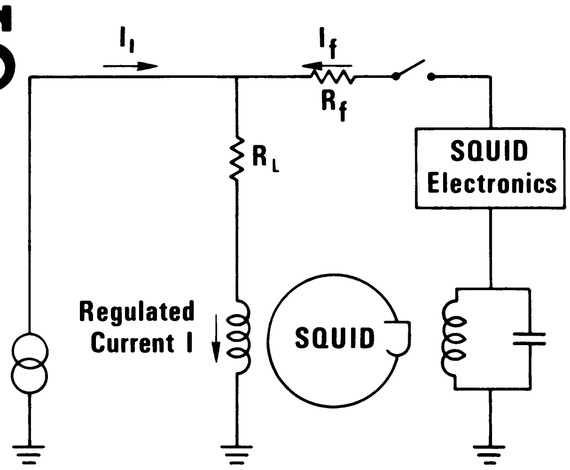
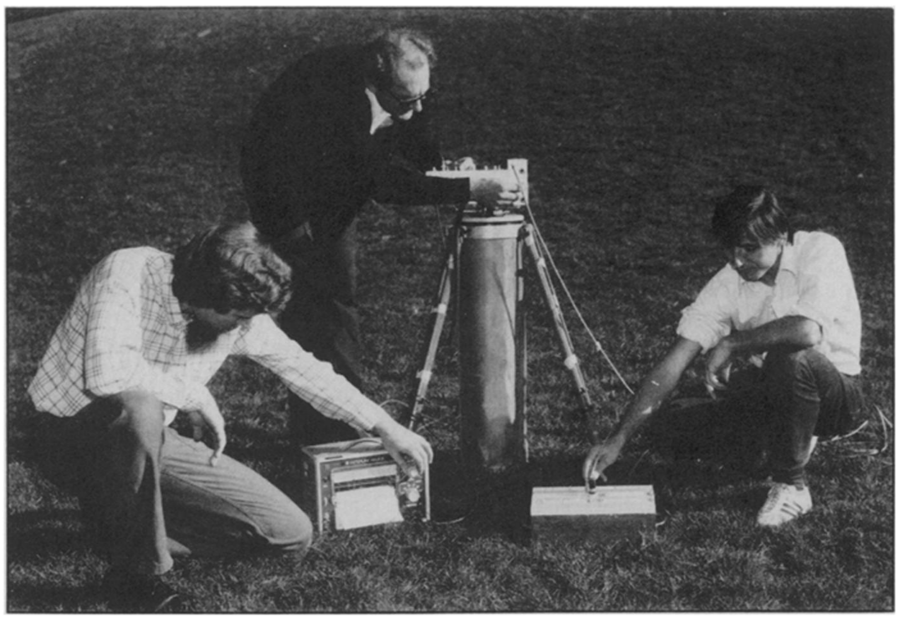
MEASURING MINUTE MAGNETICS

From the human heart to the bowels of the earth tiny magnetic fields reveal important information

BY DIETRICK E. THOMSEN



A squid current regulator. Magnetic flux changes induced in squid by current through center coil feedback current through R_L and coil.



LBL

Tom Gamble, John Clarke and Wolfgang Gobau use a magnetometer made of squids.

Many years ago at a meeting of the American Association for the Advancement of Science the chairman of a session on plasma behavior opened by warning the audience that "this is not part of the symposium on hematology." More and more sciences borrow each other's terms, and familiar words appear in unfamiliar contexts. This is especially so with the modern craze for acronyms that spell something. Take SQUID, for example. This is not what you will get if you ask a Greek waiter for kalamaria plaki, nor would a marine biologist be able to taxonomize it. It is, in fact, an artifact of solid-state physics, a Superconducting QUantum Interference Device.

SQUIDs are very sensitive devices for measuring weak magnetic fields, and they are finding applications wherever such fields are of interest, especially in medicine, psychology and geophysics. Someday they may be used in predicting both heart attacks and earthquakes.

Squids are an application of the Josephson effect, the discovery of which brought Brian Josephson the 1973 Nobel Prize for physics. The effect is manifest in what is usually called a Josephson junction. A Josephson junction is a "weak" connection between two superconducting electric circuit elements. Its weakness may consist of a thin layer of insulating oxide or simply poor contact because of minute roughness of the surfaces of the superconductors. In the ultracold world of superconductivity (liquid-helium temperature of 4° K) the electrons that make the supercurrent can pass through the weak connection by what is called quantum-mechanical tunneling. This action produces an unusual relation between current and voltage across the junction.

If there is a magnetic field through a portion of the circuit in which the junction is located, the current that flows across the junction will oscillate in response to changes in the magnetic field. The effect is a stepwise, or quantal, one. There is a minimum permissible value, or quantum, of magnetic flux. Magnetic flux is the magnetic field strength multiplied by the cross section over which the field is spread. The junction current oscillates once whenever the flux changes by one quantum. (Indeed it was equipment using Josephson junctions that first gave experimental evidence of flux quantization.)

If two Josephson-junction circuits are arranged in parallel so that both surround a certain area, the current will oscillate once for every time the flux changes by an amount equal to the quantum divided by the enclosed area. This is the way a squid is made: The two parallel circuits are laid down around a cylinder through which the field to be measured is passed. Field strength equals flux divided by area, so with a large enough area in the cylinder's cross section, extremely small changes of field strength can be measured. A figure recently quoted by John Clarke of the University of California at Berkeley is 10^{-10} gauss. The earth's field, which is extremely weak compared to industrial magnets, is about half a gauss.

Thus, squids are proving useful in a number of studies where sensitivity to minute magnetic fields can yield information. Medicine, psychology, geophysics and metrology are especially active right now, and physicists representative of those working in these fields were invited to discuss squids at the recent meeting of the American Physical Society in Chicago.

Geophysics is one of the most magnetic branches of science. Many of its particular phenomena are noted for imposing minute fluctuations on the earth's ambient magnetism. Clarke says he and his associates at Berkeley have been in the field testing the usefulness of squids in prospecting for such things as geothermal energy sources or oil deposits. Other minerals too are possibilities. And then there are earthquakes. Mechanical strain on a geologic fault—the San Andreas, for example—produces changes in the local magnetic field. Assuming that the strain is useful in predicting earthquakes, squids may become an effective way of monitoring it.

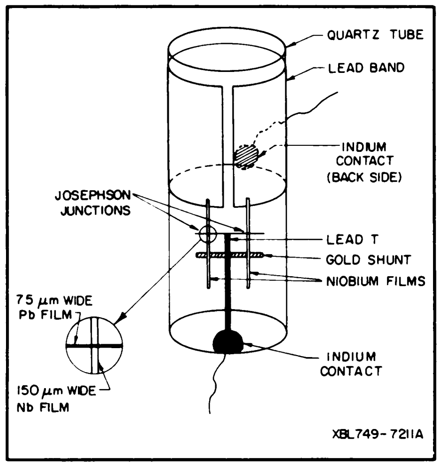
Biology, medicine and psychology account for particularly intense experimentation on the possible application of squids. Many of the body's organs generate minute electrical currents: the heart, the brain, the muscles, etc. These have been exploited in medical diagnosis for a long time. Where there are electric currents, there are also magnetic fields, and squids are being used to determine what the magnetic fields can reveal about the health and functions of the various organs.

As Samuel J. Williamson of New York University points out, there is a severe technical difficulty involved in measuring these physiological magnetic fields: They are characteristically about a billionth of the earth's field. So how to measure them in the presence of fields from power lines and electrical appliances that are characteristically much stronger? One approach is to construct a magnetically shielded chamber in which to do the work. David Cohen of the Massachusetts Institute of Technology is said to have the chamber with the lowest magnetic noise yet.

But such an approach takes space and expense. The NYU people have succeeded in altering the circuitry of squids so that they respond only to changing magnetic fields and not to steady ones. This effectively subtracts out the noise due to power lines and such, and Williamson says his group can work quite well "on the ninth floor above a BMT line in Manhattan."

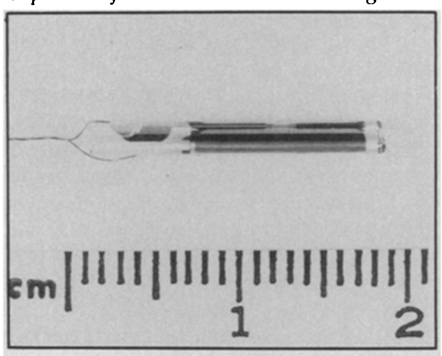
Much of the current work is concentrated on seeing what magnetograms can tell physicians and psychologists that other means of observation cannot. It is already clear that magnetocardiograms can show up conditions that electrocardiograms miss. One of the advantages of magnetocardiograms is that they can sense effects of direct currents, which electrocardiograms cannot. Also, the magnetogram can be taken without skin contacts. This means it is faster to take and that it senses the heart's condition more directly. In electrograms, the skin adds a contribution of its own. The exercise right now is to make magnetic surveys of a large number of hearts and then have the data studied by experienced cardiologists so as to establish norms and criteria for distinguishing health from diseased conditions.

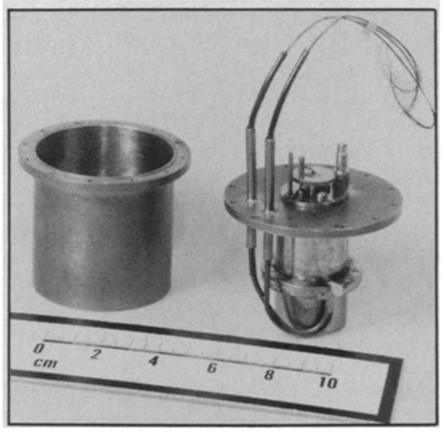
Much of the NYU work, Williamson says, is psychological. In one such experiment subjects are shown a pattern of stripes and asked to press a button to signal that they have apprehended it. The more complicated the pattern, the longer



LBL

A schematic of how a squid is made and a photo of one that shows how big it is.





NBS

A squid device for comparing currents.

the response time. But, Williamson says, the magnetograms indicate that the difference lies in the motor response. The response time of the visual cortex seems to be the same in all cases. People with diabetes or renal disease seem to take longer. Preparations are under way to compare the responses of psychotics with those of less psychotic subjects.

These are just a few of quite a number of magnetophysiological studies going on in half a dozen or more laboratories around the world. There is even a possibility of using squids to distinguish suspect or tumorous tissue from healthy tissue. At least one such experiment has been proposed, but Williamson could not comment on it because he is a member of the board that has to evaluate it.

Less likely to turn up in a future television series but very important economically and scientifically, is the application of squids to metrology. One of the main purposes of the National Bureau of Standards is to maintain the United States's official standards of measurement, and as Donald B. Sullivan of the NBS laboratories at Boulder, Colo., put it, the bureau has "the motivation to stay ahead of measurement technology." Squids may do for electromagnetic measurement what krypton lamps did for standards of length.

Originally, the standard meter was the distance between two scratches on a platinum-iridium bar kept at the International Bureau of Weights and Measures in Sèvres, a suburb of Paris. National standards were compared with the one at Sèvres. Standards used in industry and science were established by comparison with the national one at NBS, and so on through many removes till one reached the meterstick hanging by the blackboard in the schoolroom. The succession of comparisons introduces many opportunities for degradation of accuracy. Now the meter is defined as a number of wavelengths of a particular color emitted by krypton, and any laboratory with the proper lamp and a good interferometer to count wavelengths can set up its own accurate standard meter independent of the bars at Sèvres or Gaithersburg.

Similarily, Sullivan suggests, the squid's ability to measure magnetic flux quantum by quantum could lead to a redefinition of electric and magnetic units in terms of flux quanta instead of the standard ampere that defines them today. Then any laboratory with a squid could set up its own independent electromagnetic standards. Squids will be especially useful, Sullivan thinks, in establishing more precise standards for oscillatory quantities in the high range of radiofrequencies. It is possible to extend such accuracies to the range above 10 billion hertz. "It's very appealing," Sullivan says.

This very appealing instrument with the somewhat marinebiological name also seems susceptible to mass production. The technique of making the squid itself, of laying down the superconducting circuits, and the Josephson junctions on a cylinder is not difficult to do industrially, and technology can supply the refrigeration necessary to maintain the liquid-helium temperature. It will still be a somewhat bulky apparatus, and prospectors are unlikely to carry squids in the pockets of their Levis, but according to the estimates of cost given by these speakers, an organization that can afford a new automobile can afford a squid. The estimates range from \$5,000 to \$13,000 depending on how much of the ancillary technology is counted in the cost of the squid. □