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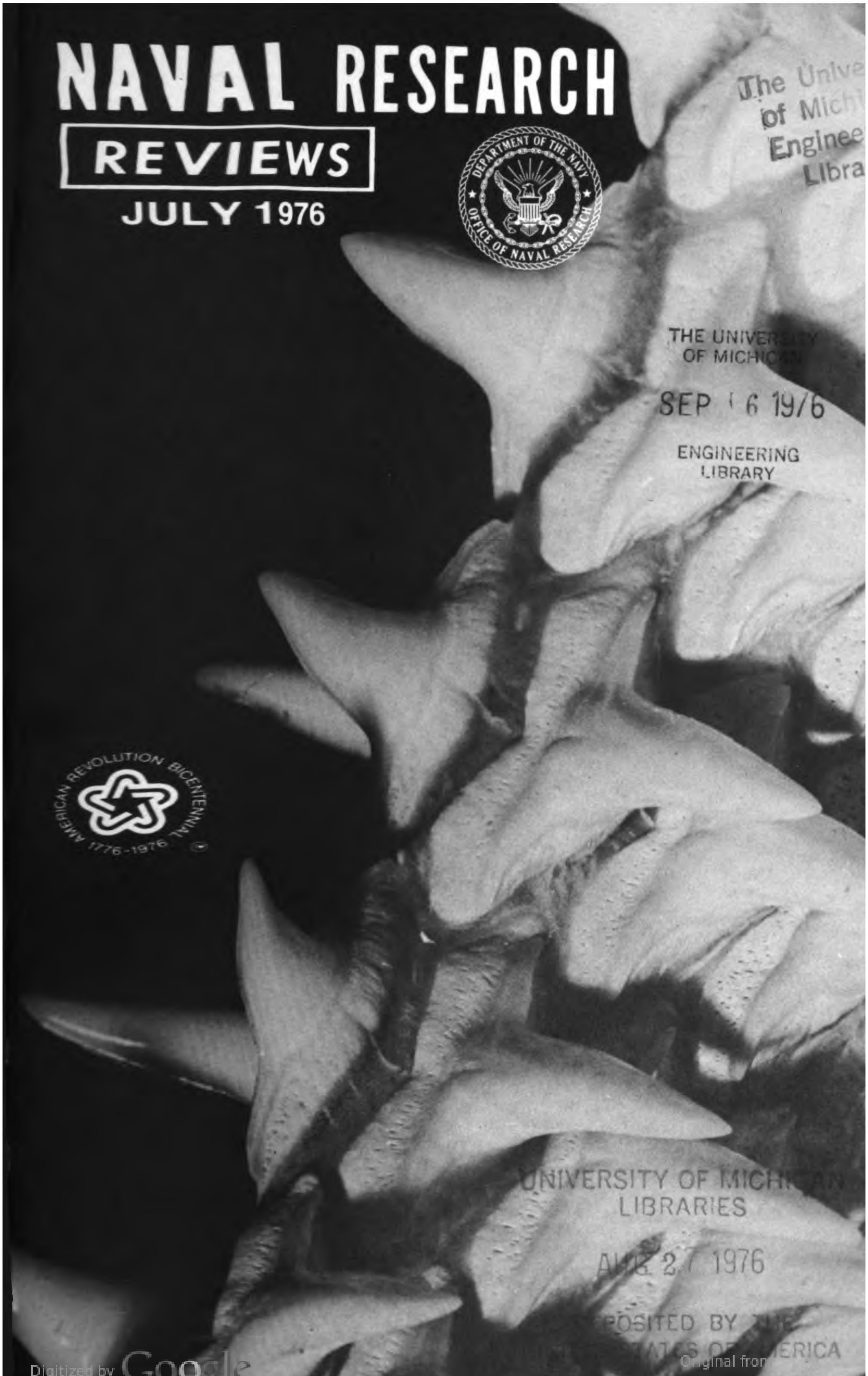

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PROFILES IN SCIENCE

Dr. Alphonse Chapanis

Dr. Alphonse Chapanis, Professor of Psychology at the John Hopkins University, is widely recognized as a founder and pioneer in the field of human factors engineering. He has authored many books and articles in general experimental psychology, vision, experimental design, and human engineering. Dr. Chapanis has served as consultant to several governmental and industrial organizations, including the National Research Council's Committee on Undersea Warfare and the NRC Vision Committee. In 1960-61 he served as a Liaison Scientist at ONR, London. His current research on telecommunications and teleconferencing, supported by ONR, is attracting widespread attention.

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Behavior of Sharks — A Continuing Enigma

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The aggressive behavior of sharks towards humans and their possessions has been of great concern for many years. Yet only rather recently has there been a concerted effort to gain factual information about the functional biology of this group of animals so that man might gain, not only insight into the role played by such animals in the ecology of the oceans, but also knowledge that might reduce shark hazards (1-3). Despite this effort, however, our most profound ignorance still centers on that one aspect of shark biology that relates most directly to that hazard—their behavior.

A few moments consideration will, however, clarify why this is so. Knowledge about the behavior of any animal requires, in most instances, direct, detailed and repetitive observation. This is especially the case when information is needed about moment-to-moment sequences of behavioral activities or how such activities are affected by specific environmental factors. The necessity for such observations requires, in turn, physical facilities that are adequate not only for the controlled scrutiny that given experiments demand, but also in the quality of conditions with which experimental animals must contend during, as well as between, experimental sessions (Figure 1). If one is interested in determining only the capability of a sensory system such as vision, smell or hearing, or the message-carrying capacity of a nervous system, the demand to reflect natural state conditions is reduced in priority since any fact arising from such a study will tell us only what that system can or cannot do under the conditions of testing; it will tell us nothing about how the animal will use that system as it moves about in its natural state. Also, studies of capability often require precise determination of the limits at which a factor will affect a given sensory or behavioral system, and this preciseness, in turn, demands controlled conditions that are at variance with those encountered, for the most part, by an active animal in its natural habitat.

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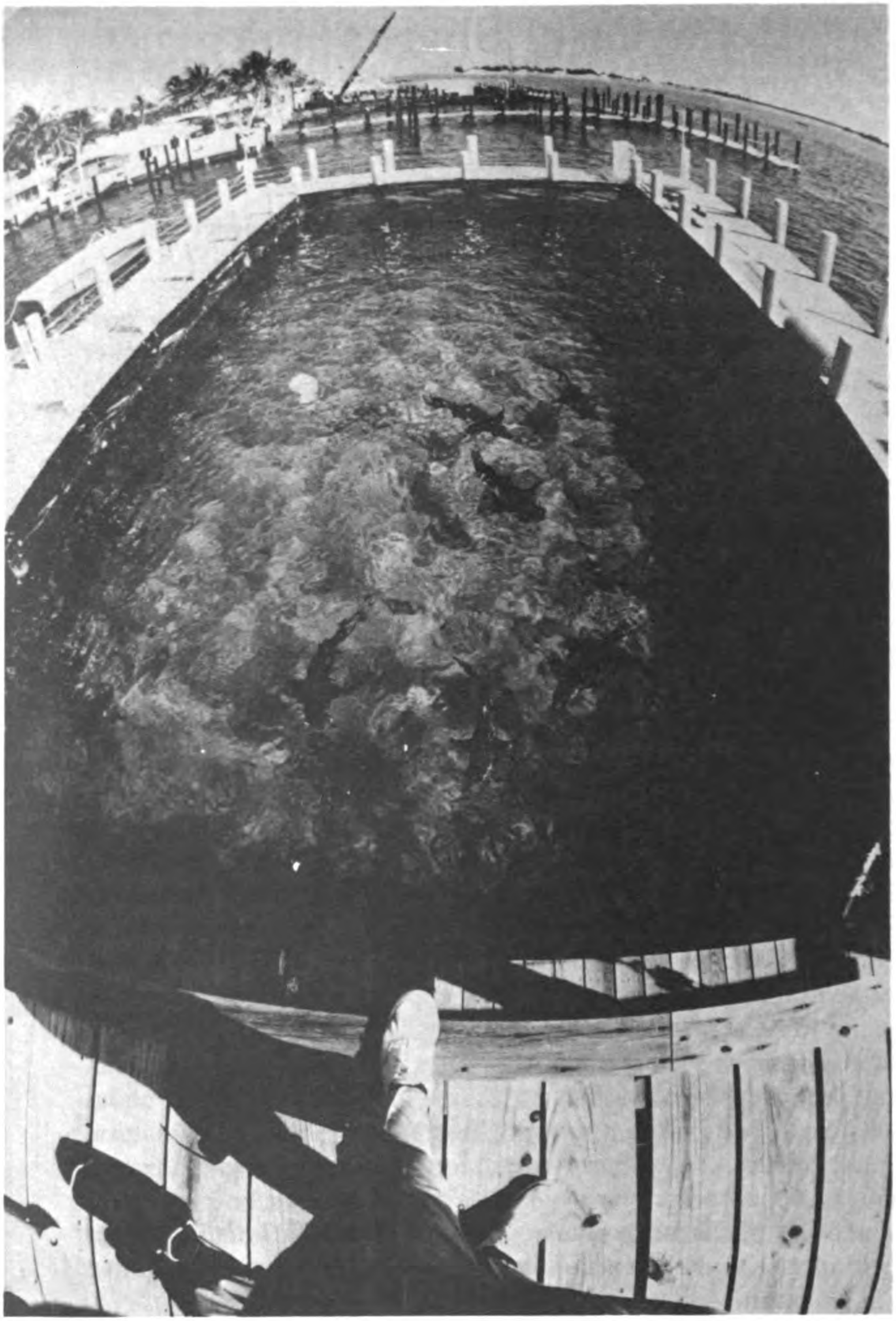

Figure 1 — Example of open water shark pens for maintaining sharks under semi-natural conditions. Photo taken at the Lerner Marine Laboratory of the American Museum of Natural History of Bimini in the Bahamas. (photo by Edward S. Hodgson).

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On the other hand, when one wishes to determine facts that are directly applicable to a given species in the natural state, the demand for facilities mimicking such conditions increases dramatically. And the degree to which laboratory findings attain validity, in this respect, is often correctly judged not only by the precision of the measurement but also by how accurately the laboratory conditions, themselves, reflect those of the natural habitat. If these conditions differ greatly, such findings again must relate only to behavioral or sensory capability—and not to that of actuality. Thus, to study the behavior *per se* of an animal or those factors which affect that behavior in hopes of applying relevant findings to events in the animal's "real world," conditions must be chosen carefully, and this, of course, assumes that the scientist already possesses sufficient knowledge to recognize the appropriate natural state conditions.

With these few points in mind, let's return to the subjects of this report—sharks. If we wish to learn about the behavior of sharks and to have a store of knowledge that is based on a commonality of repetitive findings and appropriate controls rather than on the ever-present, isolated stories and speculations that inspire fascination, sensationalism and momentary interest, it's obvious that adequate facilities are needed, not only for holding and observing sharks, but also for capturing and transporting them to such facilities. Yet, what is an adequate facility? It has long been known that almost all species of gray or requiem sharks, i.e., those of greatest immediate interest to man, succumb rapidly in the usual laboratory setting. Members of most species can be kept, if by good fortune brought in alive, for only a day or two in restricted enclosures before death overtakes them—even when these enclosures are quite large. Others show obvious signs of distress within a few days but they die more slowly—lasting a few additional days or perhaps a few weeks. Although data can, indeed, be obtained on such animals, any behavioral scientist worth his salt, would not equate interpretations and conclusions, based on data obtained from obviously distressed or dying sharks, to knowledge about adaptive behavior as carried out by those members of the species found in their natural state.

One can, of course, ask the reasonable question—what constitutes a healthy animal or how can one tell a distressed shark or one that is, in fact, dying? In some cases, the answer would be obvious to almost anyone who has minimal observational experience with members of the species in question; and as the hours progress, the answer would probably become even more obvious. In the majority of cases, however, the answer must rest with a judgment that is based on experience gained from concentrated observations of the behavior of a given species in a variety of situations over tens, hundreds, or even thousands of hours. This is where the term "expert" is truly deserved and applied in the field of behavior. One can surely become knowledgeable in behavioral methodology and theory by reading and assimilating the established works of

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others, but there are no books or published studies that will ever provide expertise on the behavior of any animal. And it is just that expertise, along with a reasonable knowledge of methodology and theory, that results in the elegant and conclusive experiments that are based not on intuition, luck, or genius, but rather on knowing the behavior of a given species to such an extent that the experimental result is not what is in question—rather it is the manner in which the experiment will be run so that the answer will be forthcoming in a clear, repeatable, and efficient manner.

So let's, for the moment, assume, albeit incorrectly, that ways were known that would allow the requiem sharks and their relatives to prosper in either the laboratory or even under semi-natural conditions. Would our frustrations end? Unfortunately, no. We now run straight on into the next problem, viz., that those species of primary interest to man are of such a size and mobility that the facilities and personnel required just to maintain them would demand such a financial investment that high returns might well be expected shortly. Yet, since behavioral studies demand, initially, a broad-based descriptive foundation preceding experimental manipulation, and considering the state of our present knowledge, the time required would probably be looked upon with some misgivings for the entire venture.

An obvious alternative to the above frustrations is to leave such problems and move behavioral studies into the field and enter the sharks' own environment; there adapting whatever materials and methods that are available to the new restrictions that invariably accompany any biological field study that demands accuracy of findings. In the case of sharks, these problems increase dramatically since their range of movements is often quite large, and this prevents continual direct observation. Even the best thought-out study may be completed in 3 weeks, 3 months, or 3 years, depending on uncontrollable conditions such as vagaries of movement and the weather. Also, direct observation often requires one to enter the ocean and remain in the near vicinity of large, unrestrained sharks. Safety precautions become paramount so as to prevent mishap, caused by the sharks, themselves, or by the ocean. The above points perhaps clarify why there are so few scientists willing to pay the exceptionally high price to study the behavior of this highly interesting group of animals. Thus sharks comprise one of the last remaining large groups of animals, commonly known to man, that have consistently evaded his attempts to gather direct behavioral information. What little solid information there is has come from relatively few scientists, along with their dedicated students, who have faced these formidable problems and have brought forth, nevertheless, reliable and often startling information.

The following paragraphs provide a relatively brief summary of findings obtained by various workers in recent years that relate directly to the

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behavioral activities of sharks. For the most part, these studies have been carried out on the young or small juveniles (less than one meter in length) of a few of the hardier species known to science. Although some of these species certainly do not possess the reputation of the requiem sharks, they nevertheless indicate the sophistication of sensory and behavioral capabilities possessed by those animals. Such studies have been almost invariably directed at sensory functions since extrapolation to other life stages is easier at that level than is often allowed at the strictly behavioral level. This is due to the reasonably well known fact that the behavior *per se* of a young shark is oftentimes far different from that shown by a mature individual of the same species.

A few studies will also be mentioned that have dealt with adult sharks in the field, as well as in large enclosures. Studies incorporating both of these techniques for the same problem, are probably the most difficult to organize, schedule, and carry through to completion—but the positive feedback that results from the knowledge gained in these quite different situations eventually pays off, I believe, in greater dividends.

It's commonly believed that sharks and other elasmobranchs are inferior to bony fishes and higher vertebrates in the extent to which they can modify their behavior through learning processes. Recent work has demonstrated, however, that young lemon and nurse sharks can be trained as easily as many mammals, and they retain learned tasks for considerable periods of time. These sharks have undergone testing in discrimination learning as well as other operant conditioning tasks (4-6). Additionally, they do as well as mammals in another type of learning paradigm, i.e., classical or Pavlovian conditioning (7). In this latter case, they also show the typical events following cessation of reinforcement, i.e., extinction and spontaneous recovery of the learned association. Free-ranging Bahamian sharpnose and Pacific reef whitetips have also demonstrated a third type of learning process—habituation—during field tests of acoustic attraction. This "learning to ignore" an irrelevant stimulus is well known in many animals besides sharks, of course. Thus, sharks can clearly modify various aspects of their behavior, and such knowledge indicates that experiential factors may well influence the effectiveness of any technology intended to thwart or predict shark behavior, especially in a restricted area.

Yet, it is also known from recent work on a few species that sharks possess numerous species-typical patterns and postures of behavior that are sufficiently stereotyped in form and orientation that they can be easily recognized by observers (8, 9). The behavioral activities of all animals studied thus far by ethologists often include such discrete units, and sharks appear, again, to be no exception to the rule. The distribution and frequency of such patterns, when analyzed under specific situations, provide basic data for determining such functions as: (a)

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the type of social organization maintained by a group, (b) the predictability of events based on their sequential and/or temporal nature, and, finally, (c) the interplay between underlying motivational (physiological) systems controlling behavioral sequences.

One example of the importance of such patterns in predicting future events, as well as in gaining insight into the motivational control of behavior, can be noted from observations of the unique "hunch" postures of small bonnethead sharks, as well as the dangerous silky and gray reef sharks (8-10) (Figure 2). This particular pattern is, in fact, known to have preceded a number of attacks on man by the last mentioned species. The posture appears to occur in similar situations in all three species, viz., with the presence of a nearby intruder. The posture is suggestive of an expression movement of ambivalence between attack and withdraw, thus relating a condition of probable threat. Further examination of this posture and others shown by sharks may well provide needed information about the social interactions among sharks, as well as interactions between these animals and man, himself.

A second example of the usefulness of species-typical patterns and postures is shown by specific findings relative to the "give-way," as demonstrated by the bonnethead shark (9) (Figure 3). Analysis of its occurrence among members of a colony, studied in a very large enclosure, showed that a subtle, but clear social organization was operating among these animals, that organization being based on a straight-line, size-dependent, dominance hierarchy in which females were clearly cautious of males. Sharks are notorious, however, for their individuality and apparent lack of concern regarding events involving individuals of the same or other species. Although this may be true under certain circumstances, gross observations may be overlooking actual facts. Reports of social relationships, besides the often reported segregation of the sexes and segregation by size, may well increase in scope and meaning as observations continue (9, 11).

The best known facts concerning the behavior of sharks deal with their sensory abilities. All species studied, thus far, have demonstrated extremely sensitive chemical-reception. This has involved substances ranging in concentrations from parts per thousand to even one part per million (12). Evidence has also been brought forth that at least one

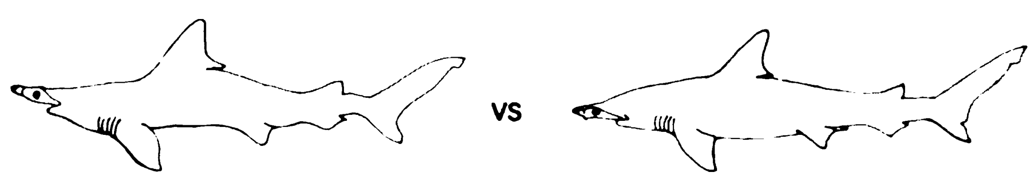

Figure 2. — Illustration of the "hunch" posture shown by bonnethead sharks; the normal posture of a patrolling bonnethead is shown on the right for the purpose of comparison.

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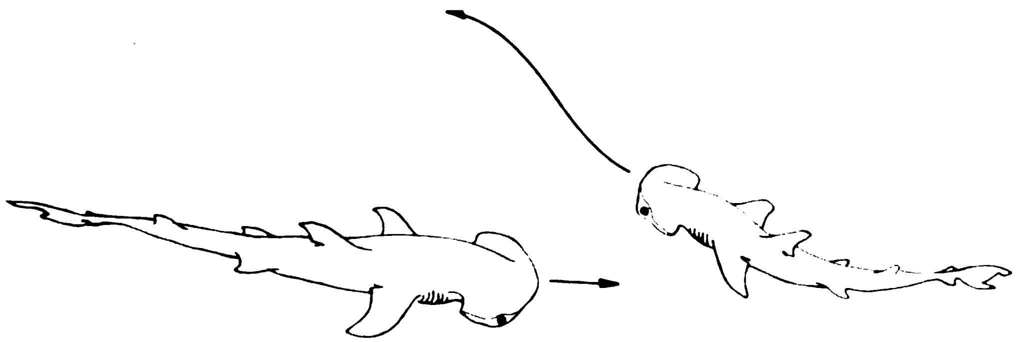

Figure 3 — Illustration of the "give-way" pattern, as shown by the bonnethead on the right, when confronting another bonnethead during patrolling.

carcharhinid shark could rapidly detect by chemical means alone water that had held healthy, free-living fish from that which had held these same fish, but following mild stress by having their container slightly shaken (13). These sharks, as well as other species, have also demonstrated their ability to follow olfactory "corridors," so long as the "trail" was still "warm" (14). On the other hand, extremely small concentrations of organic chemical factors may, in specific cases, result in refusal to feed, as noted recently in one species of requiem shark (15).

Finally, it has been shown that shark shave at least two methods of orienting to a chemical source, i.e., by direct orientation upstream (e.g., the lemon shark) or by successively noting the concentration gradient as they move directly to a given source (e.g., nurse shark) (16). It must be mentioned, however, that such studies of chemoreception, as well as studies dealing with other sensory capabilities, have been carried out on only four or five species out of some 200 to 250 species, and specific predictions, dealing with a species not yet studied, are unwise except at the broadest speculative levels.

The sense of hearing, in those few species of sharks tested thus far, is also excellent within the frequency range from 10 Hz to about 600-800 Hz (17-19). Although it's doubtful that these or other related species can hear frequencies above 1000 Hz (i.e., approximately high C on the piano), their sensitivity to sounds in the very low register, i.e., from 10 to about 40 Hz, is clearly many times better than that of man. Sounds, having frequencies within the region of 10 to 800 Hz, have been found to be highly attractive to numerous species of sharks, including many dangerous to man, e.g., the oceanic whitetip, the tiger (Figure 4), the bull (Figure 5), and the gray reef. Such sounds are especially attractive when they are rapidly and irregularly pulsed with no sudden increases in intensity (10, 20-24). Such animals orient rapidly to the sound sources and can cover 100's of meters in only 10's of seconds. Although the characteristics of such attractive sounds reflect those noted in the erratic hydrodynamic sounds made by fish when they are actively feeding,

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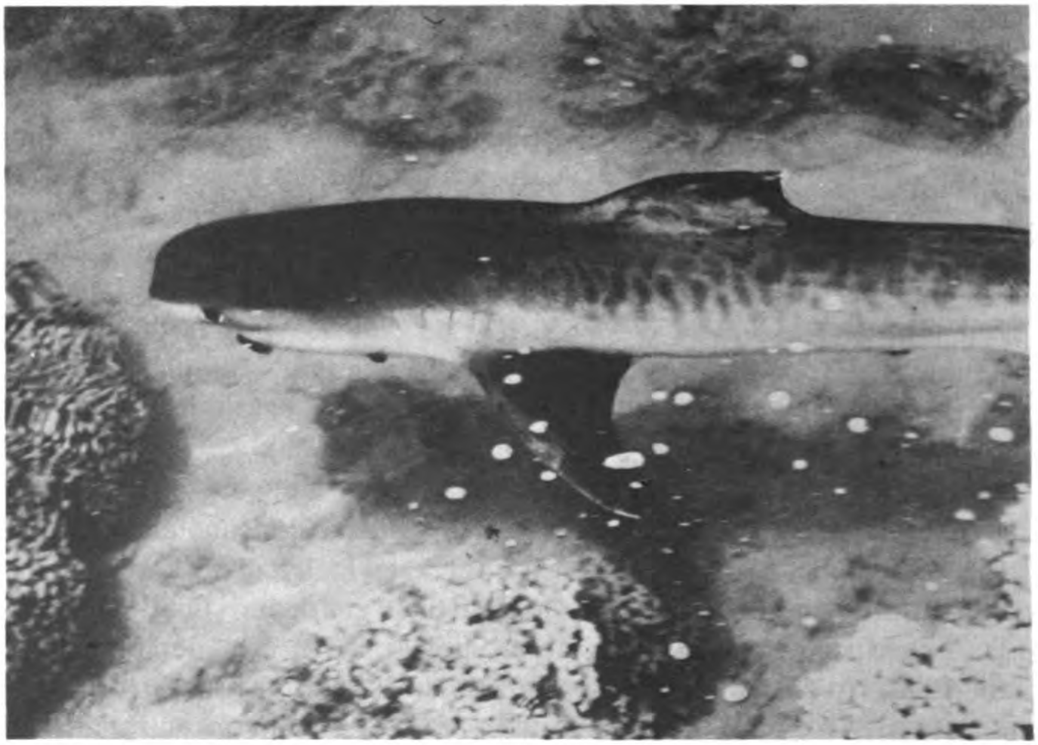

Figure 4 – Tiger Shark (photo by Edward S. Hodgson).

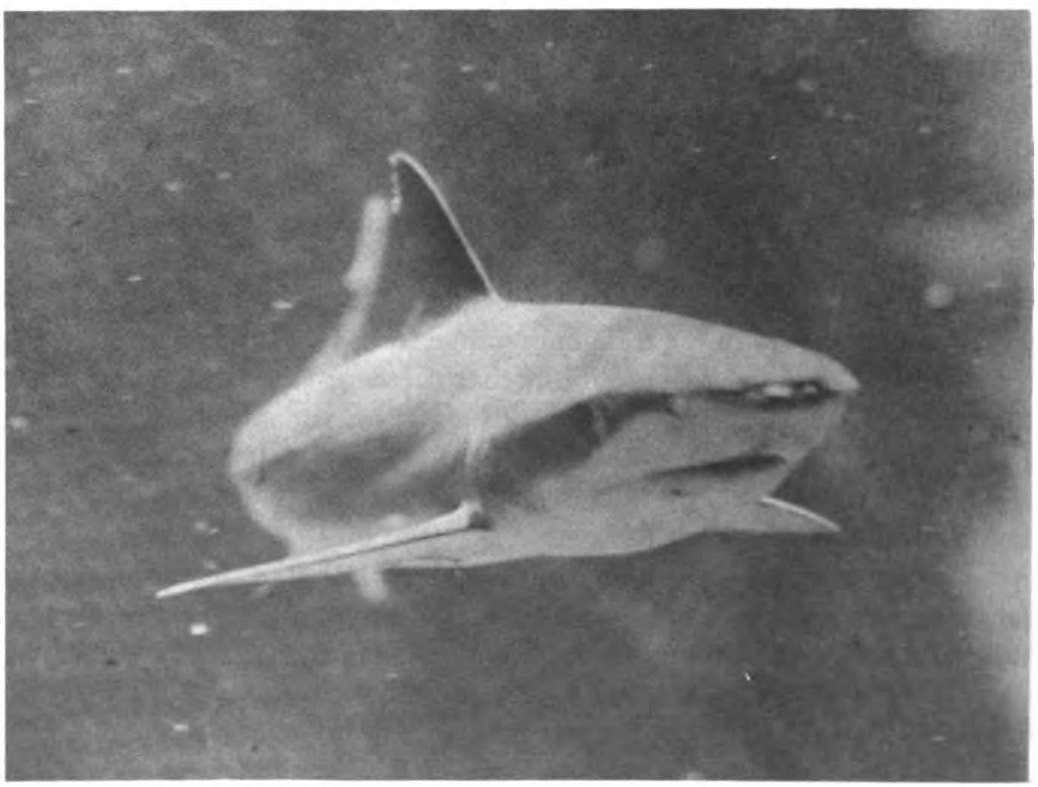

Figure 5 – Bull shark (photo by Edward S. Hodgson).

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fleeing or fighting, the production of similar sounds by man and his machines should create some concern when produced in areas where humans must enter the water and dangerous sharks are known to occur.

Recently, the antithesis of rapid approach—i.e., rapid withdrawal—has also been studied by our small team at Miami, and results have shown that this phenomenon can also be elicited in those few species studied thus far, by using even the same type of sounds as those that are considered attractive. The answer to this paradox seems to rest, clearly, in the manner by which a sound changes its intensity or level as a shark approaches its source. We hope that this research will be continued, since although our primary interest is increasing man's knowledge about the acoustic biology of sharks through basic research, it would appear that this type of study has clear spin-offs in the direction of human safety.

Moving on to vision—there can be no question that this sense is an important modality in the lives of many species of sharks. At least in the few species studied thus far, excellent visual sensitivity has been revealed (25, 3). Although little or nothing is known about spatial resolution in sharks, at least one species, the lemon shark, has a temporal resolution similar to that achieved by man, a highly visually oriented animal. Many species show the morphological evidence of a duplex retina (rods and cones), and physiological evidence is now present for such a mechanism in a number of species (25). The role of vision in the field behavior of sharks is still speculative, except that there is no question that this modality is used during approach to possible prey.

Besides the modalities briefly mentioned above, an extremely sensitive electric sense has recently been demonstrated in two species of small sharks and a skate (26-28). Sensitivity is at the amazing level of 0.01 μV/cm, representing the greatest electrical sensitivity known in the animal kingdom. Although the system appears to be used by the above-mentioned animals in locating nearby prey (for example, when the latter are hidden under the sand), there is no question that this sensory system should be studied in other species and should be examined under field conditions, when methodology permits. Such sensitivity also allows reasonable speculation that navigation and obstacle avoidance may, indeed, occur in such animals, based on an awareness of changes in the earth's magnetic field.

Finally, the universality of biological rhythms certainly extends to the subjects of this report. Quantitative evidence on changes in levels of activity exists presently for only three species of small sharks (9, 29), but the findings show clear daily effects, of both an endogenous and exogenous nature (depending on the species—again showing the difficulty of predictions when based on little knowledge). Likewise, effects of seasonal changes on various species of sharks, as demonstrated by their migratory habits, clearly show that temporal rhythms probably play an

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extremely important role in controlling numerous aspects of their physiology and behavior—as is already well known in many other animals, including man.

Thus, this brief review points out that although much of our knowledge about the behavior of sharks in the past has been obtained from casual observations, we now have some accurate knowledge based on careful observations and measurements, although the amount is still extremely small. The point is, such accurate knowledge is extremely difficult to obtain and is hence costly in many ways. However, if we are to understand the behavior of sharks and if we are to remove the word "unpredictable" from general discussions about sharks, then we must continue to study them carefully and accurately, in the field as well as in the laboratory.

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Closed-Cycle Liquid - Metal MHD

John R. Satkowski*
Office of Naval Research

Introduction

In recent years the rate of growth of electric power production in many advanced countries has been equivalent on average to a doubling of output every ten years. Prognoses made in various countries indicate that the growth rate of electric power generation is unlikely to decrease substantially before the end of the present century and that the main burden of the increase will be borne by thermal power stations. The figures represent a colossal growth in the use of fossil and nuclear fuel. They also indicate the likelihood of increasingly adverse effects on the environment by the discharge of low grade heat by all plants and stack emissions from plants fired with fossil fuel. To reduce these effects, energy conversion should be improved as far as possible by increasing the efficiency of electric power stations and by taking measures aimed at reducing harmful effluents. Implementation of these measures should be undertaken in such a way as to minimize the cost of electric power generation.

The results of intensive research and development work carried out in a number of countries during the past 14 years indicate that many present problems of power generation could be solved by introducing the magnetohydrodynamic (MHD) method of conversion at power stations operating on both fossil and nuclear fuel. The fossil-fired steam-turbine stations designed in 1972 had an overall efficiency of about 40% and a cost per kilowatt in the range of $140-180, depending on fuel and location. It was stated at the Fifth International Conference on Magnetohydrodynamic Electrical Power Generation in Munich (1) that at the present level of knowledge and technology first generation, large open-cycle MHD plants are expected to have an overall efficiency of 50% and about the same capital cost, thus resulting in a lower overall generating cost. There is every ground to believe that later their efficiency would be still higher and the benefits accordingly greater. The gain in the efficiency would be associated with a substantial decrease in the waste heat from

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electric power stations; for instance, if the efficiency rises from 40 to 50%, the amount of low-grade heat released to the environment per kilowatt of electric power would decrease by a factor of 1.5. It has been estimated that power plants of the future may use an MHD system in conjunction with conventional turbine generators to achieve overall plant efficiencies approaching 60 percent, compared to today's optimum 40 percent.

Electric power is generated by MHD when a high-speed flow of ionized gas, a plasma hot enough to act as a gaseous conductor of electricity, is passed between poles of a magnet (Figure 1). In today's conventional power plants, by contrast, electricity is produced by passing a metal conductor through a magnetic field.

Closed-cycle MHD differs from open-cycle in that an inert gas, such as argon, helium, or neon, replaces a combustible gas, and is recirculated rather than vented to the atmosphere. Moreover, operating temperatures of a closed-cycle system are one to two thousand degrees lower than those required for open-cycle, thereby substantially increasing the prospect of high reliability while reducing the need for new high-temperature materials.

Investigations during recent years have also demonstrated that MHD power conversion in fossil-fired plants is capable of increasing substantially the purity of the flue gases released to the atmosphere. By suitably controlling the processes occuring in the combustion chamber and the channel of an open-cycle MHD plant, it is possible to achieve a nitrogen oxide concentration of 1 - 1.5% in the combustion products (2). This would make it economic to extract nitrogen oxide together with

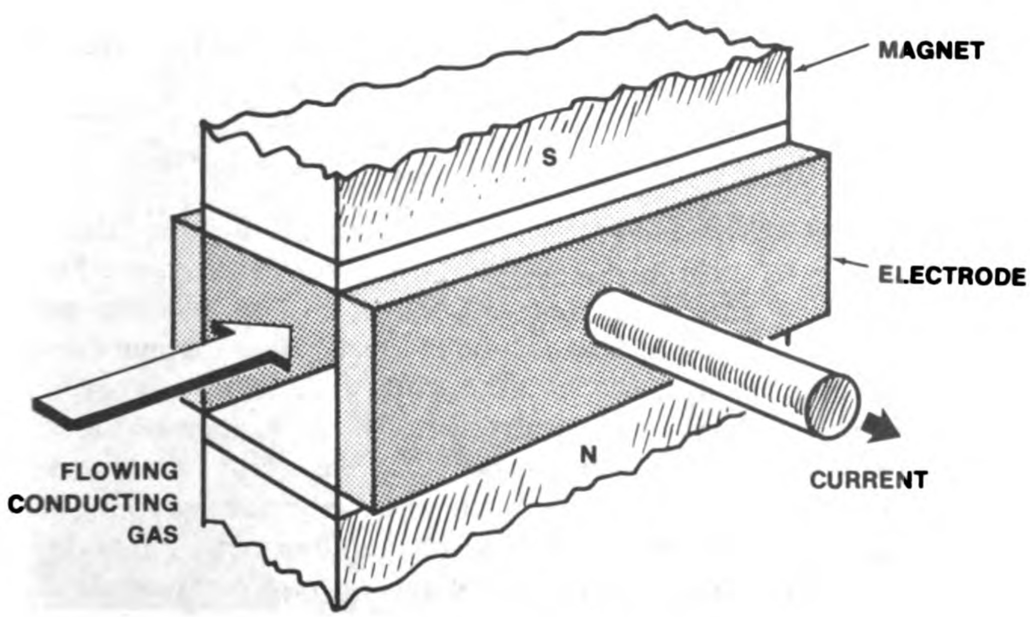

Figure 1 — How MHD works

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sulphur oxides and to manufacture nitric acid and sulphuric acid simultaneously.

In addition to using MHD plants as base-load stations, they are also attractive for peak-load and semipeak-load installations. The modern pattern of electric power consumption is characterized by considerable fluctuations in the course of a day and for seasonal considerations. The result is that during a year high load peaks account for from 500 to 700 hours and semipeaking or emergency conditions for 1500-2000 hours. It has been shown (3-5) that simplified MHD plants operating under peak-load and semipeak-load conditions could attain an efficiency of about 15% at a cost of 30 to 45% of a fossil-fuel base-load plant. These figures suggest that peak-load and semipeak-load MHD plants would be preferable to the gas-turbine ones used at present.

The Office of Naval Research is an important pioneer in exploring the promise of closed-cycle MHD power. The Navy is considering MHD applications for simplified, lightweight, and more efficient power and propulsion systems of the future.

History of Closed-Cycle Liquid-Metal MHD

Work on liquid-metal MHD plants, as on MHD plants of other types, goes back to about 1962. At the very outset the main advantage of liquid-metal plants was obvious; liquid metals possess high electrical conductivity irrespective of temperature. This in turn makes it possible to achieve a cycle with moderate maximum temperatures and to employ AC generators. Moreover, some liquid-metal MHD plants are absolutely static since the compressor used in them can be replaced by an MHD pump or even an MHD-compressor. At the same time, investigators encountered at an early stage those characteristic disadvantages that must be taken into account when building such plants.

Systems with different electro- and thermodynamic working fluids

The concept of a liquid-metal MHD plant presupposes that the mechanical energy of a liquid-metal stream is converted in the MHD generator proper into electrical energy. This implies that one has a unit in which this mechanical energy is produced from thermal energy. Such conversion is reasonably efficient if use is made of another compressible working fluid such as a gas or a vapour. A plant of this type should therefore have two working fluids: an electro-dynamic working fluid (liquid metal) and a compressible thermodynamic working fluid (gas or vapour - for example, a vapour of the same metal); in addition, it should have a device for transmitting energy from one working fluid to the other. Subsequent work showed that the efficiency of such devices (injectors and separators) was low. Furthermore such plants were

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intended at first to work in space where the temperatures of the cold source cannot be much lower than 700°C and the calculated overall efficiency of a liquid-metal MHD plant operated within an acceptable temperature range would at best be 7-8%. Even with this low efficiency, the attractive simplicity of such liquid-metal MHD plants, which have no moving parts, may still open the way for their use as topping devices in large-scale power engineering. Accordingly, in considering possible applications for liquid-metal MHD plants of this type, there is a tendency to think first of special-purpose devices - for example, devices designed for space applications where features such as simplicity are decisive. In addition to establishing the principal possibilities of such plants and a more thorough study of the processes occurring in them, the work done during recent years has been directed at the building of complete plants. In Moscow the entry into operation of a self-circulating loop using a liquid-metal MHD generator with an accelerating injection device having a nominal electric power of 1 kW was a great success (16). The construction of a pilot plant with a hollow-core jet condenser having a rated thermal power of 1000 kW is nearing completion in Berlin (17). Figure 2 shows the thermodynamic section of its experimental system disassembled so that the ends of the 60 parallel two-phase nozzles can be seen. The system was constructed by Böhler Edelstahlwerke, Kapfenberg. The Jet Propulsion Laboratory in Pasadena is carrying out investigations in a model facility with a separation-type acceleration

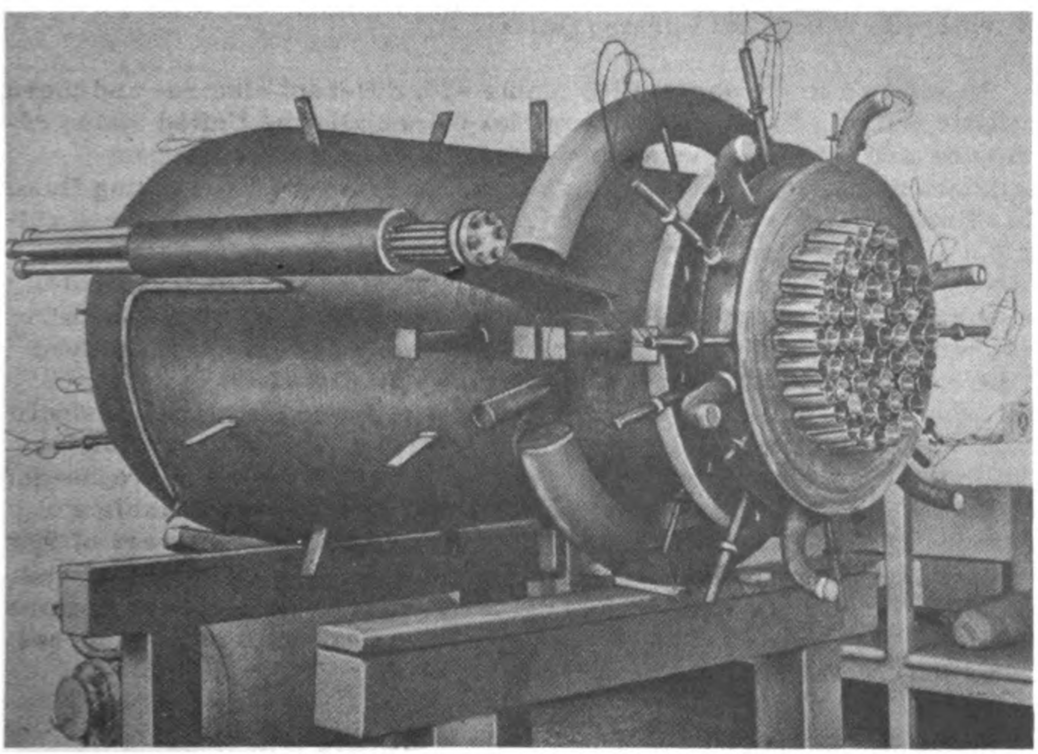

Figure 2 – Part of the experimental system of the liquid-metal MHD facility, West Berlin.

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device (Figure 3) (8). NaK is used as liquid metal and nitrogen as accelerating gas. Operation is at room temperature. An output power of 1.0 kW at 400 Hz, 6-phase, 120 V was obtained in the initial tests.

Calculations of economic prospects are being refined as information on the operating features of such plants is accumulated, and it is already possible to state that the addition of an MHD topping unit to a conventional steam-turbine plant using fossil fuel may be profitable (9).

Status of Closed-Cycle Liquid-Metal MHD Systems Today

The emphasis on liquid-metal MHD (LMMHD) systems has changed significantly in the last 4 years. There has been a decrease in LMMHD activity as the work on the separation and condensing-injector (jet condenser or ram jet) cycles has tapered off. These cycles, originally intended for space power systems or commercial topping cycles, have inherently low efficiencies (theoretical maximum of about 15%). Studies at Jet Propulsion Laboratory (10) have shown that a cesium-lithium separator system as a topping cycle improves the efficiency and appears to be economically attractive, but that program has been terminated. A large potassium jet condenser experimental facility is in the preliminary operational stages at Sonderforschungbereich Magnetohydrodynamik (11).

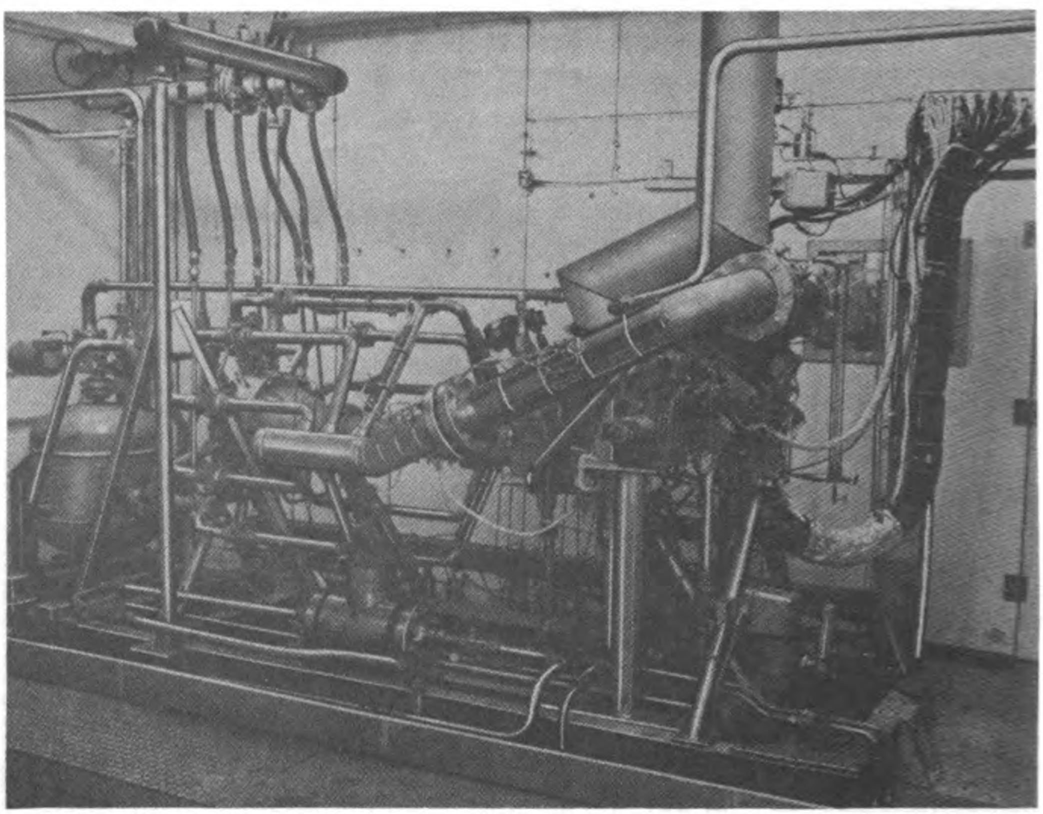

Figure 3 – Experimental liquid-metal MHD converter, Pasadena.

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The two-phase (gas and liquid) liquid-metal MHD power cycle has been shown to have the potential to effectively generate electric power from heat sources in the range of 260 to 1090°C (500 to 2000°F) (12). Thus it is directly competitive with steam systems for commercial or special applications, and possesses the potential to give moderate increases in conversion efficiency for moderate increases in temperature that are within the range of current technology. It appears attractive for future liquid-metal-cooled heat sources, such as the liquid-metal-cooled fast-breeder reactor (LMFBR) and the controlled thermonuclear reactor (CTR), because there is no liquid metal to water interface and the higher source temperatures can be effectively utilized. The LMMHD concept also couples to fossil-fueled heat sources without requiring high temperatures. It readily couples to any heat source since heat can be added to the gas, the liquid, or both; and can utilize dry cooling towers as there is no vapor to condense. Significant programs on two-phase LMMHD have existed at Argonne National Laboratory and Cie Electro-Mechanique, but at present only the Argonne program is active. There is also a LMMHD program in Japan.

Generators

Liquid-metal generators can be divided into four groups; dc generators with pure liquids, induction generators with pure liquids, either type operating with a two-phase gas-liquid mixture, and jet generators.

The characteristics of dc (conduction) generators with pure liquids are well understood, and it should be possible to design and build them with efficiencies in excess of 85%. Numerical solutions are available that solve Laplace's equation for the fluid currents and end effects. There is currently little research on pure-liquid dc generators because of the lack of an efficient thermodynamic cycle using pure liquid in the generator.

Single-phase liquid-metal MHD (LMMHD) generator flows have been thoroughly investigated, but certain areas of study are still needed to improve potential generator efficiencies. For example, in the end region the interaction between the gradient of the fringe magnetic field and the streamwise component of the fringing current induces a component of vorticity which produces an M-shaped velocity profile between the electrodes (13, 14). This phenomenon may not cause additional electrical losses, but some power is lost in creation of the vorticity and in increased wall friction.

The analyses of induction generators can be broken up into two categories - the linear induction motor (LIM) type of analyses that does not include the distinctly MHD aspects, and the MHD type that includes these aspects. Most analyses have fallen into the former category. Recently many techniques have been proposed to include finite length

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correctly, mostly in the extensive LIM literature (15, 16). Significant advances are the mesh-matrix method (17), the Fourier-series method (18), and the numerical iteration method (19). All include detailed models along the direction of motion and some method of treating finite width (see below); all can include conducting channel walls, but only the last work can treat variations over the air-gap length. A new Fourier-series method provides a more detailed analytical solution for the empty-channel and stationary-secondary cases, but the method used to include secondary motion assumes infinite iron length for the secondary magnetic field, and this limits its validity (20). There is still controversy over how to include finite iron length, and this appears to be a key issue as different assumed iron contours can yield big differences in the fields and power (21). Still to be decided is the optimum method of minimizing end effects (21, 22).

With the MHD version other effects enter. Finite width is especially important. Stationary side bars cause a previously-neglected loss, and care is needed in their design (23). Without the correction for the side bars, none of the recent analytical models came close to agreeing with the data from an experimental generator (24). The interaction of the fluid velocity profile and field solutions has received little attention recently, but may have a large impact.

An important aspect of all generator studies is finding a suitable thermodynamic cycle, and this has led to the study of two-phase generators. Two-phase generators suffer from all of the problems of the pure-liquid versions plus the addition of two-phase flow effects.

By far the largest additional losses at high void fractions, high ratios of gas to liquid by volume, are due to the slip velocity between the gas and liquid phases (14, 25, 26), and due to the fluctuating and inhomogeneous character of the flow (25, 27). Experimental measurements have shown high slip, fluctuations, nonuniformity of void fraction profiles, and decreasing load factors in the flow direction (14), all suggesting the existence of churn-turbulent flow patterns. Since efficient generators require load factors close to unity, relatively-small fluctuating voltages may result in appreciable fluctuations of the current density and the Lorentz force.

Other interesting aspects of two-phase generator flows are the uniformity of the two-phase mixture across the generator and the variations along the flow direction. Experimental data show that there is more liquid in the wall layer and more gas in the center (25, 27). This means that the effect of the wall layer is magnified, as the equivalent-circuit or open-circuit voltage depends not on the average velocity but on the weighted average of the velocity times the conductivity. It is probable that either a very-uniform two-phase mixture or a method of eliminating the wall layer, such as gas injection along the walls, is required (28). Though creation of gas layers at the walls involves complex stability problems,

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success would result in at least an order of magnitude decrease of friction and shunt losses. The two-phase mixture means that either the channel area or the liquid velocity or both must vary along the flow. Constant liquid velocity is probably optimum, at least for conduction generators, but will only occur at the design point.

The dc generator program at Argonne National Laboratory has made considerable progress in the last few years (14, 25). The generator efficiency has increased with time to be in excess of 0.50. In the third, and most recent, generator the liquid velocity is essentially constant, as desired. The initial results from the use of gas injection to eliminate the pure-liquid wall layer were encouraging (19), but later results showed that the method used was not working. There is not enough understanding of the dynamics of the two-phase flow, as shown by the comparison of calculated and measured gas and liquid velocities along the flow, etc. A high-temperature (up to 540°C (1000°F)) sodium-argon experimental facility is under construction to observe the effect of changing liquid properties on the gas-to-liquid velocity ratio and the generator performance.

The electrical conductivity of the two-phase mixture has an important effect on generator performance, and on the boundary layer. For accurate performance calculations it is necessary to know the conductivity as a point function of the void fraction and flow structure. A pronounced drop of the mean value of electrical conductivity (29) and large increase in fluctuations (14, 27) have been reported when the void fraction exceeds a value on the order of 0.2 to 0.3. This has been explained as a transition of the flow pattern from a uniform bubbly to a slug flow. New conductivity data have been reported (26, 27). The former includes conductivities based on induction generator measured powers and the voltage-current characteristic between the electrodes of a dc conduction generator, the latter average air-water data and data with a magnetic field.

The influence of the turbulence level (due to a throttling grid plate) in a two-phase flow mixer on the velocity difference and the two-phase flow pattern has been reported (26). The results indicate that a mixer design should attempt to minimize the turbulence, and hence the bubble coalescence downstream of the mixer. This effect had not previously been considered.

In two-phase-flow LMMHD generators the main factors preventing the attainment of high conversion efficiencies are slip, fluctuations, and inhomogeneities associated with the turbulent slug-flow pattern caused by rapid coalesence of the bubbles. An interesting solution to this problem is to use the surface-active property of dilute liquid-metal solutions to create a foam flow (14). It might be possible to create foams that are stable inside the generator at high void fractions, but this remains to be demonstrated.

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The possibility of generating ac directly from the two-phase mixture has resulted in considerable interest in two-phase induction generators, though it is not clear that the concept is practical. A method of statistical averages was developed to treat the two-phase generator in terms of the pure-liquid version (27). Good agreement between theory and experiment was obtained at low void fractions, 0.2 gas by volume, but no experiments at higher void fractions were reported. In (26) the effects of conductivity and velocity variations along the flow and across the flow have been accounted for by means of integrated averages.

The free-jet generator may eliminate some of the velocity profile and viscous flow problems, but the practical aspects of stability and the creation and catching of the jet have yet to be established. The jet generator is particularly significant for the high-velocity pure-liquid systems where viscous losses are high. Stability studies (30, 31) have shown some stabilization due to the magnetic field.

Systems

Systems studies with an LMFBR heat source (12) have shown an efficiency of 0.37 with a maximum reactor coolant temperature of 649°C (1200°F) for a LMMHD system with a gas turbine in the gas loop after the MHD generator. With the same heat source a LMMHD-steam binary cycle, where heat is transferred to the steam from the gas only, has an efficiency of 0.45.

A LMMHD-steam binary system coupled to a coal-fired fluidized-bed combustor results in a significant improvement over the steam cycle performance along (32). The steam-bottoming-cycle thermal efficiency used was 0.391. This is compared to the range of 0.453 for helium-sodium at 740°C (1300°F) and to 0.483 for helium-lithium at 815°C (1500°F) found for the binary cycle. The LMMHD topping cycle initially did not interface effectively with the steam bottoming cycles using regenerative feedwater heating. More recent results have found solutions to the interfacing problems and increased the thermal efficiency to 0.513 at 815°C with a high-performance steam bottoming cycle (thermal efficiency of 0.457). An additional possibility (33) is a system using a coal-fired plasma MHD generator as the topping cycle, a LMMHD dual cycle (with a gas turbine driving the gas compressor) as the bottoming cycle, and a heat-recovery steam cycle.

Dynamic modeling and analysis studies reported in (34) are aimed at component analysis, plant simulation, and overall system dynamic behavior of a two-phase LMMHD power system. A distributive dynamic computer model solved the governing system differential equations using a sparsely-spaced discrete (nodal) model. Preliminary dynamic analysis has indicated that the system is at least locally stable. Global system stability must still be investigated with a nonlinear model.

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Acceleration of the liquid metal by means of boiling volatile droplets of another substance within the liquid has been proposed (35). This is in contrast to the two-phase cycle which mixes the liquid and gas mechanically. In either system, as the gas expands heat is transferred to the gas from the liquid metal, and the gas provides the driving force for the liquid metal. The evaporated vapor is separated from the liquid after the generator and then condensed, with the heat being rejected to a bottoming cycle. The pump work of this Rankine cycle is virtually negligible compared to the gas compression work of the two-phase Brayton-type cycle. Experimental results were shown to be consistent with the theory developed for two-phase bubble flow either with or without boiling. Using cesium as the boiling liquid and lead as the liquid metal with high and low cycle temperatures of 1500°K and 1000°K, a maximum cycle efficiency of 0.16 was predicted. (This system is essentially a Rankine-cycle version of the two-phase Brayton Cycle.)

There has been a shift in emphasis in the LMMHD programs. Substantial progress, however, has been made with the two-phase LMMHD concepts, with the performance potential appearing quite attractive.

The possible spheres of application of closed-cycle MHD plants of both the plasma and the liquid-metal type have not yet been clearly defined. There are two main reasons for this. Firstly, less work has been done to develop this type of installation and there are no large experimental plants incorporating all the components of a future electric power station; secondly, the prospects of closed-cycle plasma and liquid-metal systems place specific constraints and requirements on a nuclear heat source. In the case of space and other special application, less stringent requirements are placed on the reactor than for commercial power systems. Accordingly, a possible route to the development of closed-cycle MHD systems is through these special applications; if they prove to be viable, this would aid their introduction into large-scale power generation. In addition, these closed-cycle systems can also be considered for fossil-fuel firing through a heat exchanger.

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Improved Defense Communication

The science of optical holography is being extended to radio frequencies with meter wavelengths. The theoretical work has been completed and an experimental test to verify the results has been designed by the Naval Electronics Laboratory Center (NELC). The research is sponsored jointly by ONR and ARPA.

The test facility now under construction at the NELC observatory in La Posta, CA, will be used to measure the ionospheric irregularities which produce the well-known phase and amplitude scintillations in VHF and UHF radio and radar signals as they pass through the ionosphere.

The experimental test will use an array of fixed UHF antennas and record the phase and amplitude of UHF signals from a transmitter aboard an orbiting satellite. Knowing the characteristics of the wave transmitted from the satellite and the effects of charged particles on UHF radio waves, and having measured the characteristics of the modified wave at the receivers, it should be possible to reconstruct mathematically the ionospheric irregularities which produced the observed phase and amplitude scintillations. A computer program has been written to accomplish the mathematical reconstruction.

Firm establishment of the holographic technique will lead to improved defense communication satellite design capability by providing more rigorous and extensive knowledge of ionospheric scintillation parameters. This knowledge is needed to improve cost effectiveness by avoiding satellite system over-design or system performance inadequacy.

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Research Notes

Cayman Trough Provides Window into Earth's Interior

Scientists diving in the research submersible ALVIN found a "window" into the earth's interior in the Cayman Trough early this year. Through their portholes, scientists from the Woods Hole Oceanographic Institution and other Institutions observed deep layers of the earth's crust never seen before in recognizable sequence. Using the sub's mechanical arm, they were able to take documented samples of rock that had previously only been collected in jumbled dredge samples or indicated in records from seismic instruments which use sound waves to "explore" beneath the surface of the earth's crust (Figure 1).

The geological phenomena that provided this window into the earth's interior are two gigantic near-vertical fault scarps within the Cayman Trough, where the earth's crust has split and the rock on one side of the split has been thrust upward to reveal some 6,000 feet of subsurface rock. Diving to 12,000 feet, the bottom of the scarps, ALVIN worked up their faces making more than 75 sampling and observation stations and providing science with the first documented series of samples obtained from the deep layers of the oceanic crust. (Attempts by the drill ship GLOMAR CHALLENGER to penetrate these layers have reached 1,900 feet into the crust.)

Seismic studies indicate that the earth is divided into three layers. The outer layer or crust is six to thirty miles deep; the mantle beneath the crust extends 1,740 miles; and the core takes up the rest of the distance to the center of the earth, which is some 3,800 miles from the surface. "Rock samples from the lowest parts of the steep scarps in the Cayman Trough are of peridotite and dunite,

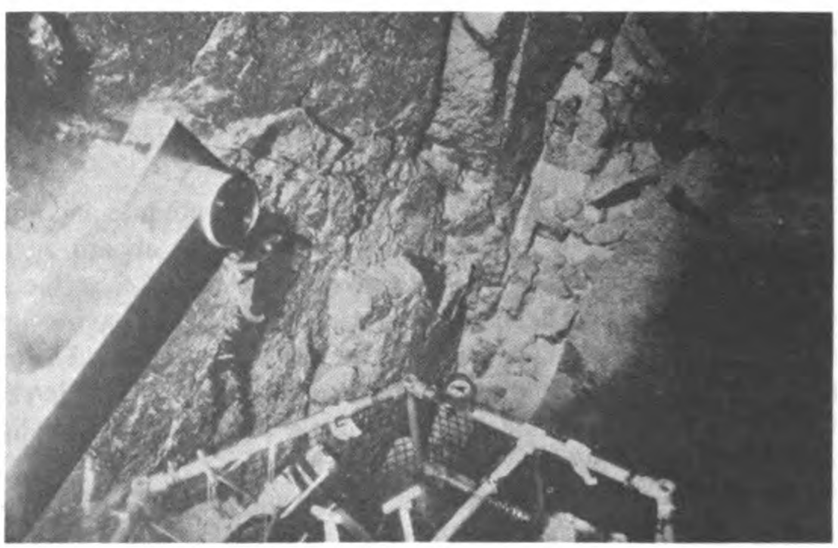

Figure 1 — Near-vertical face of 6,000-foot scarp in the Cayman Trough presented scientists with a window into the earth's interior. ALVIN's arm aims for rock sample.

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which we believe are from the upper mantle," expedition Chief Scientist Dr. Robert Ballard said. "This indicates that the layers may be compressed in this area for some reason or possibly that previous estimates of the layer depths may be in error" (Figure 2).

Dr. Ballard is from the Woods Hole Oceanographic Institution as are several other scientists participating in the Cayman Trough work along with colleagues from the Office of Naval Research, the State University of New York at Albany, Wesleyan University, Oregon State University, Dalhousie University, and the Scripps Institution of Oceanography. Two guest investigators from the Jamaican Geological Survey also participated. Funding for the January-February 1976 field work in the Cayman Trough came largely from the National Science Foundation. The ALVIN dives are jointly funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, and the Office of Naval Research. The Navy will support extensive surveys of the Cayman Trough in April when a new botton topography system will be used. Resulting high-precision maps will aid the scientists in choosing areas for further examination by TRIESTE II next year. The National Geographic Society provided photographic support to the expedition, quickly developing great quantities of film to help the scientists in their day-to-day planning. An article in the *National Geographic* magazine on the expedition is planned for the August issue.

The 15 ALVIN dives made during the Cayman Trough expedition in January and February provided scientists with their second close-up look at the geology

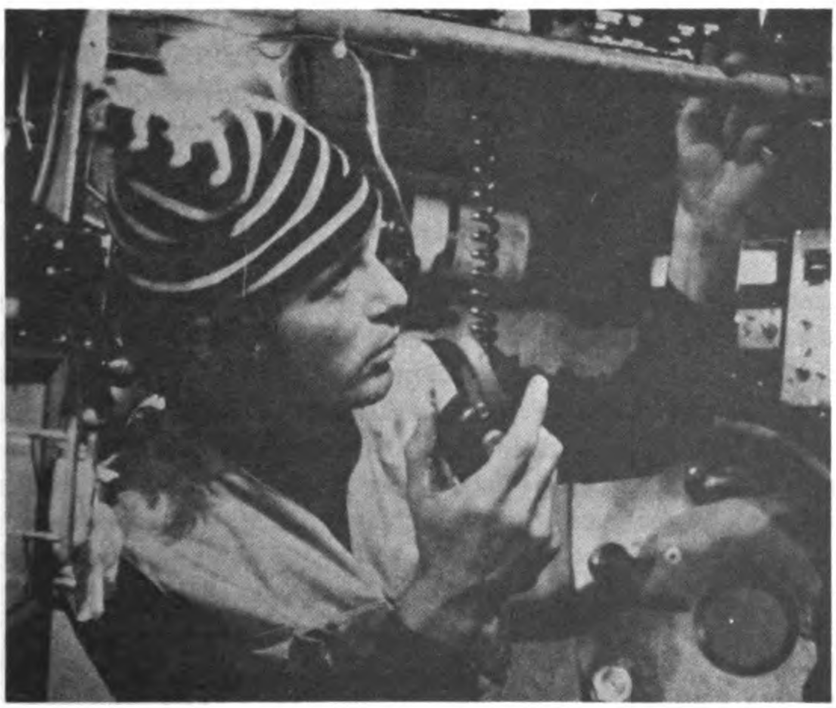

Figure 2 — Dr. Robert Ballard, Chief Scientist for the Cayman Trough expedition, is shown inside the personnel sphere of ALVIN using the underwater telephone to communicate with mother ship LULU. Scientist's viewport is at lower right.

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of the deep ocean. The first look came during Project FAMOUS (French-American Mid-Ocean Undersea Study) in 1974 when ALVIN and two French submersibles made 41 dives on the Mid-Atlantic Ridge. Analyses of samples and data from Project FAMOUS and the Cayman Trough expedition are yielding a better understanding of the forces and conditions which lead to the creation and subsequent movements of the earth's crust. The jigsaw-puzzle fit of continental shapes has been observed for centuries, but only in the last decade has there been acceptance of the theory that the continents ride on huge crustal plates and very slowly change position with relation to one another.

The driving force for movement of the plates is unknown, but the greater knowledge about the composition of the plates gained from the deep-earth samples of the Cayman Trough is expected to bring scientists closer to understanding continental motions, also known as plate tectonics.

The Cayman Trough, some 750 miles long, is located along the boundary between the North American and Caribbean crustal plates. Along most of this boundary, the plates are moving laterally with regard to one another, the North American plate westward and the Caribbean plate eastward. As the Caribbean and American plates grind past one another, periodic interlocking causes a build-up of forces. If such a build-up continues for a long period of time without relief, a sudden release may result in a devastating earthquake. The Cayman Trough is part of the plate boundary that extends to Guatemala, where thousands lost their lives and many more thousands were made homeless by a major earthquake registering 7.5 on the Richter scale on February 4 when the Caribbean and American plates moved three feet relative to each other.

Such plate boundaries are characterized by more or less continuous mini-earthquakes, and the scientists of the Cayman Trough expedition, beginning their work just after the large earthquake in Guatemala, recorded the subsequent smaller earthquakes along the boundary. Dr. Kenneth MacDonald, Scripps Institution of Oceanography geologist, said, "This is the first time that we have been able to record major shocks on a subsea boundary. The floating listening devices we deployed and monitored from the Research Vessel KNORR recorded aftershocks up to magnitude 5.0 on the Richter scale following the large quake. We also recorded the second large quake, which registered 6.0 on the Richter scale and centered in the Oriente Fracture Zone between Cuba and Jamaica. These recordings should help us to learn whether and how the major quakes and aftershocks may be related and what is their relationship to the spreading center."

The spreading center, the existence of which was first suggested by Dr. Troy L. Holcombe and colleagues of the U.S. Navy, is a 90-mile section of the plate boundary running across the floor of the Cayman Trough where the two plates are actually moving apart rather than grinding against each other as they move in opposite directions. This is a similar phenomenon to that studied during Project FAMOUS on the Mid-Atlantic Ridge, where the major tectonic activity is moving the American, African, and Eurasian plates away from each other at approximately one centimeter per year. Volcanic material from some inner reservoir of the earth wells up and hardens to become part of the plates as they move. The Cayman Trough spreading center offered scientists a comparison of phenomena at this short spreading center with what they found at the long

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spreading center on the Mid-Atlantic Ridge. ALVIN's 12,000-foot depth capability easily took her to the bottom of the 9,000- to 10,000-foot rift valley of the Mid-Atlantic Ridge but limited her to the upper half of the 20,000-foot-deep Cayman Trough. Additional dives in the U.S. Navy's deep diving bathyscaphe TRIESTE II are planned for early next year to complete the exploration.

Camera lowerings from the Woods Hole Oceanographic Institution Research Vessel KNORR to the floor of the Cayman Trough brought back photographs of the volcanic region in the center of the trough at 15,000 feet. The photographs show such phenomena as pillow lava formations and fissures parallel to the central rift of the Trough almost identical to those on the Mid-Atlantic Ridge. This indicates that the various spreading centers, which are nearly all covered by waters of the world's oceans, are probably very similar to one another. Dredged samples of the Trough volcanic material were so fresh that they still had a shiny outer coating of volcanic glass, which disappears over time. Some of the samples popped and crackled on the deck as gases not released during the cooling process escaped in the reduced pressure of the atmosphere. The scientists estimate that these rocks — very "fresh" in geologic time — are less than 1,000 years old.

Precision Low-Angle Tracking Radar

A team of Naval Research Laboratory (NRL) scientists has designed a unique millimeter wavelength, precision monopulse tracking radar system, following the success of an experimental radar built and operated at the Laboratory's Chesapeake Bay Division.

The new design, dubbed TRAKX (Tracking Radar at K_a- and X-band), calls for the K_a- and X-band monopulse antennas in the experimental "piggyback" version to be combined into a single unit for range instrumentation applications at missile sites. Combining the K_a-band and X-band antennas into a single unit provides a compact, high servo performance antenna system with computer-control from a small central control unit. The system uses a mobile Nike/Hercules precision pedestal with a shelter that is mountable on a truck bed for transportability.

Dual-band tracking is accomplished in a single parabolic dish by using a dichroic material (reflective at K_a-band and transparent at X-band) as a cassegrain sub-reflector (designed by RCA). The K_a-band portion operates as a cassegrain. Its monopulse feed (radome covered) extends from the center of the dish, illuminating the sub-reflector which reflects energy back to the dish (which focuses it to a narrow (0.25°) beam into space) (Figure 1).

At X-band, the monopulse feed (radome covered) is located at the focal point (end of quadropod in front of the dish) where it looks through the dichroic sub-reflector illuminating the dish directly to form the X-band energy to a 1° beam in space. Both beams are centered on the antenna axis. The X-band energy flows between the radar and feeds through the legs of the supporting quadropod.

TRAKX will be tested at the Patuxent Naval Air Station when fabrication of the engineering prototype system by the NRL science team has been completed.

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To prove the effectiveness of their millimeter-wave tracking concept, the NRL research team had retrofitted an X-band monopulse radar at the Lab's Chesapeake Bay Division site, by adding a 35 gigahertz (GHz) tracking instrumentation radar with a 0.2° beamwidth.

The experimental "piggyback" system, with the X-band dish mounted on top of the K_a-band antenna, successfully skin-tracked aircraft at 100 feet altitudes to 15 nautical mile ranges with negligible elevation errors. Comparative tracking with the 1.0° X-band system alone showed the expected large elevation multipath errors at three to four mile ranges and loss of track by eight to ten nautical miles on the same 100 feet altitude aircraft. The Naval Air Systems Command is providing NRL with the funds for the development of TRAKX.

The millimeter-wavelength precision-tracking radar will offer several improvements and extended capabilities for missile and training range radars. The major improvement is precision low-altitude target tracking. At millimeter wavelengths, the narrow beamwidth is obtained with convenient antenna size to provide angle

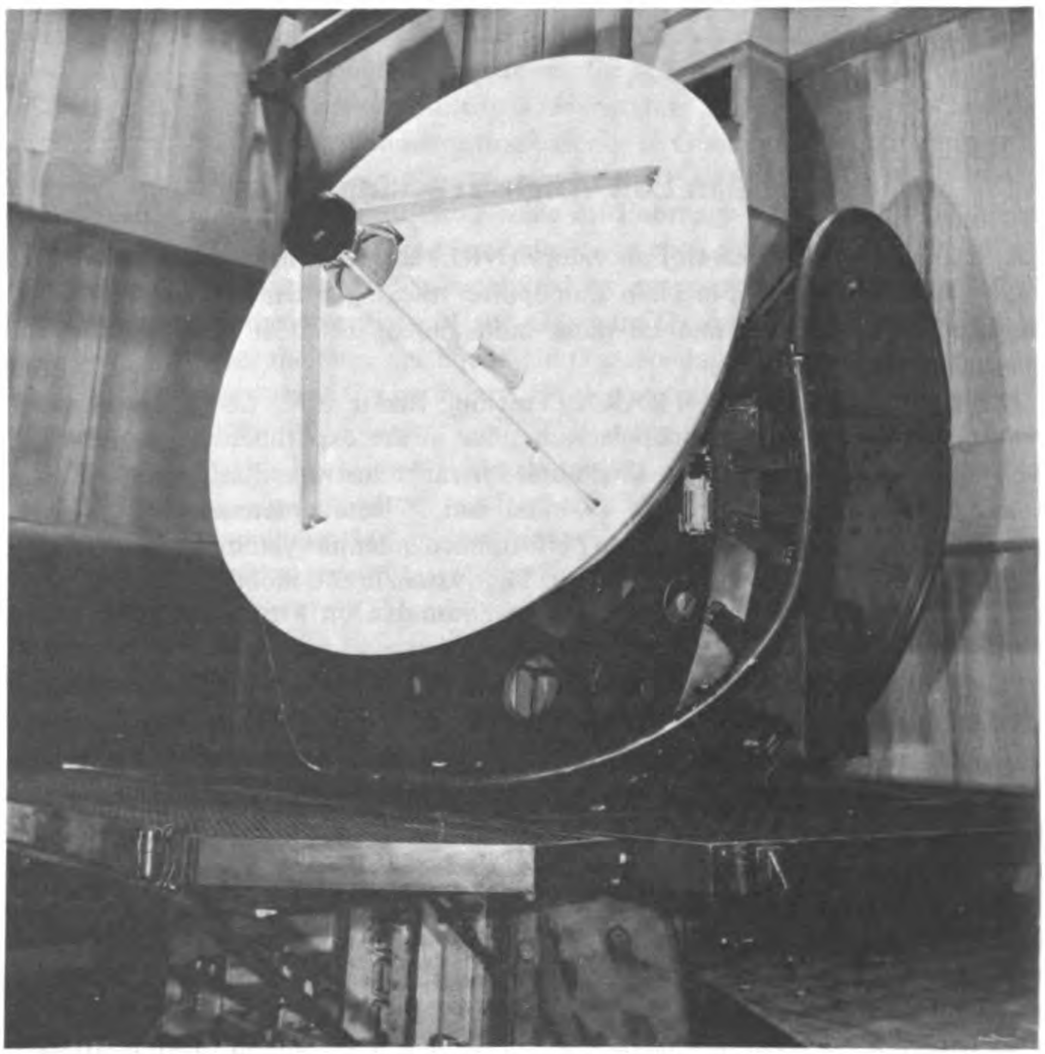

Figure 1 – The Dual Band Monopulse TRAKX (Tracking Radar At K and X Bands) system is now in development by a team of Naval Research Laboratory scientists.

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discrimination against sea reflected signals that cause the large multipath errors in microwave tracking radar. Furthermore, the short wavelength results in more diffuse scattering of sea reflected signals for a given surface roughness, further reducing multipath error.

The narrow beamwidth also provides angle discrimination against clutter and undesired targets, which present a difficult low-angle problem at microwaves, causing tracking error and possible loss of track to large objects. Similarly, improved tracking precision is obtained in multi-target and other tactical environment.

The narrow beam also gives a reduction of receiver noise contribution of tracking error proportional to wavelength, and the short wavelength reduces errors caused by target angle scintillation by spreading a large part of the scintillation energy above the tracking servo bandwidth.

The NRL scientists report that all three military services, as well as the National Aeronautics and Space Administration and the Federal Aviation Administration, are interested in the new development.

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Editor: WILLIAM J. LESCURE

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IN THIS ISSUE

VOL. XXIX, NO. 7

Cover Caption

Teeth of a lemon shark viewed from inside the jaw. The rows of reserve teeth pointing inward replace the outer grinding teeth, which are seen on the crest of the gum, as they are broken.

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