig and that the down-hole logging, testing, and casing requirements will be the same. Using these assumptions, cost savings will

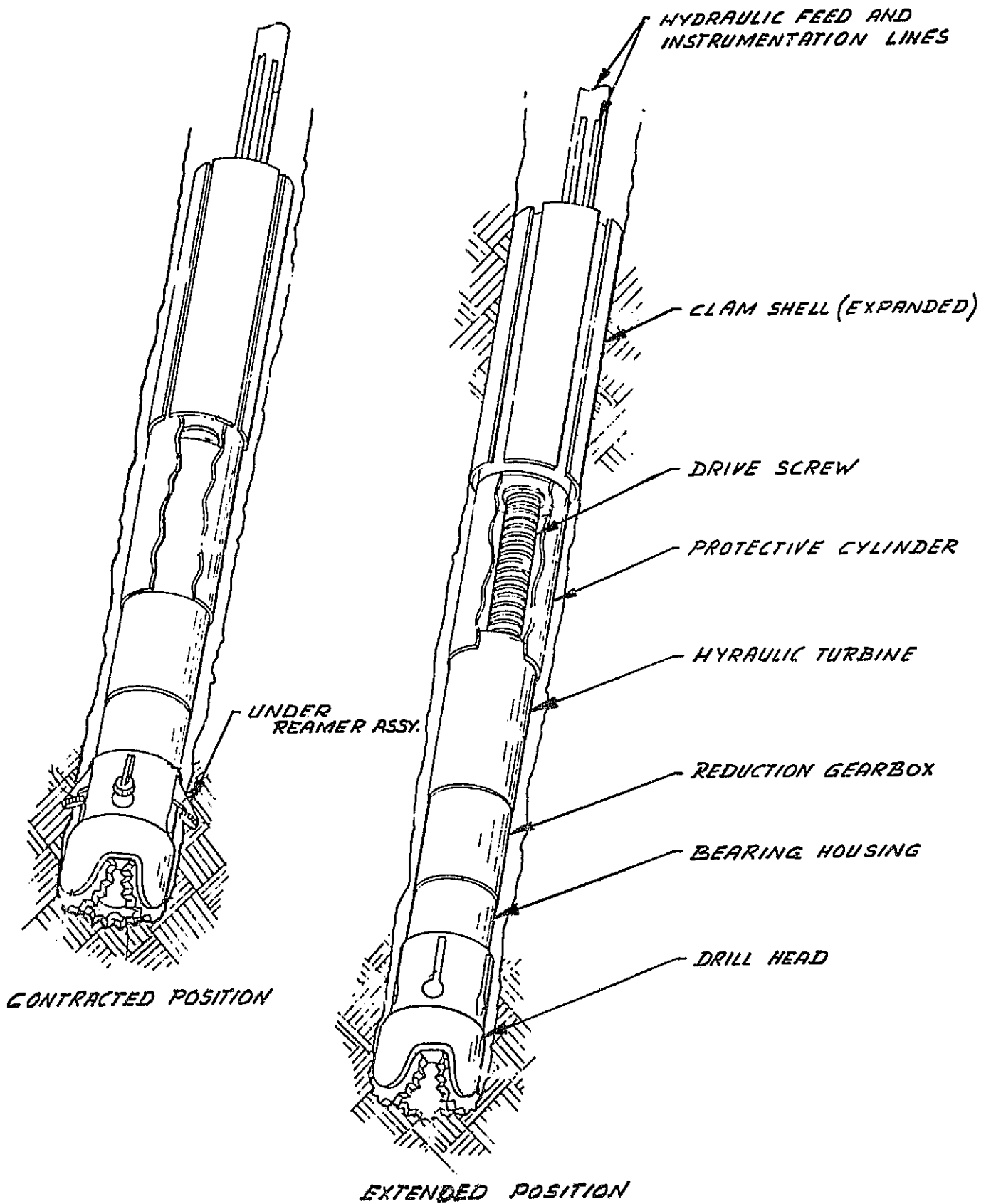


Figure 3-D-2. Rocketdyne Down-Hole Drilling Device

result from increased drilling rates, provided bit and equipment life remains the same, and operating costs are not increased excessively.

Assuming that the down-hole motor is used on an offshore platform costing \$250 per hour and that additional costs for the new drilling method are \$125 per hour, savings will be about 50% if the drilling rate is increased by a factor of 3 (see Appendix U).

f. Findings and Aerospace Contribution

It should be possible to develop a reliable down-hole motor drilling system for future deep drilling as well as more efficient medium-depth drilling, both on shore and off shore. Shallow-depth wells would not be candidates for this system for economic reasons. Aerospace contribution would include expertise in vibration control, fluid flow, pumps, mechanical design, and material selection for hostile and remote environments.

g. Recommendations

If industry interest is sufficient, development of an improved down-hole motor should be initiated. This effort should include the tasks of generating conceptual designs, testing prototypes, and field testing of the most promising designs.

7. Concept 18: Combustion-Fracture Drilling

Statement of Concept: Drill the hole without a mechanical bit by using a modified rocket engine down-hole. The engine would not melt the rock but would chip it away by thermal and mechanical shock. The shock is provided either by pulsing the engine on and off or by setting up a controlled oscillation in the exhaust gas. Fuel and oxidizer would be pumped down the string and mud circulated in the usual way.

a. Problem Addressed*

The problem addressed by this concept is

Better drilling methods (Problem 37).

b. Background

Liquid rocket-engine technology embodies the delivery, controlled release, and maximum utilization of the energy contained in liquid propellants within the minimum possible physical bounds. The use of liquid propellants in well drilling would provide energy at the drill in latent form more efficiently than could the transporting of energy the length of the hole from ground level as does the conventional drill string and some other attempted new drilling techniques (Ref. 18) which utilize pressurized fluids. The next step, clearly, is to couple that energy to the removal of rock through some mechanism, preferably nonmechanical, likely to survive and function for the entire duration of the well-drilling operation. Three methods for fracturing of rock through the combustion of liquid propellants are described below.

Two of the methods would utilize characteristics of the typical rocket engine; these being: (1) the high temperature and velocity of the products of propellant combustion, and (2) the large-pressure gradients in the shock-wave structure of the exhaust.

Method (1) should be evaluated for its capability to transfer heat into the rock, to produce temperature-gradient-induced stresses sufficient to fracture the rock. Reference 18 describes a similar mechanism which is referred to as the forced-flame drill and which has some experimental background and produced chips through spalling.

*Problem number corresponds to that in Appendix D where the problem is discussed.

Method (2) would enlist interaction between the reflected exhaust and the diffuser efflux to cause the exhaust shock-wave structure to oscillate thereby subjecting the rock face alternately to low- and very high-pressures in the manner of an impact bit as well as to high temperatures. Some preliminary tests of this method are reported in Appendix Q.

A third method would employ intermittent propellant combustion to propel high-velocity jets of drilling mud in bursts at the rock face, re-priming with propellants and mud between bursts (somewhat in the manner of the internal combustion engine, but minus pistons).

c. Costs

Because of the major research and development activities that would have to be carried out to permit use of this concept, no attempt was made to estimate the recurring cost of a production design. However, it is anticipated that an initial research effort of approximately \$750,000 would be required to address the tasks of propellant selection, propellant properties, propellant verification testing and design, fabrication, and laboratory testing of a prototype device.

d. Points Needing Further Attention

Possible prior invention.

For technical points, see the next subsection.

e. Findings and Aerospace Contribution

Liquid rocket-engine technology offers a way of getting larger amounts of power to the drill head with smaller more portable rigs than the conventional drilling platform. Faster drilling rates thus obtained could substantially reduce the costs of drilling wells.

Selection of the most effective propellants requires understanding of propellant properties, ignition characteristics, combustion thermodynamics, reaction-product properties, etc., at the very high-ambient pressures encountered at typical well depths. It will require selection of candidate propellants based upon theoretically grounded projections, and confirming tests.

Selection of the most efficient mechanisms for coupling of the delivered power into the fracturing of rock requires an understanding of the resonant properties and failure modes of the various types of rocks. These characteristics are also affected by the surrounding pressure to which the rock is subjected.

Initial development efforts should address the effects of pressure on the following:

- 1) Rock properties and fracture mechanics.
- 2) Candidate propellant combinations.

- 3) Propellant density, viscosity, boiling point temperature, solubility.
- 4) Candidate hypergols (as a third, igniter, component - if required.
- 5) Ignition characteristics.
- 6) Heats of reaction.
- 7) Ratio of specific heats of combustion products (to determine required chamber pressures).
- 8) Solubilities of combustion properties.
- 9) Heat transport properties and specific heat of combustion products.

The optimization of hardware design must also take into account rock properties and failure mechanisms which vary with type of rock and which have also been found to vary significantly with the surrounding pressure to which the rock is subjected. The most efficiently destructive stress distribution and fluctuation occurring within rock subjected to high-temperature, high-pressure gaseous jets and to high-velocity liquid jets could be determined for the range of brittle through plastic rock conditions encountered, through a combination of empirical measurement and analytical modeling. The various rock-drilling methods based upon liquid rocket-engine technology, such as those described above, could then be evaluated with respect to their capabilities to produce the required stresses in various types of rock when embodied in actual hardware and operating in the deep-well environment. The methods should also be evaluated with respect to the expected survival capabilities of the hardware, site power requirements, ancillary equipment needs, and complications entailed by any special handling, and operating practices.

Aerospace contribution is the technology of the rocket engine itself, plus background in the supporting areas of propellant chemistry, thermodynamics, combustion, heat transport, subsonic and supersonic fluid mechanics, and solid mechanics.

f. Recommendation

Initiation of a research program along the lines outlined above.

8. Comparison of Various Drilling Concepts

- 1) The automated drilling rig offers improved rig operation efficiency which may lower costs and increase safety factors. Costs are still uncertain, however. The approach appears most attractive for remote areas where drill crews are scarce and in offshore locations where rig operating costs are very high. Since most of the components necessary to automate the drilling operations are available, a demonstration project should be successful. With the increased needs for petroleum exploration, the concept is very timely and is considered first priority.
- 2) Improved down-hole motors are viewed as a high priority because of the advantages of such a system in drilling deep holes. A model of an improved hydraulic motor has been built and operated, but its down-hole drilling performance is not yet demonstrated.
- 3) High-pressure drilling may be an attractive drilling method. Its drilling-rate performance improvement has been demonstrated by well drilling, and development is the furthest along of any of the methods. However, past failure to produce an economic drilling system with this approach has temporarily halted development. It is recommended that pump research and development be continued to put this improved method into the field as soon as possible.
- 4) Combustion-failure drilling has not yet been demonstrated. A lengthy research and development program would be needed before design could be undertaken. As a first step in the program, it is recommended that a research project investigating the resonant-failure properties of various rock types be conducted. This information would be of general value to conventional rock-bit designers as well as essential to the combustion drilling concept.
- 5) The resonant-vibration technique is considered fifth in priority. Brief well-drilling tests have been run, and an increase in drilling rate, as compared to conventional methods, was shown. However, rapid failure of the equipment has not been eliminated although large sums of money have been invested. More recent design innovations coupled with improved materials may improve the equipment life to make this system economically feasible.

E. TOPIC E - REMOTE SENSING OF GEOCHEMISTRY

1. Need and Significance

Present techniques for finding petroleum in the U.S. are primarily geophysical, especially seismic. Companies active in petroleum exploration have noted important limitations of the present geophysical techniques; in particular, they often miss stratigraphic traps and thin but economically producible beds. Moreover for the most part, surface geological and geophysical techniques do not indicate the presence of petroleum but only of the occurrence of geological conditions or physical properties that may be associated with petroleum. There is therefore much interest in the possibility of surface geochemical techniques that would directly indicate the presence of petroleum at depth. Information from petroleum companies suggests that better geochemical methods could lead to at least a moderate increase in petroleum found. More reliable methods would save significant cost by reducing the number of dry holes.

The geochemical method of petroleum exploration is based on the assumption that certain chemical species are to be associated with the presence of subsurface oil/gas. A wide variety of analytical methods (Ref. 19) have been tried, analyzing for hydrocarbons, other organics, and inorganic indicators in soil, near-surface water, and air. Microbiological indicators (Ref. 20) have also been tried. There does appear to be a multiple parameter correlation of some chemical species in underground brines with the presence of petroleum deposits (Ref. 21). Somewhat discouraging is the opinion generally gathered from U.S. oil companies that geochemical techniques based on analyses of surface soil or near-surface water have not been reliable indicators of oil below. Thus, geochemical techniques are not generally used by American companies. (Some foreign companies and a few of the smaller U.S. companies do use them.) Levinson (Ref. 22) believes that the difficulty lies less with the analytical techniques than with inadequate understanding and modeling of fluid transport from subsurface reservoirs to the surface.

The most pertinent area of aerospace technology application to geochemical exploration for petroleum appears to be remote sensing. For geochemical indicators of oil/gas and at the present state-of-the-art, remote sensing will probably be limited to exploration on land. A remote-sensing approach already under investigation by U.S. Geological Survey (Ref. 23) is satellite detection of surface bleaching which may arise through reduction (probably microbiological) of Fe^{+++} to Fe^{++} and the subsequent bleaching of the Fe_2O_3 stains on the rocks by hydrocarbons reaching the surface from underlying petroleum.

2. Concept 19: Remote Geochemical Sensing

Statement of Concept: Obtaining an indication of subsurface petroleum by remote sensing, using optical spectroscopy of localized concentrations of molecular iodine and other indicators in the air over petroleum reservoirs.

a. Problem Addressed*

The problem addressed by this concept is

Improved surface geochemical techniques (Problem 35).

b. Approach

It is proposed to use optical spectroscopy as a remote-sensing technique, detecting molecular I_2 in the air arising from iodine compounds in the soil over a petroleum reservoir. The spectroscope would be carried on an aircraft or satellite (Figure 3-E-1).

c. Methods Used in This Study

Information was obtained from literature on geochemistry, spectroscopy, instrumentation, remote sensing, pollution detection, and air sampling. Personal contacts were made with individuals working on petroleum geochemistry and geobotany and the other fields mentioned. Laboratory tests were made to determine the effect of pressure on the width of optical lines in the spectrum of I_2 and the feasibility of constructing masks for a correlation spectrometer designed to detect atmospheric iodine (described below).

d. Background and Discussion

This concept was put forth in earlier NASA-sponsored work by Barringer et al. (Refs. 3 and 24). Preliminary tests were run on the ground, looking horizontally and slightly downward over the producing Midway-Sunset oil field, and a plume of I_2 was reported over and downwind of the field.

Iodine is known to be concentrated in formation waters associated with some but not all petroleum deposits (Ref. 21). The iodine concentrations are believed to have originated from marine organic deposits. Marine plants are very efficient at concentrating iodine from sea water. Petroleum also

*The problem number corresponds to that in Appendix D where the problem is discussed.

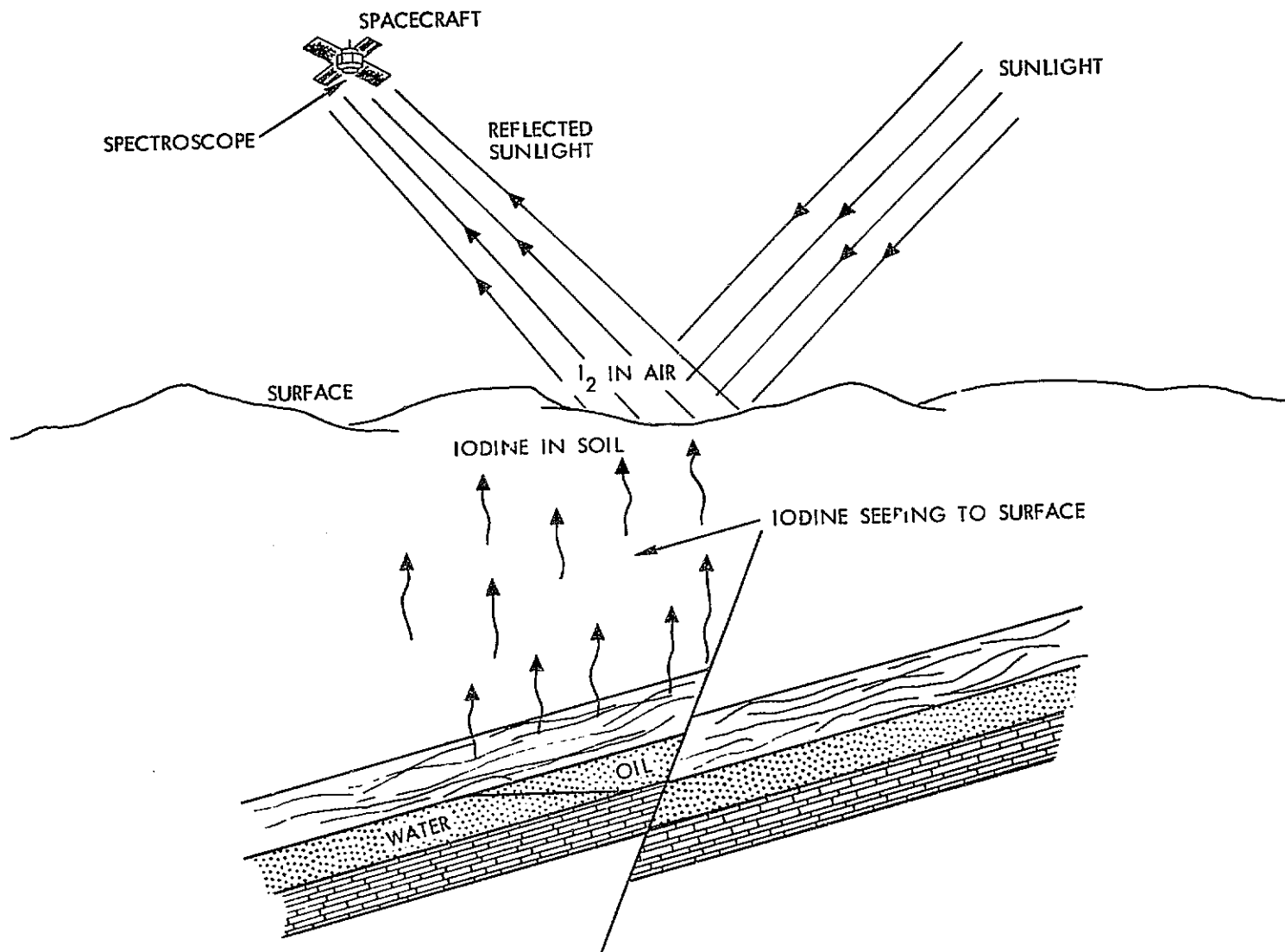


Figure 3-E-1. Exploration for Subsurface Petroleum by Remote Sensing of Atmospheric Iodine over Potential Oil/Gas Reservoirs

originates from marine organic deposits and thus, the correlation. Presumably the iodine in the form of iodide in aqueous solution diffuses or is convected to the surface (perhaps on a geological time-scale). It may then be oxidized, probably biochemically, by atmospheric oxygen and released to the atmosphere or, alternatively, released biochemically as methyl iodide, for example, and then photolytically dissociated or oxidized. H. Cannon and J. H. McCarthy, Jr., of USGS (Denver) have indicated (oral communication, 1976) that biochemical transfer of iodine from soil to air probably occurs. Younger marine sediments overlying possible petroleum reservoirs may interfere with the use of the process to detect petroleum remotely.

More recent work (A. R. Barringer, personal communications, 1976) suggests atmospheric I_2 concentration anomalies and the presence of other correlatable chemical elements (including all chemical states of iodine) in the aerosol over an undrilled prospect subsequently found to contain oil. The latest field trials tend to indicate that atmospheric I_2 anomalies by themselves are not the best indicators of subsurface petroleum; however, iodine is the most critical element in a multiparameter geochemical discriminator (see Appendix R). If that is the case, it would be a fortunate coincidence since I_2 has an appreciable vapor pressure at ordinary temperatures and very low concentrations can be detected in the atmosphere*. The background levels of I_2 are extremely low, (0.05-0.5) g/m^3 (Ref. 25).

The iodine technique is especially attractive in that it offers a possibility of detecting, with some sensitivity, indications of underground petroleum remotely from aircraft or spacecraft using spectroscopic instruments to be described later. Thus, it might considerably reduce the cost of finding petroleum. Furthermore, an aerial sampler could quickly acquire aerosol over a wide area to bring back to some sensitive microanalyzer to determine the surface composition (Ref. 26). Provided that there really exists a dependable multiparameter correlation with the occurrence of oil/gas fields, the spectroscopy as well as the microanalyzer results will indicate whether follow-through exploration should take place. Work on remote sensing of air pollution using similar types of instruments is underway under the sponsorship of the NASA Office of Applications and the Environmental Protection Agency (Ref. 27).

Readers interested in a more detailed critique should consult Appendix R.

e. Results/Technical Evaluation

Geochemical aspects left unresolved by previous work include (1) the availability of iodine in probable petroleum source sediments; (2) the mechanism of migration of iodine from these sediments, and the bearing this will have on the proposed association of iodine with petroleum; (3) the iodine concentrations in petroleum per se as opposed to subsurface waters; (4) the plausible explanation (mechanism) of why high-iodine brines display a preferred association with paleozoic but not with mesozoic oils (Ref. 21); (5) the role of hydrodynamics

*Since the highly toxic radio-active I^{129} may be a long half-life, low-concentration emission product from nuclear reactors, ERDA is greatly concerned with advancing the state-of-the-art of gaseous iodine detection.

in controlling iodine distribution and especially its expulsion to the surface; (6) the mechanism of iodine release to the atmosphere; and (7) the ground-truth verification of the reported atmospheric I₂ concentration anomalies. The solution of these problems will help establish a sound geochemical basis for the proposed exploration technique.

There is as yet no satisfactory explanation of how I₂ may migrate more or less vertically (to be useful as a geochemical indicator) from the underground brines to the surface nor is it fully understood how many of the other elements found to be correlated with oil fields find their way to the surface and from there to the local aerosol. It is worthwhile to point out that most of the geochemical reasonings against vertical transport of chemical species correlatable to subterranean oil/gas reservoirs are based on recent hydrodynamic flow and gradient regimes and on highly eroded and metamorphosed surface lithology. It is important to remember that existing lithological structure may indeed be quite different from the original lithology overlying the hydrocarbon reservoir at the time of initial hydrocarbon entrapment. It is well known that sudden removal of overburden by rapid glaciation may indeed give rise to exhumation of underlying strata and extensive vertical cracks and faulting which could conceivably give rise to vertical transfer of correlatable chemical species either in gaseous form or in solution. Laboratory simulation of compaction sediments under suitable conditions has demonstrated selective pore filtration of different chemical species.

If iodine is an indication of petroleum, the source of I₂ vapor should be determined further. If organic iodine compounds originate from plant metabolism, it might be feasible to determine them directly by remote sensing. It is rational to believe that unless an anomaly can be documented with "ground truth" data, the likelihood and usefulness of anomaly detection by remote geochemical sensing are meager. It is known that for some vapors there is a great enrichment in the soil relative to the atmosphere. This enrichment is evidently associated with physical adsorption of the element on the soil particles and may sometimes amount to a factor of 50 (Ref. 28). This indicates that the search for field areas for remote-sensing tests should be preceded by soil-gas profiling using some of the instruments described in Appendix R.

f. Cost

Development costs including hardware development and field testing are estimated at \$325,000. Most of the development costs are for modification of existing remote-sensing optical spectrometers and breadboarding of an aircraft-mounted version. Commercially available current in-situ aerosol samplers have adequate performance characteristics and need no further development. The capital cost of truck-mounted soil sampling and survey equipment is estimated to be \$100,000. Costs of using the method, once developed, are estimated to be \$25,000 per 100-square miles of surveyed terrain. The cost will include equipment mobilization, ground-based survey, laboratory work and data processing by a service company. The time required for a 100-square mile survey employing three people is 1 week followed by 2 weeks of laboratory work and data processing.

g. Findings and Aerospace Contribution

The concensus among those contacted during this study seems to be that is is worthwhile to look for a multielement inorganic/organic chemical discriminant (fingerprint) over potential oil/gas fields.

The system would work best under the following conditions:

- 1) On shore, away from the ocean.
- 2) Uniform albedo over the area.
- 3) Mild wind conditions.
- 4) Petroleum reservoirs not overlain by young marine sediments associated with glacial drift.
- 5) Vertical or local hydrodynamic gradient and regional hydrostatic conditions.
- 6) Iodine-rich oil field brine and ground water, not recharged by meteoric sources.
- 7) Large oil reservoirs shallower than 5000 feet with somewhat permeable and fractured overlying lithology.

If correlation of I_2 in air and other chemical species in aerosol with undrilled or unproduced petroleum reservoirs can be confirmed, the probability of proving the technical feasibility of this geochemical technique within the next 3 years is very good. Aerospace experience can provide expertise in spectroscopy of iodine and remote sensing of atmospheric constituents which will be needed for establishing such a feasibility. Instrument development is another possibly applicable area of aerospace technology. The suggestion of using atmospheric I_2 as an indicator of petroleum, and of optical spectroscopy to detect the I_2 remotely, originated in the course of aerospace work.

h. Recommendations

It is recommended that a program be initiated on in-situ measurements of iodine over areas expected to be drilled. Details are given in Appendix R.

TOPIC F: SEA-FLOOR IMAGING AND MAPPING

Concept 20: Acoustic Imaging of Large Areas of the Sea Floor

Concept 21: Detailed Bathymetric Charting

Statement of Concepts:

Sea-Floor Imaging: An integrated system to provide high-quality images of large areas of sea floor. It employs a high-powered side-looking sonar carried by a towed "fish", to provide sonar image data over a 2-km range and with resolution comparable to Landsat imagery (50-meter element size). The sonar data are recorded digitally on magnetic tape. They are computer-processed by techniques developed for spacecraft optical and side-looking radar data to provide enhanced high-quality images of the sea floor on photographic paper or film.

Detailed Bathymetric Charting: An integrated system to provide detailed bathymetric charts and shaded relief maps. Conventional echo-sounding equipment provides bathymetric data along closely spaced tracks of a chosen survey pattern. The sounding data and precision navigation data are recorded digitally on the same magnetic tape. They are processed to provide computer-drawn bathymetric contour charts and computer-produced shaded relief maps.

1. Problems Addressed*

The problems addressed by these concepts are

Topographic mapping of large areas of sea bottom (Problem 1).
Detecting surface geological expression of possible traps (Problem 5).
Cheaper offshore reconnaissance methods (Problem 47).

2. Needs

Current hydrographic standards of the National Ocean Survey do not provide for sufficiently close-spaced measurements of ocean depth to provide a definitive determination of the bottom topography. The need for better topographic information about the sea bottom falls into two categories:

*Problem numbers correspond to those in Appendix D where the problems are discussed.

- 1) Needed are images of the sea bottom that will enable geologic interpretations of regional areas and detection of surface geological expression of possible traps. The resolution of these images should probably be comparable to that provided by Landsat imagery and should cover the whole region of interest to the desired water depth. These images are needed in the early stages of exploration to determine geologic formations of interest and resonance potential but would also find use in site selection and engineering operations.
- 2) Bathymetric charts of the ocean floor are required to provide topographic detail in addition to more accurate depth and position delineation of sea-floor features than on presently available charts. More accurate depths are needed to plan production facilities and to avoid underwater obstacles in the areas under consideration for platforms and pipelines.

3. Study Approach

The study approach included examination of literature on sonar, sea surveying, and remote sensing. Conversations were also held with experts on offshore exploration and sea-bottom mapping. Concept synthesis and analysis based in part on prior oceanographic experience, were also employed.

4. Results

Detailed results are given in Appendix S. A summary follows. A system functional block diagram that provides sea-floor imaging and bathymetric charting simultaneously is shown in Figure 3-F-1.

a. Sea-Floor Imagery

The study noted that side-scan sonars installed in a towed "fish" can provide acoustic images of the sea floor. Present commercial units can provide coverage swaths up to 800-meters wide (400-m range each side). These units can provide resolutions order of magnitude finer than the Landsat element (80 x 80 m) thought to be needed for this application.

A sonar with a range of 2 km would be appropriate to the petroleum-exploration effort and could be used to the maximum range in 300-m deep water. The range would be proportionally less in shallower water. This sonar would have to be developed, as present units are either short-range or very long-range; a deep-water unit of 22-km range is being used in research work.

At the 2-km range, 50-meter element coverage could be achieved at 38 knots if acoustic noise and ship capability permitted. At the more practical speed of 10 kts, 900 km²/day could be imaged in 300-m deep water.

The received sonar signals would be digitized and stored on magnetic tape. Corresponding positional data would also be stored on the tape. An accurate locating system, such as satellite navigation augmented by LORAN-C in the rho-rho mode, would be needed to provide the positional data.

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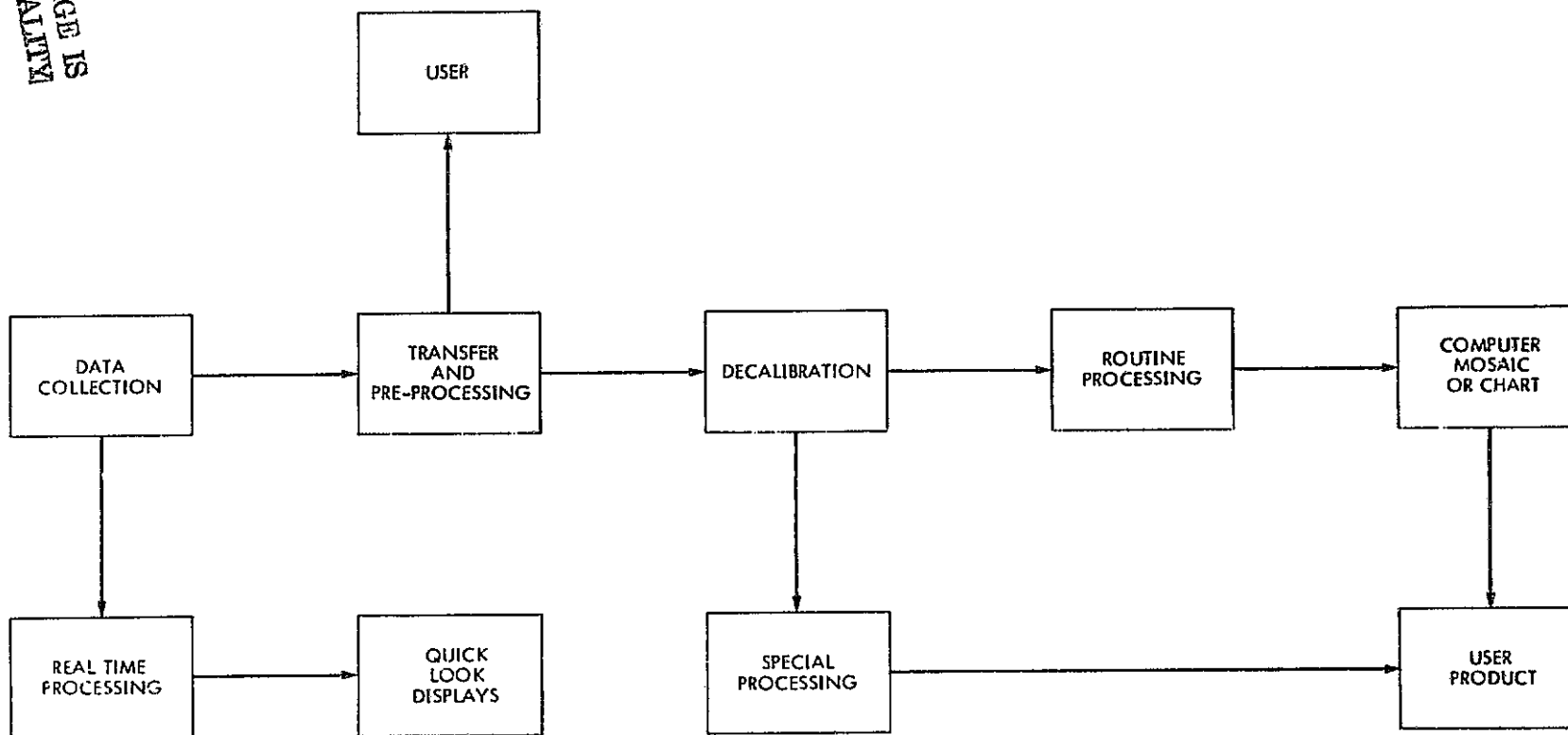


Figure 3-F-1. System Functional Block Diagram for Sea-Floor Imaging and Charting

3-F-3

A quick-look capability would be provided aboard ship to insure proper system operation and real-time decision data for the conduct of the survey.

The sonar data tapes would then be computer-processed by techniques developed for NASA planetary imaging programs of the earth, moon and other planets. These techniques lead to high-quality photographic prints. These image-processing techniques provide for a substantial amount of user interaction enabling the emphasis of particular features of interest.

b. Bathymetry

The implementation mode for bathymetric data collection may be by surface ship (boat) or an instrumented towed submersible "fish." The primary instrument will be a commercially available echosounder, with digital tape recording. This measures and records water depth below the sounder. If a towed "fish" is used, then a measurement of the "fish" depth (pressure gage or up-looking sonar) is required to be added to the echosounder value to obtain total water depth.

Coverage is solely along the track. The accuracy of measurement is about 1 part in a 1000. The cone or pyramid covered by the sound waves is usually about 200 mrad between the half-power points, or an area with linear dimension on the sea floor equal to 20% of the depth. The quantity measured is the shallowest depth within this area. The track (survey line) spacing to be used is dependent upon the required data and bottom characteristics (slope, average depth, material, etc.). Bathymetry measurements are not limited by ship speed but by acoustic noise and ship capabilities. Since the area to be evaluated during site surveying for rigs or pipelines is usually limited, coverage per day may not be a prime consideration. Position accuracy and close spacing of survey tracks to provide topographic detail of the sea bottom are likely to be more important.

Site and pipeline bathymetry surveys require a more accurate positioning system than that needed for side-scan imaging. Numerous high-accuracy--radio, radar, and acoustic--beacon or transponder systems are available.

The bathymetry and position data would be digitally recorded on magnetic tape for preliminary real-time processing, if desired, and subsequent definitive processing. A quick-look depth monitor would also be provided.

The subsequent processing of the depth and position data to yield bathymetric contours is current practice. Processing of the bathymetry data to generate computer-produced relief maps, with controllable shading to emphasize the relief, would be added using currently available aerospace techniques.

c. Combined Imagery and Bathymetry System

As stated earlier, the system can be designed to take bathymetry and side-scan image data simultaneously. Bathymetry would be obtained at wider spacings than the side-scan imagery. The depth data would provide useful inputs to the side-scan sonar processing. The depth data would allow more precise slant-range corrections to be made to the sonar images thereby allowing preparation of truer images of the sea-bottom and facilitating the production of regional mosaics.

Also possible are systems that combine side-scan sonar imaging and bathymetry with shallow seismic surveying. If this is done, the ship speed would be limited by the constraints of side-scan imaging and precision hydrographic surveying.

5. Costs

Shown below are the budgetary estimates for developing the system hardware and software. It is understood that navigation equipment may already be available aboard a survey ship, and hence, this cost may be deleted.

a. For Sea-Floor Imagery*

Development		
System design, development, and integration		\$150,000
Side-scan sonar		\$500,000
Software		\$ 25,000
Total, development		\$675,000
Shipboard equipment		
Sonar interface, record, display		\$ 50,000
Navigation and location equipment (if not already aboard)		\$250,000
Operation		
Ship at \$6000/day	or	\$ 7/km ²
Data Processing		\$20/km ²

b. For Bathymetry**

Development		
System design, development, and integration		\$ 75,000
Software		\$ 15,000
Total, development		\$ 90,000
Shipboard equipment		
Echosounder and associated equipment		\$ 10,000
Navigation and location equipment (if not already aboard)		\$250,000
Operation		
Ship at \$6000/day	or	\$250/km ²
Data Processing		\$ 5/km ²

*Based on side-looking sonar having 2-km range with 50-m element size, area coverage 37-km²/hr at 10 knots.

**Based on echosounding at 75-m line spacing, area coverage of 1-km²/hr at 15 knots.

b. Findings

a. Imagery

Imagery of the sea floor comparable in quality and superior in resolution to Landsat imagery can be provided by side-scan sonars with digital recording capability and subsequent data processing. Such a system is within the present state-of-the-art and estimates of operational and data-processing costs are moderate.

An arbitrary resolution of 50-meter element coverage at a 2-km range was established during the study for the purpose of achieving agreement from petroleum geologists that this or some other resolution would provide sufficient detail in the image for geologic interpretation. However, individual geologists gave widely different estimates of the resolution needed to identify adequately the morphology of the sea-floor. Part of the difficulty was that petroleum geologists are generally unfamiliar with sonar- and image-processing capabilities and techniques. Therefore, a requirement for the resolution that the system must achieve remains to be established. This would have to be decided prior to the design and fabrication of equipment and would have a marked effect upon the operating and data-processing cost per square kilometer. For further information, Appendix S discusses side-scan sonar performance characteristics.

b. Bathymetric

Bathymetric data can be obtained with commercial equipment, and computer-generated contour charts are quite common. These charts can be useful in exploration surveys and construction operations to avoid navigation and other hazards if the soundings are made on closely spaced grids with precision echosounders. The depth accuracy of commercial echosounders appears to be adequate for petroleum requirements, and the survey-line spacing can be established based on survey and system equipment costs. Aerospace data-processing techniques can be used to generate bathymetric charts and relief maps of the sea floor from the digitized bathymetry. Appendix S discusses bathymetry techniques and echosounder performance characteristics.

7. Advantages in Exploration

Sea-floor image mosaics, shaded relief maps, bathymetric charts, and other diagrams obtained with the suggested system could be used for two main purposes: (1) geologic interpretation of sea-floor topography and morphology and (2) operations and construction planning.

1) Geological Interpretation of Sea-Floor Topography

- (a) Side-scan sonar images that are enhanced and processed to produce controlled mosaics can aid exploration reconnaissance through extended regional coverage, improved resolution, and minimized image distortion. Having this imagery at a resolution comparable to or better than LANDSAT photos, the geological interpreter can evaluate, map, and describe the sea floor; recognize its structure (such as faults and folds, anticlines, domes, and synclines), rock types and outcrops; and note other anomalies for further, more

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detailed investigation. Image enhancement techniques which can emphasize the geologic structure and anomalies can greatly increase the potential for locating oil and gas deposits as well as potentially valuable minerals.

2) Operations and Construction Planning

(a) Better and more detailed bathymetric data can improve operations and construction planning in the areas noted below:

- (1) Engineering can better plan the structural design of bottom-mounted production platforms to suit the sea-floor contour.
- (2) Selection and preparation of the best pipe-laying route to shore.
- (3) Knowledge of where underwater hazards are and what risks they represent to operations.

8. Aerospace Contribution

Aerospace contribution includes technology for digitally processing and enhancing imagery and for transforming this imagery into high-quality photographic and mosaic products and computer-produced shaded relief maps. It also includes the technology of systems engineering and integration, plus instrumentation expertise.

9. Recommendations

The demand and requirements for a sea-bottom imaging system like that described should be verified and established. Test, development, and demonstration should then be initiated along lines outlined in Appendix S.

G. COST-BENEFIT ANALYSIS

The plan for this study called for a cost-benefit analysis of the presented concepts. This is common in aerospace work. Costs have therefore been estimated to the extent that seemed possible and are given in the preceding discussion of each concept. Estimating benefits in a quantitative way (e.g., dollars or percentage) has proven difficult, however.

The benefits can be placed in two categories: those that reduce cost and those that yield better information. That is to say, some concepts would perform a function equivalent to an existing system but at a lower cost; others would enable the acquisition of information that could previously not be obtained. This point is important because exploration is, essentially, a process of obtaining information.

We attempted to approach the problem in two ways: One used a formal methodology commonly referred to as a "decision-theoretic Bayesian" analysis. The other was an informal procedure of soliciting opinions and comments from the petroleum industry and petroleum service industry.

The decision-theoretic analysis looks at the exploration as one which is inherently uncertain: one seeks potential sites, but at any site one is uncertain whether or not any oil exists, and if it does, one is uncertain as to the size of the field. In this light, the performance of an exploratory survey is seen as purchasing information to reduce the uncertainty associated with a given site. Once the uncertainty has been decreased, the decision-maker is in a better position to judge the attractiveness of a prospect than he was previously.

The earliest references to this approach were circa 1960 (Ref. 29), and the process has been discussed extensively in the literature since. It is illustrated in Appendix T. The method is a formal and sound way to approach the problem of evaluating an exploration concept. For this application, the approach requires as input, the judgement of one or more exploration experts as to how the evaluation of a variety of prospects would be affected by the information that the method could provide. Thus, subjective judgements are involved, but they are utilized in as efficient a way as possible.

An attempt was made to apply the decision-theoretic approach to one of the concepts suggested in this study. This attempt, documented in Appendix T, showed that considerable effort and time would be needed to evaluate even one concept in this way. To evaluate 21 concepts by such a procedure was, clearly, not possible with the resources available for this study.

Accordingly, the less costly process of industry interviews was tried. The philosophy underlying this approach is that those who will choose, use, and pay for a proposed technique should be the judge of the benefits to be expected from its use. Accordingly, a series of questions concerning the economic benefits to be expected from successful development of each concept was prepared. (The questions are listed in Appendix V.) These questions were addressed in the course of interviews to knowledgeable executives and managers engaged in petroleum exploration and to individuals who would be responsible for a decision to use the concepts developed. Several difficulties emerged.

The first problem encountered in interviewing industry personnel was their understandable lack of familiarity with the suggested concepts. This made it extremely difficult for them to evaluate a concept's potential benefits. To familiarize themselves with all of the 21 concepts would take a long time. Closely related to this problem is the fact that the concepts exist only on paper. Thus, even if one took the time to familiarize himself with the concepts, there would still be a tremendous amount of uncertainty associated with the feasibility of building such a system and therefore even more so with system performance.

One can consider three stages of development: an "on-paper" stage; a working-model, proof-of-concept stage; and a mature, in-use stage. It is at the final stage that the industry decision-making processes are best established and most practiced; it is an everyday occurrence to judge the value of a survey of a known level of quality and to decide to use or not to use it on the basis of its cost. It is a bit more difficult to evaluate a concept at the working-model stage, as practicality of the concept, its acceptability, and its actual wide-scale use in the field are uncertain. At the on-paper stage, any assessments are extremely "ifly" and tend to be highly qualitative. The uncertainty referred to above is commonly reflected in the comment that no one would be the first to use a new technique but that once somebody used it, they all would.

Some quantitative estimates of benefits were provided by the interviewed persons. Most of the estimates, however, were at best qualitative. The industry attitude has been summarized by F. Sabins (Ref. 30): "Many different geological and geophysical methods are used before a wildcat well is drilled, and today, it is unrealistic to credit an oil field discovery to a single method or individual. For this reason, experienced explorationists react with amusement and disdain to press releases announcing 'New...technology will find oil fields, ore deposits, spot crop diseases, etc.' The reader can insert any remote-sensing method in the blank space and have a recognizable press release. Such announcements hinder the acceptance of new methods by experienced explorationists.

"I have been interviewed by a number of government-funded cost benefit surveys seeking to learn, in terms of dollars, how much our company (or the industry) has gained through using various remote-sensing methods. Oil exploration is a lengthy and complex process. Attempting to assign a dollar value to a single exploration activity is a futile venture, and any estimates are of doubtful significance."

It appeared impractical, therefore, to obtain adequate and meaningful quantitative estimates of the benefits to be expected from development and utilization of each concept. The qualitative comments made in the interviews were useful, however. To these were added the oral and written comments made by participants in the workshops and advisory panels and by other industry and university contacts. These comments were used generally in preparing and revising this report and specifically in drawing up the list of benefits included in the discussion, above, of the individual concepts.

SECTION IV

CONCLUSIONS, RECOMMENDATION, AND PLANS

A. CONCLUSIONS

The following conclusions have been reached:

- 1) In discussions during this study, members of the petroleum industry and petroleum service industry identified a large number of exploration problems.
- 2) Preliminary assessment indicated that aerospace techniques may be of help in solving some of the significant problems.
- 3) More detailed consideration led to 21 concepts for problem approach employing aerospace techniques. These fall in the areas of seismic-reflection systems, down-hole acoustic techniques, geological analogies, drilling, remote geochemical sensing, and sea-bottom topography, as follows:

	<u>Concept No.</u>
<u>Topic A: Seismic-Reflection Systems</u>	
Systems approach to seismic prospecting	1
Seismic sources:	
Swept-frequency explosive source	2
Swept-frequency solid-propellant source	3
Oscillation-free bubble source	4
Oscillation-free implosion source	5
Aerial seismic survey	6
Telemetry of data from ship to computing center	7
Data processing:	
Low-cost data-processing system	8
High-resolution seismic system	9
Time-delay spectrometry	10
<u>Topic B: Down-hole Acoustic Techniques</u>	
Down-hole seismic tomography	11
Acoustic backscatter log for fracture patterns	12
<u>Topic C: Geological Analogies</u>	
Improved computer aid in recognizing geological analogies	13

Topic D: Drilling Methods

Automated drilling rig	14
Improved high-pressure drilling	15
Resonant-vibration drilling	16
Improved down-hole drill motors	17
Combustion-fracture drilling	18

Topic E: Remote Geochemical Sensing

Remote optical spectroscopy of airborne iodine and other indicators	19
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Topic F: Sea-Floor Imaging and Mapping

Acoustic imaging of large areas of the sea floor	20
Detailed bathymetric charting	21

B. RECOMMENDATION

It is recommended that further effort be directed toward development of those concepts on the above list that appear of interest to the petroleum industry and petroleum service industry.

C. PLANS

This report concludes the study effort that has been funded by the NASA Office of Energy Programs. Any further development of the concepts outlined will depend on the interest of government or private organizations in supporting further work.

The concepts have been developed only to the extent detailed in this report with its appendices. They are believed to be technically feasible. Some of the concepts could now be taken up by the petroleum exploration and service industries for further development. Others would probably require further participation by their designers. All would need development and demonstration as indicated in the report before they could enter exploration service.

NASA's ultimate goal in initiating this study was to attain routine use of aerospace technology in petroleum exploration; this study was pursued to that end. NASA and JPL will therefore actively encourage those interested in further development and utilization of the concepts which emerged from this study.

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