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PROFILES IN SCIENCE

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Microstructure: Signature of Mixing in the Ocean

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Mixing in the Ocean

The goal of physical oceanography is to understand the processes that transfer substances and energy in the ocean. These processes act over a wide range of time and length scales from the slow movements of relatively large water masses that take hundreds of years to travel several kilometers in the vertical and thousands of kilometers in the horizontal, to the rapid motions of centimeter-scale turbulence that are damped by viscosity in a few minutes. Since the average energy and concentration levels of the sea change only over slow geologic time scales, the various transport processes must be in balance; those that increase the momentum or heat content in a given region must be offset by those that produce decreases.

Differences across the globe in the intensity of solar radiation, together with the geography of the planet, result in regional variations in the net fluxes of heat between the sea and atmosphere. There are also contrasts in the mean stress of the wind on the surface and in the rates of evaporation and precipitation. The net effect is to produce measurable differences in the mean temperature, T, salinity, S, and water velocity, V, of the surface waters from one place to another. The colder and more saline surface waters are also more dense than the others and sink, carrying the variability of temperature and salinity into the interior.

In order to identify these transport processes and then to estimate the components of the basic balances of heat, salt, and momentum, oceanographers must be able to measure and describe a wide range of fluctuations, both in space and time. Microstructure research is aimed at those transport processes that tend to make the ocean more uniform, or well mixed, by the irreversible actions of viscosity and diffusion. These molecular, or dissipative, processes smooth the fluctuations of T, S,

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and V at rates that depend upon the intensity of the small-scale fluctuations themselves as well as upon the molecular properties of the water; fluctuations of smaller scales are produced by higher energy dissipation rates. The energy levels in most of the ocean are so low that fluctuations are smoothed over lengths much greater than molecular dimensions; typically the significant dissipation occurs in fluctuations with length in the millimeter to centimeter range. These microscale features last only a few minutes before they are smoothed to larger scales that do not significantly contribute to the dissipation.

Although the understanding of mixing processes in the sea is at an early stage, the framework in which it is being developed can be seen by considering some of the balance equations. These formulations relate the time rate of change of a quantity such as momentum or heat in a small, or local, volume to the net fluxes into the volume and to the local rate of production, or destruction. The rate of change of some scalar quantity, a, in a small moving volume of fluid is expressed by the substantial derivative,

$$\frac{Da}{Dt} = \frac{\partial a}{\partial t} + \underline{U} \cdot \nabla a.$$

The first term on the right expresses the evolution of "a" within the volume. Changes due to the motion of the parcel through a gradient of "a" are given by the second term to the right.

One of the most fundamental of the balances is the entropy equation

$$\rho \frac{D\eta}{Dt} = - \nabla \cdot \underline{J}^{\eta} + \sigma \qquad (W \cdot K^{-1} \cdot m^{-3}) \tag{1}$$

where ρ is the density, η is the entropy per unit mass, $\underline{J}^{\eta}$ is the entropy flux, and σ is the rate per unit volume at which entropy is generated. The units of the equation, shown in parenthesis, are watts per degree Kelvin per cubic meter. This equation is a statement of the second law of thermodynamics for a restricted, or local, volume of fluid.

Fundamental work in thermodynamics has shown that σ has the form:

$$\sigma = \frac{K(\nabla T)^2}{T^2} + \frac{\rho \epsilon}{T} + \begin{matrix}\text{terms involving} \\ \text{concentration gradients}\end{matrix} \tag{2}$$

where K is the thermal conductivity, T is the temperature, and ϵ is the rate per unit mass at which kinetic energy is dissipated by viscosity and is given by:

$$\epsilon = \frac{\nu}{2} \sum_{i,j} \left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right)^2 \qquad (W \cdot kg^{-1}) \tag{3}$$

where ν is the viscosity and the gradients $\partial U_i/\partial X_j$ are the velocity shears. Thus, both of the terms we have examined in the σ expression are positive definite; regardless of the sign of the temperature or velocity gradients diffusion and viscosity act to produce entropy, not to destroy it. It can also be shown that the concentration terms represent entropy production.

Equation (1) is an embodiment of the second law of thermodynamics and expresses the direction in which the ocean, or any other thermodynamic system, will tend to evolve. Although the flux terms, $\underline{J}^{\eta}$, generally have not been evaluated, the form of the production term shows that measurements made to study the balance must be sufficient spatial resolution to give good estimates of the variances of the gradients, i.e. $(\nabla T)^2$ and $(\partial U_i/\partial X_j)^2$.

Morc practical results have been obtained from the heat equation

$$\rho C_p \frac{DT}{Dt} = -\nabla \cdot \underline{J}^q + \rho\epsilon \qquad (W \cdot m^{-3}) \tag{4}$$

where C_p is the specific heat and $\underline{J}^q$ is the heat flux. This equation is derived from the entropy balance by neglecting terms involving salinity variations. This is a very good assumption under most circumstances and, in fact, the heat generation by viscous dissipation, $\rho\epsilon$, is also generally negligible in comparison to the other terms.

In its simplest form, known as Fourier heat conduction, the heat flux depends upon the thermal conductivity of the medium and upon the temperature gradient, i.e., $\underline{J}^q = -K\nabla T$. Although this form for the flux worked well for laboratory solids, attempts to use it in balances for natural fluids, such as the ocean, were not successful. For example, studies of seasonal heating at shallow depths were done by comparing repeated profiles obtained from wire-lowered thermometers. The seasonal change in the heat content at a fixed depth was determined from the successive temperature readings on different profiles. Since the temperature was assumed to vary smoothly with depth, the gradients in a particular profile were taken from the temperature differences when successive thermometers, 10 to 100 m apart, were compared. The simplest form of heat balance was to assume that the progressive changes in the heat content were due to vertical heat transport by conduction down the temperature gradients.

Equation (5) then took the simple form of

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial Z^2} \qquad (K \cdot s^{-1}) \tag{5}$$

where Z is the vertical coordinate, and $\kappa = K/\rho C_p$ is the thermometric conductivity, or more commonly the thermal diffusivity. In water

$K = 1.4 \times 10^{-7}\ m^2 \cdot s^{-1}$. The two terms did not balance; the time rate of change of the heat content was about 1000 times greater than could be accounted for by simple, or molecular, heat conduction along the smooth mean gradients.

Similar discrepancies were obtained in the early part of this century by scientists considering momentum transfer in the upper ocean and in the lower atmosphere. V. W. Ekman (1905) proved that, due to the earth's rotation, a steady wind stress on the sea surface produces a net transport of the surface waters at right angles to the wind direction. He also showed that the depth of water directly affected by the wind is limited and depends upon the rate at which momentum is transferred downward from the surface; the depth of the Ekman layer is proportional to the square root of the viscosity. If the molecular viscosity coefficient, $\nu = 1 \times 10^{-6}\ m^2 \cdot s^{-1}$ is used, the Ekman layer depth is less than 1 m, a ridiculous result. To obtain a reasonable depth, about 75 m, a rate of momentum transfer 10,000 greater must be assumed, equivalent to a viscosity coefficient of $.01\ m^2 \cdot s^{-1}$. Ten years later G. I. Taylor independently arrived at essentially the same conclusions regarding the lower levels of the atmosphere. Without knowledge of Ekman's work he based his results on the deflections of ballon tracks launched from a research ship.

These investigators concluded that the increased vertical transports were due to turbulent motions that were much more effective than simple molecular action. Based on laboratory work, Osborn Reynolds had earlier proposed a formalism for including turbulent transport in the various balance equations. His approach was to express a variable like temperature, as a sum of mean and fluctuating terms, e.g., $T = \overline{T} + T'$. Averages of the primed terms are zero, as are cross products of fluctuating and mean quantities, e.g., $\overline{T'\overline{T}} = 0$. If a similar decomposition for the velocity is also substituted into eqn. (4) and the resulting equation averaged, the expression becomes

$$\rho C_p \frac{D\overline{T}}{Dt} + \frac{\partial}{\partial Z}\overline{(U'_Z T')} = \frac{\partial}{\partial Z}\left(K\frac{\partial \overline{T}}{\partial Z}\right) \tag{6}$$

where the turbulent heat transport is given by the net correlation of the vertical velocity fluctuations, U'_Z, and the temperature fluctuations, T'.

At the time none of the fluctuating terms could be measured directly, so Taylor proposed a model of turbulent mixing based on an analogy to molecular conductivity. Later Prandtl independently made a similar proposal. He assumed that coherent fluid masses move a small distance up or down and then completely mix with their surroundings. If there is a mean gradient this results in a net transport. A measure of this is given by the turbulent thermal diffusivity, κ_z^t, which is defined by the following expression.

$$\overline{U'_Z T'} = - \kappa_Z{}^T \frac{\partial \overline{T}}{\partial Z} \quad (7)$$

Lacking direct measurements of $\overline{U'_Z T'}$, $\kappa_Z{}^T$ is an adjustable parameter which can be chosen to balance the other terms in eqn. (6). The assumption is that the value of $\kappa_Z{}^T$ determined this way can be used in similar flow regimes where not all of the other terms in the balance are known. Although not a very satisfying procedure, it has proved useful to oceanographers for the past 50 years, enabling them to construct both analytical and numerical models of the ocean.

One of the most prominent examples of this approach is a model proposed for the main thermocline. At depths greater than a few hundred meters the seasonal heating cycle at the surface is rarely felt, and the mean temperature, at a given depth changes very slowly in the horizontal. Profiles from wire-lowered thermometers, separated by hundreds of meters, showed that the temperature decrease with depth can be closely fitted by an exponential curve. The upper part of the curve, where the temperature decreases most strongly is known as the thermocline. It occurred to investigators that a simple form of equation (6),

$$\overline{U}_Z \frac{\partial T}{\partial Z} = \kappa_Z{}^T \frac{\partial^2 \overline{T}}{\partial Z^2} \quad (8)$$

has an exponential solution which can fit the observed profiles. The temperature change with depth is proportional to $e^{-Z/H}$, where the scale depth, $H = \kappa_Z{}^T/\overline{U}_Z$, has a value of 1 km. The dynamics suggested by the balance are that the downward turbulent transport of heat, represented by the term on the right, is balanced by the slow upward movement of the cold deep water. From estimates of the rate at which the deep water is formed in the Antarctic, $\kappa_Z{}^T$ was taken to be 1×10^{-4} $m^2 \cdot s^{-1}$, or about 1,000 times greater than the molecular value.

It was obvious to the early investigators that, to progress beyond this gross statistical approach to ocean mixing, observations with higher resolution were required. This progress, however, has been slow even with temperature, which has proved the easiest of the measurements to make.

Development of High Resolution Temnerature Profiling

Some of the earliest continuous profiling was done in the less difficult environment of lakes, rather than in the ocean. An early device reported from Vienna by W. Schmidt (1914) had a bi-metallic coil for a temperature sensor. The expansion and contraction of the coil drove the temperature axis of a pen by means of a mechanical linkage. The works and chart paper were contained in a bell jar. As the jar was lowered the air inside compressed with the resulting movement of a float advancing the paper along the depth axis. Schmidt, successfully using this system to depths of 60 m in Alpine lakes, showed that the temperature did not decrease smoothly with depth, but had an irregular profile.

This work was interrupted by World War I and was not resumed until the late twenties, when Schmidt (1927) published a description of an improved instrument. The bi-metallic probe was retained; but a glazed glass slide was substituted for the chart paper, and the depth scale was made more linear. This was accomplished by letting the instrument slide down a heavily weighted cable. Rollers on the instrument turned a worm screw, advancing the slide at a rate proportional to the falling velocity. It fell at 0.3-0.5 $m \cdot s^{-1}$ and could sense temperature fluctuations of 0.05 to 0.1°C. Walter Hacker (1933) used the instrument to study seasonal cycles in Alpine lakes as part of his doctoral research.

Mixed layer studies in the ocean were begun, using a device very similar to that of Schmidt, by Rossby and Montgomery (1934). Named the *oceanograph*, their instrument also had a bi-metallic coil, but used a pressure sensitive bellows to move a slide with a smoked brass foil. Sensitivity was reported to be about 0.1°C in temperature and 1 m in depth. This prototype had several defects. At Rossby's suggestion, Spilhaus, (1937, 1939), redesigned the instrument in the late 1930's to make it more usable. The modifications included a Bourdon tube pressure sensor, to eliminate the hysteresis previously found, and a smoked glass slide. The result, termed the *bathythermograph*, was further modified by Maurice Ewing and Allyn Vine to become the instrument that was used for 30 years by oceanographers, and the Navy, to study the upper ocean, revealing a wealth of detail that has become known as finestructure.

Efforts to develop electronic systems for vertical profiling began after World War II, but little impact was made upon our view of the ocean until 1964 when the first commercial salinity-temperature-depth (STD) systems produced by the Bissett-Berman corporation were sold to oceanographic institutions. The platinum resistance bridge thermometer was much more stable and sensitive than the bathythermograph. The data, in the form of a frequency modulated signal, was transmitted up an electrical cable for display and recording onboard ship. This development had begun several years before as one of the components to be used for several naval projects, the Anti-submarine Warfare Environmental Prediction System (ASWEPS) and the Shipboard Oceanographic Survey System (SOSS). Similar systems were developed in several other countries.

In 1974 N. L. Brown, who had been the lead engineer on the Bissett-Berman STD project, designed an updated wire lowered profiler while at the Woods Hole Oceanographic Institution. This system, which also measures electrical conductivity and is known as a CTD, encodes the data as digital information to 16 bits of accuracy, or 1 part in 65,536. It can sense temperature fluctuations to 0.0005°C over vertical distances of about 0.6 m and is capable of operating to the bottom in most locations.

Although a wealth of information has come from the STD or CTD instruments, the systems do not have either the sensitivity or spatial resolution to resolve the temperature gradients. This required a new approach. In 1968 C. S. Cox at the Scripps Institution of Oceanography, achieved measurements of the microscale, or dissipation, range structures by using a free-fall vehicle, Cox et al (1969). This instrument used a small, 0.02 inch diameter, thermistor to sense temperature fluctuations. A thermistor is made of semi-conductor material that has a large change of resistance with temperature. This approach has proved capable of detecting temperature fluctuations of a few microdegrees (millionths of a degree) over distances of 1 cm. Although not able to fully resolve the most intense gradients found in some locations, this instrument has yielded a detailed view of some of the features which had been noticed since the early days of the BT.

A graduate student, T. Osborn, and Cox also developed several less sensitive finestructure instruments, which could be put down in patterns, Osborn and Cox (1972). In 1973 Peter Hacker, son of the Walter Hacker who studied alpine lakes, published his doctoral dissertation which included observations made in Lake Tahoe with these finestructure sensors. This truly marked the second generation of finestructure work! The improvement in both spatial resolution and sensitivity was a factor of 100.

Let us now see what some of the fruits of this development have been.

Structures and Processes

Both the character and intensity of microscale fluctuations depend upon the finestructure settings in which they occur. Observations to date have identified two principal finestructure regions. In one, the temperature decreases with depth, but in a non-uniform manner. The profile has thin steps, or kinks, separated by thicker regions of much smaller change, as seen by the example in Figure 1. The kinks in the normal profile were noticed in the earliest continuous soundings from both lakes and the ocean. The other type of finestructure has sections of the profile that show temperature increases with depth that are several meters or more thick, as seen in Figure 2. Since this is contrary to the normal situation, these features are known as temperature inversions. In a lake an inversion is statically unstable and would be in the process of overturning. However, in the ocean there are frequently corresponding salinity increases that stabilize them.

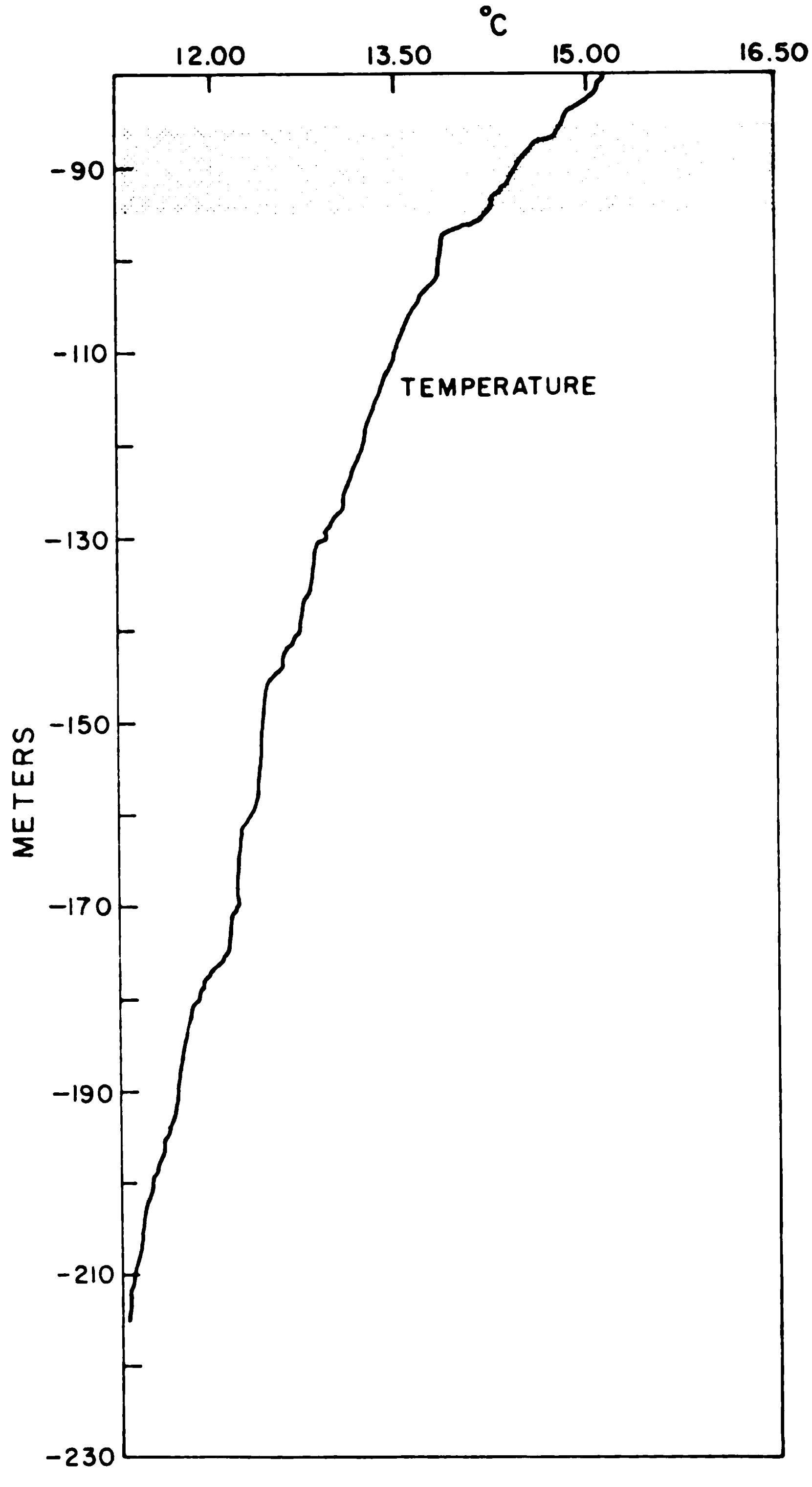

Figure 1 — Temperature profile that has regions of rapid temperature change separated by thicker regions with weaker temperature changes. This profile was taken off the southern tip of Baja California (Gregg, 1975) but is typical of conditions in many of the mid-gyre regions in that the temperature decreases monotonically with depth. The plot contains one data point every 3 cm.

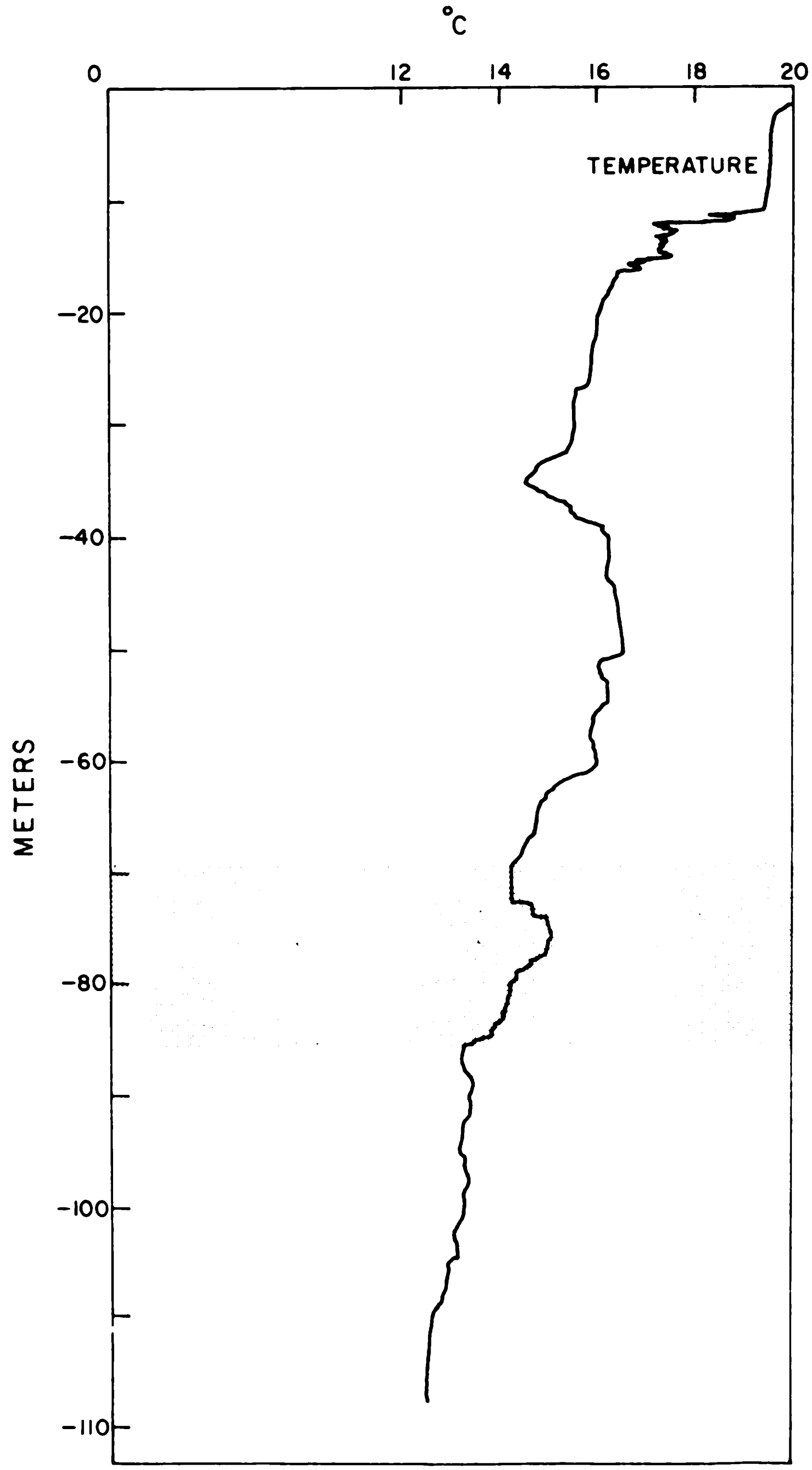

Figure 2 — A temperature profile that has numerous sections that show temperature increasing with depth. These features are known as temperature inversions. This was taken only a few miles away from the profiles in Figure 1. Regions with prominent inversions tend to occur in locations where large water masses are brought into close lateral proximity by the mean currents.

Since some of the temperature inversions occur over vertical scales of tens or hundreds of meters they were noticed in observations with wire-lowered thermometers 200 years ago. In 1939 Spilhaus published a very prominent example from a BT trace.

Direct measurements of the turbulent transports, such as $\overline{U'_Z T'}$, that are occurring in these finestructure regimes have not yet been made. In their absence the data has been interpreted by using the signatures provided by temperature and salinity fluctuations as indicators of the type of activity taking place. For example, an overturn of the water in a normal profile will produce an S-shape in the temperature quite different in appearance from the inversions in Figure 5. The accompanying turbulence would also produce a number of centimeter-scale inversions and a high value of the mean square temperature gradient.

Since there are no significant sources or sinks of temperature in the interior of the ocean, balance equations for the temperature fluctuations have been found useful. Although these balances do not have the same physical significance as the heat equation they serve as a quantitative means for discussing the generation and decay of microstructure. The one for temperature is formed by substituting the Reynolds decomposition for temperature and velocity into equation (4), multiplying by T′, and then averaging.

$$\frac{\partial \overline{T'^2}}{\partial t} + \overline{\underline{U}} \cdot \nabla \overline{T'^2} + \nabla \cdot (\overline{\underline{U}'T'^2} - \kappa \nabla \overline{T'^2}) = \qquad (9)$$

$$- 2\nabla \overline{T} \cdot \overline{\underline{U}'T'} - 2\kappa \overline{(\nabla T')^2} \qquad (K^2 \cdot s^{-1})$$

The terms on the left of the equality express the rate of change of the mean square fluctuation, $\overline{T'^2}$, and the rate at which temperature fluctuations are brought into the reference volume by the mean currents, turbulence and molecular diffusion. These are balanced by the local production of $\overline{T'^2}$ by turbulent motions in the presence of a mean gradient and by diffusive smoothing. The last term is similar to one component of the entropy production from equation (2).

The physical model of the thermocline expressed by eqn. (8) implies that the local $\overline{T'^2}$ production and smoothing terms are in balance, and in particular that the local production is due to vertical turbulence. Thus, the definition for the turbulent thermal diffusivity, eqn. (7), can be used in equation (9) to yield

$$\kappa_Z{}^T \left(\frac{\partial \overline{T}}{\partial Z}\right)^2 = \kappa \overline{(\nabla T')^2} \qquad (m^2 \cdot s^{-1}) \qquad (10)$$

or

$$\frac{\kappa_Z{}^T}{\kappa} = \frac{\overline{(\nabla T')^2}}{\left(\frac{\partial \overline{T}}{\partial Z}\right)^2}$$

If the thermocline model is correct the ratio of the turbulent to the molecular diffusivity is about 1000:1, consequently, the mean square temperature gradient, determined from microstructure measurements, will be that much greater than the square of the mean gradient. A high resolution record should thus appear very wiggly.

An example of high-resolution data in a "steppy" profile is shown in Figure 3, which is an expanded view of the mottled section of Figure 1. The sharp temperature step at 87 m is 0.6 m thick and has nearly the same net temperature decrease across it as does the 5 m section below. In the upper ocean about half of the total temperature decrease occurs in these kinks and the other half in the thicker, lower gradient regions. These are ubiquitous features throughout the upper ocean. Their three-dimensional structure and time history have not yet been detailed, but individual kinks have been followed in one direction for several kilometers as well for several hours by repeated measurements at one location.

Several processes have been proposed to produce the kinks. One is that the kinks are transient distortions created by the shear of the internal waves in an otherwise smooth profile. If the internal wave motions were suddenly to cease the kinks would disappear. Experimental evidence for this point of view comes from time series STD observations which show the kinks migrating vertically in temperature as well as depth. This type of motion is consistent with the vertical propagation of internal waves. The second possibility for the origin of the kinks is that they are the transitions between distinctly different layers of water. The water in the layers had been previously mixed and then was spread out into long thin layers by the stratification. In this case the kinks would be little changed if the internal wave field suddenly ceased. Experimental evidence comes from combined temperature and salinity differences across the kinks that could not have been formed by internal wave strain.

Both of these methods of formation probably occur. However, determination of their relative roles is important to the mixing balances. If the kinks are mostly due to internal wave strain, the change to the temperature profile is reversible and their mixing effectiveness is very low. On the other hand, if they are mostly transitions between different types of water, the processes leading to the formation of the water types will be a strong agent of vertical mixing. One possibility suggested by numerical models and theoretical arguments is that the mixing is due to the breaking of large amplitude internal waves. So far such events have been conspicuously absent from high resolution profiles. Another possibility is that the mixing may occur as a longer-term lower intensity turbulence due to the shear of low frequency internal waves. Observations to test this are presently being made.

The temperature gradients in Figure 3 show several centimeter-scale inversions at the kink, which are largely responsible for the relatively high mean square gradient, shown on the right-hand plot. Due to the relatively rapid rate at which molecular diffusion smoothes fluctuations over these scales the maximum time that these inversions could have existed was 10 minutes. Whether or not the kinks were formed by internal waves, they are locations where the shear due to these motions has a maximum tendency to destabilize the water column. It appears that the microstructure fluctuations resulting from this shear tend to dissipate, or smooth, the kinks.

The larger section of ocean from which Figure 3 was taken, i.e., the entire profile in Figure 1, had a mean square gradient only 10 times greater than the square of the mean gradient. The level of wiggliness

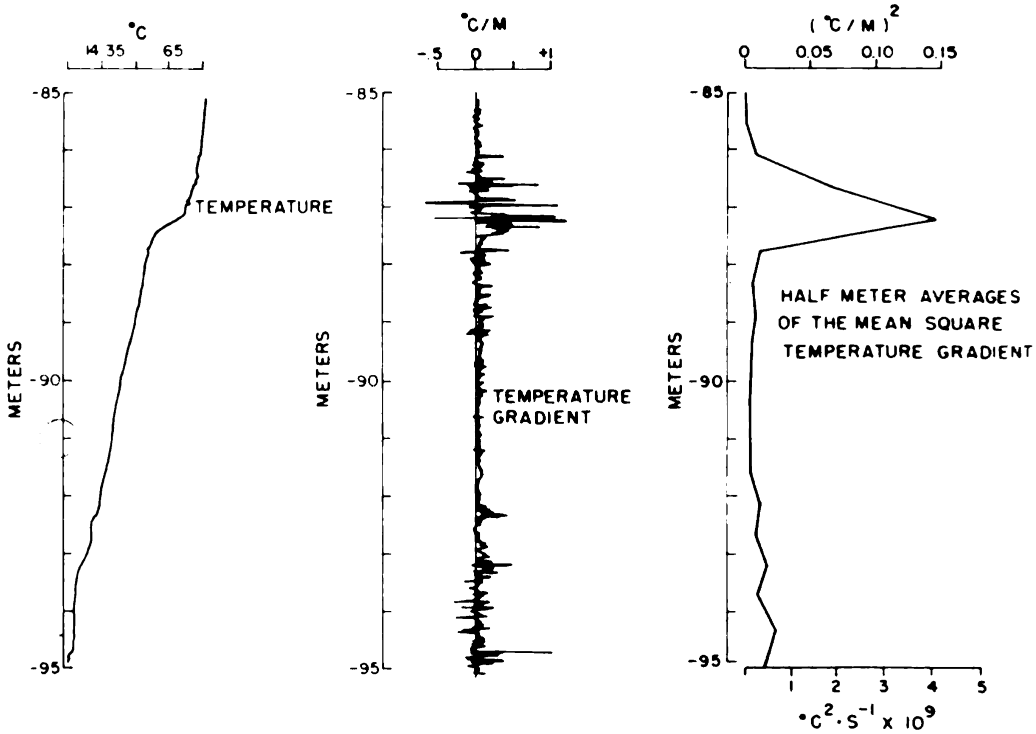

Figure 3 — Expanded view of the mottled section in Figure 1, plotted with a data point every 1.5 mm. Half-meter averages of the variance of the temperature gradient are shown on the far right. This quantity is proportional to the dissipation term in eqn. (9); the dissipation values are given by the bottom scale. The principal dissipation in this section occurs at the sharp gradient region at -86 m and is due to the small-scale temperature inversions.

is quite low, a factor of 100 less than supposed by the thermocline model. This has been found to be characteristic of large sections of ocean, particularly in the central regions, away from boundary effects. Thus, at least most of the time, these regions do not appear to have strong levels of vertical turbulent heat fluxes, but actually have low levels of mixing. Since these results are corroborated by studies of geochemical tracers alternate thermocline models are being considered more seriously.

Due to the prominence of the inversions, it has proved possible to determine their extent in at least a two-dimensional plane of closely spaced stations. An example, taken 15 miles offshore from San Diego, is shown in Figure 4. The very complicated structures were formed by cool, and low salinity, water from the California Current interleaving with warmer, and more saline, water which was moving northward along the coast. A tongue of the cooler water is shown coming from the right between 160 and 200 m depth. This produced an inversion in the profiles, with the temperature maximum shown by the dashed line below.

Inversions of this prominence are not common at all locations in the ocean. Rather, they occur most frequently in the boundaries between the major current systems, which bring different water masses into close proximity. The horizontal density differences between these different water masses cause them to intrude to produce a more stable stratification.

The temperature and salinity characteristics of the water in the inversion off San Diego were formed on the surface in the eastern tropical Pacific, several thousand kilometers to the south. The fact that the characteristics of this southern water were found intact off San Diego indicates that very little diffusion has taken place during the passage. However, the significance of the intrusions to the heat balance of the ocean is in the slow transport that occurred in the movement from the surface in the tropics to several hundred meters depth off California.

Many of the intrusions show patterns of microstructure through the inversions that are similar to those in Figure 5. The actual inversions occur as a series of very sharp steps. The rise in temperature often occurs over jumps of 2 to 20 cm thick, with low gradient regions in between. The temperature maximum has a smooth profile and very low levels of microstructure. The underside shows intense, but irregular microstructure, with many sharp centimeter scale inversions. In a profile with multiple inversions, the minima are nearly isothermal, as seen at the top of Figure 5a and the bottom of 5b. Some inversions several hundred meters thick show prominent 20 m thick steps on the undersides.

The distinctive microstructure on the upper and lower boundaries of the inversions is due to convective motions generated by the differing

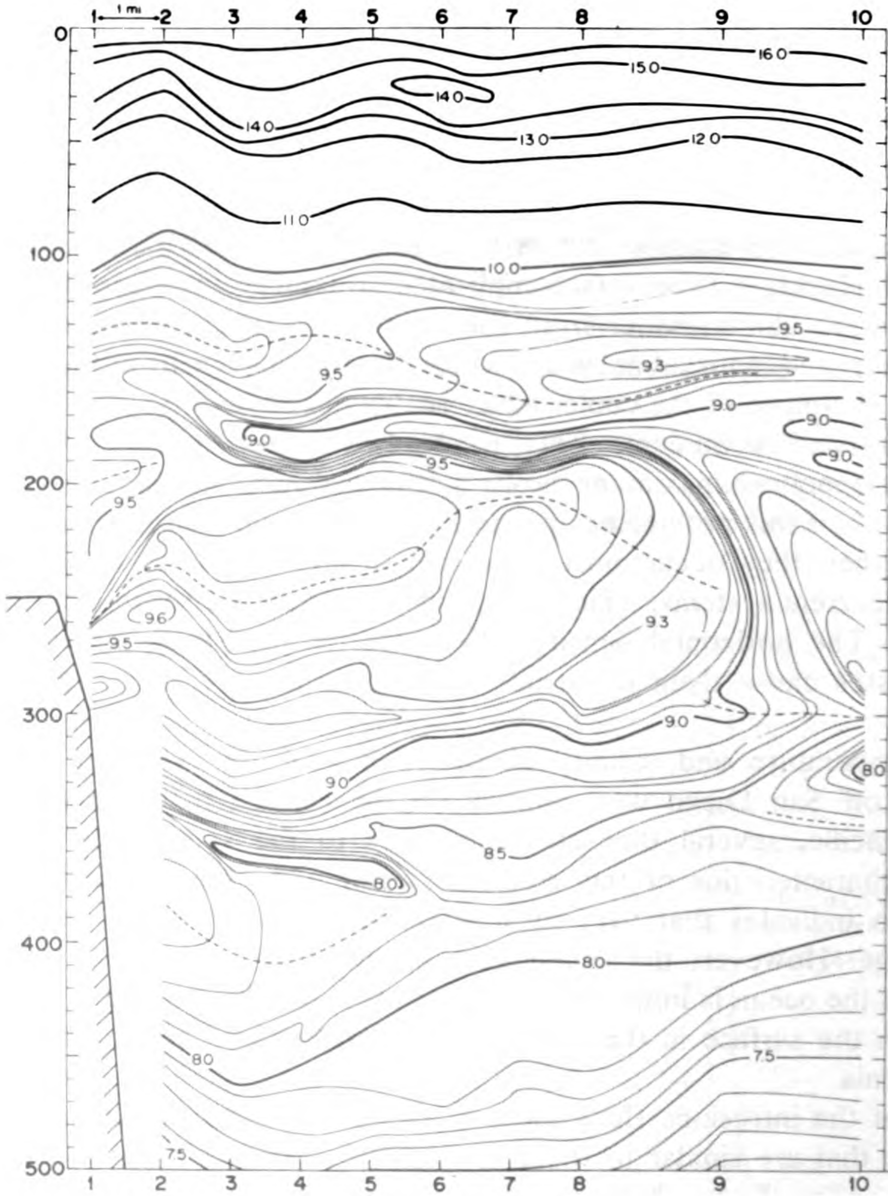

Figure 4 – Temperature contours made from closely spaced profiles in the San Diego Trough. The sea floor at the edges of the trough is shown by the hatched lines, the California Coast is to the left. An intrusion of cold water into the warmer water near the coast is seen at 180 m. A deeper feature, with completely closed contours is seen at 300 m. Individual finescale intrusions such as these are transient features in the temperature field.

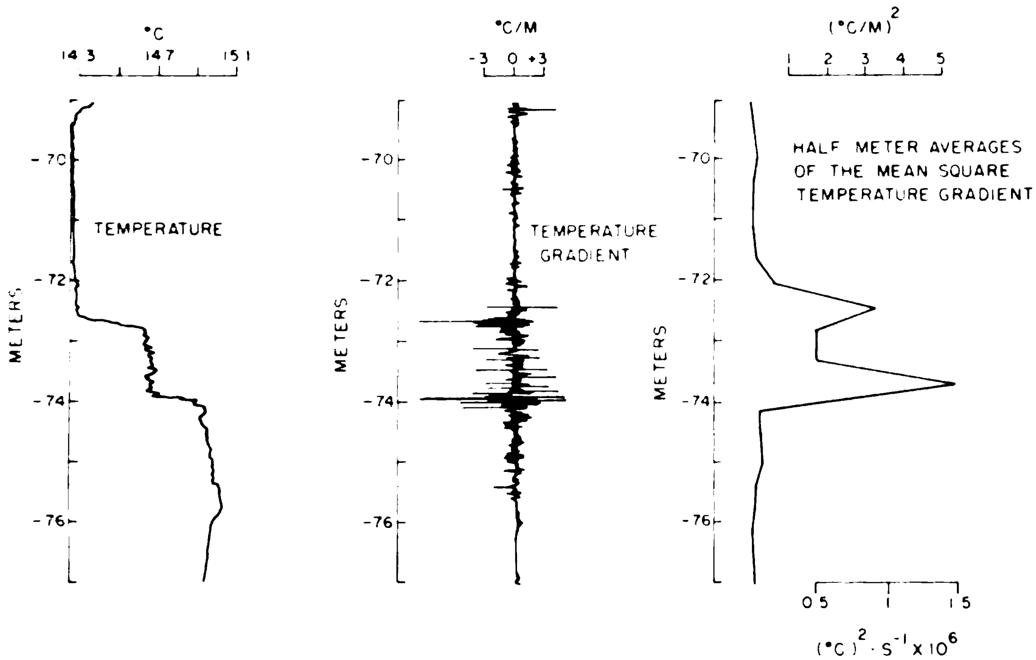

Figure 5 — Expanded view of the upper half of the temperature inversion shown in the mottled section in Figure 2. The sharp step structures and increased microstructure are characteristic of many finescale inversions. They are apparently produced by convective motions driven by differences in the diffusion rates of heat and salt.

molecular diffusion rates of heat and salt. The lateral intrusive motions that form these features set up an unstable situation; strong vertical temperature and salinity contrasts are established, but the density contrast is relatively weak. Heat tends to diffuse out of the inversion more rapidly than does the salt. The resulting changes in the small-scale density field set up motions of the water which accelerate the flux of both heat and salt from the inversion. These convective instabilities, known as double diffusivity motions, act to rapidly dissipate the inversion as an identifiable feature. In so doing they mix the water and alter its characteristics. As seen in Figure 5, the mean square gradients produced by these processes are a factor of 100 or more greater than those associated with the kinks. The inversions are thus major dissipative factors in the fluctuation balances of the ocean.

At shallow depths large inversions occur even in the mid-gyre, or central, oceanic areas at certain times of the year. During the storm season the combined effect of surface cooling and wind-driven turbulence can produce a region of nearly uniform temperature and salinity up to several hundred meters deep. Local differences in the intensity of the storm or in the water properties prior to the storm frequently result in lateral variations in the density of water in this surface mixed layer. After the storm winds diminish, the more dense waters underrun those which are less dense. If the denser water happens to be warmer and more saline an inversion will be produced. If not, a double step structure in which temperature decreases, may result.

The picture of how mixing takes place in the ocean is gradually being pieced together from patterns in microstructure profiles as well as studies of the distribution of chemical tracers quantities. Some of the results have been surprising, such as the fact that the differing molecular diffusivities of heat and salt have major consequences in the ocean; for most oceanographers the arguments that led to the turbulent diffusion coefficients implied that the molecular values would have no importance in the ocean. The principal result is that little evidence has been found in most of the ocean for the intense small-scale mixing required to produce vertical heat transports 1000 times greater than that due to molecular conduction along the mean gradients. Rather, at least part of the transport appears to be due to the vertical component of the slow motion of lenses of fluid moving along inclined constant density surfaces. Even though this general picture is emerging and some specific processes have been identified, we are a long way from being able to evaluate balances such as eqn. (4).

Implications of the Fine and Microstructure

High resolution profiles are also altering our views on how pollutants and naturally occuring substances mix in the ocean. The statistical approach assumes that the concentration of a substance can be predicted from knowledge of the mean currents and turbulent diffusion coefficients. Mathematical models constructed with these inputs show surface of equal concentration decreasing smoothly from the source, but stretched in the direction of the mean currents. Although this general picture has been well verified, more detailed temperature and salinity measurements, as well as some of the work with chemical tracers, show that there can be individual blobs of water that carry the source concentrations virtually unaltered for hundreds or possibly thousands of kilometers before appreciable mixing occurs.

Thus, mixing processes are considerably more complex than can be represented by a few eddy coefficients and it is necessary to consider the maximum concentrations that might persist for considerable distances as well as the large scale averages. This situation results from the relatively strong stratification in the ocean in comparison with the levels of turbulence. In the atmosphere, which has weaker stratification, we commonly observe the relatively rapid dispersal of plumes from smoke stacks. When the air near the surface is very stable and relatively calm some plumes can be observed to persist downwind for tens of miles, but not for a thousand. The analogy with the ocean would be if blobs of gas from a smoke stack in Texas arrived in Atlanta with virtually the same concentration as they left the stack. This situation will not always occur in the ocean, but it appears that it can and that this must be considered as one of the possibilities when the ocean is used to dump highly toxic or radioactive wastes.

In addition to their importance in mixing processes, the temperature, and to a lesser extent salinity structures strongly affect the sound velocity field. Structures in the velocity of sound field refract acoustic wavelengths which are of shorter wavelengths and scatter those of comparable length. Acoustic frequencies commonly used in the ocean are the range of 10 Hz to 60 kHz, with corresponding wavelengths of 150 m to 0.02 m. Some of the structures that have been discussed have both the right scale and amplitude to significantly affect acoustic propagation.

Figure 6 shows contours of the velocity of sound for the intrusion found off San Diego. The tongue of cooler low-salinity water at 180 m produced variations of $3\ m \cdot s^{-1}$ over vertical distances of 20 to 40 m. Frequencies greater than about 100 Hz would experience strong focusing effects due to this laterally coherent structure. Acoustic anomalies of this sort are common throughout the California Current and in many other boundary regions, such as the transition between the subtropical and subarctic gyres at about 40°N in the Pacific. Even stronger ones are frequently found near the Kuroisho and the Gulf Stream.

Another example of finestructure, closer to the surface, is shown in Figure 7. These data were taken in the Central Pacific at the end of the winter season. Stations 3 and 4, separated laterally by only 7 km and temporally by less than 2 hours, have extremely different sound speed profiles in the upper 200 m. The sequence of events producing this variability is not known but was related to the spreading motions of small parcels of water which had been mixed by passing storms to produce slightly different densities. Anomalies of this sort are not present during summer or early autumn.

As in the case of mixing, the picture of the fluctuations in sound speed that is emerging is quite different from the dominant approach taken by acousticians in the past. In a statistical approach very similar to the use of eddy coefficients for mixing, it had been assumed that the sound speed inhomogenities were distributed in random patches, whose characteristics were stationary in time. Measurements of a correlation length from one location and time were thought to be a fair representation that could be applied to different times and places. It is now apparent that some of the significant fluctuations are related to slower processes that can be observed in detail, permitting their dynamics to be studied. Eventually new statistical approaches will be constructed for both mixing and acoustics, but they now have the promise of being based on widespread detailed observations of the ocean rather than upon very limited

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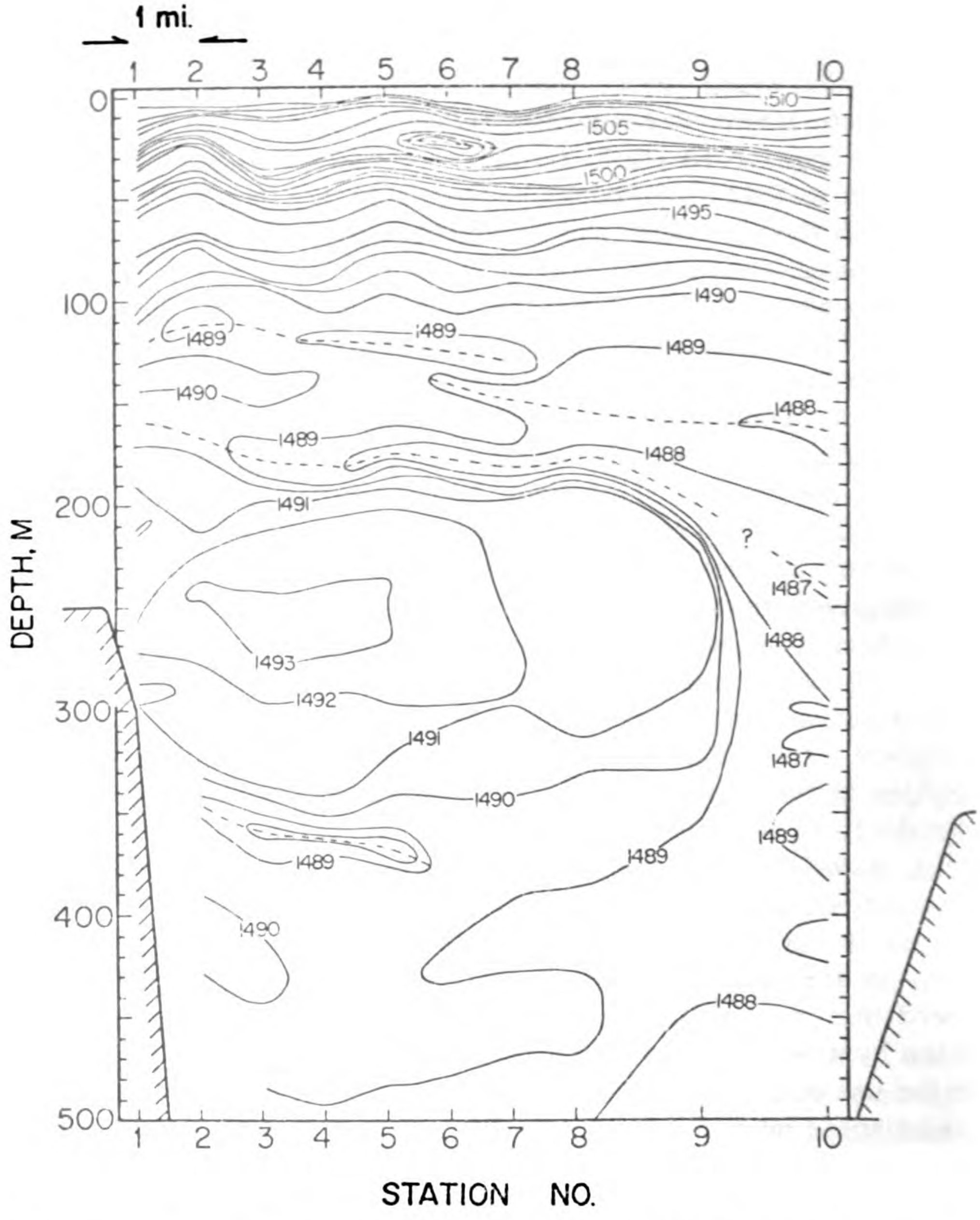

Figure 6 – Contours of the velocity of sound for the same data shown in Figure 4. These intrusions caused coherent perturbations of several meters/sec in the sound speed.

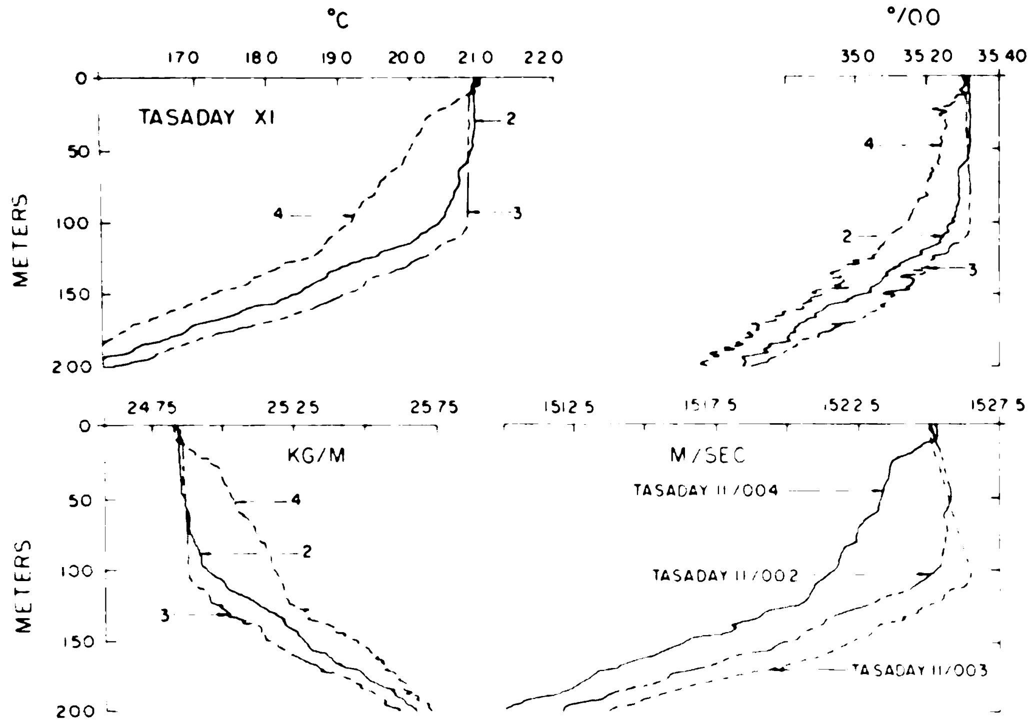

Figure 7 — Profiles 2, 3, and 4 were taken within a three hour period at stations less than 10 miles apart at a site about 500 miles north of Hawaii. The extreme variability is frequently found in winter or early spring. During summer and fall the profiles are much more uniform.

data and much speculation. Such a pattern recently occurred in the development of a new statistical approach to internal waves by Garrett and Munk (1972, 1975) that was in turn used as a basis for treating related acoustic fluctuations.

Comments

When the developments outlined above are compared with progress in other fields it is apparent that improvements in oceanographic profiling instruments have been quite slow in relation to the general development of technology; the increased spatial resolution and sensitivity of the instrument used by Peter Hacker is quite modest in comparison with that used by his father. In Spilhaus' discussion of the temperature inversions found with the BT he remarked that the data would be more valuable if a continuous salinity profile could have been taken at the same time. However, he allowed that "...the development of such an instrument, while entirely possible, will take some considerable time...". I doubt that he realized it would be 30 years! Compare this with progress in other fields. To an astronomer of the thirties studying the temperature of Venus with a thermocouple or spectroscope at the focus of his telescope it would have been inconceivable that by now we would have profiled the Venusian atmosphere from a descending spacecraft.

From even a brief survey of one field of oceanographic research the very intimate connection between subjects of interest to the scientific community and those of naval relevance is apparent. This encompasses the instrumentation as well as the ideas about the structures in the water and the processes that produce them. Some of the equipment discussed, such as the BT, was conceived for basic research applications but the usefulness to the Navy was perceived early and strongly influenced further development. Others, such as the components for the STD system, were developed for applied studies and then used for general oceanographic work. However, in most cases the quality of the data was poor until the instruments were widely used in research for publication, with public scrutiny of the results by colleagues.

In a similar vein, the solution of specific naval problems dealing with the characteristics of the oceanic environment have often made major advances after new insights have been developed in our basic understanding of the sea. In view of our ignorance of so many basic aspects of the ocean many applied studies have not had sufficient scope to really answer the problems they addressed. An example from another field can be seen in the revolution in continental geology that is taking place as a result of the acceptance of sea floor spreading and plate tectonics. These results from *marine* geology and geophysics have stimulated work on many of the old problems in other areas, such as the building of mountains, which in turn is leading to new ideas about possible locations of mineral deposits. Had a national program been established with a narrow charter to search for continental ore deposits, it is doubtful that much effort would have been given to a global study of the floor of the deep sea, or that the results of the investment would have had as many dividends. Since the speed of sound is determined by the temperature and salinity field, the work now in progress on internal waves and oceanic mixing is providing the basic understanding for a much deeper insight into the nature of many types of acoustic fluctuations than achieved by previous work aimed solely at sound studies.

The revolution in the science of the solid earth had its origins in the rapid development of marine geophysics that began after World War II, when a variety of new instruments, such as precision fathometers and magnetometers, became available for widespread use. Once the structures on the sea floor were mapped, it became possible to construct hypothesis about the processes that formed them, and to test other consequences of these hypotheses against observation. My own conviction is that physical oceanography finally has the potential for a *golden age* similar to that recently experienced by marine geology.

The development of reliable and low power instruments that can operate freely in the ocean is providing a data base comparable to that yielded by the widespread use of shipboard bottom sensors, gravimeters, and magnetometers after World War II. The benefits over the next several decades to our understanding of the ocean, and to our ability to use it, promise to be sizeable.

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Superconducting Machinery for Ship Propulsion

Arthur H. Post, Jr.*

Introduction

Superconductivity as a technology is in a transition status: it is no longer just a laboratory curiosity, but it has not yet become a commercial reality. With improvements in superconducting materials and with more reliable sources of refrigeration, interest in the practical applications of superconductivity is increasing worldwide. The energy economies offered by superconductivity have provided an added inducement to pursue projects such as large central power station AC generators (1,2).

For a number of years, the U.S. Navy has been actively investigating the uses of superconductivity in several different areas, including magnetometry, communication applications, solenoids, and ship propulsion (3,4). These investigations have been carried out by government scientific personnel in government laboratories, as well as by civilian scientific personnel, under contract to the Navy, working in university and industrial laboratories.

Among the civilian investigators has been Professor Joseph L. Smith, Jr., Professor in Charge, Cryogenic Engineering Laboratory, Massachusetts Institute of Technology. Under an ONR contract monitored by the Boston Branch Office of ONR, Professor Smith, assisted by others, has been studying the application of superconducting electrical machinery to ship propulsion (5). This application of superconductivity is of particular interest to the U.S. Navy because the propulsion requirements for some new ship concepts cannot easily be satisfied with conventional propulsion machinery. Professor Smith's study, which began in 1972, has sought to consider the widest range of technical possibilities on a fundamental level by employing an interdisciplinary team of investigators.

The first task performed was a general review of possible rotating field machines for various ship propulsion systems. This preliminary review enabled the investigators to select the superconducting machines which promised the most potential over the widest range of possible applications, including conventional ships and advanced concept ships. Superconducting DC homopolar machines were not considered because

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their potential is under intensive investigation by other research laboratories (3).

The conclusions of this preliminary general review were that a wide range of superconducting ship drive systems could be assembled from the following four basic rotating field machines:

1. Gas-turbine-driven superconducting synchronous generators
2. Multiple-pole low-speed superconducting synchronous motors
3. Dual-armature superconducting motors
4. Thyristor-switched superconducting motors

The gas-turbine-driven superconducting synchronous generator is a prime candidate for mechanical-to-electrical power conversion in a superconducting propulsion system. Research at MIT and elsewhere has indicated that such machines would be compact, lightweight, and potentially economical (6,7).

The multi-pole low-speed superconducting synchronous motor was investigated analytically early in the study. One conclusion reached was that a critical parameter is the pole pitch, the distance between the geometric centers of two adjacent field coils. At less than a certain minimum pole pitch, the power density for a superconducting machine is not significantly greater than that of a normal machine. Thus, there is a practical limit to the minimum diameter and minimum power of such a superconducting machine if it is to have a higher power density than a conventional motor. Speed control of such a motor could be achieved by controlling the frequency of the supplied electric power, within limits; or such a motor could be operated at constant speed if a reversible, controllable-pitch propeller were coupled to it.

The concepts of dual-armature and thyristor-switched superconducting motors were devised by the MIT team from the background formed by earlier work funded by the Edison Electric Institute. The dual-armature concept has the characteristic that the superconducting magnetic field does not have a net torque imposed upon it. This can be a desirable design characteristic, as significant conductive heat path along torque-resisting mechanical connections can be avoided. The thyristor-switched concept provides an AC motor with the desirable speed control characteristics of a conventional DC motor. The efforts of Professor Smith's team were then focused upon these two concepts. The sequence of tasks in the program to evaluate each of these concepts was as follows:

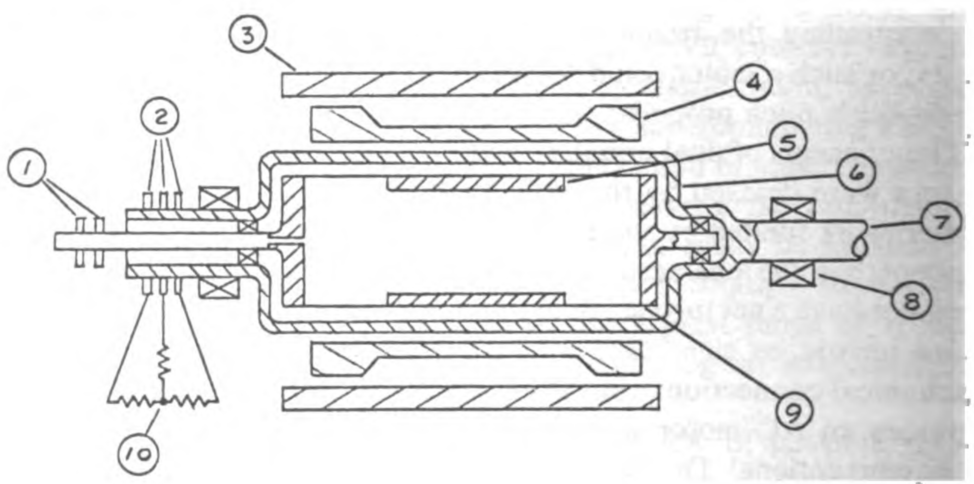
- Identify and define the problem areas associated with the concepts
- Develop basic methods of analysis for both steady-state and transient conditions
- Design and construct normal-conduction experimental model machines

- Verify analytical results experimentally
- Refine analytical models using experimental results
- Evaluate the concept relative to other concepts

The Dual-Armature Superconducting Motor (8)

This AC machine has a normal polyphase AC stator winding, a normal polyphase AC rotating armature, and a DC superconducting field that is free to rotate. The stationary AC winding establishes a flux wave rotating at synchronous speed. The superconducting field winding locks into synchronism with this rotating flux wave, producing a very intense rotating flux wave in the machine. Currents are induced in the rotating normal armature as it slips relative to this rotating flux wave. These currents interact with the strong flux wave to produce torque that rotates the normal armature. The propulsion shaft is an extension of the normal rotating armature.

The mechanical arrangement of such a motor is presented in simplified form in Figure 1. The innermost rotor contains the superconducting field winding. This rotor has no shaft connection and is free-spinning. The outer rotor operates at room temperature and carries a polyphase armature winding connected to slip rings. The fixed stator winding is a polyphase winding whose terminals are the electrical power connections of the machine.



COMPONENT IDENTIFICATION

1. DC FIELD SLIP RINGS
2. INDUCTION ROTOR SLIP RINGS
3. MAGNETIC SHIELD
4. STATOR
5. SUPERCONDUCTING WINDING
6. INDUCTION ROTOR
7. MAIN SHAFT
8. BEARINGS
9. SYNCHRONOUS ROTOR
10. INDUCTION WINDING CONTROL RESISTORS

Figure 1 — Dual-Armature Superconducting Motor.

The torque characteristic of such a machine is similar to that of a conventional induction motor. The shaft normally operates at a speed slightly less than synchronous but unlike a synchronous machine, will produce torque at any speed. These machines, however, have a field winding rotating at synchronous speed which provides the capability of controlling reactive power. The torque available may be controlled by regulating current flow in the induction rotor circuit by adjusting the resistance in this circuit (Figure 2).

An experimental model machine was designed and constructed so that the performance characteristics of such a machine might be investigated experimentally. The model machine was designed to operate at ambient temperature, but to be closely modeled to its superconducting counterpart. The stator of a 7.5 HP, 230-volt induction motor was used as the basic structure of the machine. Special rotors were designed and built to fit inside. In the final version, the machine was rated at 3.1 HP, the power reduction being due primarily to the increase in the total air gap of the machine (Figure 3).

When testing began, there were initial problems with interferences between the two rotors due to shifting of induction rotor laminations. Once these problems had been resolved by potting the laminations with

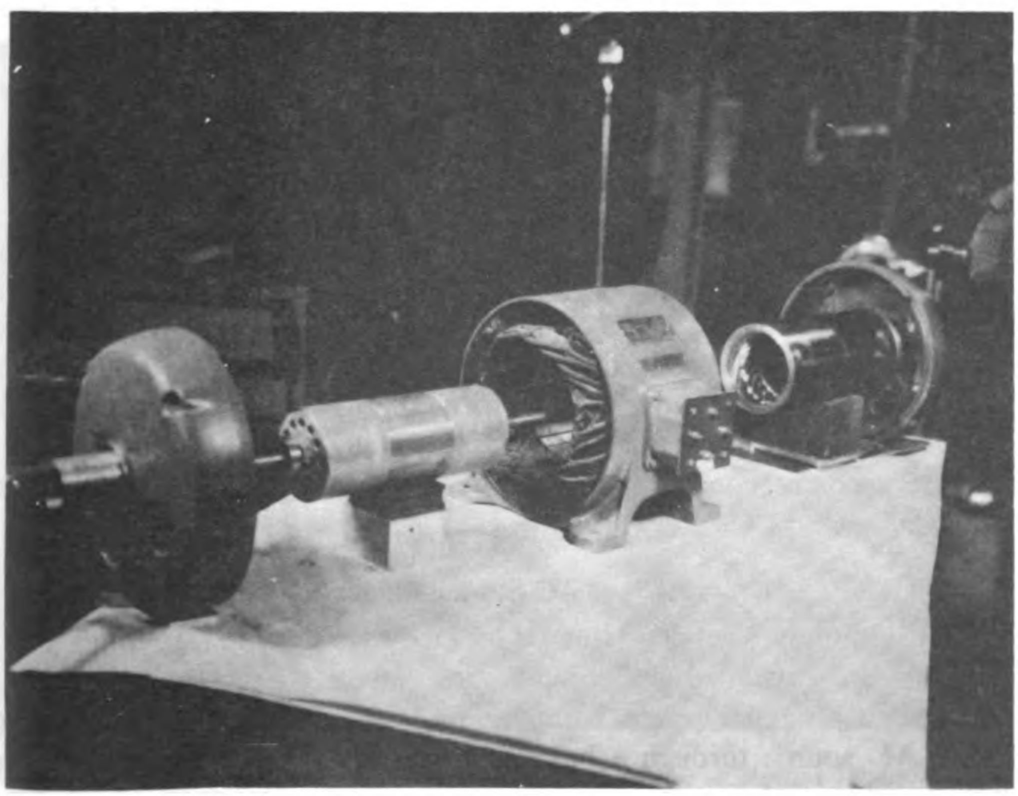


Figure 2 – Exploded View of Dual Armature Machine

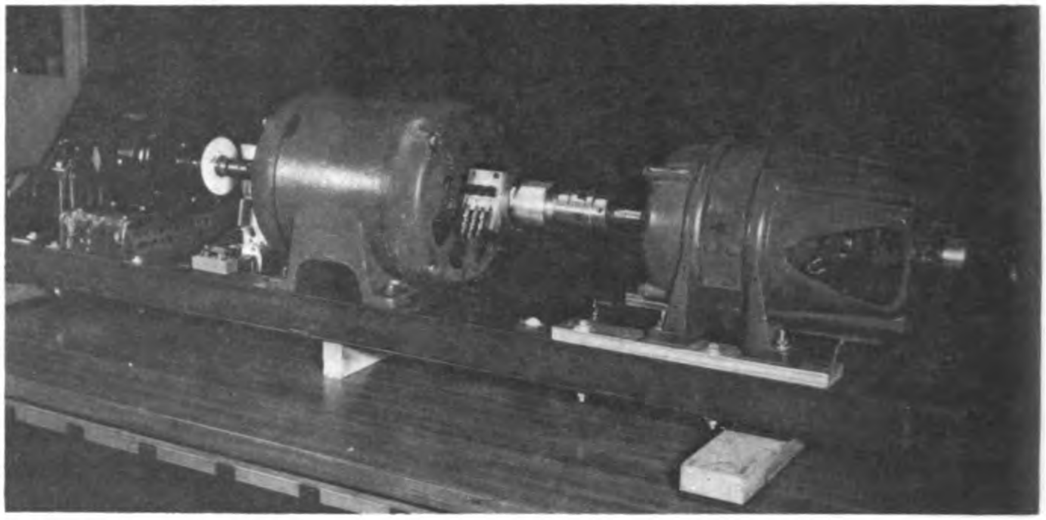


Figure 3 — Experimental double armature machine. This is a non-superconducting experimental machine constructed to demonstrate the operation of double interaction machines. It has two rotating elements. The inner rotor (shaft to the left) contains a D.C. winding, while the outer rotor contains a three-phase winding connected to slip rings.

epoxy, steady-state testing was started. Measurements were taken to establish the saturation of the iron, effective air gap, internal flux levels, and speed-torque characteristics as well as other characteristics.

During the testing, other problems were encountered. The free-spinning rotor did not start by itself and did not accelerate to synchronous speed as it had been expected to do. Although the difficulty was overcome by using a small starting motor, this problem is still not completely understood. Later, electrical losses within the motor were discovered, and this problem also is not yet understood.

Currently a full-scale design is under study, with the knowledge gained during testing being applied to a motor having a size representative of ship propulsion machinery. The purpose of this design study is to discover how advantageous this design would be when compared with conventional high-performance electric motors or other superconducting designs. Additional tests or extended mechanical and electrical analyses will be recommended only if this design appears to offer significant advantages.

Thyristor-Switched AC Superconducting Motors (9)

A second motor concept studied by Professor Smith and his team was the thyristor-switched superconducting motor. This motor consists of a segmented polyphase winding on the stator which is connected to an AC source through a bank of thyristors. The thyristor gates are connected in such a manner as to keep the rotating magnetic field of the stator 90° ahead of the magnetic axis of the rotor. The switching of the thyristors is controlled by a sensor responding to the rotational position of the rotor (Figure 4).

The rotor is equipped with a superconducting DC winding that produces a strong magnetic field.

By keeping the axes of the magnetic fields of the stator and rotor always 90° apart, the maximum torque is produced for any combination of armature flux and field flux.

Motors employing this concept may be practical in smaller size ranges than the dual-armature motors described earlier. The thyristor-switched motor may be designed with fewer, larger poles and thus avoid the problems associated with minimum pole pitch, referred to earlier.

A model was designed and constructed to simulate the operation of this type of motor. The model was constructed by reconnecting the windings of a 1 kw two-pole alternator.

During initial operation of the model machine there were problems associated with reliable operation of the thyristors. Refinement of the design of the thyristor circuitry remedied these problems and resulted in more reliable operation of the motor. There are, however, still occasional problems believed to be related to the mechanical components of the switching system. A photo diode switching system will be installed and may eliminate some of the difficulty. Professor Smith believes that while this design has had a number of developmental problems,

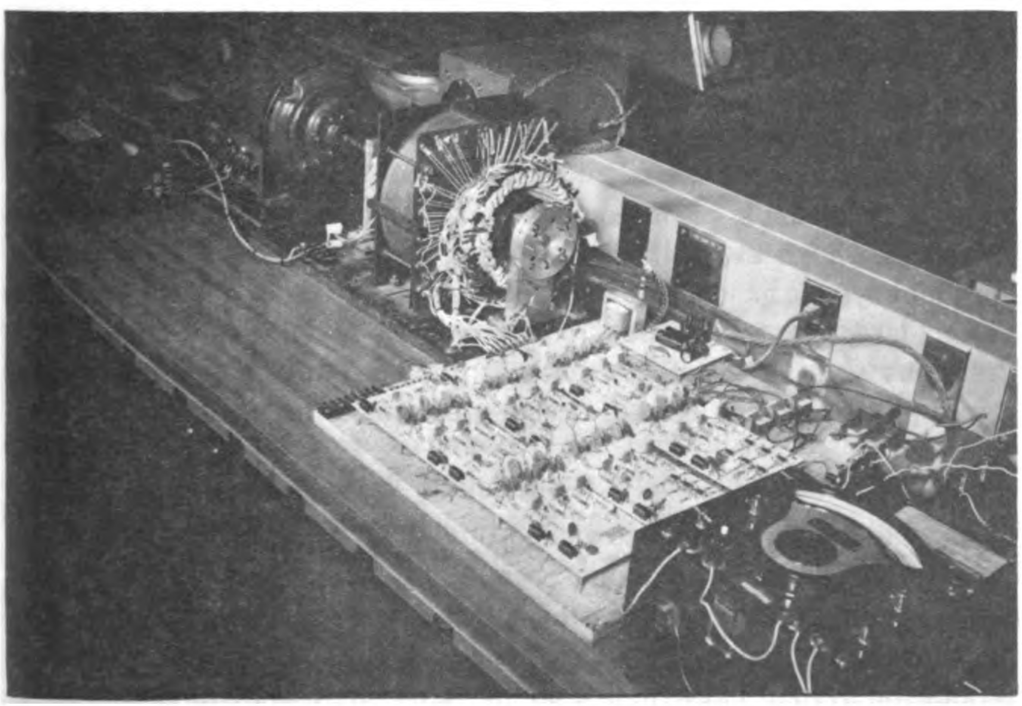


Figure 4 — Experimental thyristor commutated AC motor. A position detector which uses optical sensors is mounted at the near end of the machine. This controls a bank of thyristors on the breadboard circuit in the foreground.

it may be the more useful of the two design approaches for the Navy. The design of a full-size motor of this type is now under study, also.

Professor Smith has maintained a close working relationship with the technical staff at NSRDC, Annapolis, who are also studying concepts and testing models of superconducting machines. On occasion, the team at MIT has assisted NSRDC efforts, as in the review of cryogenic refrigeration requirements for superconducting machines and in the analytical evaluation of a design concept employing salient iron pole elements.

Professor Smith is also aware of recent developments in force-cooled normal machines. He believes some of these machines may approach closely the power density of superconducting machines. Both types would be high-performance machines and quite different from conventional electric machines. The force-cooled high-performance normal machines would have an advantage in standby power consumption since the superconducting machines require continuous operation of a refrigeration system to maintain cryogenic operating temperature. With a cryogenic system, the electrically-induced thermal loads in the motor or generator represent only a small fraction of the total refrigeration
eration load, most of the heat inflow being attributable to parasitic sources. Hence, the refrigeration system must be kept running at nearly normal capacity whenever the superconducting propulsion system is in a standby status. Such continuous operation places great importance on the long-term reliability of the cryogenic system as a whole and also imposes an energy consumption burden on the overall system.

For a particular naval application, the choice between a high-performance normal electrical system and a superconducting system may not be a simple or obvious one. The decision will have to be based upon a thorough evaluation of the specific application if it is to be an optimum system.

For large central station power generators, the superconducting machines seem to have the greatest potential advantage, but even in this application there are still design problems to be resolved.

Conclusions

Beyond the technical knowledge obviously generated by this study, there is an added educational benefit to be appreciated. The work provides an understanding that these high-performance electrical machines are complex, dynamic devices and that the high-performance propulsion system likewise is a complex, dynamic system. Experimental verifications of designs will be vital because not all problems will be revealed by analytical studies. Mechanical-electrical interactions may prove especially difficult to predict.

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New Monitoring Technique for Electric Motors

In line with the Navy's emphasis on improving the reliability of shipboard equipment, the David W. Taylor Naval Ship Research and Development Center is conducting research on the development of a condition-monitoring technique for electric motors.

The technique, aimed at providing an uncomplicated quality assurance check, is a practical means of assessing the mechanical condition of an electric motor by measuring its coastdown time after repair or overhaul has been completed. Coastdown is that time required for a rotating mass to become motionless after the power is shut off.

Measured coastdown time is compared with a calculated coastdown time based upon motor, bearing, and lubricant parameters. Since the dissipation of the kinetic energy during coastdown depends upon friction, the coastdown time provides a measure of friction and is, therefore, an indicator of the mechanical condition of the motor.

Significant deviation between the calculated and measured values is evidence of a probable mechanical problem and signals the need for investigation. But when the two values are in agreement, the motor is properly assembled and ready for shipboard use. The motor will then begin its service life in sound mechanical condition and it can be expected to provide a higher probability of trouble-free, mechanical operation.

Research Notes

OTH-Tracked Drogue Buoy

Two ONR contractors, Louisiana State University's Coastal Studies Institute and ITT's Electro-Physics Laboratory, Inc., demonstrated last year a way to use current, following drogue buoys, to collect environmental data over continental shelves and in broad ocean areas. Over the Horizon (OTH) radar using a ground wave mode has been used to locate, track and interrogate the buoys, which are fitted with sensors and drogue traps that can be placed at various ocean depths to provide information on the velocity of subsurface currents and other environmental parameters. This project is part of a program to provide certain naval forces with adequate observations and models for predicting environmental conditions in the shallow waters of the continental shelves.

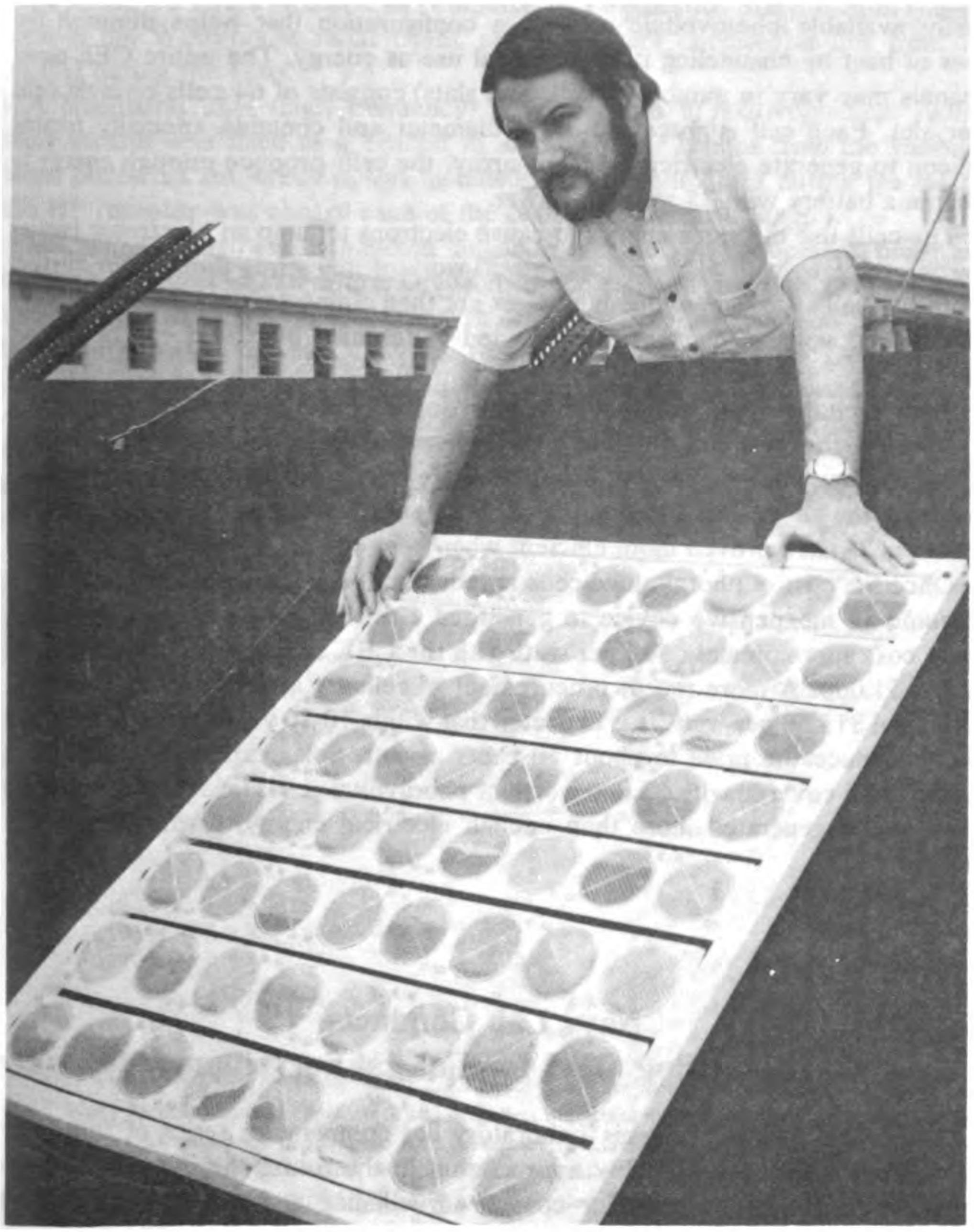
Several Navy groups have already shown an interest in this OTH-tracked drogue buoy for operational use in conjunction with ASW surveillance nets and as a covert instrument for collecting environmental data in support of amphibious operations.

The value of this system would be enhanced by adding passive acoustic and air drop capabilities. The following options are also desirable: improved locational accuracy (via ULF/LF/link), optional satellite readout capability (VHF/UHF/link), improved anti-jam/secrecy capability, speeded-up readout capability, and a cloud cover sensor (solarimeter). The availability of this sophisticated data gathering system would speed up the Navy's study and understanding of continental shelf waters (coastal processes). Many operational applications could also be accelerated.

Solar Energy Window

A new type of solar energy window is being developed by the Civil Engineering Laboratory (CEL), Naval Construction Battalion Center, Port Hueneme, Calif. Looking like a three-pane storm window, the concept features a middle panel of plastic slats on which a series of photovoltaic cells are located. This configuration, two panes of common glass sandwiched around an energy-absorbing venetian blind-type device, serves three functions: 1) to provide heat to a house, 2) to generated electricity, and 3) to serve as a sun shade.

The photovoltaic panel concept was conceived by Dr. Richard Field, research mechanical engineer at CEL. He said a triple window of three panes of common glass, at times, could introduce too much heat into a room. But with the insertion



A Panel of 64 Photovoltaic cells has been incorporated into a new solar energy window developed by Dr. Richard Field, research mechanical engineer at the Civil Engineering Laboratory, Port Hueneme, Calif. Field adjusts one of the slats of the venetian blind-type device. His configuration of two panes of common glass sandwiched around the panel of cells provides heat to a structure, generates electricity, and serves as a sun shade.

of a middle panel of photo cells, the heat can be collected and distributed elsewhere while still maintaining sufficient amounts to warm the room in which the window is installed.

Normally much heat escapes through windows. Dr. Field adapted commercially available photovoltaic cells to a configuration that helps diminish the loss of heat by channeling it for practical use as energy. The entire CEL panel (panels may vary in number of cells and slats) consists of 64 cells or eight cells per slat. Each cell is three inches in diameter and contains specially treated silicon to generate electricity. In this array, the cells produce enough energy to charge a battery with 25 watts of power.

The cells use the sun's energy to cause electrons to jump an electronic barrier and produce voltage. Each cell has a grid work of tiny wires that gather current from the cell's surface. Individual wires are then connected in series to achieve the desired voltage. Current is conducted to terminal blocks at the bottom of the panel.

Since a photovoltaic cell converts approximately 10% of the sun's energy into electricity, the system will utilize the balance of potential energy. The CEL triple window allows a flow of air to circulate over the cells, keeping them cool while at the same time distributing excess heat to other parts of the building. Photo cells have proven more efficient when kept cool.

Once the cost of photovoltaic cells is reduced, the solar energy window could become an inexpensive device to generated electrical power for a house. The cells cost approximately $30 per watt with the CEL experimental panel costing about $1,000. A more recent procurement of cells by a government laboratory averaged $15.50 per watt. It is expected that within 10-20 years, mass production would reduce the price to about 50 cents a watt. Solar experts predict that if a roof were covered with $3,000 worth of photovoltaic cells (at 50 cents per watt) they would generated more than enough electrical energy to run the average house.

Navy Lab Conducts Tests Using OTH for Coastal Surveillance

The Naval Coastal Systems Laboratory has completed a series of feasibility tests from which it reasonably appears that in the future the over-the-horizon radar concept can be used for coastal surveillance and detection of surface craft.

Such a concept would prove to be a valuable asset during amphibious operations in providing an alert and warning of approaching enemy surface combatant ships and for protection of sensitive areas and floating assets in the coastal region.

Carried out as an exploratory development effort sponsored by the Naval Sea Systems Command, the tests conducted in the waters off Panama City involved NCSL and the integration of the specially configured radar systems of the Office of Naval Research (ONR) experimental field site in Whitehouse, Virginia.

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From the Whitehouse facility in Virginia, five different targets were detected in the Gulf during the NCSL tests.

The two NCSL offshore research platforms, known as Stages I and II, were also utilized as radar targets. State II, smaller of the two, is closer to land, being about 1.6 miles offshore, as compared to 11 miles for Stage I. Both stages were in the Whitehouse radar beam, and both were detected at one time or another during the tests.

A broadband HF (high frequency) repeater with a relatively large radar cross section was used as a beacon to identify radar echoes from the various target platforms on which it was installed. At different times during the tests, this HF repeater was aboard each of the two vessels and on Stage I.

The experiment was conducted as an exploratory development program of the Naval Inshore Warfare Division of the Coastal Warfare Department, with Ed Parker as task leader. He was assisted in the tests by Hal Dufilho of the Environmental Science Division of the Coastal Technology Department.

Electromagnetic energy is transmitted in a particular direction, based upon the orientation of the transmitting antenna. This energy is refracted by the ionosphere above the earth and directed back to the earth's surface to an area where surveillance is required. Energy is reflected from the target and follows a reverse refractive path back to the radar control center where it is received and processed for verification of target detection.

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Microstructure research is aimed at those transport processes that tend to make the ocean more uniform, or well mixed, by the irreversible actions of viscosity and diffusion.

A wide range of superconducting ship drive systems can be assembled from four basic rotating field machines.

Cover Caption

The superconducting motor seen in the background is in the laboratory developmental stage. The liquid helium tanks at the right are for cooling the motor.

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