A BUBBLE IS BORN

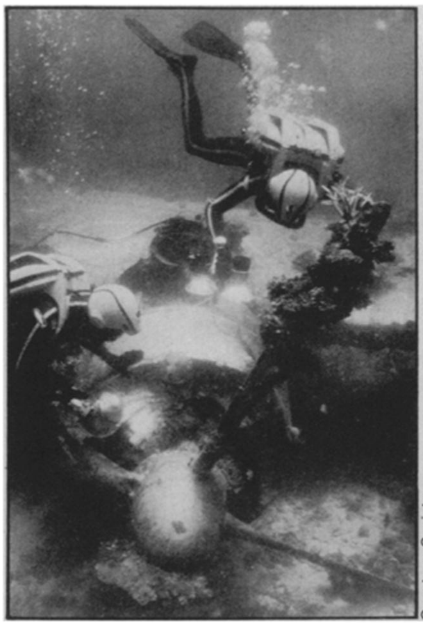
A recently reported theory of bubble formation has important applications in diving medicine

BY LINDA GARMON

Deep in the crystal-clear waters surrounding the Hawaiian Islands, a scuba-diving fisherman is hard at work. After nearly 20 minutes at depths between 140 and 160 feet of sea water, the diver quickly surfaces with a portion of his day's catch. Before the day is over, he completes two more similarly strenuous dives, ending with rapid "jumps" to the surface.

According to a special set of guidelines for surfacing divers, this Hawaiian fisherman is risking a case of decompression sickness, or "the bends" — a debilitating and sometimes fatal diving malady caused by the formation of bubbles in the diver's bloodstream and body tissue (see p. 181). To ensure that the gas absorbed by the diver's body while under pressure diffuses out safely and forms no bends-causing bubbles when pressure is decreased (when the diver begins to surface), one set of diver's guidelines — the U.S. Navy Air Decompression Tables — states that the fisherman should conclude his third dive with a 354-minute ascent, consisting of eight "decompression stops." Nonetheless, the nondecompressing diver goes home with an apparent "bends impunity," and he returns, day after day, to similar diving schedules.

How the diving fishermen of Hawaii avoid falling prey to decompression sickness has long puzzled the experts in diving medicine. Now, researchers from the University of Hawaii in Honolulu — physicists and medical doctors who call themselves the "Tiny Bubble Group" — report they may have found the solution to the mystery in gelatin, hen's eggs and human blood tissue.



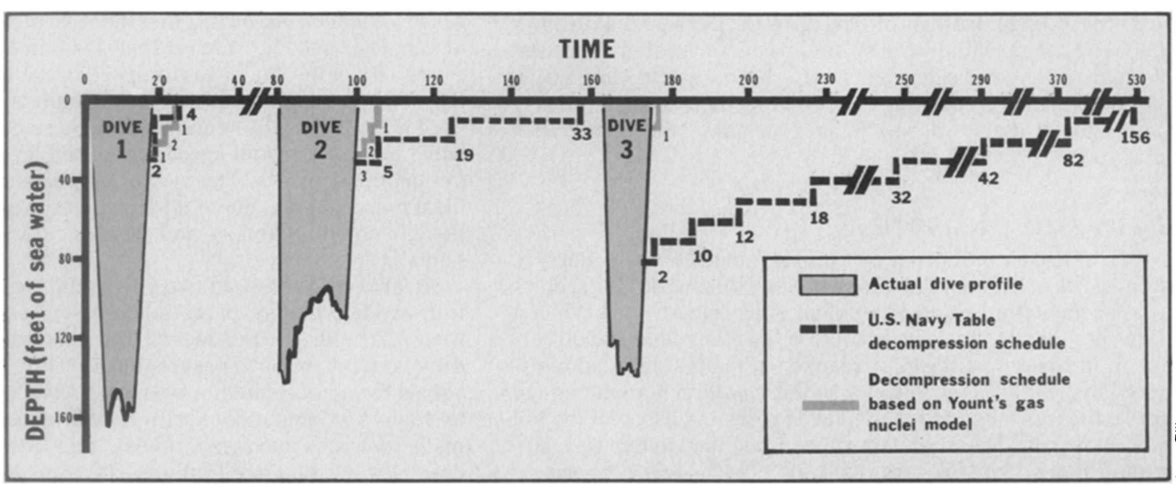
Cousteau Society

The bubble group has spent the past seven years studying the formation of bubbles in these watery substances. At the recent American Chemical Society meeting in Las Vegas, Nev., group member David E. Yount presented the culmination of that work — "an explicit model which describes bubble formation in watery fluids." According to the model of Yount and colleagues, bubbles form from preexisting micronuclei — microscopic gas-filled spherical gaps in a liquid. Yount says a micronucleus is like a cross between a balloon and a colander — the sphere is enclosed by an organic skin, but that skin is permeable to gas. Predicting when these skin-stabilized nuclei become bubbles "is what the model is all about," he says.

Applying the bubble-predicting model to diving medicine will result in "dramatic changes in the approach to deep-sea diving," Yount says. "The traditional ideas upon which virtually all accepted diving decompression tables are based are flawed," he explains; the bubble nucleation model can correct certain of those decompression misconceptions. It is far from time to throw out the conventional tables, says Yount, but the Tiny Bubble Group has computed new decompression tables that — although not yet thoroughly tested — "appear to be both faster and safer than those prepared by the U.S. Navy." In actual field experience, for example, bubble group members assisted the Nippon Salvage Co. in salvaging the liner *Caribia* — which sank in Apra Harbor, Guam, in 1974 — by recommending changes in diving and decompression techniques that cut the rate of bends cases by one-tenth.

The work in Apra Harbor is "just one of the many applications of nucleation theory," Yount says. The range of potential applications — from avoiding bubble formation in kidney dialysis to overcoming the limitations that gas nuclei impose in water pumps — reflects the complexity of the field, says bubble researcher Richard D. Vann of Duke University Medical Center in Durham, N.C. "Bubble nucleation is hidden all over the place," he says.

The field of bubble nucleation can be divided into mechanical and dissolved gas nucleation. Mechanical nucleation is at work when a vapor cavity forms in the



A scuba dive profile is compared with recommended ascent schedules based on Navy tables and new bubble theory.

John Ellis

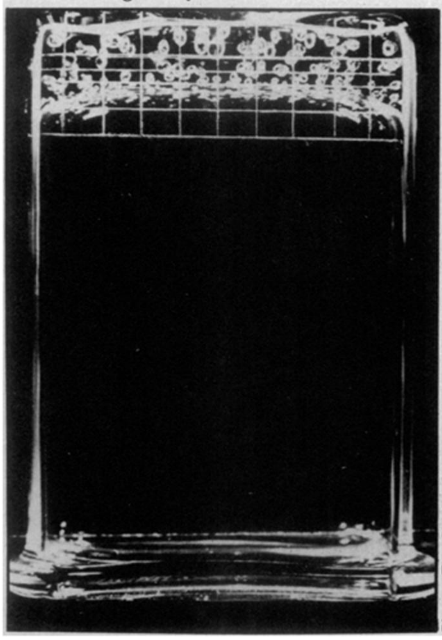
water surrounding rapidly turning boat propellers. Because it cannot "keep up" with the turning blades, the water "pulls away," Vann explains. The resulting cavity is corrosive and causes pitting and failure of the propeller. One obvious application of mechanical nucleation theory, therefore, is in the design of ship propellers.

The Tiny Bubble Group's skin-stabilized nuclei model shares the other half of the nucleation field — dissolved gas nucleation — with several additional theories. One of those theories states that de novo formation of bubble nuclei is possible because of the natural motion of fluid molecules. One type of de novo bubble formation is easily illustrated by using a box filled with marbles to represent fluid molecules. Shaking the box — to simulate natural molecular fluctuations — causes de novo gaps between the "molecules." Under certain pressure conditions, according to the de novo theory, bubbles form from those gaps.

Yount says that the de novo theory could explain the gaseous nucleation that occurs in divers only if those divers were under 1,000 atmospheres of pressure, or about 10,000 meters of sea water: Fluids have to be supersaturated with gas under those high pressures before bubbles form from the small, de novo gaps. Since the gas bubble formation in divers involves pressures much lower than that, another mechanism of bubble formation must be involved, Yount says.

Experiments with transparent shrimp provided some of the earliest and most dramatic evidence that the bubble mechanism in divers involves those precursor micronuclei so vital to the Tiny Bubble Group's nucleation model. A. Evans and colleagues of the University of Newcastle upon Tyne theorized that if gas micronuclei do indeed exist and can expand to form visible bubbles, destruction of those micronuclei should decrease bubble formation. The British researchers, in studies reported in the April 19, 1969, NATURE, first observed bubble formation through the translucent carapace of shrimp when they decompressed the sea creatures to altitude pressures, or less-than-atmosphere pressure. Evans and co-workers then subjected another group of shrimp to a

Yount and colleagues observed bubble formation in gelatin (below) — in which bubbles can easily be counted — and in a hen's egg (above) — an example of an intact biological system.



Photos: Tiny Bubble Group

New ingredients for diver's dozen

Decompression tables are like opinions, says Richard D. Vann: "Everyone has one, and there is something wrong with every one of them." And, continues the researcher from Duke University Medical Center in Durham, N.C., the set of U.S. Navy Air Decompression Tables — a schedule of underwater ascents widely used by military and civilian scuba divers to prevent cases of the bends — is no exception.

In fact, a study released early this year reports a 1.25 percent incident rate of decompression sickness among Navy divers. "This means that the U.S. Navy can on an average expect about one case of decompression sickness every 8 or 9 working days," says report author Thomas E. Berghage of the Naval Health Research Center in San Diego, Calif. While this rate is acceptable for Navy divers who have decompression chambers and medical personnel close at hand to treat the bends, "The tables probably should be revised for civilians," Berghage says. For that reason, Vann, Berghage and 21 other researchers recently met for an Undersea Medical Society workshop in Bethesda, Md., to review and update 12 assumptions incorporated in the Navy's decompression model.

The objective of all decompression tables, whether formulated by the Navy or by companies engaged in underwater salvage work, is to prescribe safe rates of gas-eliminating ascent for scuba divers. A quantity of gas is absorbed by the blood and tissues during every dive and released when the pressure decreases — when the scuba diver begins to surface. To ensure that most of the gas will diffuse safely out of solution without forming the bubbles associated with the bends, different schedules of ascent are specified for different depths and exposure (bottom) times of dives. According to the Navy tables, for example, a 210-minute dive in 40 feet of sea water (fsw) requires a 2-minute decompression stop at 10 fsw.

The 12 assumptions underlying the Navy's schedule of such decompression stops consist of five ideas on gas uptake in the diver, three concepts of gas elimination and four assumptions governing phenomena associated with pressure reduction, or a diver's ascent. One of the gas-uptake assumptions is that only the partial pressure of inert gas need be considered in the decompression problem. In other words, theorists have based their decompression schedule calculations solely on the amount of nitrogen gas absorbed by the body during the dive, disregarding the possible effects of the other gas constituent in the scuba diver's air supply—oxygen. While this is a logical assumption — unlike the inert gas nitrogen, oxygen seldom attains very high pressure in the tissues because it is constantly being consumed — workshop participants agreed that it is an oversimplification of the decompression problem. That the partial pressure of oxygen is an important factor in constriction of blood vessels, for example, should somehow be incorporated into future decompression models, Berghage explains.

Another gas-uptake assumption discussed at the workshop is that compression procedures have no effect on decompression. This means that decompression theorists assume that certain types of decompression procedures — defined by the rate, number and depth of descents — *cannot* play a role in lessening the risk of decompression sickness. The decompression schedules, therefore, ignore the possibility that "spikes" of compression — such as quick, deep dives — crush gas nuclei, the theoretical precursors to bubbles, thereby eliminating some of the potential for bubble formation upon decompression.

But results of studies presented at the workshop by David Yount, formerly of the University of Hawaii and now of Stanford University in Palo Alto, Calif., seem to confirm the existence of crushable precursors to bends-causing bubbles. Although the implications of his studies are still a matter a debate, the research of this bailiwick of bubbles is a much needed novel approach to the problems of decompression, Berghage says. Prior to physicist Yount's entrance, the field of decompression theory was limited to the specialties of physicians and physiologists, Berghage explains. "It took someone totally divorced from the area to shed some new light on the problem; it took a fresh view like Yount's to really change our thinking."

"spike" of high pressure — similar to the pressure of a deep dive — and found a "drastically reduced" incidence of bubble formation when those same shrimp were decompressed. Apparently, pressure spikes crushed the micronuclei that normally would have formed bubbles during decompression. "It has been shown that for bubbles to form, there must be present some agency which is eliminated by extreme compression, and which we assume to be gas micronuclei," the researchers concluded.

To further test for the existence of gas micronuclei, Yount and colleagues put gelatin through various schedules of compression and decompression. In these early bubble group experiments, the researchers reported the ability to "denucleate," or crush, the nuclei in gelatin samples by applying pressure spikes.

The most recent confirmation of the micronuclei theory, however, comes from the "diving" rat studies of Vann and colleagues. In research reported in the June UNDERSEA BIOMEDICAL RESEARCH, these Duke University researchers subjected rats to various pressure-chamber schedules to show that a pressure treatment before a decompression reduces the incidence of decompression sickness in rats. "These experiments suggest that bubbles responsible for decompression sickness in the rat originate from [destructible] gas nuclei," Vann and co-workers reported.

The shrimp, gelatin and rat studies not only lend credence to the Tiny Bubble Group's nucleation theory, but also may explain how the diving fishermen of Hawaii can violate the traditional decompression tables and still escape the bends. The daily series of deep dives may involve "a repetitive crushing of nuclei" that protects the diver from dangerous bubble formation, Yount explains. In addition, he says, extension of these micronuclei studies have added a predictive value to the nucleation model.

Yount and colleagues first extended their studies by passing gelatin samples through a series of filters to generate samples with micronuclei of varying radii. The bubble group subjected each gelatin sample to various pressure schedules to determine the critical initial radius — the minimum initial micronuclei size capable of initiating bubble formation—for a given pressure schedule. The researchers calculated mathematical curves that related the parameters of micronuclei radius, pressure schedule and bubble number.

Yount and co-workers then substituted rats for gelatin; this time, instead of counting the bubbles that result from different pressure schedules, the researchers counted cases of decompression sickness. Again, mathematical curves were made.

By coupling the information from the two sets of curves, Yount says he was able to establish a correspondence between the number of bubbles produced (represented by the gelatin curve) and the incidence of decompression sickness (observed in the rat experiments). This information in turn was compared to compression data from humans. The result of this pool of information is a new set of decompression tables based on the Tiny Bubble Group's model of bubble formation.

Interestingly, these new tables pass the Hawaiian diving fisherman test: "Whereas the U.S. Navy decompression obligation following Dive #3 is 356 minutes, the ... [Tiny Bubble Group] model requires only 1 minute," Yount reports. This model prediction, he adds, "is not inconsistent" with the diver's "zero-minute" decompression.

Still, the general consensus in the bubble nucleation field is that Yount's theory is still just that — a theory. "Yount's hypothesis is something that needs more testing," explains one bubble researcher: "You can't rule it out with existing evidence, and you can't rule it in with existing evidence." Although Yount agrees it is too soon "to say we're ready for new Navy [decompression] tables," he says the bubble theorists are on the "right track" toward improved decompression schedules. The Tiny Bubble Group, he adds, has taken some of its first steps on that track. □