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MANNED SUBMERSIBLE OPTICAL REMOTE SENSING WITHIN THE GULF STREAM†

by

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ABSTRACT

Three optical remote sensing experiments have been installed on the Ben Franklin, a 48-foot-long manned submersible. They are designed to measure

- Chlorophyll
- Minerals/gelbstoff
- Bioluminescence.

This summer the submersible pursued a 30-day Gulf Stream drift mission at depths up to 2000 feet, starting at West Palm Beach, Florida. The results provided continuous in situ subsurface measurements, which were supplemented by surface ship measurements.

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1. INTRODUCTION

The oceans are one of the earth's great natural resources, covering about 70 percent of the globe. Life on this planet, in all its forms, is thought to have originated in the sea. Remote sensing of the oceans has already been utilized to locate fish, to investigate the oceans' effects on weather and the weather's effects on them, to enhance studies of water pollution (both chemical and thermal) and sea traffic, and to assist rescue missions and coast and geodetic surveys. Nevertheless, the seas have not been explored in as great detail as have the land masses, and much remains to be accomplished to attain a thorough understanding of the ocean's physical-chemical properties. The ultimate objective in studying the sea as an earth resource is to be able to exploit it more fully as a source of food and energy for the generations yet to come.

Optical techniques that have been highly developed for remote sensing may be adapted for the study of the sea. Optical oceanography is the special branch of oceanography that considers the interaction of light and the sea. Various dissolved and suspended particles in sea water, in association with the water itself, largely determine its optical properties. The earth's atmosphere is primarily a scattering medium, but in the ocean both absorption and scattering are important (Ref. 1). The properties peculiar to the ocean make optical remote sensing within it possible.

The most efficient, experimentally adaptable technique for continuous optical investigations within the ocean involves continuous in situ measurements from a manned submerged oceanographic research platform that interacts minimally with the environment. The advantages of a manned submersible are that experimental investigations can be adapted to ever-changing conditions and data analyses can be made on the spot. Experimental procedures can also be varied to acquire the most useful information. Acquiring some types of information in oceanographic investigations is easy enough, but the need is for useful information that can be correlated with other data to enhance our understanding of natural phenomena.

Most current oceanographic investigations follow a station sampling technique (Ref. 2). However, information about continuous dynamic processes is generally not acquired through this technique unless there is frequent and cumbersome periodic sampling by manned expeditions.

Ultimately, synoptic world oceanographic coverage may be accomplished via an automated system employing in situ sensors together with satellite interrogation and reporting. The current state of oceanographic instrumentation has been described as a crisis of national neglect (Ref. 3), as indeed it is. Sophisticated oceanographic instrumentation that can be incorporated into earth resources-sensing systems requires effective interplay of investigator and oceanographic sensors. Sensors can be employed with minimal interaction effect on the oceanographic environment by arraying them in a drifting submersible equipped with a closed biological life-support system. Such a manned submersible has been constructed — the Ben Franklin, built by Grumman in collaboration with Jacques Piccard for a drift cruise within the Gulf Stream. The vessel is 48 feet long and has a gross weight of 147 short tons. Outfitted at the Port of West Palm Beach, it is capable of 30 to 42-day submerged drift missions with a crew of six, has a closed biological life support system and provision for extensive scientific instrumentation. It can conduct continuous operations at depths of up to 2000 feet.

To set the background for the optical experiments on the Ben Franklin, the ocean environment is pictured in Fig. 1. A coastal water is shown, since most plant nutrients are available there in quantity as a result of continental runoff, which incidentally includes pollution. (Pollution is detrimental to the life processes in the ocean, even though sewerage, for instance, may be considered "cleaner" than sea water because of chlorination.) Phytoplankton utilize nitrates, phosphates (and sometimes silicates), and CO_2 to form organic matter by photosynthesis in light. This is the basis of life in the ocean. The phytoplankton are microscopic, mainly diatoms and dinoflagellates, which contain chlorophyll. The amount of chlorophyll usually varies with population size and variety of flora. The varieties are very much fewer than those on land.

Refer to Fig. 1 for the discussion in this and the following three paragraphs. Ocean fauna feed on the flora, using O_2 in respiration to produce CO_2. The fauna include minute animals, the zooplankton, which serve as food for the benthos (sea floor animals) and the more highly mobile nektons (fish).

Carbon dioxide is released from carbonic acid produced by bicarbonates dissolved in the water, and which exist in equilibrium with carbonates. In addition, CO_2 and O_2 from the atmosphere dissolve in the ocean; it is remarkable that although the CO_2 produced by industrialization is tremendous, the world climate has not been changed thereby. This is probably the result of the sea's ability to absorb a 60 to 100-fold excess of carbon dioxide in physical and chemical combinations, so that any change in the gaseous phase produces a change that is noticeable from the outside of only 1 to 1.5 percent (Ref. 4).

Fauna may live at great depths, feeding on other fauna or on decayed organic matter (gelbstoff). Circulation in the ocean can be caused by surface winds, ocean temperature or salinity differences, and differences in the height of the ocean. Thus the Gulf Stream drift is caused by the higher elevation of the ocean near the Florida Keys (Ref. 2).

Dinoflagellate populations can be investigated with the Ben Franklin. Dinoflagellates are a class of animal organisms producing bioluminescence, are mobile and able to move around in the ocean. The mechanism for bioluminescence is not well understood, although surface bioluminescence is hypothesized to be produced by the oxidation of luciferia (a protein) with the aid of luciferase. Deep sea bioluminescence may be excited by mechanical agitation (Ref. 1).

The Gulf Stream Drift Optical Experiment Concept is shown in Fig. 2. It is composed of two systems: the primary experiments (Group I) aboard the Ben Franklin, and supplementary experiments (Group II) in a surface vessel (the Lynch) following the Ben Franklin.

Specifically, Group I consists of three optical experiments:

- Chlorophyll determination
- Minerals/gelbstoff sensor
- Bioluminescence detector

Supplementary measurements related to the three experiments have been made, so far as operationally possible, of ocean temperature, conductivity, downwelling light/background illumination, and local circulation effects.

The chlorophyll information is valuable in that it yields an index of productivity of various areas in the Gulf Stream, information that can be used to locate certain fish types. (Shrimp feed on plankton, and tuna feed on shrimp, for example.) In general, fish habits greatly affect the areas where they are to be found. In its operating principle, the chlorophyll experiment makes use of the fact that chlorophyll fluoresces at a wavelength of about 6700Å when it is irradiated with broadband ultraviolet light centered at 4000Å (Ref. 6). This fluorescent light is sensed by a photomultiplier. Thus the chlorophyll (contained in elemental plant forms such as phytoplankton) can be continuously sensed in situ without the cumbersome technique of taking continuous water samples. The technique has high sensitivity (Ref. 5), in contrast to ordinary spectroscopic techniques (Refs. 6-9).

The minerals/gelbstoff sensor forms a basis for the detection of fluorescent minerals and decayed organic matter (gelbstoff or yellow material). Again, a fluorescence technique is employed, except that the irradiation is now at a wavelength of 2537Å and the photomultiplier sensor is broadband between 4000Å and 6500Å. Minerals occurring as surficial deposits on the continental shelf or on rock outcrops (Ref. 10) can be dissolved by ocean currents; they are located by tracing the concentrations, which may conveniently be accomplished in certain instances by fluorescence. Gelbstoff (decayed organic matter) is generally prevalent in all oceans, increasing on the continental shelf because of continental runoff. Changes in its level can indicate effects of ocean currents (Ref. 11), bottom ooze, or the effect of dying of plankton.

Bioluminescence is the emission of light by marine organisms, dinoflagellates. It is the result of stimulation. Surface bioluminescence has been studied, but there is very little information on subsurface bioluminescence caused by mechanical agitation. Such luminescence could be used to locate fish, vehicles, or survivors.

The Group II experiments supplement the Group I by furnishing information useful in explaining the Group I results. Thus, for example, where such nutrients as phosphates and nitrates occur in the proper form and a healthy plankton population develops, the pH would be reduced (Ref. 2). The samples could be taken by the conventional Nansen-bottle technique and coincident sensors used for temperature, but only to furnish "ground truth" for the optical remote sensors aboard the Ben Franklin.

2. INSTRUMENTATION

The experimental implementation of Group I is shown in Fig. 3. Essentially, two 4-watt ultraviolet lamps, in pressure housings designed to take 1000 psi, emit radiation at broadband 4000Å and 2537Å. Two photomultipliers with high voltage supplies (all in pressure-withstanding housings) sense the fluorescent light at 6700Å and between 4000 and 6500Å. This system is entirely battery-powered and controlled from the main battery box.

The ultraviolet sources and photomultipliers are mounted on the port-aft motor guard of the Ben Franklin (Fig. 4) just behind the propulsion motor. The propulsion motor agitates the water near the photomultipliers for the bioluminescence investigations; it is then oriented horizontally, with the propeller aft. The connections to the ultraviolet lamps and the photomultipliers are made through hull penetrators to the power supply in the interior. The pressure-withstanding housing for the photomultiplier and power supply is shown in Fig. 5; two such units are used. The exterior arrangement on the motor guard is shown in Fig. 6. Shields are mounted on the ends of the photomultipliers to limit the sensed volume and reduce the extraneous light entering. The system is quite sturdy, and if necessary the units can be removed by a skin diver for surface adjustments without disconnecting the wires.

The control unit within the Ben Franklin is shown in Fig. 7. The present battery configuration provides for 30 days of operation at one hour a day, the fundamental limitation being the energy necessary to light the fluorescent lamps. A battery supply is used to avoid adding an additional load to the Ben Franklin's storage battery power supply. There is no fundamental limitation on operating time, other than battery life. The photomultipliers are turned on with switch #1, the ultraviolet lamps with switches #2 and #3. The dc voltage outputs are measured by the Amphenol Field Effect Transistor Voltmeter shown above the battery box (Fig. 7). An Ortec Model 430 scaler (basically battery powered but also drawing 2 W, 110 V, 60 cycle ac from the Ben Franklin supply) is used to count bioluminescent pulses, and the Field Effect Transistor Voltmeter measures average background light.

3. CALIBRATION

The usefulness of any set of quantitative scientific observations is strongly dependent on the calibration. The calibration technique in our experiment is based on a method, using fluorescence, for the determination of phytoplankton chlorophyll and phaeophytin, described by Yentsch and Menzel, who used the Turner fluorometer with suitable filters to measure fluorescence.

The technique requires taking a sample of 250 to 500 ml of water. During calibration dives on the Ben Franklin, these water samples were obtained as necessary from a sea valve, at the depths at which optical measurements were made. The water sample is pumped through a glass fiber filter, to concentrate the plankton. An acetone extract, which is prepared from the filter, contains the concentrated chloroplastic pigments. The extract is then measured in the Turner fluorometer to yield a value F_o (the original fluorescence) due to chlorophyll and phaeophytin. The concentrate is then acidified and the fluorescence now measured is that due to phaeophytin alone. The amount of fluorescence due to pure chlorophyll (F_{chl}) can thus be computed.

The quantity F_{chl} is the total chlorophyll in the sea in μg/liter, and plankton density can be inferred from the variety or distribution of varieties. The gelbstoff is more simply measured by a relative fluorescence for short wavelength ultraviolet radiation.

Bioluminescence did not permit a convenient calibration to be made at this time. Calibration measurements of the sea water samples were made at the Nova University Physical Oceanographic Laboratory, Fort Lauderdale, Florida.

4. MISSION PLAN

The Gulf Stream drift mission plan was arranged to permit taking measurements of chlorophyll, minerals/gelbstoff, and bioluminescence at least three times a day. Most measurements were expected to be made at night at depths of less than a few hundred feet, because the sensors would be less sensitive to small changes if there were a high background light level. It was anticipated that measurements would be made before and after the location of the Ben Franklin was changed, either by propulsion in the Gulf Stream or by change in depth, and whenever unusual phenomena were noted on other instrumentation within the vessel. The mission was started on July 14, 1969, and terminated on August 14, 1969.

5. RESULTS

Initial results from test dives off West Palm Beach are presented in Figs. 8, 9, and 10, and in Table I.

Figure 8 shows the results of two dives, one to 240 meters, the sea floor (May 19, 1969), the other to 210 meters (May 28, 1969). During both dives, sea water samples were taken for laboratory calibration measurements, and the chlorophyll concentration (in μg/liter of sea water) is plotted in Fig. 8 as a function of depth. The exact station location was not logged because the only purpose was to compare the chlorophyll content of a particular location in the Gulf Stream with the indication by photomultiplier (Group I) sensor. The scattered light level, indicated by the same photomultiplier that was used to sense chlorophyll fluorescence (6700Å peak sensitivity), gives a relative indication of the amount of light. The photomultiplier used to sense the wavelength band between 4000-6500Å was saturated by the high light levels at the shallower depths.

It can be seen in Fig. 8 that the scattered light is highest near the surface, indicative of light available in the euphotic zone to cause photosynthesis. The chlorophyll is also highest near the surface; however, there is an increase in F_{chl} at the sea floor in the cruise of May 19th, indicating plant life at the bottom. This increase of chlorophyll could be the result of ocean circulation bringing surface phytoplankton toward the sea bottom (Refs. 2, 8).

From the laboratory observations on the sea water collected during the dive of May 28th and the initial test dive chlorophyll measurements presented in Fig. 9, a calibration curve has been drawn for the Ben Franklin chlorophyll sensor (Fig. 10). The curve is extrapolated to zero, since zero voltage represents zero chlorophyll.

Table I presents calibration and observational data on gelbstoff and additional observational data to indicate an increase in bioluminescence with depth. There appears to be a relatively large scatter in both calibration (on sea water samples) and *in situ* observations of gelbstoff. Perhaps these variations are actual.

6. CONCLUSIONS

As a result of the optical remote sensing experiments aboard the Ben Franklin, it appears that continuous *in situ* chlorophyll determinations from a manned submersible are possible. The adaptability of the measurement to the experimental conditions can be used to advantage.

Optical instrumentation of this type can apparently be attached to a buoy for continuous monitoring of an ocean area for chlorophyll and gelbstoff levels. This information can be used as "ground truth" for wider range aircraft or satellite observations of the ocean surface.

Additional information has been obtained on bioluminescence.

7. FUTURE WORK

The optical observations aboard the Ben Franklin (made during the mission) and supplemented by surface investigations from an oceanographic research ship (the Lynch) are being analyzed and correlated, and will be reported in the near future. The areas of investigation will include other locations, with additional measurements being made by aircraft. It is envisioned that ultimately pH, conductivity, dissolved O_2, temperature, and pressure will be measured by the same experimental sensor package that includes the optical experiments.

ACKNOWLEDGMENTS

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TABLE I. INITIAL GELBSTOFF AND BIOLUMINESCENCE MEASUREMENT

Depth (Meters)	5/19/69 Gelbstoff Calibration	5/28/69 Observed Gelbstoff	Bioluminescence 5/28/69 Counts/minute @ 8 1/3 HP Motor Power
75	4.0	---	---
122	2.0	---	32,454
151	4.0	2.0	37,732
210	0.0	1.0	61,324

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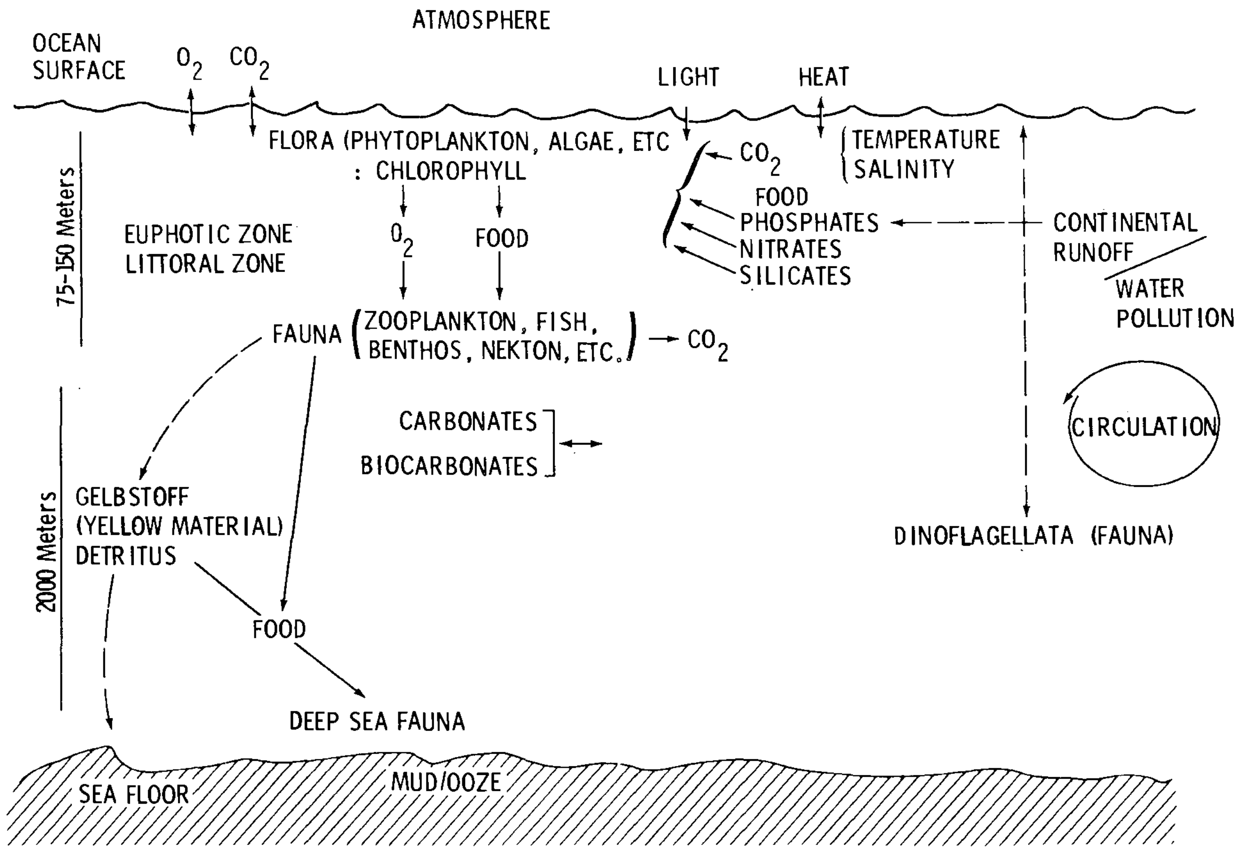

FIG. 1 THE OCEAN ENVIRONMENT (COASTAL WATERS)

Group I (in *Ben Franklin* Submersible)

UV (4000Å) → Chlorophyll → 6700Å Fluorescent Light → Photomultiplier 1

UV (2537Å) → {Yellow Material / Fluorescent Minerals} → 4000-6500Å Fluorescent Light → Photomultiplier 2

Mechanical Agitation → {Luminescent Fauna (Dinoflagelata)} → Blue Light

Conductivity / Temperature → Chlorinity/Salinity

Downwelling light/background illumination

Circulation Information

Group II (in Surface Vessel)

Water Samples (Nansen Bottle) →

- pH → Dissolved CO_2
- Dissolved O_2 → Inversely Proportional to Dissolved CO_2
- Temperature
- Phosphates
- Nitrates
- Atmospheric Parameters (Wind, Temperature, CO_2)
- Fluorescence

FIGURE 2. GULF STREAM DRIFT OPTICAL EXPERIMENT CONCEPT

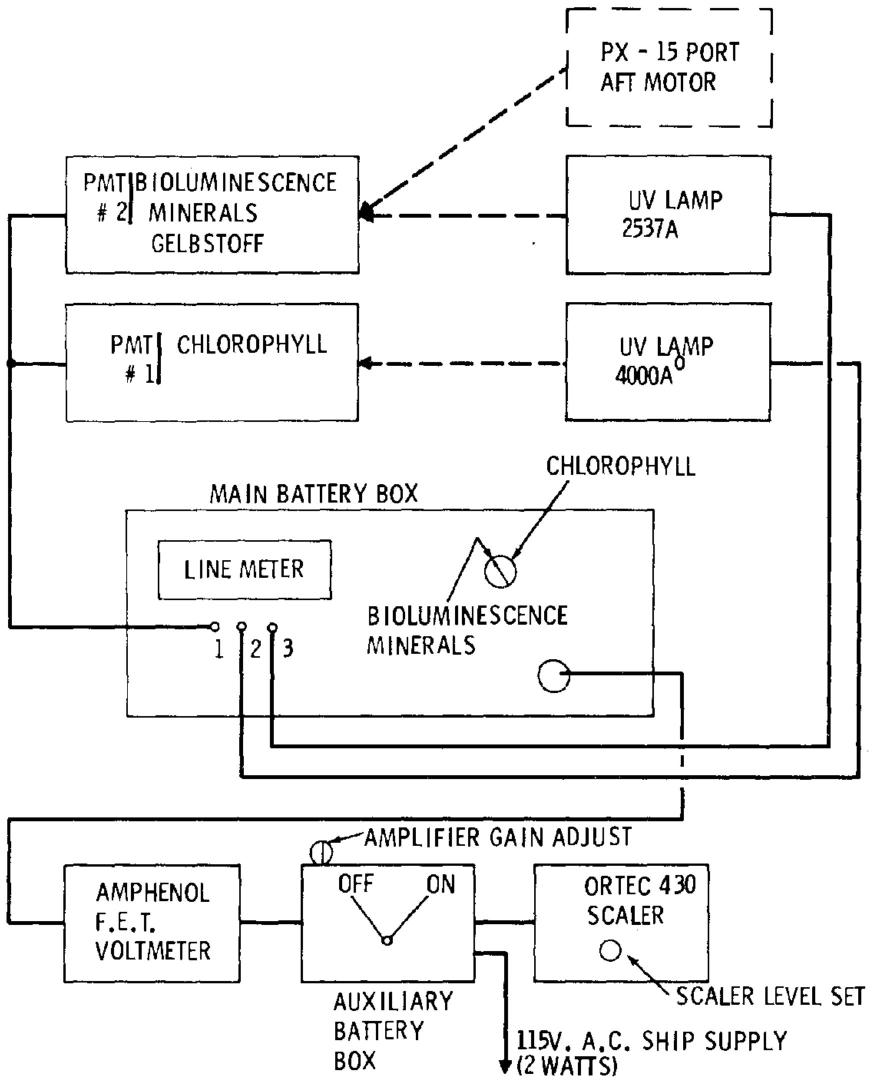

FIG. 3 OPTICS EXPERIMENTS GROUP 1 IMPLEMENTATION

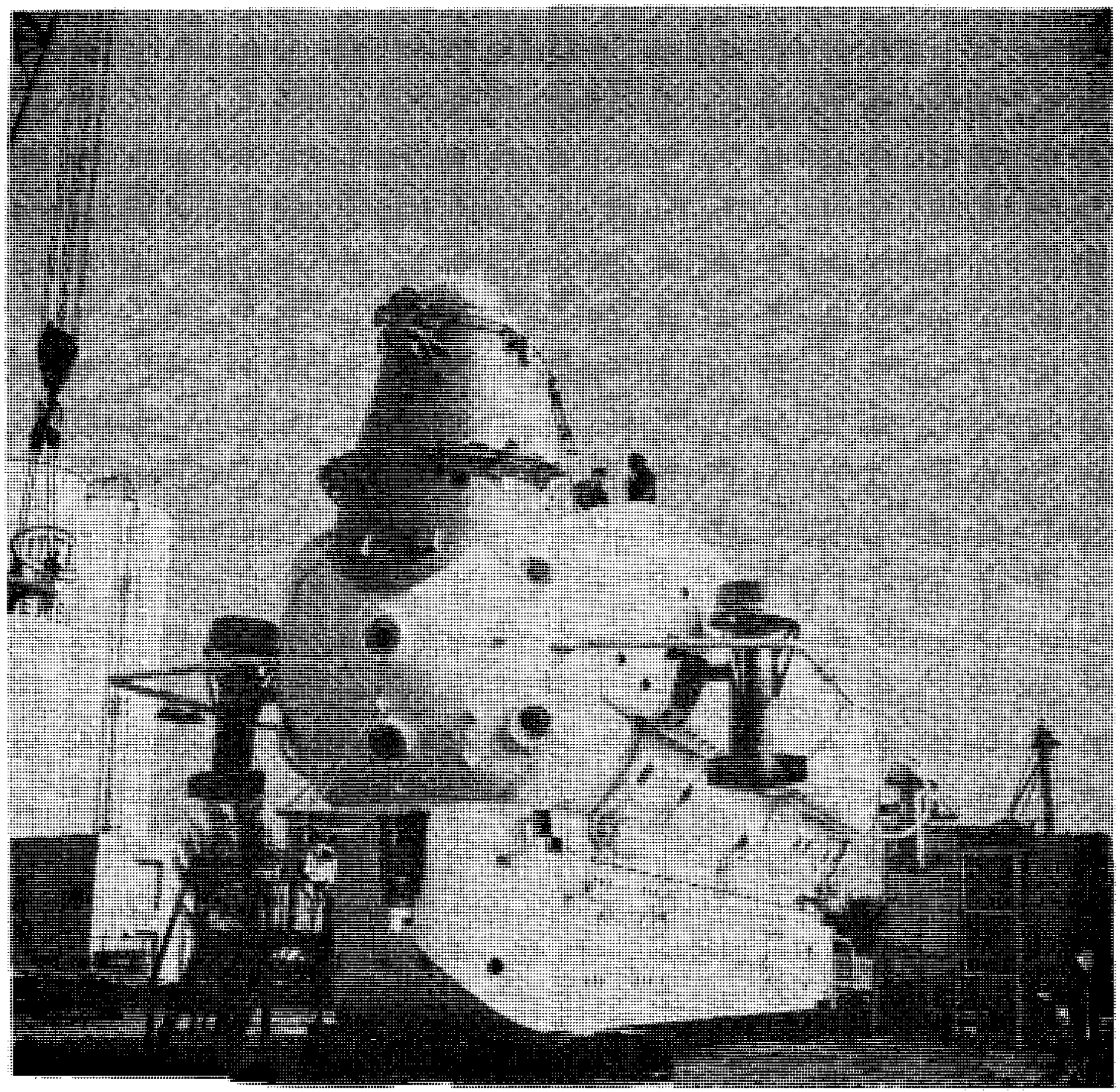

Fig. 4 THE BEN FRANKLIN

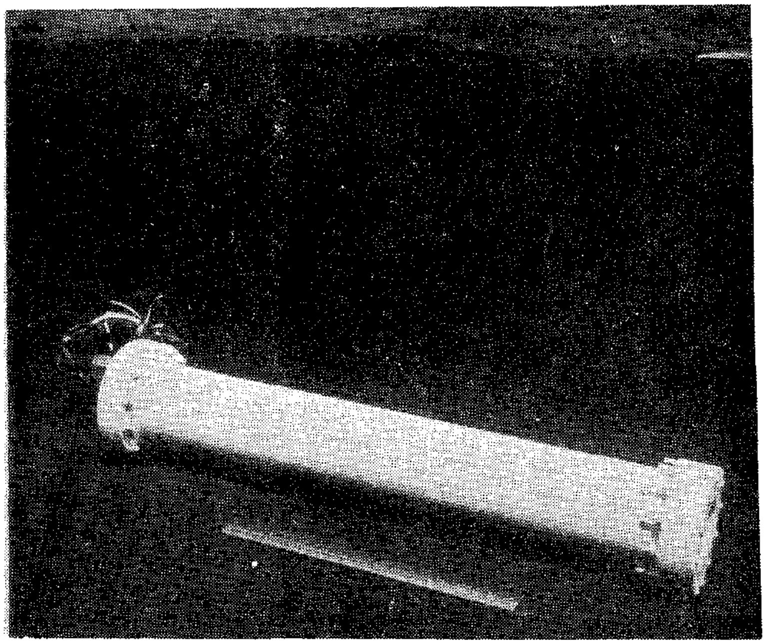

Fig. 5 PHOTOMULTIPLIER PRESSURE WITHSTANDING HOUSING AND POWER SUPPLY

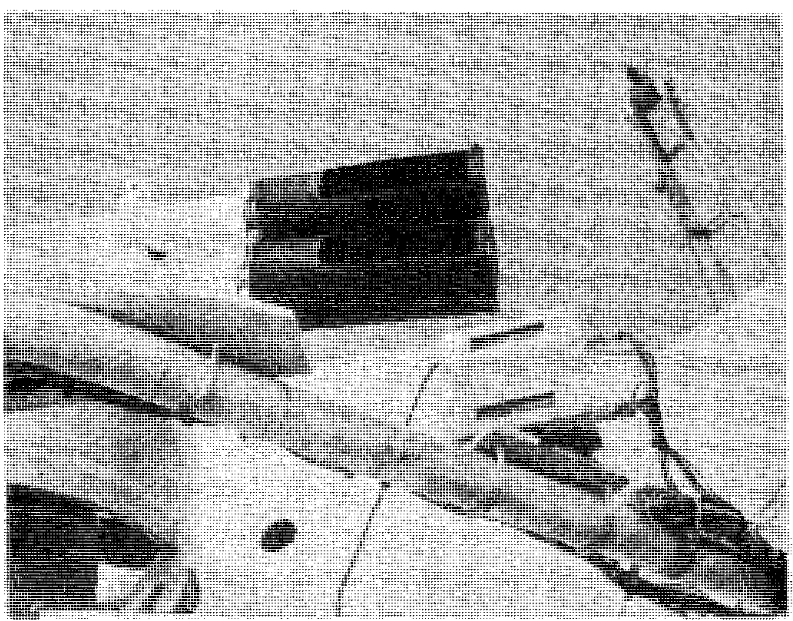

Fig. 6 EXTERNAL EXPERIMENTAL CONFIGURATION

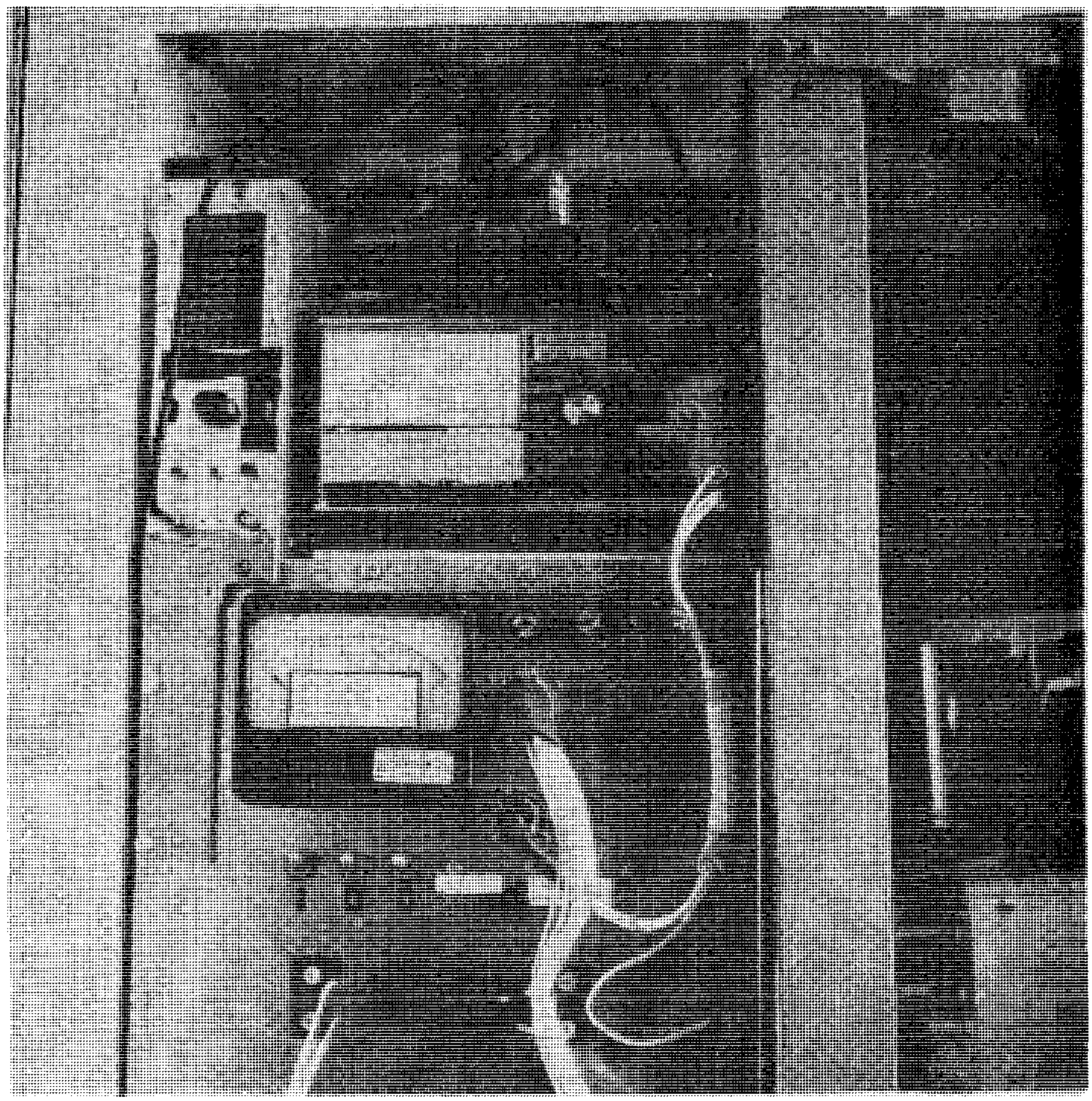

Fig. 7 EXPERIMENT CONTROLS AND POWER SUPPLIES

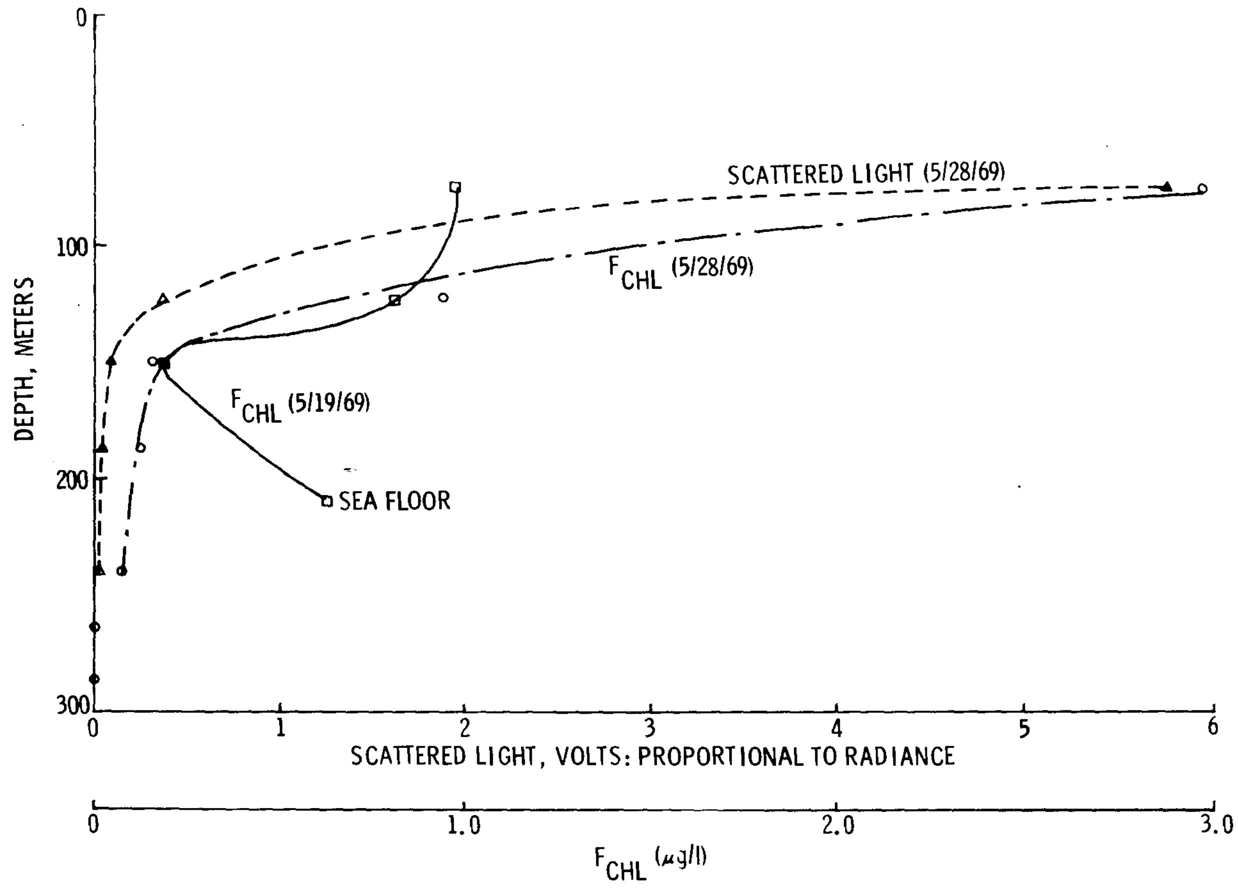

FIG. 8 MEASURED CHLOROPHYLL AND SCATTERED LIGHT WITH DEPTH

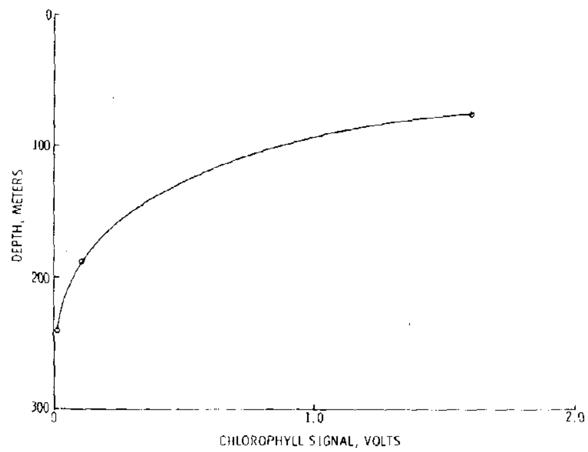

Fig. 9 INITIAL TEST DIVE RESULTS (5/28/69)

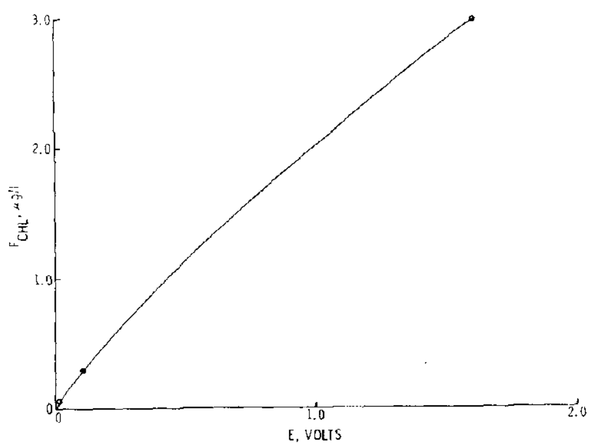

Fig. 10 CALIBRATION CURVE FOR CHLOROPHYLL SENSOR