Current Problems of Fluid Dynamics

Subjects from sonic boom to tidal waves occupy fluid dynamicists. When the American Physical Society held its joint meeting with the Japanese Physical Society in Hawaii, they discussed boundary-layer flow, kinetics of dense gases and applications of their subject in contemporary engineering. They worry because study of fluids is declining even as its importance increases.

by Richard G. Fowler

A PARADOX CONFRONTS contemporary physicists: although scope, importance and utility of fluid dynamics in physics have grown spectacularly, teaching of the subject in physics departments has been receiving less and less attention. Not only are advanced courses becoming rare, but fluids are often eliminated from introductory physics for lack of time. Even when they are included, outdated aspects are usually presented, and modern contributions are ignored.

Students of fluids had an unusual chance to reässess their field during the 1965 joint summer meeting of the American and Japanese physical societies in Honolulu. The 78 papers delivered by American physicists and their Japanese counterparts fall roughly under the following headings: boundary-layer flow at rigid and flexible boundaries, vortex motion, turbulence, surface waves, foreign-body motion and wakes, convection, viscous flow, superfluids, shock waves and tubes, shock-tube chemistry, laser-generated flows, kinetic theory of fluids, sound, magneto-fluid-dynamics and politics. (The last refers to a NASA request that fluid mechanics find methods to deal with sonic booms.) Among the most discussed subjects at the Hawaiian meeting were boundary-layer flow, tidal waves, dense-gas kinetics and new experimental techniques.

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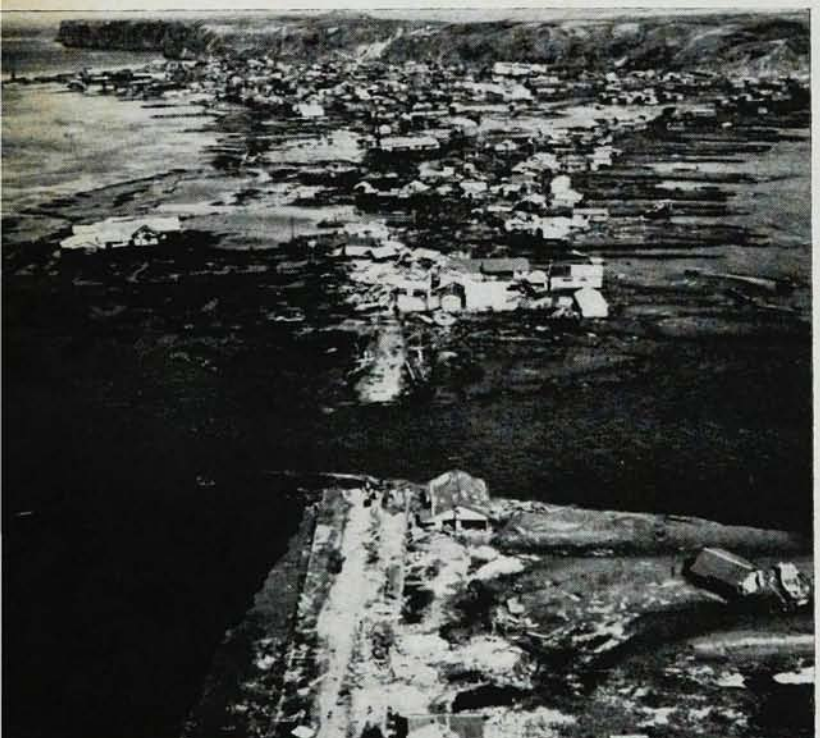
Boundary-layer flow

Flags have rippled in the breeze for millenia, but experimental data on the waves that propagate along a flexible boundary remained largely untaken. At the Hawaiian meeting Sadatoshi Taneda (Kyushu University) compared theory and experiment for free and constrained cloth in a uniform flow and in a one-sided flow. His measurements include velocities, frequencies, waveforms and modes of the waves.

One might describe the subsequently presented theories and experiments of Julian Cole and Jerome Aroesty (Cal Tech) as an attempt to make the ordinary rigid boundary of a solid more flexible. Whereas much attention has been given to removing the boundary layer by pumping it away through the airfoil, Cole and Aroesty examined the converse problem of inflating the boundary layer even to blowing it off the body, a process that seems to show some aerodynamic promise.

François N. Frenkiel (David Taylor Model Basin) and Philip S. Klebanoff (National Bureau of Standards), reported on measurements of statistical characteristics of turbulence with fast computation. They reported the first data on two-dimentional probability distributions and time correlations in turbulent flow up to the eighth order.

TSUNAMI RUNUP. On 4 March 1952 a wave caused by the Tokachi-oki earthquake reached a height of about 3.4 meters above normal tide at this village on Hokkaido.



ANOTHER TSUNAMI, this one on 24 May 1960, cut sand bar that formed a peninsula of part of the same village. This tidal wave was caused by an earthquake in Chile.

It is evident that Gaussian distributions cannot be carried far as a model for turbulence calculations.

Tsunamis—or tidal waves

An aspect of fluid mechanics most appropriate both to a Hawaiian meeting place and the homeland of Japanese guests is tsunamis—the much-feared tidal waves that race across oceans at speeds up to 1000 km/hr. Tsunami has become the accepted name for this phenomenon in recognition of intensive Japanese work and linguistic confusion whereby even those who have Greek at their disposal cannot distinguish verbally between tsunamis and the diurnal waves of the tide.

Kinjuro Kajiura (University of Tokyo) outlined the state of tsunami theory. Although arrival time of a tsunami wave front at a certain location can be predicted from seismic information with accuracy satisfactory for warning services, the characteristics of a tsunami, such as maximum wave height, apparent period and duration of a wave train, are very difficult to estimate beforehand. Among many factors that control tsunami character, the following must be considered: geometry of crustal deformation, dispersion of ordinary water waves and effect of a shallow continental shelf. Although the gravity-wave dispersion law controls the character of a wave train generated by an impulsive source of small horizontal dimensions, it is not sufficient to explain the wave train of a tsunami generated by an earthquake.

The continental shelf, near which most of the rapid crustal deformation responsible for tsunami generation occurs, gives rise to additional dispersion in the edge-wave modes along the coast. Also multiple reflection of a tsunami at the coastal boundary and at the edge of the shelf generates wave trains propagated into open ocean with periods corresponding to possible shelf oscillations. As a result, along a coastal boundary far from the source, a wave train has a dispersive characteristic for which the maximum amplitude appears near the group velocity minimum of the fundamental edge-wave mode. On the other hand, the wave train in the open ocean has a period similar to the "seiche" periods of the continental shelf near the source and an amplitude that decreases exponentially with time. Seiche is not a Japanese word, as it seems, but Greek; it refers to the sloshing of water, for example in a washbowl or in Lake Geneva (where first applied).

Data observed

William Van Dorn (Scripps Institution) ranged critically over observational data on tsunamis. According to generation theory, a tsunami can, in principle, be produced by any rapid localized event that deforms the free surface. These include earthquakes, volcanic eruptions, landslides, meteorite impacts and man-made explosions. Most important tsunamis are believed to be produced directly by vertical dislocations of the sea floor associated with large earthquakes. Landslides and explosions are usually relatively inefficient. The explosive eruption of the Krakatoa volcano in the Sunda Strait, British East Indies, however, generated one of the largest tsunamis in history; it was observed in all oceans of the world. Meteorite impacts of noticeable importance have not been experienced in the oceans within recorded history.

Large tsunamis have been generated about every ten years as far back as one can trust the records. About 80% of these events have occurred in the Pacific Basin, and more recently the incidence of Pacific tsunamis has increased sharply to about one every four years. Currently the most active seismic belts are located off Japan and South America and have accounted for about a third of all tsunamis produced since 1800.

Some information about tsunami sources can be obtained from analysis of the wave patterns recorded at a remote location. If the generation process can be assumed to be linear with a relatively uncontaminated spectrum, one can, in principle, reconstruct the source by Fourier inversion of the recorded spectrum and summation of all component frequencies. As the spreading wave system encounters such objects as mid-ocean islands, however, wave pattern and amplitude become distorted. As usual with diffraction effects, the degree of perturbation depends markedly on the ratio of obstacle size to local wavelength. This ratio steadily increases with time from its initial value at the wave front because of the dispersion of the water-wave system.

Detection of a large barometric anomaly following the great Alaskan earthquake of 28 March 1964 is reminiscent of the Krakatoa explosion and has opened up the possibility of source analysis by this method. Such techniques may also prove useful for tsunami warnings, because it is increasingly evident that severe tsunamis exhibit abundant energy at low frequencies.

Because the average depth of the ocean is reasonably uniform, if one could take a snapshot from a great altitude of a tsunami an hour or two after generation in the deep sea, he would observe a nearly circular wave pattern despite any pronounced irregularities in source shape. Source asymmetry, however, can result in marked azimuthal differences in amplitude. These differences grow smaller with increasing distance from the source but at a much slower rate than do asymmetries in the wave pattern.

Wake Island happens to have one of several small island observation stations equipped with special instrumentation for recording tsunamis. It has operated intermittently since 1954. These small islands were selected as being the nearest approach to midocean recording for lack of a stable reference platform in the open sea.

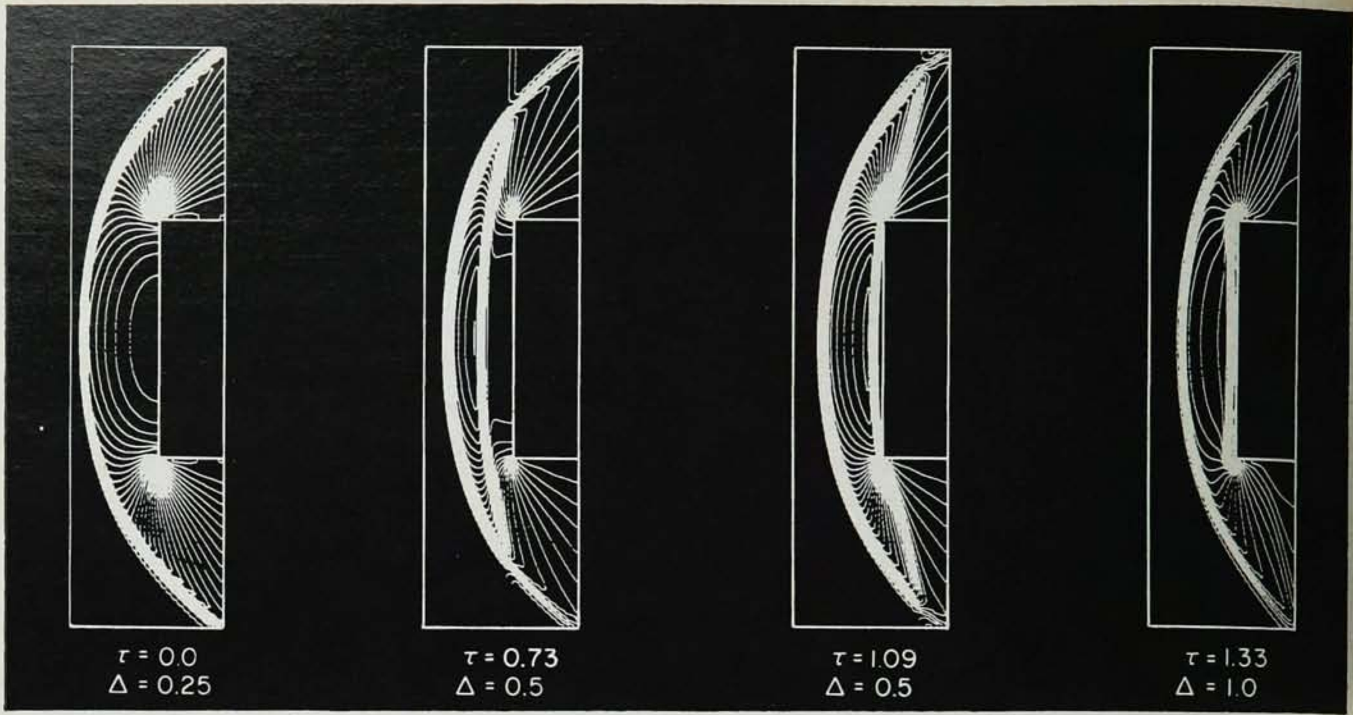
Runup paradox

One of the really challenging tsunami problems is the runup paradox: First, how does a tsunami wave train, comprising a low-amplitude spectral continuum in the open sea become transformed in the near-shore region into a series of highly periodic oscillations producing runup heights along the coastline more than ten times as high as the maximal amplitude of the disturbance in the open sea? Second, how can such anomalously high coastal oscillations exhibit such an extreme variability in amplitude from mile to mile along the coastline when the characteristic oscillation frequency is almost always much lower than that frequency usually associated with the spectral maximum of the offshore disturbance?

At least a dozen competent theoretical attempts have tried to explain tsunami runup. All have been limited to propagation in one dimension as have almost all of the experimental attempts to verify these theories. There is considerable disagreement between theory and experiment.

Tsunamis can be the agency of cataclysmic worldwide disaster as well as local disaster. It follows from the linear theory of gravity waves that a body of water of uniform depth can support stable waves on its surface about 80% as high as the water is deep. Since the Pacific Ocean is 6000 meters deep in the average, it could conceivably support waves 4800 meters high. If it were possible to produce a depression of the sea surface of this order in deep water, a stable tsunami-like wave system would be generated and would disperse under gravitational forces alone according to linear generation theory.

Consideration of the frequency of lunar craters (and more recently of those that appear on Mars) leaves little doubt that at some time in the earth's history the oceans have been bombarded by objects large enough to produce such surface deformations. From estimates of the kinetic energy of interplanetary objects and the laws of cratering, one can estimate the size of objects that produce the lunar



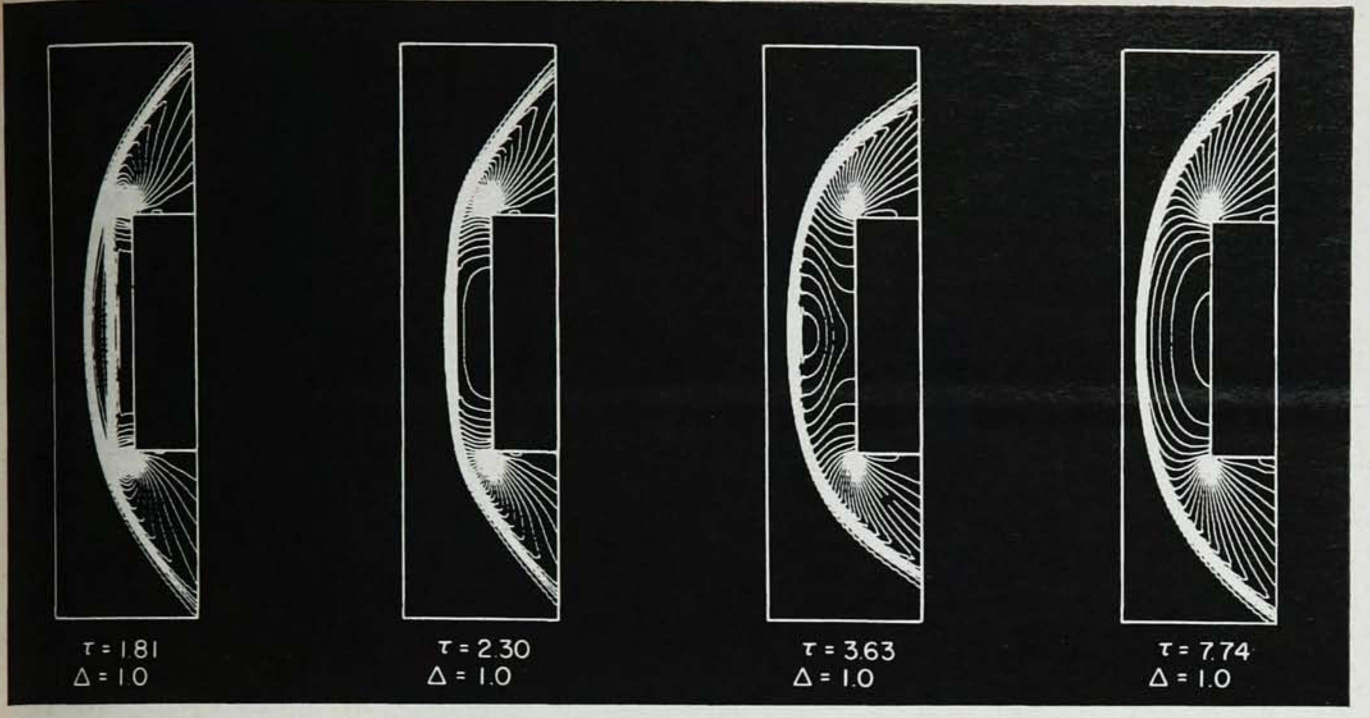
COMPUTER-DRAWN CONTOURS show pressure field that occurs near flat-faced cylinder when detached bow shock interacts with a plane shock wave. Δ is contour plot interval and τ is dimensionless time between frames of picture made by running experiment on IBM 7030.

craters. These computations give a meteorite dimension about a tenth of the crater diameter. Thus a meteorite one mile in diameter impacting the ocean would produce a crater about ten miles in diameter and about as deep as the ocean. The collapse of this crater would result in the formation of a wave system of which the maximum height would approach 4800 meters. The degradation of wave height from such a small crater would go approximately as the reciprocal of distance from the source, and therefore the maximal wave height at a distance of 2000 km would still be about 50 meters. In the frequency range of the highest waves the runup would probably not exceed the offshore wave height by a factor of more than four, but this brings us back up to a runup height approaching 200 meters. Despite the fact that almost all of the important waves would break before reaching shore, inundation effects would be indescribable, and there is no question that seven of the ten largest cities in the world would be eradicated. If lunar statistics can be applied to the earth, about 2000 such events have occurred in geologic time, but estimates of the present probability based on the size-frequency distribution of known asteroids is, fortunately for us, only about $1/10^5$ years.

One physicist at the Hawaiian meeting was overheard to suggest that in keeping with the noble spirit of its Mohole Project, the National Science Foundation might well undertake to trim some mid-Pacific island into a well defined contour about 3 miles high and a half mile in diameter for tsunami observations, since lack of a canonical diffraction generator seems to be one of the principal obstacles to detailed study.

Kinetics of dense gases

Three invited papers presented in Hawaii dealt with kinetic theory of dense gases. E.G.D. Cohen (Rockefeller University) was concerned with the theory of viscosity η and heat conductivity λ. Although these coefficients are usually treated as constants, they depend in reality on the (local) density n and the (local) temperature T. It is one of the prime objects of kinetic theory to find the dependence of η and λ on n and T, that is, their equation of state. Two methods have been used: the distribution-function method (which goes back to Boltzmann) and the recently developed time-correlation-function method. Both methods lead, for a moderately dense gas, to kinetic equations that in turn lead to identical density or virial expansions of the transport coefficients. Recently divergencies that make for infinite virial coefficients for η and λ have been discovered in these expansions. They throw doubt on the existence of a kinetic equation and any virial expansions for the transport coefficients. In fact there are strong indications that no such expansions exist and that instead transport coefficients have a nonanalytic dependence on density.



Ryogo Kubo (Tokyo) has done much to establish a fluctuation-dissipation theorem. The theorem arises directly when one considers Brownian motion, the classic example of stochastic processes in physics. As a phenomenological theory, it starts from a few assumptions, which, to form a physical theory, must then be justified in terms of the more basic principles of physics. This is a task for statistical-mechanical theory.

The classical Langevin equation can be generalized to include a friction force with retardation, a random force and an external force. The random force satisfies the condition that its average value is zero. The frequency-dependent friction can then be defined as a Fourier transform, which can be related to the random force by another Fourier transformation when the random force is due to thermal agitation in equilibrium. This is a logical consequence of the well known equation for the mobility that is often called the "Kubo formula." It is in fact a general statement of the fluctuation-dissipation theorem, which has been recognized in recent years as a basis of the statistical mechanics of irreversible processes.

Experimental problems

Hakuro Oguchi (Tokyo) reported in Hawaii on results obtained in a shock tunnel driven in the true Lagrange fashion by a moving piston. Mach numbers of 10 in air and 19 in argon were obtained with a shock Reynolds number of 50, permitting application of the technique to low-density-hypersonic-flow problems. In particular, Oguchi has investigated the flow around a sphere; results show that shock thickness becomes greater as the Reynolds number based on the sphere radius decreases, whereas the viscous-layer thickness appears to be the same or slightly smaller. Slope thickness of the shock wave is roughly the same for different Reynolds numbers, and it appears to depend mainly on the free-stream mean free path, which was held fixed. Oguchi found that the slope thickness appeared to have consistently the order of magnitude predicted for a high-Mach-number shock wave.

In the same vein, Hiroshi Sato (Tokyo) discussed axially symmetric subsonic wakes and their stability. Experimental and theoretical investigations indicate that the wake is divisible into four regions: laminar, linear, nonlinear and turbulent. In the laminar region the separated laminar boundary layer develops into the laminar wake. In the linear region the mean-velocity distribution stays almost unchanged and the flow is almost parallel. Here small-amplitude velocity fluctuations are either amplified or damped depending on frequency. Measured wavelength, amplification rate and distributions of amplitude and phase are in good agreement with results of linear theory. Phase measurements in azimuthal and axial directions indicate that the line of constant phase forms a helix and not discrete loops. In the nonlinear region the production of an irregular velocity fluctuation is observed but the second harmonic component has not been found. The regularity in the waveform of fluctuation is gradually lost in the

Fluid Dynamics—
a Division with Problems

Several recent actions have been taken to reilluminate a fading interest in fluids on the part of physics faculties. At the January 1964 American Association of Physics Teachers meeting in New York a panel gathered by Raymond Seeger reviewed the range and impact of modern fluid physics and stressed the need for a restoration of continuum mechanics to its time-honored place in the physics curriculum. The panel spoke with a unanimity and passion rarely found among physicists. To a man, they deplored the opinion that fluid dynamics is a closed field best left to applied mathematicians and engineers for teaching and research, pointing out egregious errors that have been made recently by research workers ignorant of their fluid physics.

The second major effort in the campaign to promote continuum physics was made at the University of Hawaii meeting. The 1965 American Physical Society Summer Meeting in the West had been planned as a joint meeting with the Physical Society of Japan. The Division of Fluid Dynamics sought and obtained financial support for travel to this meeting from the Air Force Office of Scientific Research, thereby making it possible for a substantial number of distinguished Japanese and American fluid dynamicists to meet and exchange their thoughts on matters of an exceptional diversity. Arrangements for the Japanese and American contributions to the program were handled by the individual and joint efforts of Isao Imai and Otto Laporte. To the latter Felix Bloch, president of APS, then assigned the privilege and responsibility to welcome the visitors from abroad in both English and Japanese. Ryogo Kubo, president of the Physical Society of Japan, responded in kind.

nonlinear region. The turbulent region is established without any burst of sudden breakdown.

Experimental techniques

Richard Hartunian and Paul Thompson (Aerospace Corp.) have mated the shock tube and a large glow discharge to the study of important reaction rates among simple molecules such as those between nitric oxide and oxygen and those between carbon monoxide and oxygen. The possibilities of this method in unravelling the confusion in this area seem limitless. Not only should ionospheric physics profit, but so should flame physics.

Another development that will have a profound effect on all phases of science is the new technique developed at Los Alamos and described at the Hawaiian meeting by Richard Gentry. It can best be summarized as "running an experiment on a computer." Here the best available flow equations are solved stepwise from given initial conditions so that the flow field can be seen to develop in time on the plotter output from the computer. The particular application presented was to a shock-shock interaction, and in the motion picture that was shown the audience watched the evolution of a remarkably faithful likeness of the expected flow. Adjustment of the terms employed in the equations can, of course, give insight into the role they play if one can afford to pay for the numerous variant runs needed.

What to do with sonic boom

Speaking at Hawaii on behalf of the Sonic-Boom Committee of the National Academy of Sciences, Everett Cox (Whirlpool Corp.) implored fluid dynamicists to aid aeronautical engineers in their efforts to mitigate sonic booms for supersonic aircraft. An invitation for unsolicited proposals bearing on this subject has been issued by NASA. As things now stand, there is honest doubt whether commercial supersonic transports will be permitted routes over inhabited areas. Without doubt the sonic contents of the two rapid pressure rises associated with the N wave constituting a boom are psychologically startling; human beings can adapt to them only at the risk of lowering their sensitivity to proper alarm stimuli. Any means of reducing even the audible components of the far-field N wave would be a boon to the aircraft industry, national prestige, long distance travelers and quiet living. It would, Cox said, also help erase the popular impression of twentieth-century technology expressed in A. P. Herbert's poem

Great science nobly labors
To increase the people's joys,
But every new invention
Seems to add another noise.

Unfortunately, fluid dynamicists are not sanguine about their chances to be helpful.

At a ceremonial gathering of the executive committee of the APS fluid-dynamics division and the corresponding members of the Japanese Physical Society, each side discussed its own society problems and found them to be nearly the same. Of particular interest was whether fluid dynamics is included in the teaching of physics in Japanese universities to a greater extent than is current in the United States. Americans found from this conversation that the situation is much the same in both countries. There is great engineering interest in basic aspects of shock phenomena, flows involving ionization radiation and active chemistry, heating and turbulence phenomena. These concerns stimulate interest among a growing number of physicists, but most basic research is done outside physics departments. □