

Aqueous Foams

They now have a wealth of uses, of which some are surprising.

Yet the ability of a water-based liquid to become a frothy mass of bubbles requires a balance of forces not entirely understood

by James H. Aubert, Andrew M. Kraynik and Peter B. Rand

The suds of a shampoo, the lather of a shaving cream, the head on a glass of beer—each of these commonplace sudsy objects exemplifies a material whose properties are far from common. Each is an aqueous foam, an impermanent form of matter in which a gas, often air, is dispersed in an agglomeration of bubbles that are separated from one another by films of a liquid that is almost but not entirely water. Although aqueous foams have been a subject for scientific investigation since the 17th century, much remains to be learned about the complex chemical and physical phenomena that interact in even a single foamy bubble.

Like any other form of matter, an aqueous foam maintains its configuration only when it cannot readily transform itself into an arrangement embodying less energy. In the case of a foam the energy includes the energy of the gas contained in the bubbles of the foam, the chemical energy of substances in the liquid films that form the walls of the bubbles and most notably surface tension: the energy of the surfaces of the films. The molecules at each surface represent more energy than molecules deep in the film; thus each surface is thermodynamically unfavorable. To put it another way, a foam always "seeks" to adjust the details of its intricate structure in such a way as to minimize the total expanse of its films.

Each film, however, encounters an energy barrier. As liquid drains from the film, causing the film to thin, surface forces arise that are opposed to further thinning. The forces can be electrical, or they can be steric: they can result from the order that surfaces impose on molecules in the film. They can result from the presence of the very molecules, called surfactants, or surface-active agents, that enabled the liquid to foam in the first place. When destructive and preserving forces are

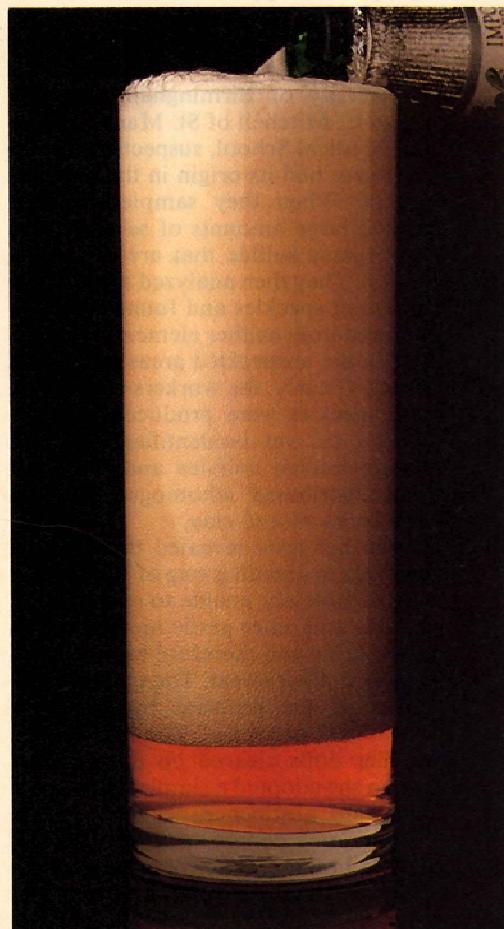
in equilibrium, the films in a foam are rendered metastable, that is, stable with respect to small disturbances. This intricate balance has remarkable consequences. For example, all beer drinkers must have observed that in the moments after beer is poured into a glass the volume of the head shrinks while that of the liquid grows. Yet surely few beer drinkers know that as the foam drains, increasing the volume of beer, the bubbles remaining in the foam respond to a changing balance of forces by changing from spheres into polyhedrons.

Aqueous foams are typically 95 percent air and only 5 percent liquid, and remarkably the liquid is often 99 percent water. The remaining 1 percent consists of surfactants and other additives, such as alcohols and polymers. By means of these additives many familiar manufactured products (including shampoo, shaving cream and beer) provide a controlled amount of foaming, primarily for aesthetic reasons. In contrast, many aqueous foams are carefully engineered to perform a specific task. These include fire fighting, dust suppression, crop treatment and some tasks that may be more surprising. For example, aqueous foams are now being tested for their ability to lessen the violence of explosions. Our own involvement in the science of aqueous foams began five years ago, when we initiated at the Sandia National Laboratories an investigation of the uses of aqueous foams in geothermal wells.

Surface Tension and Surfactants

Two factors govern the ability of a liquid (under the influence, for example, of mechanical agitation) to froth into a foam. The first factor is surface tension. There are attractive forces between the molecules in any quantity of a liquid; these forces in fact cause the liquid state to exist. The principal

forces are electrical and originate from individual charges or dipoles (permanent distributions of charges) on the molecules of the liquid. Even in nonpolar and uncharged molecules, electrical forces known as van der Waals forces arise because the elec-



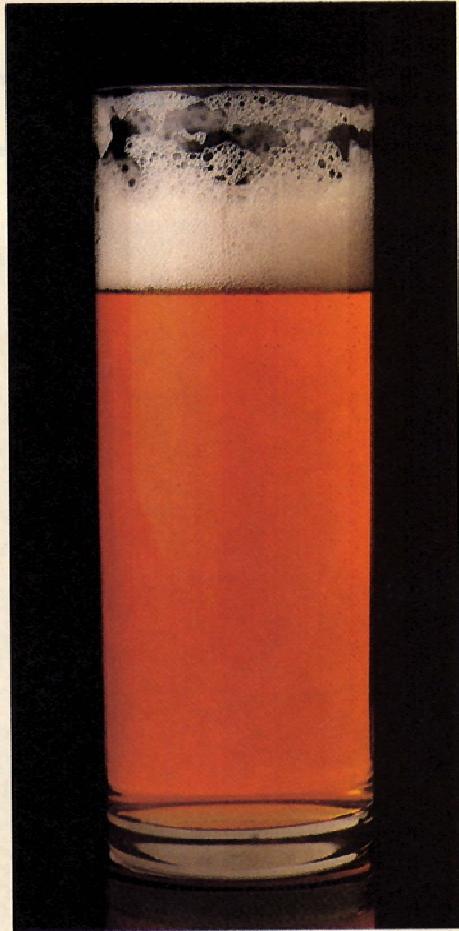
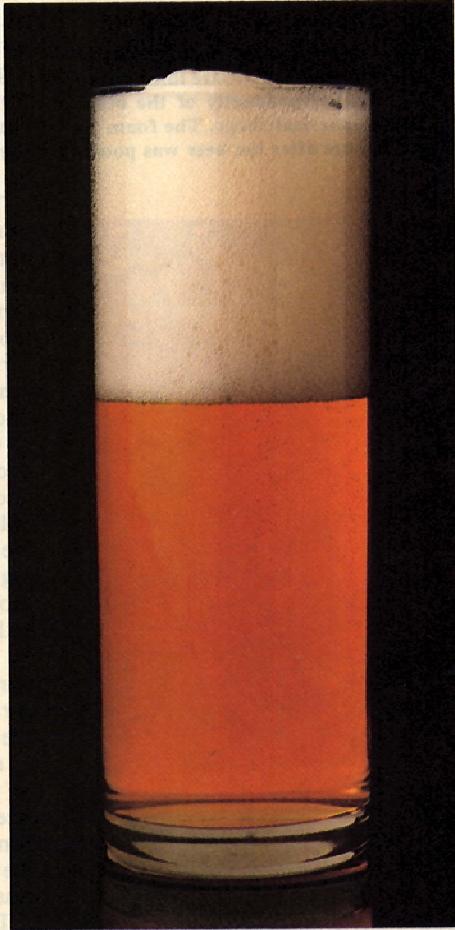
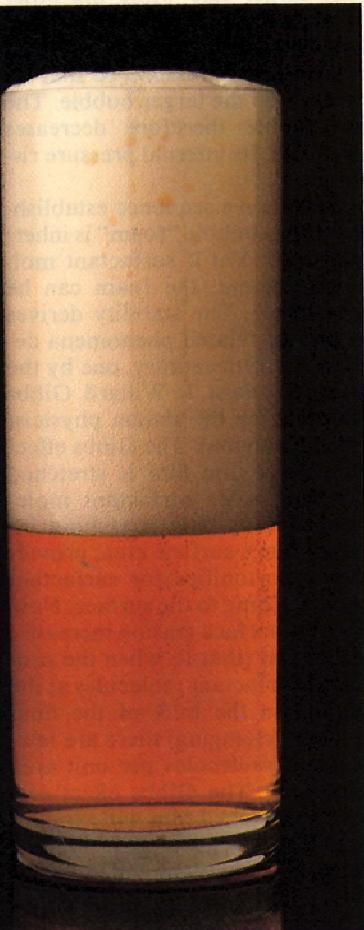
LIFE HISTORY of an aqueous foam is completed in less than an hour for the foamy head on a glass of beer. The foam is formed when the carbon dioxide dissolved in the beer returns to the gaseous state, yielding bubbles separated from one another by films of the watery liquid. At first the

tronic "shell" of each molecule is constantly undergoing perturbations that give it temporary concentrations of negative or positive charge. The net result is an electrical attraction among molecules. Molecules deep in the liquid have identical surroundings in all directions; thus they are attracted isotropically by their neighbors, that is, equally in all directions. In contrast, molecules near the surface of the liquid have few if any neighbors closer to the surface; thus they are attracted preferentially toward the bulk fluid. Moving a molecule from the bulk fluid to the surface therefore requires work against the forces in the liquid. Hence the surface is in a higher energy state than the bulk of the fluid. The unbalanced molecular forces near the surface manifest themselves as surface tension or surface energy. The terms, used interchangeably, signify that any increase in surface area (any bringing of molecules to the surface) requires an expenditure of energy.

The second factor paramount in creating a foam is the presence of an impurity. A pure liquid cannot form a metastable foam; the foamability depends on a surfactant. In the case of an aqueous foam a surfactant molecule includes two chemical groups that differ greatly in their solubility in water. One group is hydrophilic, or highly soluble in water; the other is hydrophobic, or highly insoluble in water. Some typical hydrophilic groups are OH, CO_2Na and SO_3K ; the typical hydrophobic group is the hydrocarbon chain $\text{C}_n\text{H}_{2n+1}$. A surfactant's surface activity depends on the sizes of these groups and on their relative solubilities. Because of the differing solubilities, surfactants are surface active, that is, they accumulate at surfaces. In particular, the hydrophobic groups on the surfactant molecules accumulate at an air-water interface. For surfactant molecules the surface is not as energetically unfavorable as it is for water molecules. Consequently the

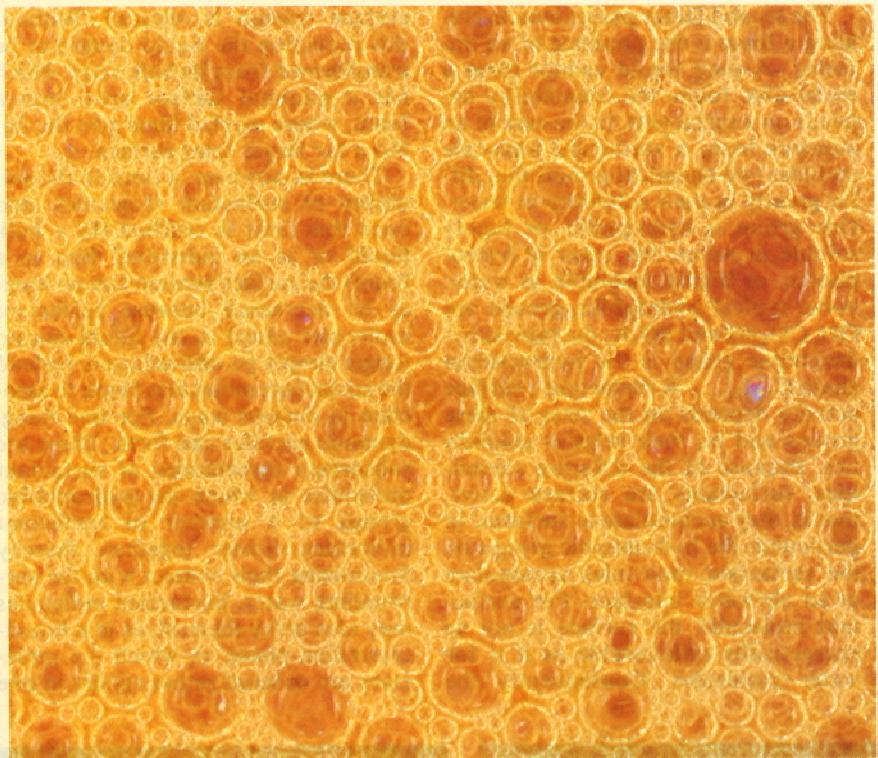
surface tension is reduced. Without this reduction the liquid could not be transformed from its bulk state, which has a minimal surface area, into a foam, whose myriad films give the liquid a far larger total surface.

There is, however, a limit to the solubility of surfactant molecules, and once this limit is reached (in a bulk liquid or in an individual film in a foam) the surface tension can no longer be decreased because surfactant molecules added to the liquid can no longer simply go into solution. Instead the surfactant molecules begin to associate in curious ways. For one thing, dynamic micelles can form. These are subsurface associations of surfactant molecules in which the hydrophobic groups of a number of surfactant molecules cluster together, thereby minimizing their contact with the surrounding water. Surfactant molecules may also array themselves in a liquid-crystalline phase, in which the molecules are ordered rather rigidly in one

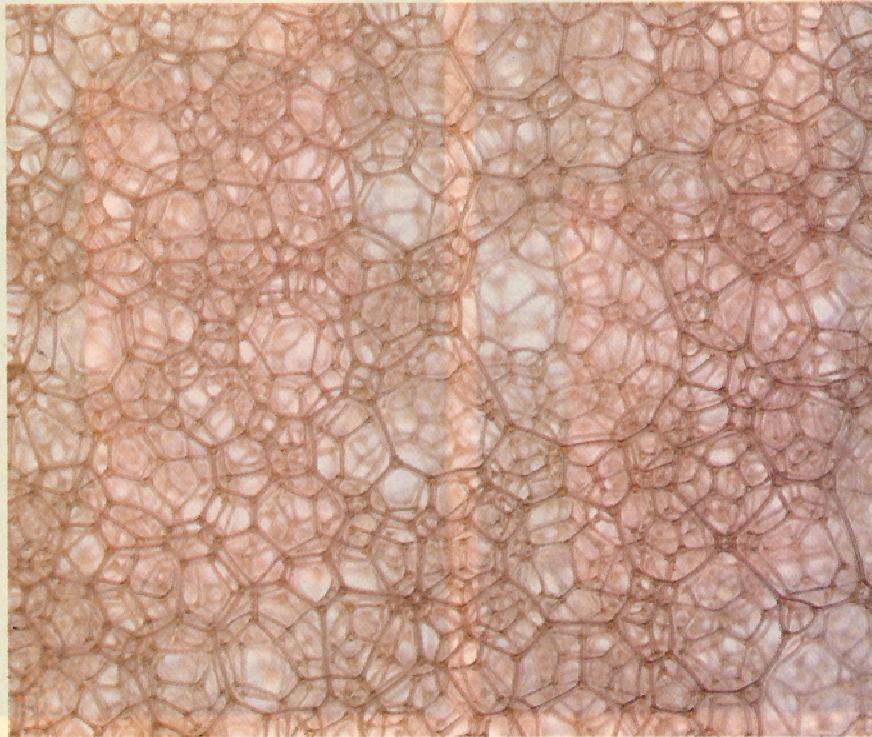


films are thick, the foam's content of liquid is great and the level of beer is correspondingly low. Like all other foams, however, the head is only metastable, or temporarily persistent: its films give it great surface area, which is thermodynamically unfavorable. Moreover, gravity draws liquid from the foam. If no other destabilizing influences came into play, the films might drain to a thickness at which they were stabilized against further thinning by electrical

and chemical forces. In addition the molecules in very thin films can orient themselves in arrays that cannot be disassembled without an expenditure of energy. Yet other forces are acting. For example, the pressure in small bubbles exceeds the pressure in large ones, and so gas tends to diffuse from the small bubbles into the large ones. Some bubbles dwindle away, others coalesce. Meanwhile water is evaporating. The foam coarsens, and eventually it collapses.



SPHERICAL FOAM marks the early part of the life history of an aqueous foam. At this stage the foam is "wet": the liquid films that form the walls of each bubble are thick enough so that the bubbles are not distorted. Hence each bubble, independently of the others, minimizes its surface area for a given volume by taking a spherical shape. The foam was photographed in the head of a glass of beer less than a minute after the beer was poured.



POLYHEDRAL FOAM marks the middle age of an aqueous foam. At this stage the foam is "dry": the liquid films are thin and the bubbles interact, becoming polyhedral. The foam now manifests the geometric properties described by the Belgian physicist Joseph A. F. Plateau a century ago. For example, each film is a smooth surface, flat only if the pressures in two adjacent bubbles are equal. Moreover, the films meet only in sets of three and at angles of 120 degrees. The foam was photographed 10 minutes after the beer was poured.

direction but are free to flow or deform in other directions.

Foam Stability

Once a liquid has foamed, the question is whether the foam can persist for any appreciable length of time. For a physicist the capability of withstanding perturbations is proof that a system is stable. A foam is no exception. An example is afforded by a simple conceptual "foam" consisting of two bubbles connected by a tube. The surface tension in each bubble amounts to a force directed inward. (One can think of the force as arising from molecules at the surface of the bubble, attracted toward the interior because the surface is in a state of higher energy.) This tension is balanced by the pressure of the air trapped in the bubble. Since the bubbles are connected, their internal pressures are equal and their diameters are identical. Suppose the diameter of one of the bubbles fluctuates to an infinitesimally larger size while the other bubble shrinks by the corresponding amount. The smaller bubble now has a greater internal pressure, so that air flows from it to the larger bubble. The smaller bubble therefore decreases further in size. Its internal pressure rises again.

This destructive sequence establishes that the two-bubble "foam" is inherently unstable. Yet if surfactant molecules are present, the foam can be rendered stable. The stability derives from a pair of related phenomena described in the 19th century, one by the American physicist J. Willard Gibbs and the other by the Italian physicist C. G. M. Marangoni. The Gibbs effect occurs when a thin film is stretched and the film holds surfactant molecules in solution. The stretching increases the film's surface area, providing new opportunities for surfactant molecules to come to the surface. Nevertheless, the surface tension increases. At equilibrium (that is, when the proportions of surfactant molecules at the surface and in the bulk of the fluid are no longer changing) there are fewer surfactant molecules per unit area of the surface. The Gibbs effect dictates that a stretched film will "try" to contract, like an elastic skin; in fact, the Gibbs effect is often called Gibbs elasticity.

The second phenomenon, the Marangoni effect, is temporary. It arises because a certain amount of time is required for surfactant molecules to diffuse to the surface of a newly stretched film. Initially, therefore, the surface has a very low concentration of surfactants and the surface tension

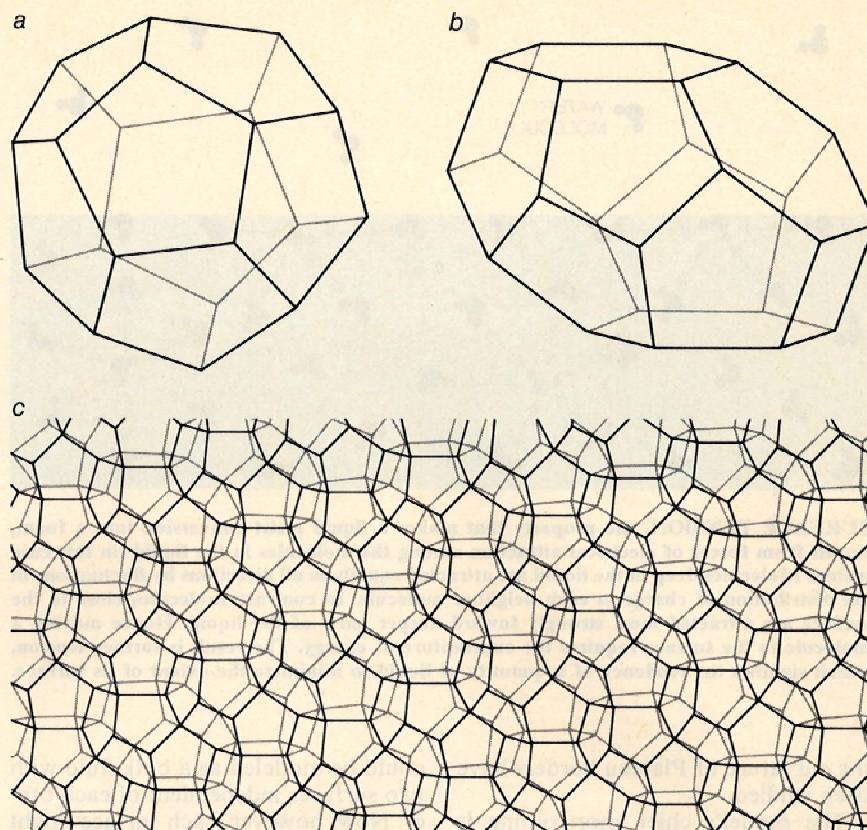
is even greater than a calculation of the magnitude of the Gibbs effect would lead one to predict. The tension slowly decreases to the Gibbs value as surfactants diffuse to the surface and the film equilibrates.

Acting together, the Gibbs effect and the Marangoni effect tend to stabilize infinitesimal fluctuations in foams. In our example of a two-bubble "foam" the combined effects increase the surface tension of the bubble that expanded, raising its internal pressure and forcing air back into the bubble that shrank. In general the Gibbs effect and the Marangoni effect stabilize the films in foams against infinitesimal fluctuations in thickness. If a fluctuation locally increases the area of a film, the surface tension will also increase, and this will stiffen the surface against growth of the fluctuation. The absence of Gibbs elasticity in a pure liquid is the main reason a pure liquid cannot foam: the films in the foam of a pure liquid are unstable to infinitesimal fluctuations.

Foam Morphology

A two-bubble "foam" is not, of course, an adequate representation of the structure of a real aqueous foam. In real foams the basic distinction is between "wet" foams and "dry" ones. In a wet foam the liquid content is high, and so the walls of the cells are thick. As a result the cells are far enough apart so that none of them is distorted by the others. Hence the cells are spherical, for the same reason that water drops are spherical: surface tension causes isolated bubbles (or drops) to take a spherical shape, which minimizes their surface area. As liquid leaves the foam, so that the foam "dries," its geometry becomes more complex. The cells, now separated by thinner walls, begin to influence one another. Thus the spherical bubbles become polyhedrons. In fact, the now traditional term for dry foams, introduced in 1953 by E. Manegold of the Technische Hochschule in Dresden, is *Polyederschaum*: polyhedral foam. (The traditional term for a wet foam is *Kugelschaum*, or spherical foam.)

The physical principles that determine the geometry of a "dry," polyhedral foam emerge from observations made by the Belgian physicist Joseph A. F. Plateau a century ago. First, the individual films forming the walls of the cells in the foam are smooth surfaces, each with a uniform curvature. A film is flat only when the pressure in two adjacent cells is equal; a curved film signifies a pressure difference between two adjacent cells. The pressure is greater in the cell on the con-



MATHEMATICAL MODEL of a polyhedral aqueous foam requires the packing of three-dimensional space with repetitions of a polyhedron. Among regular polyhedrons (ones whose faces are all the same regular polygon) the greatest success is the pentagonal dodecahedron (a). Its chief defects are that its packing leaves interstices and that the individual films in a real polyhedral foam are not all five-sided. A more realistic choice is an irregular polyhedron, the beta-tetrakaidecahedron (b, c). Although no model has yet succeeded in matching all the geometric properties of any real aqueous foam, the models do facilitate calculations of relations among liquid content, bubble sizes, film thicknesses and foam geometries.

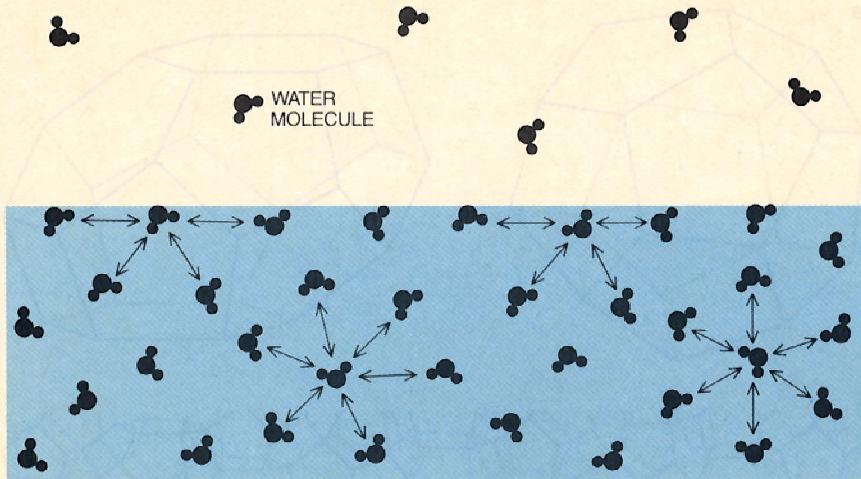
cave side of the curve. (The application of this rule to a single spherical bubble dictates that the pressure must be greater inside the bubble.)

Second, the liquid in a polyhedral foam is distributed between films and Plateau borders, the channels that form where films meet. The curvature of these borders indicates that the pressure inside a Plateau border is lower than the pressure in the cells and in the films. The resulting "border suction" is destabilizing: it tends to draw liquid out of the films. The eventual balance of forces is such that in many cases most of the liquid in a foam is in Plateau borders. When three films produce a Plateau border, the angles between them are equal, at 120 degrees, owing to a balance of surface-tension forces. A similar balance would require that four films meet at angles of 90 degrees, and so on. Yet the meeting of more than three films at a Plateau border is never observed in stable foams.

Complex mathematical arguments demonstrate that all Plateau borders must be three-film junctions. The ar-

guments proceed from two starting points: the stability of a foam requires minimization of the energy of the system, and the various forces acting on any part of a stable foam must be in balance. Energy minimization and force balance also dictate a third principle governing the geometry of a polyhedral foam: the meeting of four Plateau borders must always have the form of a tetrahedral vertex, so that the angle between any two of the borders is the tetrahedral angle of about 109 degrees.

Instances of the principles that determine the geometry of a polyhedral foam are easy to find in a foam, yet a mathematical description of a three-dimensional foam conforming to all three conditions has not been formulated. The filling of three-dimensional space with repetitions of a regular polyhedron is not a success. The 12-sided regular polyhedron called the pentagonal dodecahedron comes the closest; in fact, a packing of pentagonal dodecahedrons has served as a model in which the relations among liquid content, cell sizes, film thicknesses and



SURFACE TENSION, the property that makes a liquid resist conversion into a foam, results from forces of electrical attraction among the molecules in the liquid (in this case water). Molecules deep in the liquid are attracted equally in all directions by fluctuations in the distribution of charge in each neighbor molecule. In contrast, molecules close to the surface are attracted most strongly toward deeper parts of the liquid. Hence moving a molecule to the surface requires the expenditure of energy. The result is surface tension, which signifies the tendency of a quantity of liquid to minimize the extent of its surface.

the curvature of Plateau borders have been studied.

The model's chief shortcoming is that a real foam does not have only five-sided films resembling the faces of a pentagonal dodecahedron. A non-regular polyhedron called the beta-tetrakaidecahedron more closely approximates the range of film shapes actually found in a foam; even so, its faces would have to be distorted to satisfy all three principles. Fortunately the theoretical calculations of many properties of a foam are not very sensitive to the precise geometry of the cells in a mathematical model of a foam. Hence the mathematical relations based on simple geometries can serve as useful approximations of the elusive reality.

Forces in Thin Films

Up to this point we have discussed aqueous foams as static structures. Yet a foam has a life history, consisting of the events that drain fluid from the foam, converting it from a wet foam into a dry one, and the events that sustain the structure of the dry foam, if only for a time. The main actors in this history are the films making up the foam.

When a film forms (either individually or in a foam), it is relatively thick. It loses liquid by drainage due to border suction. At some point, if the film survives long enough, the film drains to a thinness at which its two surfaces begin to interact. Until that point the film has been much thicker than the size of the molecules composing it and

could be modeled as a bulk fluid with two surfaces independent of each other. Now, however, each surface might be said to "realize" that another surface is nearby. Hence the model must take account of new phenomena.

Several forces that act on a thin film have been identified. They include (in addition to border suction) van der Waals forces, which tend to destabilize the film, and electrostatic and steric forces, which tend to stabilize it. The short-range van der Waals forces between uncharged molecules are the cause of surface tension. The overall van der Waals force between two bodies composed of many molecules can also be significant. The overall force causes the two surfaces of a thin film to attract each other; thus the forces are destabilizing because they squeeze the film, causing it to drain.

Electrostatic forces can occur in a thin film if the liquid holds charged molecules in solution and one type of charge, positive or negative, is preferentially situated at the surfaces. Each charged surface then has a layer of countercharges subjacent to it. If the countercharge layers approach each other, as they would in a draining film, they would repel each other, inhibiting further drainage. Hence the electrostatic forces are stabilizing.

Finally, steric forces originate from the order the surfaces impose on molecules or structures within the film. They are not well understood; still, it seems clear that proximity to a surface can order molecules. For example, it is known that liquid crystals sometimes can form in a thin film even if they

cannot form in a large volume of the fluid. Layered liquid crystals are often important in thin films in their final stages of drainage. The very last stage can be what is called a black film: a film thinner than any wavelength of visible light. Black films are thought to consist of surfactant molecules arranged by the surfaces of the film into a bilayered liquid-crystalline structure. The advent of order decreases the energy of a system, and so steric forces in general are stabilizing.

If the forces opposed to continued thinning are sufficiently strong, the film may drain to a thickness at which it is metastable. In this state the thermodynamic forces acting on the film sum to zero and a further decrease in the thickness of the film would raise the system's energy. The film may then persist until mechanisms other than drainage come into play and cause the film to collapse. Three such mechanisms are the evaporation of liquid from the foam, the diffusion of gas from small bubbles to larger ones and mechanical vibration. Isolated films protected from evaporation and vibration have been preserved for years.

The Yield Stress of a Foam

The life history of an aqueous foam neglects one important aspect of aqueous foams: their mechanical properties, which are remarkable, considering that the constituents of the foam (a gas and a dilute surfactant solution) behave individually as unexceptional and quite predictable fluids. A foam can flow like a liquid or remain motionless under stress like a solid. For example, shaving-cream lather is easy to spread; it offers little resistance to flow and gives the impression of having a low viscosity. Yet the stress due to gravity is not enough to cause shaving-cream lather to flow in the hand or when it has been spread; the manifestation of what seems to be low viscosity depends on whether a parameter called yield stress has been exceeded.

The physical basis for the yield stress of a foam can be explained by a simple model in which a foam is treated as a two-dimensional honeycomb of hexagonal cells. When the cells are all the same size, the model satisfies the Plateau criteria for a real foam. Suppose the foam is subjected to a shearing force; its deformation under that force is straightforward as long as the volume of each cell can stay constant and films can continue to meet in threes at angles of 120 degrees. Then a critical strain is reached, when the cells are so deformed that some of the Plateau borders have coalesced and the films between them have disappeared.

Four films now meet at each junction—a violation of the rules. In this unstable configuration the foam has been forced to generate an energetically unfavorable amount of surface area.

The structure of the foam thus makes a sudden transition to a new structure resembling the original honeycomb except that the cells are rearranged: some cells that originally were in contact have separated. This rearrangement constitutes the flow of the foam. In addition it defines the yield stress. The yield stress is the amount of force per unit area that triggers a deformation in which cells jump past one another to take up new positions. For dry films the yield stress turns out to be proportional to the surface tension in the films and inversely proportional to the size of the cells. The latter finding should be no surprise: fine-celled shav-

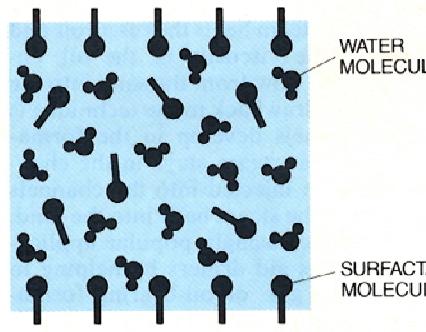
ing-cream lather is much stiffer than coarse-celled laundry soapsuds.

The Making of Foams

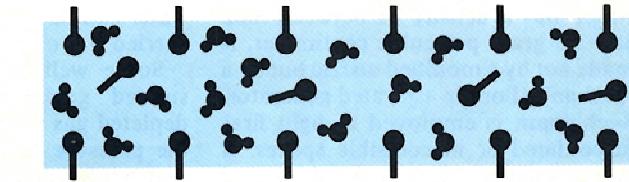
Perhaps the commonest, but also the most expensive, means of generating a foam is the method mimicked by opening a bottle of beer and pouring it into a glass, namely the aerosol method. It begins with a foamable liquid (water and a surfactant) and a foaming agent: a gas such as isobutane or a fluorocarbon compound, dissolved in the liquid at high pressure. (In beer and carbonated soft drinks the foaming agent is carbon dioxide.) The foam is produced by simply releasing the solution from its pressurized container. At atmospheric pressure the foaming agent returns to the gaseous state, thus forming the cells in the foam.

In another widely used method the foamable liquid and a gas are forced to flow through a packed column: a tube filled with obstacles that can be as simple as glass beads or a mass of stainless-steel wool. Small films form on the obstacles and the flow of gas distends the films into bubbles. The packed-column technique offers excellent control of the proportions of liquid and gas in the foam. A simplified version of the technique requires only that the liquid and gas be pumped into a pipe. If the pipe is long enough and the velocities are high enough, foam will emerge.

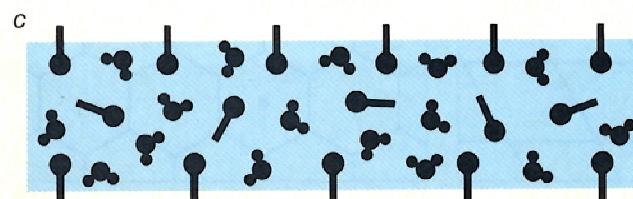
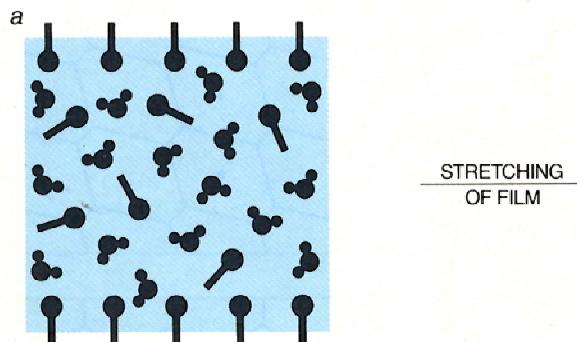
Low-density foams can be made by "mechanical" or by air-aspirated generators. In the mechanical generator the foamable liquid is sprayed on a perforated metal screen while a fan blows on the screen. The process is much like the familiar blowing of bub-



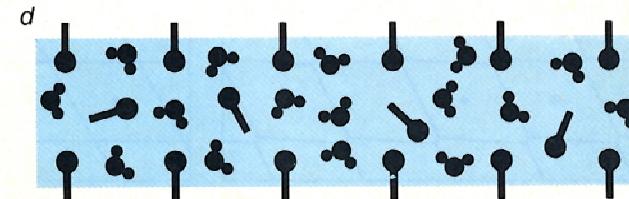
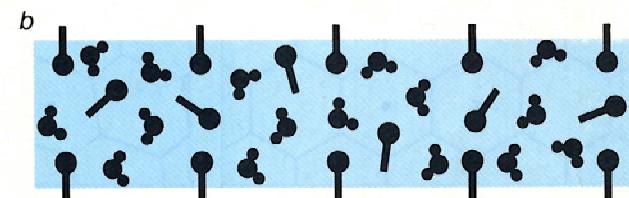
GIBBS EFFECT arises when a film is stretched and the film holds surfactant, or surface-active, molecules in solution. The stretching provides new surface area, which surfactant molecules can occupy, displacing water and reducing the surface tension; and yet when



their migration is complete, the number of surfactant molecules per unit area of the surface is less than it was. Thus the surface tension actually increases, and the film, like a stretched elastic sheet, "tries" to shrink. The Gibbs effect is also called Gibbs elasticity.



MARANGONI EFFECT arises because surfactant molecules take time to diffuse to the surface of a newly stretched film. Hence the surface tension of a newly stretched film is even greater, temporarily, than the value due to the Gibbs effect. Together the Gibbs ef-



fect and the Marangoni effect ensure that if a fluctuation slightly increases the area of a film in a foam, its surface tension will rise, stiffening the film against any further increase. Pure liquids cannot foam primarily because they are not stable to such fluctuations.

bles through a hoop. Foams with a composition of one part liquid (by volume) to 1,000 parts gas can readily be produced. The air-aspirated generator is similar except that it has no fan; the flow of air required to make the foam is induced by the spray of the liquid.

Low density is perhaps the most important property of a foam. In fire fighting, for example, two types of low-density aqueous foam are in common use. Low-expansion foams, which have a density of between .1 and .2 gram per cubic centimeter, are made by fitting the fire hose with an air-aspirating nozzle (a nozzle that draws air into the emerging stream of water) and adding surfactants to the water. The resulting foam markedly increases the effective volume of the water. Moreover, by reducing surface tension the surfactant increases the water's ability to wet other surfaces (instead of, say, beading up).

The other type of fire-fighting foam, a medium- or high-expansion foam, which has a density of between .002 and .05 gram per cubic centimeter, is made not by a modified nozzle but by a mechanical or air-aspirated generator. Such foam is employed to fight fires in confined or inaccessible spaces. It is particularly effective in ships and mines because a person can easily breathe even when covered with the foam. Since the foam contains little water, it can put out fires in build-

ings without causing the water damage characteristic of traditional fire fighting. Buildings that store paper or house computers are therefore among the best candidates for sophisticated fire-detection systems that release high-expansion foam. At present the most important use of fire-fighting foams is probably for fires in flammable liquids. Indeed, only foams have been proved to be successful for dealing with fires in large flammable-liquid storage tanks. The foam is often pumped into the bottom of the tank; it floats to the surface and spreads.

Foams for Resource Recovery

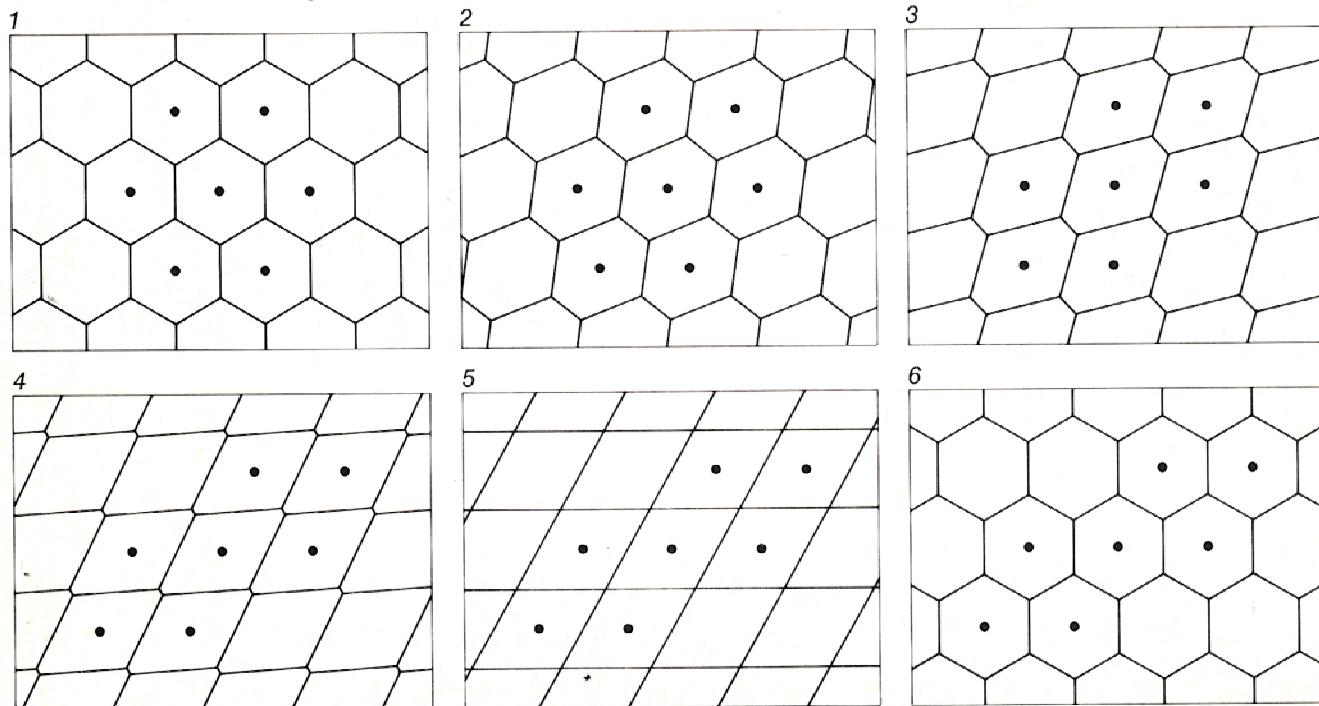
Drillers of oil and gas wells find foams useful in several ways. For one thing, deep wells often contain water, which must be removed before the well can begin to yield energy resources. If a suitable surfactant is mixed with the water and a gas is released in bubbles at the bottom of the well, the water can be converted into foam and carried out of the well.

Some wells penetrate "underpressurized" geologic formations, such as depleted gas reservoirs. In these wells the pressure in the formation is less than a reference pressure called the hydrostatic head: the pressure of a column of water whose height equals the depth of the well. The general problem in drilling is to achieve a balance be-

tween the pressure in the formation and the weight of the drilling fluid (typically a mud). An imbalance one way allows the fluid to contaminate the formation; an imbalance the other way precipitates a blowout. In the case of an underpressurized formation the drilling fluid must be lighter than water, and so a foam is appropriate. By controlling the density of the foam and the injection pressure (which is independent of the density) the pressure at the bottom of the well can be carefully governed. The foam serves all the functions of a drilling fluid. It removes drilling debris from the well; it also can bring to the surface uncontaminated samples of the formation at the bottom of very deep depleted-gas wells.

The high viscosity of foams makes them useful to drillers as a so-called diverting agent. In tar sands (a type of oil-bearing reservoir) oil is often recovered by injecting steam into the well. The steam heats the reservoir and reduces the viscosity of the oil, enabling it to flow from the sand into the well. The drawback to the technique is that channels develop in the formation, so that steam stays in the channels. Foam injected into the channels can force the steam back into the sand.

In an increasingly popular application, foams aid drillers by helping to fracture a gas- or oil-bearing formation. It is common practice in the drilling industry to pressurize a well and



FLOW OF A FOAM is actually a rearrangement in which bubbles jump past one another to take up new positions. Here a foam is represented by a two-dimensional honeycomb array of hexagonal cells (1). Under the influence of a shearing force the array is deformed (2-4); nevertheless, the cells retain their net size and films

continue to meet in threes at angles of 120 degrees. Then, at a force corresponding to what is called the yield stress, films begin to meet in fours (5). The situation is unstable: the foam immediately transforms itself into a new honeycomb (6). Dots in a constellation of cells show how the relative positions of those cells have changed.

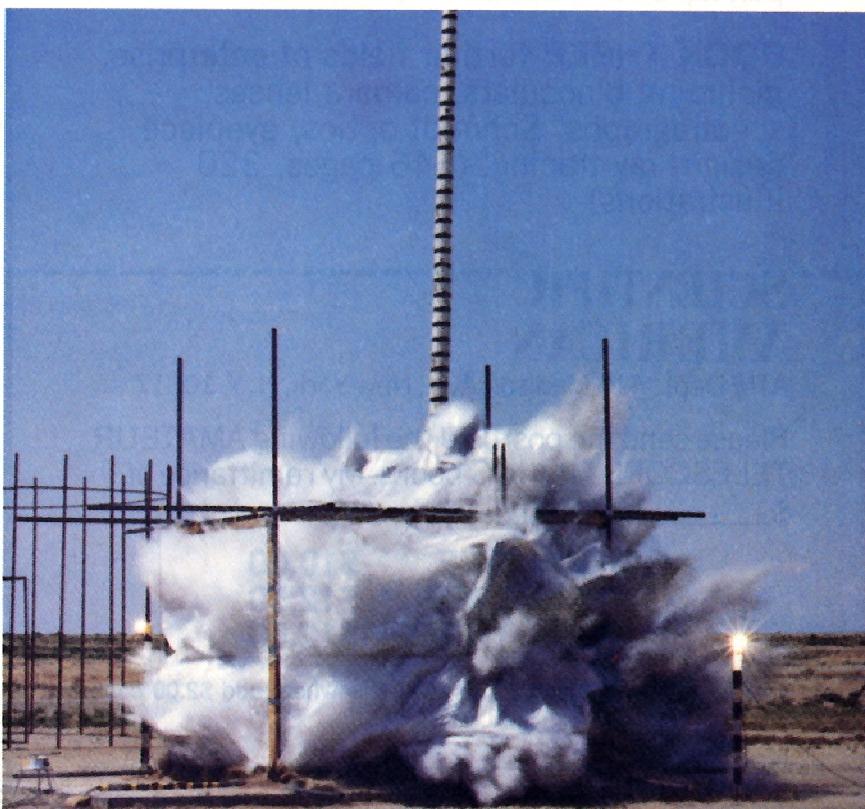
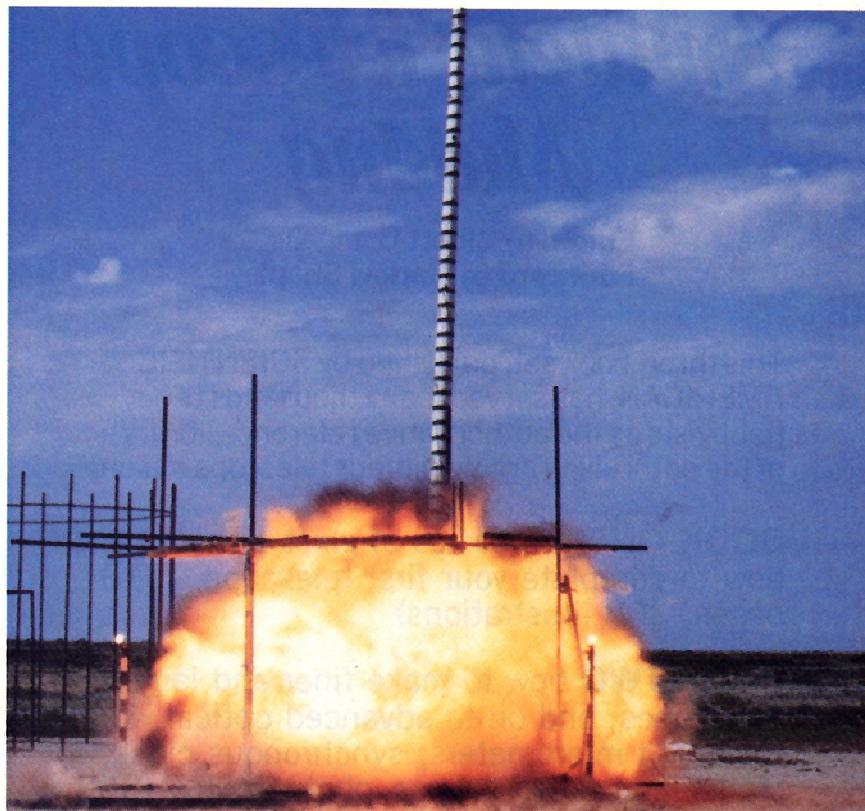
thereby make cracks in a formation, enhancing (the driller hopes) the flow of hydrocarbons. Often sand is added to the pressurizing fluid as a "propellant" to fill the fractures and keep them open after they form. When a foam is the pressurizing fluid, the settling of the propellant is reduced, which increases the chance that the propellant will distribute itself where it is needed. The small amount of liquid carried into the formation by a foam minimizes the contamination of the formation and eases cleanup when the pressure is released.

Foams as Traps

Another valuable property of aqueous foams is their ability to immobilize, that is, to contain or trap, all three states of matter: gases, liquids and solids. On the one hand, the foam can hold a desirable material. For instance, foams can distribute a material—even a small quantity of material—uniformly. Household examples include hair-setting foams and spermicidal contraceptive foams. The fabric-treating industry makes wide use of foams to distribute finishing agents such as dyes or resins uniformly. One advantage is that a foam minimizes the amount of water absorbed by the fabric. The drying of wet fabric requires time and energy.

On the other hand, the foam can blanket or trap an undesirable material. An obvious example is the trapping of a toxic material or a flammable liquid. The low density, metastability and trapping ability of a foam are all put to use in the cleanup of spills of radioactive material. The point here is to minimize the volume of contaminated material resulting from the cleanup. If a high-expansion aqueous foam is the cleanup agent, a large area can be decontaminated and yet when the foam collapses, only a small volume of contaminated material remains. In some applications the foam both contains and distributes. Crop treatment is an example: a useful chemical agent is distributed by the foam and is then kept where it will be beneficial.

Physical and chemical separation processes now exploit the trapping ability of foam. An instance of a physical process is ore refining by means of froth flotation. The ore is ground into fine particles and suspended in a foamy solution. Mechanical agitation then raises a foam. The resulting ore separation relies on the difference in wettability between the metal-poor fraction of the ore and the metal-rich fraction. The metal-poor fraction is usually hydrophilic and therefore easily wetted, so that it tends to sink. The



STIFLING OF AN EXPLOSION is an unusual use of aqueous foams now being evaluated by bomb squads and fire departments around the world. For each of these photographs five pounds of the high explosive called C4 was detonated at the Sandia National Laboratories in Albuquerque, N.M. For the second detonation the explosive was covered with 800 cubic feet of a low-density (.005 gram per cubic centimeter) aqueous foam. The foam proved to lessen the severity of the explosion by approximately 90 percent. Part of the energy of the shock wave of the explosion was consumed in converting the foam into tiny water droplets; then a further part of the shock energy was dissipated by the evaporation of the droplets.

metal-rich fraction is hydrophobic and tends to be carried off in the foam. Approximately 10^{12} metric tons of ore per year is now processed worldwide by froth flotation. An instance of a chemical process is dye separation. The process requires a fractionation tower holding a low-density foam whose surfaces preferentially attract a particular dye.

Prospective Uses

Several uses of foams are unusual. In a greenhouse designed at the University of Arizona a low-density aqueous foam helps to keep heat from escaping at night. Like most foams, aqueous foams are good thermal insulators. Each evening the foam is pumped between the two layers of translucent plastic that form the roof of the structure. In the morning the foam collapses under the heat of the sun and the liquid is collected, ready to be foamed again the next evening.

At a number of research institutions foams are being examined for their ability to decrease the pressure generated by an explosion. This dramatic ability arises from the destruction of the foam surrounding the explosive. In particular, some of the energy in the shock wave of the explosion is consumed in converting the foam into minute droplets of water; a further amount of energy is then consumed by the evaporation of these droplets. In all, a foam can consume as much as 90 percent of the pressure generated by an explosion. Bomb squads and fire departments around the world are evaluating the prospects. The foam can also act as a trap for particles propelled by the shock wave. In coal mines, for example, a foam covering the coal face being excavated by detonation reduces the pressure of the explosion in the direction of the mine workers and helps to trap coal dust, reducing the chance of a coal-dust explosion. In an extension of this technology, the U.S. Army is covering the nozzle of large guns with foam and testing the ability of foam to decrease the noise of detonations.

Aqueous foams have long been of scientific interest, at least in part because the complex chemical and physical phenomena in a form of matter notable for its great extent of surface area are well worth investigation. Certainly part of the interest comes from the fascination one finds in bubbles and films, which tend to be beautiful but evanescent. The latter property—the metastability of aqueous foams—is a clue that foams are unusual. The technological applications of foams show that the interest in foams is well justified.