Varieties of Oceanographic Experience

The ocean can be investigated as a hydrodynamical phenomenon as well as explored geographically.

Henry Stommel

When oceanographers set forth to observe and explore the ocean they are hampered by many adversities, such as bad weather, faulty instruments, and seasickness. There is often a far more serious handicap: an inadequate design of the expedition as a whole. If we regard an expedition as a scientific experiment, then we must propose to answer certain specific questions, and the strategy of exploration, the disposition of ships and buoys, and so on, must be designed with a view to obtaining quantitative, statistically significant answers to these questions. More often than not the design characteristics of oceanographic experiments are such that few statistically significant answers are obtained. This variety of oceanographic experience should be helpful in improving the design of future expeditions. It may also help us to distinguish the kinds of questions that can be meaningfully asked from those that cannot be.

Suppose we wish to map the temperature of the deep water in a large oceanic basin to within $\pm 0.05°C$; we might have in mind mid-regions of the Gulf of Mexico, or the Red Sea, or the eastern North Atlantic below 3000 meters. We know that in such basins there is very little fluctuation in water temperature over several decades, and that therefore 10^2 to 10^3 point observations would be adequate for such a mapping. It is not necessary that all the observations of temperature be taken simultaneously—indeed, they may be scattered over many seasons and years. In many cases it is not necessary to organize a special expedition to make a map of this kind. One merely makes use of data accumulated gradually, and nearly randomly, on cruises sent out for other purposes.

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Let us consider mapping another variable—the month-by-month variation in sea level in the South Pacific Ocean. At first this looks easy, but it is in fact more difficult than the first task by several orders of magnitude, and it requires an elaborate network of carefully maintained stations operating over several years. We decide to install 10^2 tide gauges at oceanic islands and along the coasts. Ideally we also would have some new and ingenious instrument for measuring sea level at places where islands are sparse, so that we could spread our 10^2 measuring points nearly uniformly over the South Pacific. We suppose that these deep-sea gauges obtain records within much the same response time as an island-based tide gauge. The annual range of sea level, we learn from experience, is of the order of 20 centimeters. Let us suppose that we want to determine mean monthly averages to an accuracy within a significant figure of 2 centimeters. How easy this would be if the only variable involved were seasonal variability. Twelve observations at each station would be sufficient; 10^3 observations in all would suffice for mapping the annual variation of sea level in the South Pacific. Oceanographic experience, however, divests us of any innocent optimism on this score. We know that there is a whole spectrum of phenomena (on both the periodic and the geometric scale) associated with variations in sea level—for example, gravity waves and tides. The biggest range is of course in the ice-age variations. There are also variations of sea level associated with geostrophic turbulence, and with synoptic meteorological events. It is convenient to depict these different components of the spectral distribution of sea level on a diagram (Fig. 1) in which the abscissa is the logarithm of period P, in seconds, and the ordinate is the logarithm of horizontal scale, L, in centimeters. If we knew enough we could plot the spectral distribution quantitatively by contours on this period-wavelength plane. Here we will only label the areas schematically.

Because so many periods and scales are involved simultaneously in the variable sea level, obtaining a significant measurement of the annual variation of sea level requires many more than 10^3 measurements. The short-period gravity waves are filtered out of the records of tide gauges by the instruments themselves. Waves of longer period, such as tides, register very nearly perfectly on tide gauges, so they must be filtered out through the use of running means, or by elaborate numerical filters if necessary. This requires that values of sea level be recorded at hourly intervals, to obtain the monthly means. Changes in sea level that occur over periods of several weeks as a result of irregular changes in the density of the sea and of other phenomena associated with meteorological conditions cannot be distinquished from seasonal change in a single monthly average. Therefore, in practice we need hourly readings for several years—at least 4—to establish the annual variation of sea level at each geographical position of the network of stations (*1–3*). We estimate, therefore, that to obtain a statistically significant map of annual variation of sea level in the South Pacific actually requires about 3×10^6 hourly observations—considerably more than a first glance at the problem would lead one to expect. Here, then, we have a clear-cut example of the way in which attempts to measure one part of the spectrum are disrupted by energy in other parts.

Islands on which tide gauges are located are very unevenly distributed, hence the mapping of the annual variation in sea level has not been as accurate as one might like. However, no one proposes to set up an international program solely to increase our knowledge on this particular aspect of oceanography because such a tremendous organized effort would be required to improve the figures we now have. For much the same reason proposals to organize extensive world cruises in the North Atlantic and Pacific oceans for the purpose of increasing our knowledge of the seasonal variation in surface temperature do not make much sense; there are already many randomly gathered data on surface temperature in the files of data depositories, and to improve them significantly would require an impossibly expensive cruise.

Therefore, it is not to install extra tide gauges or collect data on sea-surface temperatures that expeditions are launched; however, such data might be useful by-products of other types of investigation. These jobs, and others like them, are often planned as part of larger efforts, such as the Indian Ocean Expedition. The danger is that the larger effort may have as its objective simply an agglomeration of many unprofitable minor objectives, that it may not be well thought out and adequately planned.

Tides and Turbulence

If the existing tide-gauge network were operated for only 3 months, much useful information would be obtained on astronomical tides but very little would be obtained on geostrophic turbulence, because the tides and the geostrophic eddies occur on different geographical scales. To study the latter, a network of instruments with a finer grid would be necessary. This illustrates a further point: a single net does not catch fish of all sizes; the existing net of tide-gauge stations does not suffice for a study of geostrophic turbulence. It is necessary to decide which part of the spectrum of each variable one wants to measure. No economical plan for mounting an expedition or setting up an observational program can encompass all the scales and periods; each plan must provide a definite significance level within a limited part of the spectrum despite contamination from other parts of the spectrum. Finally, it must be shown that the desired significance level will be an improvement on that already obtainable from data now in the files.

The degree of contamination varies surprisingly for measures that at first seem very similar in character. For example, the degree of contamination, by internal gravity waves, of measures of the diurnal variation in surface-water temperature is less than the contamination in measures of the diurnal variation in heat storage in the upper layers. The latter determination requires a vertical integration of the temperature field, which is particularly sensitive to contamination by internal gravity waves. On the other hand, when the upper layers are nearly homogeneous, contamination from this source is at a minimum. Woodcock and Stommel (*4*) found both situations in a study of diurnal heating in the Gulf of Mexico during the early spring. At first, while the upper layers were isothermal, the diurnal heat storage could be easily calculated from hourly soundings, but only a few weeks later, when a stratified thermal structure had been established, the heat storage could not be measured. Study of this problem thus would require different strategies of investigation, applied at different times.

However, there are further complications in the study of the temperature of the surface layer of the sea. The rate of heat transfer in the vertical direction depends upon very-small-scale fluctuations in temperature and in the vertical component of velocity, due to turbulence, and direct measurement of these fluctuations poses instrumental problems of yet another sort. These turbulence processes depend, in turn, upon events with scales and periods associated with the meteorological synoptic scale. For each of these problems a particular observational network, density of stations, duration of experiment, and frequency of observation is required. One must specify what degree of precision he expects to achieve in the result, and to guarantee that previous work has not already revealed at least as much as he hopes to find. And it is not immediately obvious why any one of these possible studies of the surface-layer temperature should have highest priority.

A Cautionary Tale

One may well say that where so much is unknown, such detailed planning is impracticable—unexpected complications may arise. I reply that where so much is known we dare not proceed blindly—the risk of obtaining insignificant results is too great. Here is a tale that illustrates the impossibility of always achieving a perfect design. The equatorial undercurrent in the Pacific is so strong and steady and so fixed in position that, as Knauss has shown, its velocity can be mapped to a high degree of accuracy by ordinary current meters. The time of year does not appear to be critical. The current is narrow but long, and therefore two length scales are used. It is evidently steady over many years. Knauss (*5*) mapped it by making short north-south sections at rather wide east-west intervals. There appears to be no significant contamination of the values by low-level fluctuation in velocity such as may exist in other parts of the spectrum. In the Indian Ocean the winds at the equator vary with the monsoons. It seemed possible that observation of a similar kind made twice, once during the southwest monsoon and once during the northeast monsoon might reveal a nice annual reversal of the current (or at least show a predominantly annual component). Thus, the spectral density function for velocity at the equator might show two large peaks of different geometrical scale and of

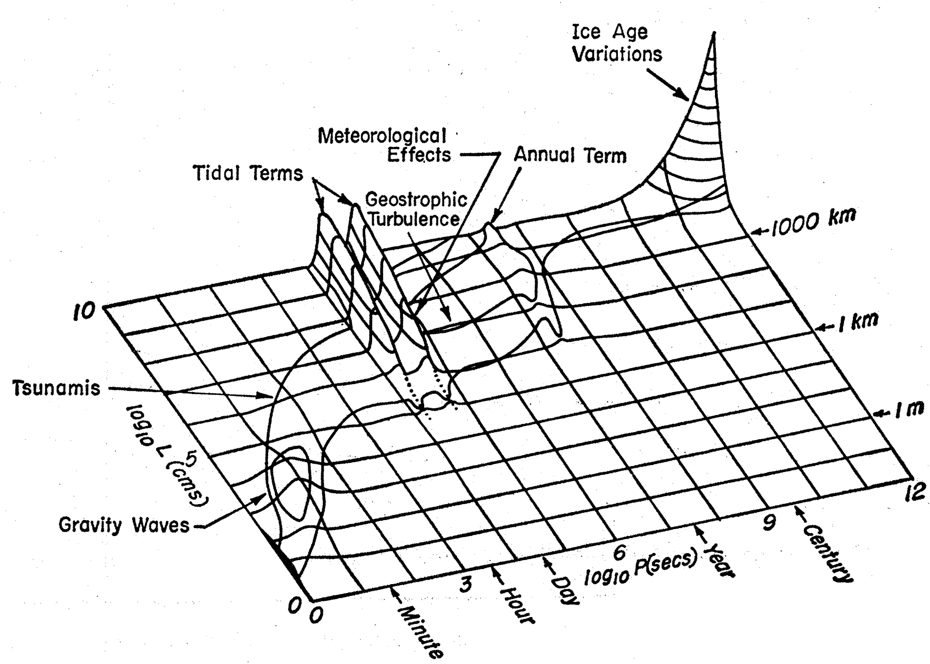

Fig. 1. Schematic diagram of the spectral distribution of sea level.

annual period, as shown in Fig. 2. Experience during the first *Argo* cruise seems to show that this simple picture does not obtain. Evidently there is some instability associated with the reversal, and the stream is broken up and meandering, with periods of less than a year and with both length scales the same. In other words, the spectral density is now in another position on the period-length scale plane. This means that the original design of the expedition to the Indian Ocean cannot show the annual component because of contamination, and cannot map the shorter period irregularities. These are inevitable vicissitudes of an oceanographer's life, but by means of our little diagram we can make the difficulties of the situation explicit, and we can see the inadequacies of the design of the expedition.

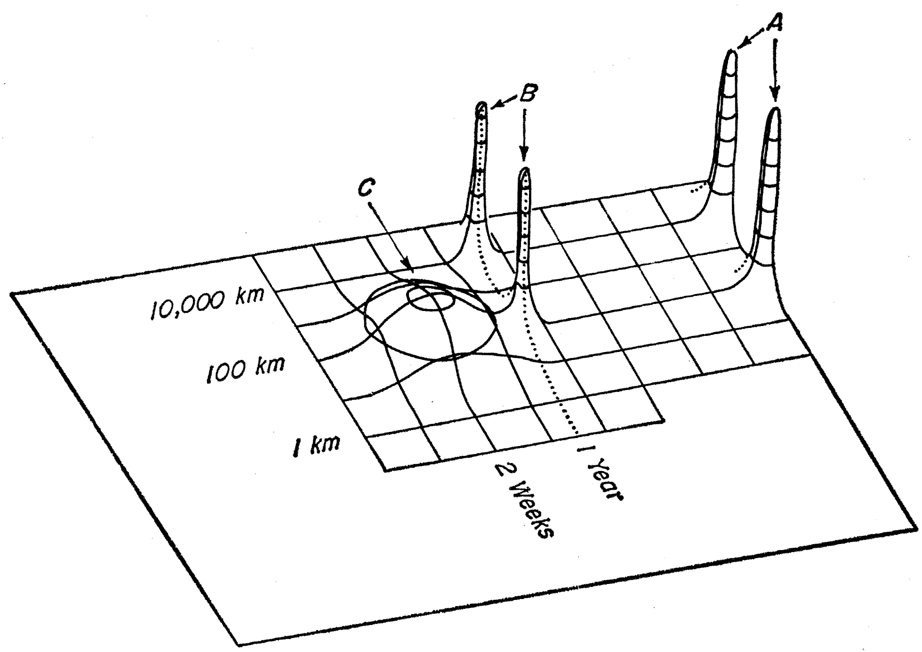

Fig. 2. Schematic diagram of velocity spectra, showing (*A*) the two peaks associated with the Pacific equatorial undercurrent; (*B*) the two annual peaks which the *Argo* expedition expected to find for the Indian Ocean at the equator and which it planned to map; and (*C*) the probable actual peak for velocity that was revealed to be present but that could not be mapped by the procedures, appropriate for mapping *B*, that were employed in the expedition. Coordinates are the same as in Fig. 1.

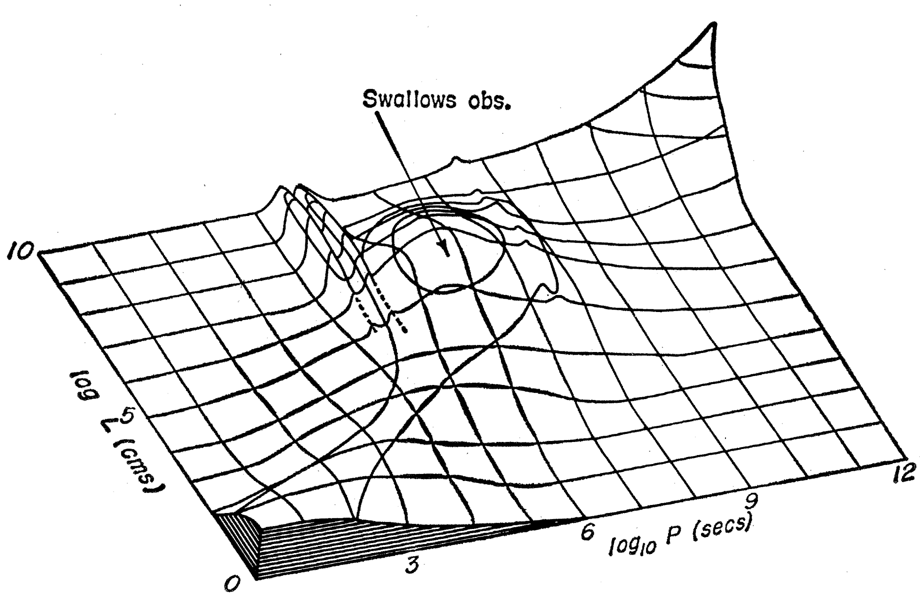

Fig. 3. Diagram of the velocity spectrum in the deep ocean, showing the large energy in geostrophic turbulence motions, observed by Swallow and Crease (*8*). Coordinates are the same as in Figs. 1 and 2.

Transport in the Gulf Stream

Years ago, Iselin (*6*) encountered a similar contamination of seasonal fluctuation of the Gulf Stream transport by irregular meanderings. At first he hoped to determine the annual variation by making a hydrographic section from Montauk Point to Bermuda every 3 months for several years. What he obtained was a random sampling of irregular meanders. In 1960 Fuglister used as many as five ships for 3 months continuously without obtaining an unambiguous description of the development of one of these meanders. The annual part of the spectral distribution of velocity is so close to a high-energy meander peak in the period-wavelength diagram that to resolve it would require several orders of magnitude more observation than Iselin had planned to make. The question of determining seasonal fluctuation now has a low priority on our list of what we consider to be feasible new programs of observation in the Gulf Stream.

The possibility of contamination from other parts of the spectrum becomes much greater when such derived quantities as correlation coefficients or turbulent transports are to be calculated, and it would also be greater if, as was recently proposed to UNESCO, direct current measurements from moored current meters be used to establish the reference level for geostrophic current calculations in an attempt to reveal the seasonal variation of transport in the large current systems of the North Atlantic and Pacific oceans. Experience [for example, that of Ekman (*7*)] shows that the velocity spectra are much noisier than density spectra, and that it is a much more difficult task to resolve the annual period from measured velocities than to resolve it from density measurements. In the proposal to UNESCO no specific provision is made for taking into account this important difference in the level of contamination in the two variables.

One needs to approach proposals of this kind with great caution, and to insist that their feasibility be demonstrated before one leaps too far into the unknown. There seems to be a peculiar fascination about the seasonal portion of the spectrum, out of all proportion to its importance and to the amount of effort required for accurate determination of the seasonal variations. I can account for this only by suggesting that those who are so greatly interested in the seasonal variation are geographically and climatologically oriented, not concerned with the physical-dynamical processes at work in the ocean. There is, of course, no completely logical priority for the investigation of scales and periods in various oceanic phenomena. Nevertheless, it is easiest to measure those portions of the spectrum that have the largest amplitude.

There is a further important point that I now want to make—namely, that the coexistence of different periods and scales leads not only to contamination in measurement programs but that the scales also interact. To achieve "physical understanding" we must map not only the variables but also their interactions (that is, we must map spectra of Reynolds stresses, and so on). In some cases it will be much more difficult to establish these values than to establish spectra of the variables themselves. But this is partly what we mean by physical understanding, and it will no doubt be hard to come by.

Currents off Bermuda

Let me illustrate in terms of a period-length diagram (Fig. 3) for velocity of currents in the deep North Atlantic Ocean. Several years ago Swallow and Crease decided to make some extended observations of currents in the deep water off Bermuda as representative of the open Atlantic Ocean. In planning the minimum requirement for ship time and the number of neutrally buoyant floats that might be followed at a time, they were expecting amplitudes of about 2 to 4 centimeters per second, scales of about 100 kilometers, and periods of several weeks. Now this is only a portion of the spectrum of velocity in the deep water, but experience showed that tides and high-frequency phenomena do *not* contaminate measurements made by means of neutrally buoyant floats. It was hoped that averaging over many eddies, perhaps for as long as a year, might reveal some large-period means. The amplitudes of motion were, surprisingly, ten times greater than expected (*8*); the original strategy of operation had to be abandoned, and it was not possible to develop as sharp a picture of the spectral distribution of these motions as had been hoped, with the minimal ship facilities that were mustered.

Because of their large amplitude, however, these motions are of even greater interest, and we are trying to design a proper network of moored instrumented buoys for gathering the right kind of data. As yet we do not have a completely reliable moored current-meter. This is a problem in instrument development. But we cannot plan a final network of observing points and intervals until we have mapped the spectral distribution of velocity roughly, so it is obvious that this program must advance in several phases, the design of each phase depending on the nature of results obtained in previous phases. We are not interested in describing these eddies in isolation; we are concerned with discovering whether they play a significant role in driving the large-scale circulation. Is there interaction of eddies and large-scale circulation in the ocean as there is in the atmosphere? The problem is basic to a theoretical understanding of the general circulation of the ocean. The evaluation of the interaction terms will be more difficult than the determination of spectra for simple velocity alone. Can we design an observational program that can be reasonably expected to yield statistically significant information on this question? Obviously not in a single try.

The first steps toward gathering data for determining the design characteristics of a large-scale observational study are being made by oceanographers at Woods Hole, using a small network of buoys in the open ocean near Bermuda. After the spectral distribution of the velocity field has been roughly mapped it will be clearer what kind of program will be necessary for evaluating the interaction terms. On the whole it seems that heavier moorings than those now being used will be necessary to reduce the present rate of loss of instruments and records, and this may require use of a commercial cable ship or its equivalent. It will be desirable to use some other types of instruments in addition to the moored current meters—for example, bottom-pressure recorders and neutrally buoyant floats that can be tracked by acoustic methods. At present, instruments of this kind exist, but they must be extensively redesigned to be useful in a project such as this. For example, the range of the present acoustic tracking devices for the neutrally buoyant floats needs to be extended at least tenfold so that hydrophones on several of the moored buoys will always be in contact with each neutrally buoyant float.

There is so much to do, in fact, that it looks as though some kind of coordinated national program involving several research institutions will be necessary. Cooperative efforts among oceanographic institutions have, in the past, been limited largely to surveys of the geographical type. One wonders whether oceanographic institutions can collaborate on a program of physical measurement such as the study of geostrophic turbulence demands, or whether some outside separate organization—such as has been used in the Mohole project—will be necessary.

In summary, then, we see that the spectra for all the physical variables of the sea are very complex, and that there is a need for more sophisticated and more physically-oriented observational programs than the geographical surveys made during the International Geophysical Year. In particular, these new programs need to be directed toward revealing the interactions between different portions of the spectra. Such new observational material will have a tremendous impact upon theoretical studies, which at present are pursued on the basis of far too little information about physical processes operating in the real ocean.

In the past there were very few points of contact between the ocean as visualized by conventional analysis of serial observations on the one hand and the ocean as portrayed by simplified laminar theoretical models on the other. I think the reason is not hard to find: neither model had been developed to a level of sophistication corresponding to the essential complexity of the oceanic phenomenon it was trying to describe. From the scattered pieces of evidence that are at present available it appears that the dynamics of the oceanic circulation, and the transport of various properties in the sea, may actually be dominated by the large-scale, transient, turbulent processes which hitherto have been ignored by observers, and which theoretical workers had hoped to bypass. There is no harm in thinking at first about the ocean in various simple ways, to see how satisfactory a model one can devise, but a time comes when consideration of the next stage in complexity can no longer be postponed. Happily, we have the technological means to begin oceanographic observation of the new type, and we can look forward to a time when theory and observation will at last advance together in a more intimately related way.

References and Notes

1. H. A. Marmer, *Geograph. Rev.* **15**, 438 (1925). This is an introductory description of the variability of sea level along the Atlantic Coast of the United States, as estimated by means of various averaging processes.
2. J. F. T. Saur, *J. Geophys. Res.* **67**, 2781 (1962). This article contains references to other recent work by Pattullo, Lisitzin, and others.
3. Saur's article is a recent study of sea level at six stations in the eastern North Pacific Ocean. Data on monthly mean sea level from year to year are given, corrected for changes in atmospheric pressure. A representative value for standard deviation of sea level at Honolulu for May is 5.2 centimeters, as estimated from measurements made over a 53-year period. The standard deviation is greater for winter months and at higher latitudes.
4. H. Stommel and A. H. Woodcock, *Trans. Am. Geophys. Union* **32**, 565 (1951).
5. J. Knauss, *Deep-Sea Res.* **6**, 265 (1960). This article is the main source of presently available information on the Pacific equatorial undercurrent, or Cromwell Current. The *Argo* study in the Indian Ocean is under the direction of Knauss and of B. Taft.
6. C. O. Iselin, *Papers Phys. Oceanog. Meteorol.* **8**, 1 (1940).
7. V. W. Ekman, *Geofys. Publikasjoner Norske Videnskaps-Akad. Oslo* **19**, 106, 122 (1953).
8. J. Crease, *J. Geophys. Res.* **67**, 3173 (1962). This is a brief preliminary report on the measurements of currents that were made near Bermuda.

News and Comment

Civilian Technology: Concern Over Pace of Growth Inspires Program for Research and Development Effort

Tucked away in the President's $98.8 billion budget is a relatively piddling item, $7.4 million, that is quite likely to grow manyfold and to have a profound effect on industry's relations with science and engineering.

Its origin is in the administration's increasing concern over the civilian economy's sluggishness in using new technology, and the money is intended to start a program that will promote and focus civilian-oriented research with some of the intensity that has paid off so well in military and space research. For, despite cheery assertions about the civilian by-products that are to be anticipated from the government's massive investment in these fields, the administration is becoming increasingly concerned over what it considers to be a lack of technical dynamism in major parts of the civilian economy. It is now frankly acknowledged that by-products to serve civilian needs are not springing full-grown from the military and space establishments, and that some new organizational arrangements seem to be needed to reduce the gap between advances in knowledge and new products and new ways of doing things.

The first outgrowth of this conclusion was the formation, early in the Kennedy Administration, of a panel on civilian technology as part of the White House science-advisory organization; the panel is under the guidance of Michael Michaelis, a member of the Office of Science and Technology staff, on leave as a senior associate from Arthur D. Little, Inc. This was followed last summer by the appointment, within the Department of Commerce, of an assistant secretary for science and technology, a post filled by J. Herbert Holloman, former general manager of GE's General Engineering Laboratory. And, under Holloman's direction, the department has started a Civilian Industrial Technology Program, which, in close contact with the White House panel, is now planning the initial steps for an extremely ambitious effort.

The administration has neither disclosed nor, presumably, decided on the ultimate size and scope of the program, but from what has been stated publicly it is obvious that it is not thinking in small terms; there has been some speculation from persons associated with the program that, in budgetary terms (Congress willing), it may eventually be on a par with the National Science Foundation, which received about $260 million this fiscal year.

As outlined in a speech last month by Commerce Secretary Luther H. Hodges, the program will have objectives as follows:

1) To provide financial support for university personnel to work on industrial research and development. "Through the award of research contracts," Hodges said, "we hope to provide incentives and training for research workers and educators in specific industrial fields, and, at the same time, develop new knowledge on which to base industrial innovations."

2) To stimulate industry to undertake research that it might otherwise shy away from because of costs or because the profit potential is too uncertain.

3) To develop an industry-university "extension service" patterned after the agricultural extension service, which has played a key role in developing and communicating agricultural technology for the nation's farmers.

4) To provide services for collecting and distributing technical information.

Of special concern to the administration is the fact that in many of the industries that account for substantial portions of the gross national product, relatively little is spent on research. Housing is perhaps the most conspicuous example. According to the Census Bureau, expenditures for residential housing last year totaled about $18.3 billion. Trade associations and manufacturers carry on some research in materials and construction techniques, but the home-building business is so fragmented that the effort to find new and better ways to build shelter is diminutive when compared to the economic significance of the industry. Administration officials acknowledge that finding better ways to build is not the whole answer, for the housing industry is beset by a maze of local housing codes that stifle the introduction of new materials and techniques; and the building trades unions are not eager to participate in cost-cutting efforts that mean less work. But, as one administration aide put it, "If someone can find a way to build a better house for less money, there's nothing in the long run that can stop him."

Underlying the administration's concern about the pace of civilian technology is the fact that the demands of the Cold War are leaving this country