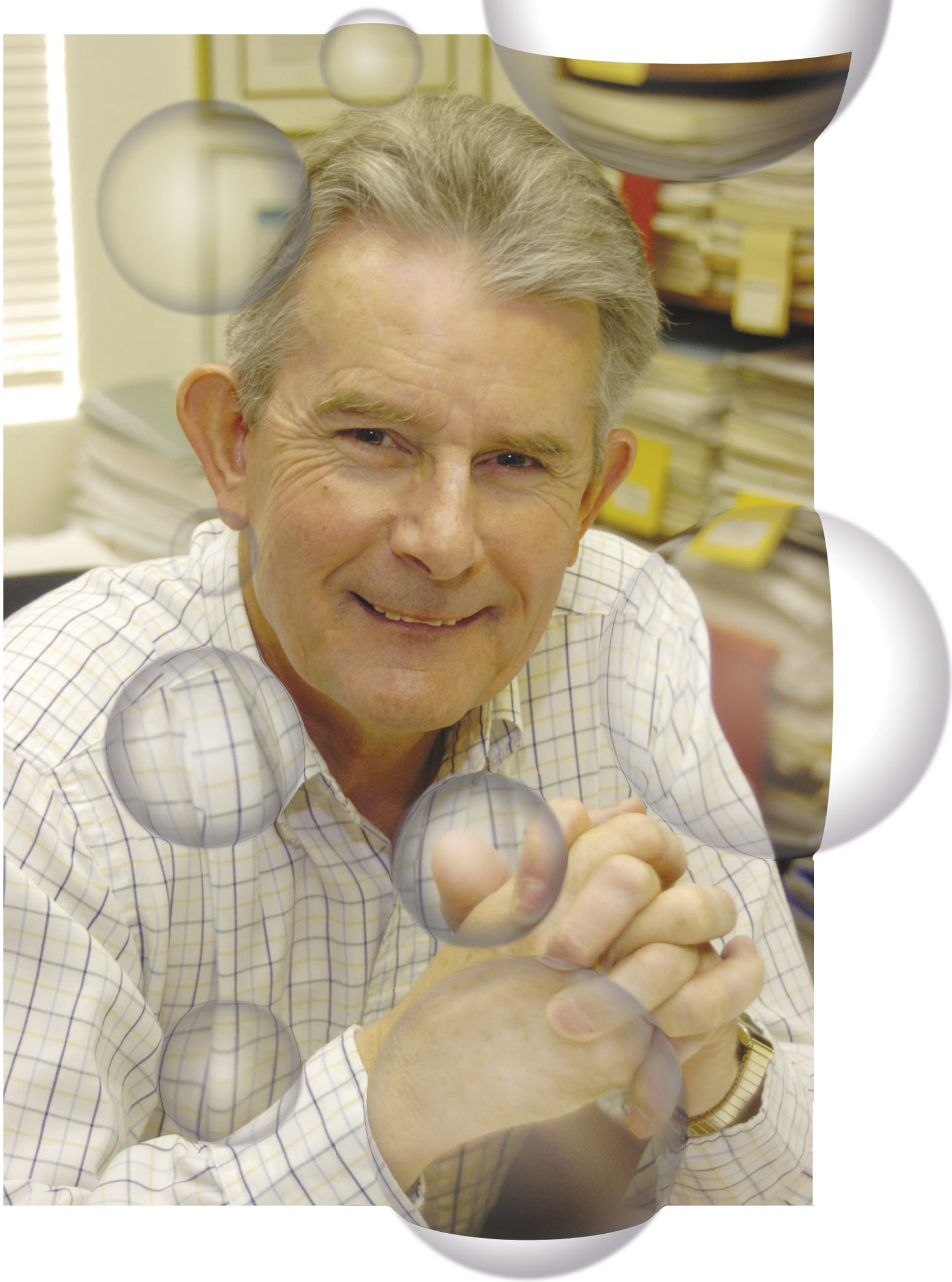
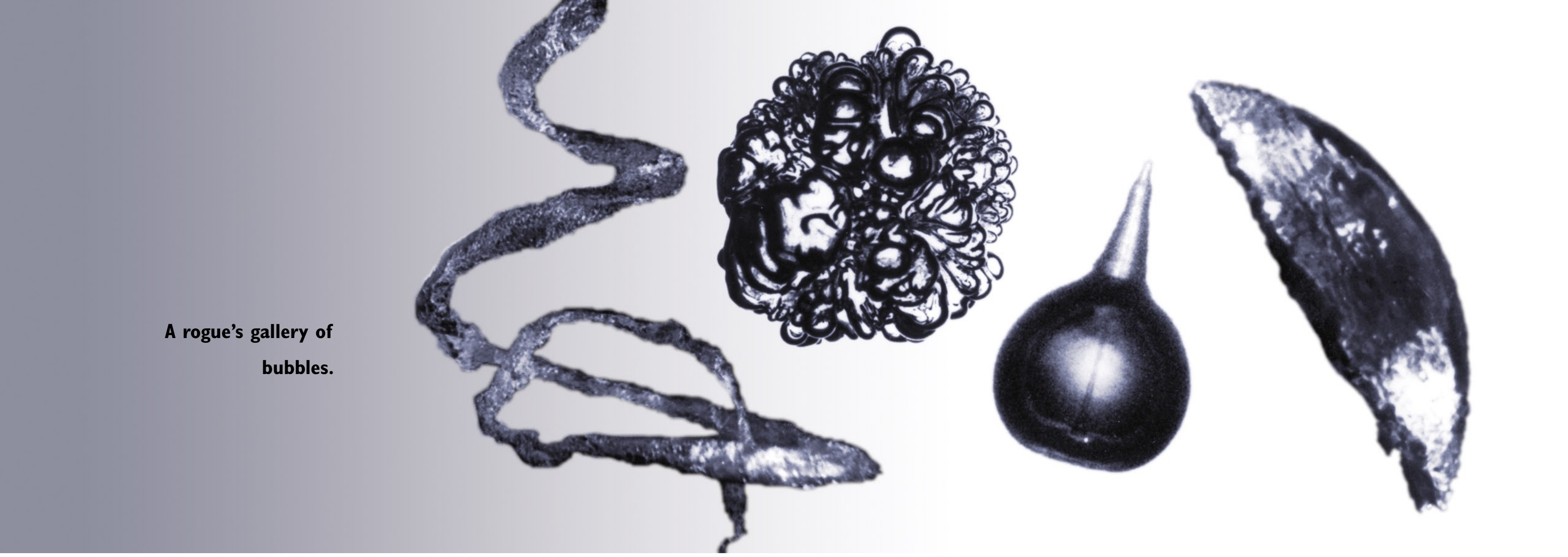
The Amazing World of Bubbles

By Christopher E. Brennen



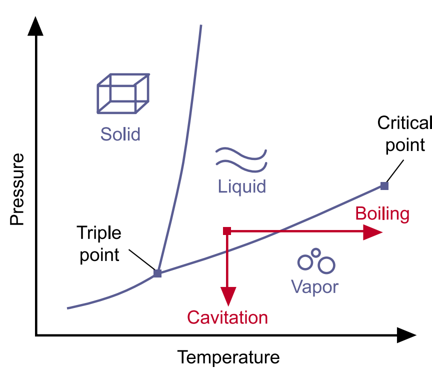


A rogue's gallery of bubbles.

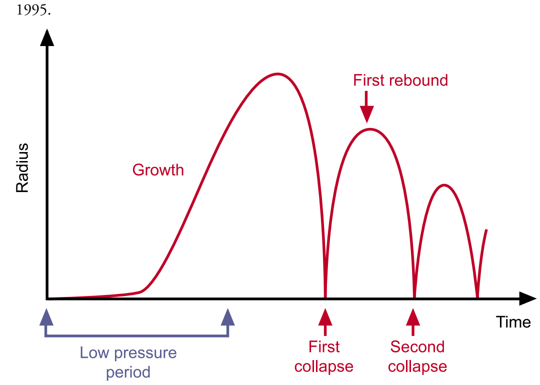
Bubbles come in all sizes, shapes, and forms, but let's begin with a very simple one. A bubble is a small pocket of vapor inside a liquid. This happens because the molecules have crossed the line separating the liquid zone from the vapor zone. Engineers and scientists like to depict this in a phase diagram, which is simply a graph that shows you whether a substance is a solid, a liquid, or a gas—or any combination thereof—at various temperatures and pressures. Increase the temperature, and the liquid boils. It forms bubbles. If you lower the pressure, a phenomenon called cavitation occurs. The resulting bubbles are essentially the same, but the consequences are not—when your teakettle boils, the bubbles don't tear it apart, but cavitation can turn steel into Swiss cheese. The difference is that bubbles formed at high temperatures contain a lot of heat and collapse relatively slowly. But if you cross the line down near the triple point, where solid, liquid, and vapor can coexist, the vapor contains very little heat, allowing the bubbles to collapse quite rapidly and very violently. What matters is not so much *how* you cross the liquid-vapor line, but *where* you cross it.

Back in the 1930s and '40s, Robert Knapp (PhD '29), a professor of hydraulic engineering here at Caltech, built the first camera with a high enough framing rate—about a thousand frames a second—that he could actually see what went on when cavitation bubbles collapsed. He made groundbreaking movies down in the basement of Karman Lab, where he had set up the lab's water tunnel so that the flow went through a low-pressure region in front of the camera. The bubbles grew quite gradually as they entered this region, but they collapsed violently as they exited. The dynamics of this process are highly nonlinear, and that's an important feature. It's also important to note that, to a first approximation, the process is scale-independent, as we shall see—big bubbles behave the same way as tiny ones. When a bubble collapses, it rebounds a few times, as shown in the plot below. A bubble contains mostly vapor, of course, which condenses as the bubble collapses, but there's a little bit of air trapped in there, too. The air can be compressed, but you can't make it go away, and eventually it can't be compressed any further and it springs back. So the bubble rebounds, and it breaks up into a cloud of lots of little bubbles. This, too, is important, because clouds of bubbles have very different dynamics than single bubbles, and I'll return to this later.

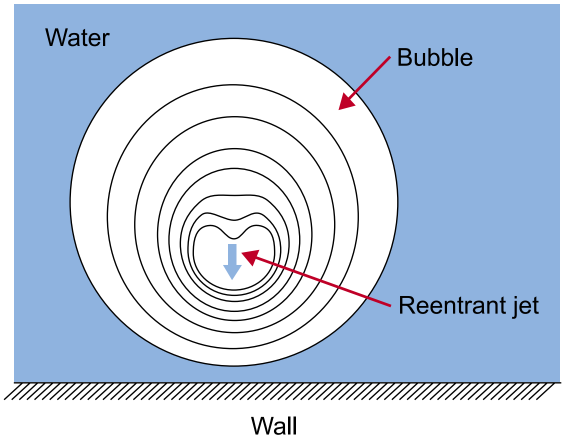
Right: A generic phase diagram. (The triple point marks the pressure and temperature where solid, liquid, and vapor coexist; the critical point is where the distinction between liquid and vapor vanishes.) There are two ways to go from liquid to vapor—raise the temperature, or lower the pressure. The first leads to boiling, the second to cavitation. Far right: The radius of a cavitation-grown bubble in a water tunnel plotted against time.



Adapted from C. Brennen, *Cavitation and Bubble Dynamics*, Oxford University Press, 1995.



When a bubble collapses near a solid surface, the water has a hard time filling the void from the wall side. The collapse, initially symmetrical, becomes directed toward the wall, and a reentrant jet develops.



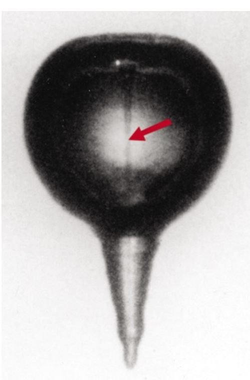
Adapted from M. Plesset & A. Prosperetti, *Ann. Rev. Fluid Dynamics*, Vol. 9, pp. 145–185, 1977.

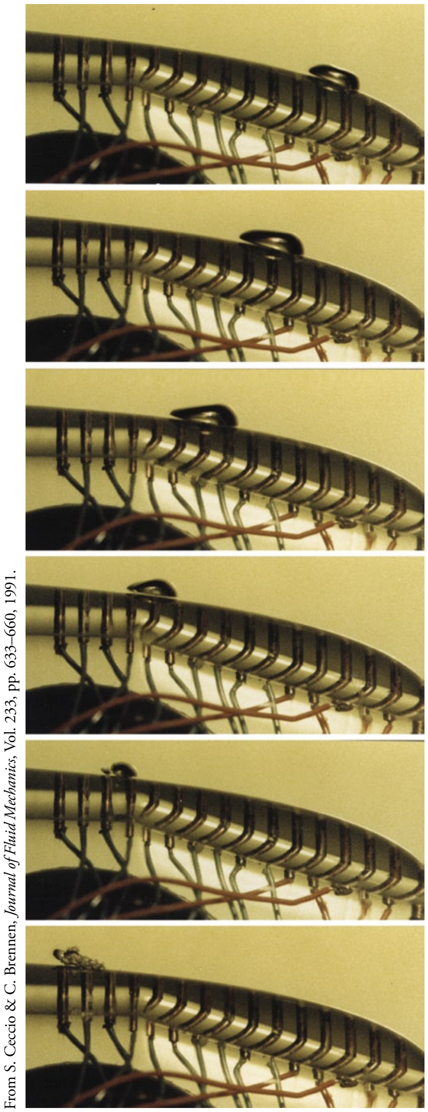
Hitting the Wall

But the most important feature arises when the bubble collapses near a "wall," which could be a steel propeller, a cement conduit, or essentially any hard surface. The side of the bubble next to the wall tends to collapse more slowly than the rest of the bubble, because the inrushing fluid on that side has to first move along the wall and then come in, whereas fluid from any other direction just comes straight in. So a jet of liquid aimed toward the wall rushes into the bubble. The jet can reach very, very high speeds—many hundreds of meters per second—and it blasts right through the bubble and into the wall, producing shock waves and other noisy trauma. (People had known about the noise for a long time, of course—that was the chief way that engineers knew that a pump was in trouble. They'd hear this horrid crackling sound, and when they took the pump apart, they'd find that its impeller blades were all chewed up.) These jets were discovered by another Caltech pioneer, Albert Ellis (BS '43, MS '47, PhD '53), who as a faculty member in the 1950s and '60s developed a number of very important high-speed cameras capable of shooting a million frames per second. He took the picture at left with one of them. The jet, marked with an arrow, is the thin, dark column in the middle of the bubble. The big protuberance is the jet blowing out through the bottom of the bubble.

More recently, grad student Steve Ceccio (MS '86, PhD '90) took the pictures at right of a single bubble growing and collapsing. We make these bubbles by inserting a cylindrical object called a headform into the flow. The cylinder's long axis is parallel to the flow and, as the water goes around the cylinder's blunt end and down the sides, a low-pressure region develops where cavitation bubbles form. Lots of them, and very reproducibly, which allows us to examine the detailed micro-mechanics of their growth and collapse. Sometimes the bubble develops wings, which is a rather curious thing.

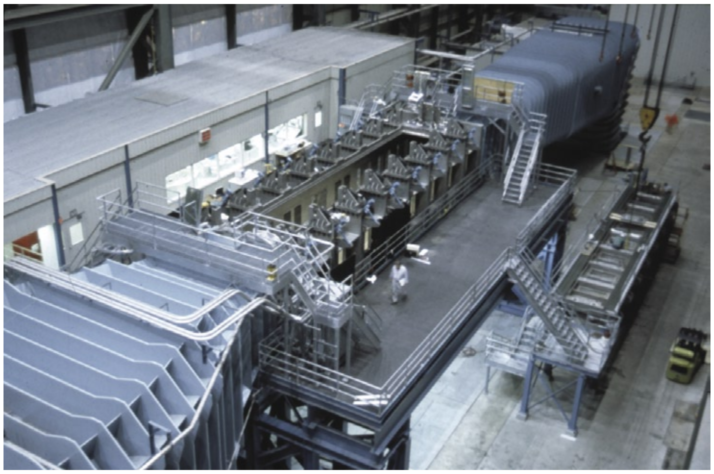
The asymmetric collapse forms a reentrant jet (arrowed), visible as a thin, dark column in the middle of the bubble.



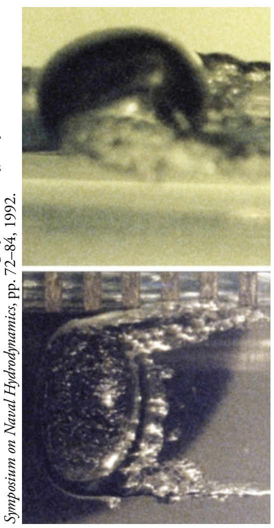


From S. Ceccio & C. Brennen, *Journal of Fluid Mechanics*, Vol. 233, pp. 633–660, 1991.

A bubble grows, splits in two, and breaks up as it travels along a Lucite headform, whose trigger system for the high-speed camera makes it look like a robotic shrimp. The shrimp's segments are a series of silver filaments, set in epoxy-filled holes and machined down to perfect smoothness, that act as electrodes. When a bubble bridges an electrode pair, the resistance skyrockets and "the bubble takes its own picture," says Brennen. "It was the only way we could do it fast enough to catch them." Brennen's second innovation was to hang an underwater mike called a hydrophone in a water-filled cavity in the headform. Water and Lucite have essentially the same acoustical properties, so a hydrophone in the headform picks up only the sounds made by the bubble itself, free of tunnel noise—the first good sound measurements of single bubbles. Brennen calls it "the cleverest thing I ever did."



The Navy's Large Cavitation Channel—catchy name!—is one of the biggest water tunnels in the world. Note the man on the working section's access platform in the middle of the photo.



From Y. Kuhn de Chizelle, et. al., *Proceedings of the 19th Office of Naval Research Symposium on Naval Hydrodynamics*, pp. 72–84, 1992.

Top and side views of a winged bubble made in the Caltech water tunnel. The bubble is about a millimeter long from nose to tail.

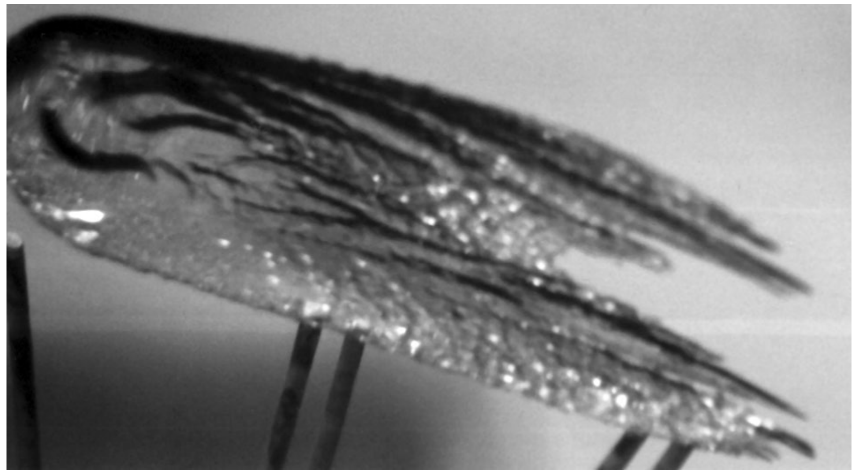
If a bubble interacts with the boundary layer and begins to rotate, the spin can generate a vortex similar to the one that forms on the tip of an airplane's wing. One vortex forms on each side of the bubble, making it look rather like a Viking helmet, or Mercury's hat. The bubble spreads out and the collapse process becomes more diffuse, making it less violent.

We took those photographs for the U.S. Navy, which is interested in making its ships, and especially its submarines, run as quietly as possible. When I showed the Navy our results, that cavitation noise depended upon the geometry of the bubble and how it collapsed, they said, "That's very interesting, but you've done these experiments on this tiny little body. How do we know that they have any relevance whatsoever to a 30-foot-diameter propeller?" Well, often you're asked these kinds of questions you can't answer, but in this instance I was soon able to give a partial reply. This happened in 1991 or thereabouts, just as the Navy was building one of the largest water tunnels in the world—in landlocked Tennessee, of all places. The working section—the part of the tunnel where you do your experiments—is about 10 feet by 10 feet in cross section, with a flow velocity above 40 miles per hour. When this thing is operating, it's like a freight train going by. It draws so much power that we weren't able to run it during the day, because the Navy said the lights of Memphis would dim. (The thought of dimming the lights of Graceland did have some appeal to me, I will admit.) So Steve, Yan Kuhn de Chizelle (MS '91, PhD '94), Douglas Hart (PhD '93), and I ran our little headform again in this tunnel, and then scaled it up to five times and 10 times larger, which is to say we went from a two-inch diameter headform to a 10-inch and eventually a 20-inch one, which we naturally named Big Bertha. This was no mean feat—it's hard to cast pieces of Lucite that big, and a number of our attempts cracked. And the cavitation exerted substantial forces on the model, so much so that I was afraid that it would be torn loose from its mount and ruin their nice new tunnel.

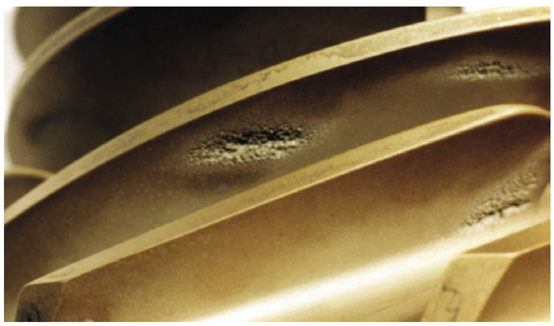
The story has a complicated end because these bubbles were even more distorted than the ones

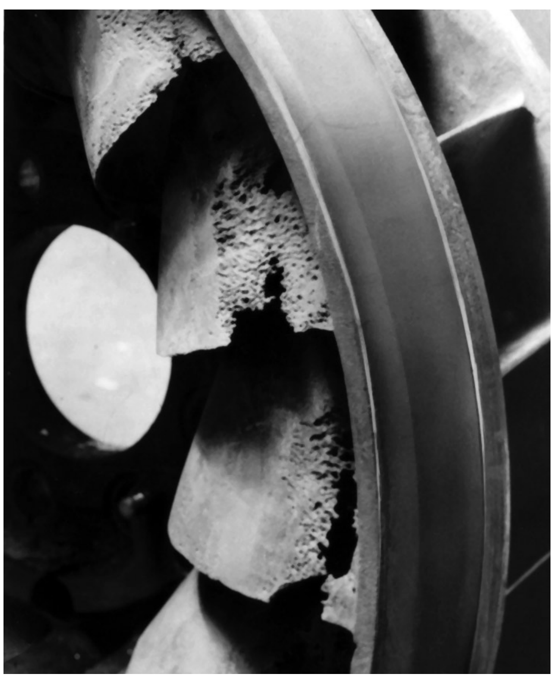
The 10-inch headform being installed in the Large Cavitation Channel's working section.

Big Bertha made big bubbles. This long, stringy specimen is about 10 centimeters long and two centimeters across; the things that look like supporting rods are the electrode pairs in the headform.



From Y. Kuhn de Chizelle, et. al., *Proceedings of the Third International Mechancial Engineering Conference*, Cambridge, England, pp. 165–170, 1992.





Top: The three pitted regions on the undersides of these blades are the early signs of cavitation damage.
Bottom: If left unchecked, cavitation can eat through steel.

in the Caltech water tunnel, but we were able to correlate the type of bubble with the noise it produced. We found that the bubbles got bigger as the headforms got bigger, so our little two-inch model made millimeter-sized bubbles, the 10-inch one made centimeter-sized bubbles, and Big Bertha made bubbles 10 centimeters long. The noise is generated as the collapsing bubble compresses that little bit of air trapped within. Each bubble makes a single acoustical pulse, and the accumulation of all the bubbles collapsing makes a sort of crackling sound that can range from a gentle hiss in our little experiments to a deafening BANG!BANG!BANG! BANG!BANG! on a 30-foot propeller blade. All the previous noise calculations had assumed a spherical bubble, and our bubbles were anything but. It turns out that, the bigger the bubble, the more the noise deviates from the spherically calculated result, and the more distorted the bubble, the quieter it is. The bubbles with tails make significantly less noise than those without. So now all the Navy has to do is figure out how to make propellers that generate tailed bubbles. They're still working on that one, as far as I know.

Shocks to the System

The shock waves I mentioned earlier continuously hammer away at any nearby surface. If it's metal, it fatigues and pieces flake off, exposing new surface for the bubbles to continue gnawing away at. It's amazing to think of a bubble eating through steel, but that's what happens. This damage is one of the most serious consequences of cavitation. Above left is the pump impeller in a rocket engine, and the damaged regions have the pitted appearance typical of fatigue failure. If this goes on long enough, it will reduce the blades to Swiss cheese.

But my favorite example is the picture above right, taken inside the conduit leading from the spillway at Hoover Dam, which is on the Colorado

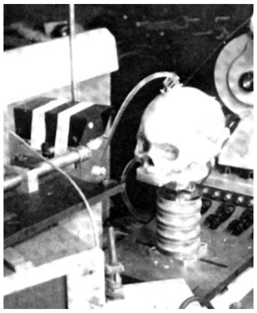
From J. Warnock, *Proceedings of the American Society of Civil Engineeers*, Volume 71, pp. 1041–1056, 1945.

Left: The conduit leading from the spillway at Hoover Dam suffered extensive cavitation damage the very first time it was used.
Below: When Lake Mead fills up behind the dam (top), the water flows over the weir in the foreground and into the spillway (bottom). The bridge crossing the spillway is part of U.S. 93, which connects Kingman, Arizona, with Las Vegas via the dam. If you look closely at the top picture, you can see several vehicles driving along the dam's top.

River out in the desert near Las Vegas. The conduit is a gargantuan concrete tube, 12.5 meters across, and the flow comes down from above at the back of the picture before turning to come straight out toward you. Cavitation has dug a hole 35 meters long, nine meters wide, and 13.7 meters deep at the point where the flow changes direction, which is where the bubbles are most likely to collapse. (By way of scale, there's a man looking into the hole from its left side.) All of that damage was done in less than four months during the winter of 1941, the first time the spillway was used. An aeration system has since been installed in the conduit to cushion the bubbles' collapse.

The spillway runs perpendicular to and behind the dam, as you can see in the top picture at right. If the water level in Lake Mead rises high enough—which can sometimes happen in periods of winter floods, although it hasn't in many years, due to the drought—the water overflows the weir in the foreground and goes into the spillway, disappearing down into the conduit, shown empty at right. It is the most awesome sight. The noise is just enormous, and the mist that rises all around is quite amazing. And everything is constantly cavitating. The pressure oscillations throughout the flow are so large that vapor bubbles are forming and collapsing everywhere.

Cavitation-induced bubbles also play a significant role in head injuries. If you have a container of liquid and you bang it on something hard—and your brain is just a container of liquid, basically, at least from a fluid-mechanics point of view; some have more liquid than others—you're going to generate lots of pressure waves that bounce around in that container. There will be points where the pressure becomes very low and the liquid vaporizes. In serious head injuries, it's almost inevitable. Bubbles will grow and collapse, and the collapse sometimes causes more damage than the blow itself. The problem is that those low-pressure regions where cavitation occurs may be quite remote from the



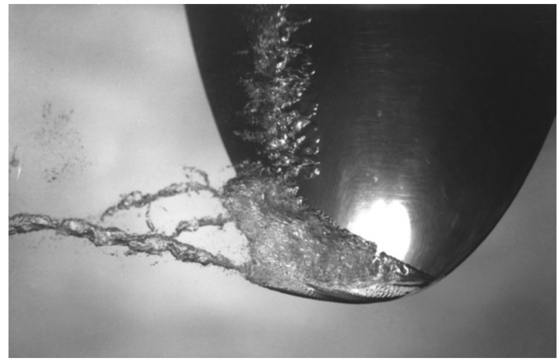
It was Halloween every day in Werner Goldsmith's lab when he was studying the fluid-dynamic aspects of brain trauma. Archival image courtesy of Werner Goldsmith.

actual impact point, so knowing where that damage is going to occur and what form it might take is important in determining how to approach a head injury. Werner Goldsmith at Berkeley spent a significant part of his career examining containers of liquid being banged around, including this one that looks like a skull.

Artificial hearts almost inevitably cavitate, which is a real problem in developing ones that will last a long time. The problem is not so much the damage to the surface of the valve, but the fact that the cavitation bursts red blood cells and destroys them. And obviously, if that happens to too great an extent, the patient is in trouble. I'll focus on one common design, the bileaflet valve, because Mory Gharib (PhD '83), the Liepmann Professor of Aeronautics and professor of bioengineering, and I have both studied it. Any heart valve, be it natural or artificial, is designed to keep the blood from flowing backward, so when the blood starts to flow backward at the end of the so-called diastolic phase, the leaflets pivot closed, as you can see below. Little jets (shown in red) shoot through the gaps between them, and between the leaflets and the walls, forming low-pressure regions that cavitate. This causes hemolysis, which is the word doctors use for busting up a red blood cell.

When surgeons do heart-valve replacements nowadays, they use pig valves. Like the valves we're born with, pig valves are flexible and forgiving, so you don't get the low pressures you do with rigid, mechanical devices. We'd like to build flexible artificial valves, but we don't really know how to make flexible, biocompatible materials that are 100 percent reliable and will last a lifetime.

A singing vortex. The vortex's braided structure is thought to be related to the fact that it sings, but exactly how remains shrouded in mystery.

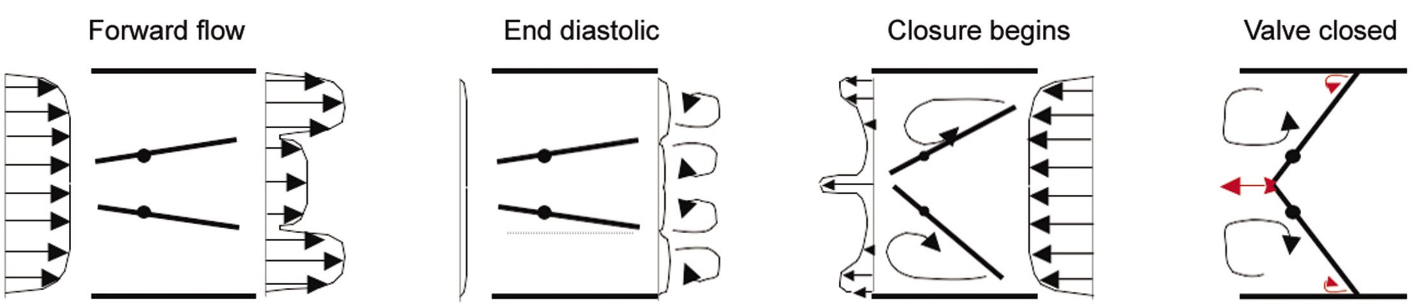


From H. Higuchi, et. al., *Proceedings of the American Society of Mechanical Engineers International Symposium on Cavitation and Multiphase Flow Noise*, pp. 101–106, 1986.

Vortices—What's Not to Like?

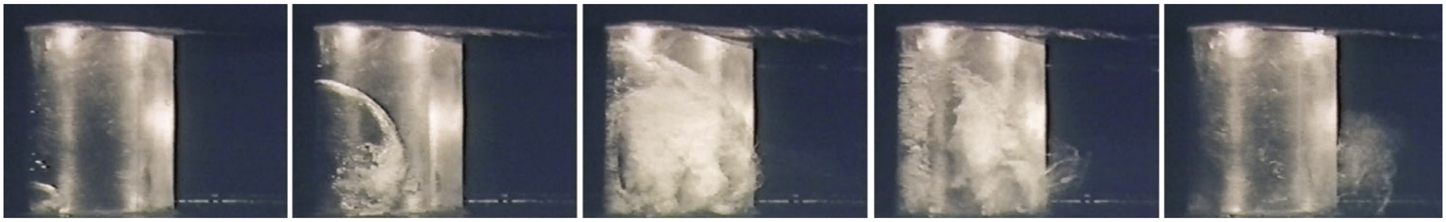
Vortices can also cavitate. (I like vortices.) If you have a rotating flow, say downstream of a propeller, a core of low pressure develops down the middle of the vortex and presto—cavitation! My colleague Roger Arndt, of the University of Minnesota, discovered that this vortex sings. It's the most amazing thing to listen to, and would make a wonderful Halloween sound effect. It's kind of an unearthly "oooooooooooo" sound, not quite a moan. As Roger lowered the pressure, making the vortex grow, the pitch of the singing got lower. Why it sings is not fully understood, but it's an acoustic resonance of the cylindrical structure of the vortex, which oscillates in peculiar ways.

From B. Moines & C, Brennen, *Sixth Annual Hilton head Workshop on Prosthetic Heart Valves*, 2002.



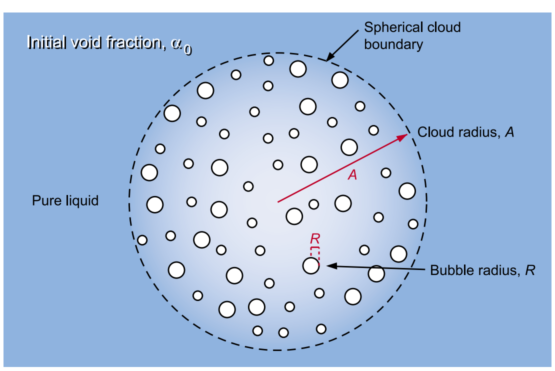
A bileaflet valve is a pair of flat plates mounted on off-center pivots. A reversing flow pushes the plates shut automatically, but also causes high-pressure jets (red) to shoot through the narrowing cracks in the final moments of closure.

Courtesy of Göran Bark.



Top: The places where the paint was eaten off these propeller blades coincided with where the white clouds of bubbles were collapsing. Bottom: This oscillating hydrofoil in Caltech's water tunnel allows collapsing clouds to be studied in detail.

Propellers make *lots* of vortices, one from the tip of each blade, leaving a trail of intertwined helices downstream. And the hub produces a vortex of its own, right down the middle. You can't get away from this—all propellers cavitate, if they rotate fast enough. This is another noise issue for the Navy, because cavitating vortices, that is, vortices with vapor in the middle, are much more stable than normal wingtip vortices and persist much longer. In fact, Mark Duttweiler (MS '96, PhD '01) showed that when one of these vortices impacts the propeller's supporting strut, it reappears on the other side, as though it went right through the strut. That's because of the persistence of vorticity, which is not a Dali painting. The whirling flow pattern is not destroyed by the strut, so the vortex reforms on the strut's far side, which then cavitates also. That's how stable vortices are.



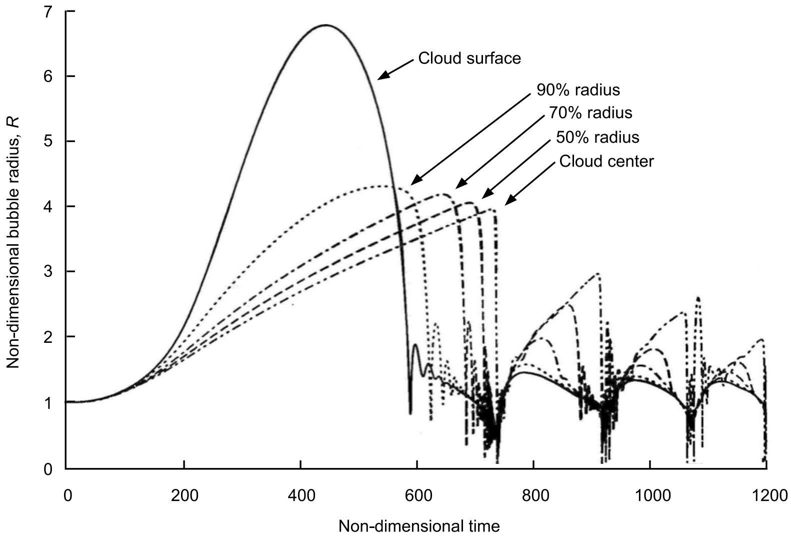
A cloud of bubbles has three important parameters—its radius, *A*; the average radius of its bubbles, *R*; and the proportion of the cloud's volume taken up by the bubbles, α.

We'll Look at Clouds from Both Sides Now

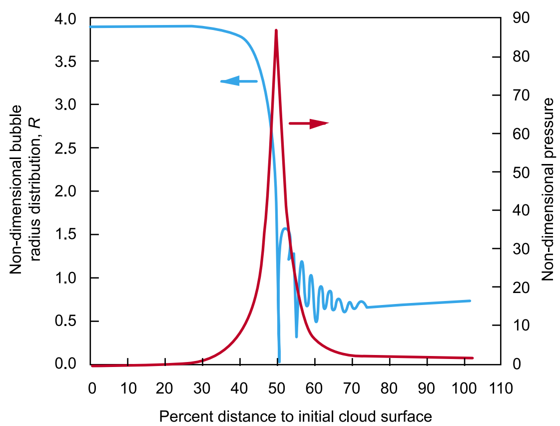
I mentioned clouds of bubbles earlier, and we're now going to turn our attention to them. A colleague of mine, Göran Bark at the Chalmers University of Technology in Göteborg, Sweden, painted a set of propeller blades red. The paint wore away where the damage was greatest, and these regions coincided with where the clouds of bubbles were collapsing. In our lab, grad student Douglas Hart (PhD '93) built an experiment where a hydrofoil's angle of attack oscillated—like driving down the freeway with your hand out the window, and rotating your wrist to vary the wind resistance—to periodically form a cavitation cloud that would then collapse. Beth McKenney (PhD '95), Garrett Reisman (MS '92, PhD '97), and Mark used this setup to try to understand the relationship between the noise generated by the flow—and believe me, it was like a machine gun going off in the lab—and the clouds of bubbles that were formed.

Luca D'Agostino (MS '81, PhD '87) had earlier discovered what's special about clouds of bubbles as opposed to single bubbles. For simplicity's sake, let's think about a spherical cloud. It has three important characteristics: the radius of the cloud as a whole, A; the average radius of the bubbles inside the cloud, R; and the volume fraction of the gas in the cloud, which I'll call α. And there's a special parameter Luca discovered, β, which we call the cloud-interaction parameter for reasons that will be clear shortly. Beta is α_0 times A_0^2 over R_0^2. (The subscript zero means the initial value, because α, A, and R all change as the cloud evolves.) Beta's value is hard to predict, because α is small but A is very much larger than R, but calculating β is of keen interest, because its size determines whether the clouds will be destructive or not.

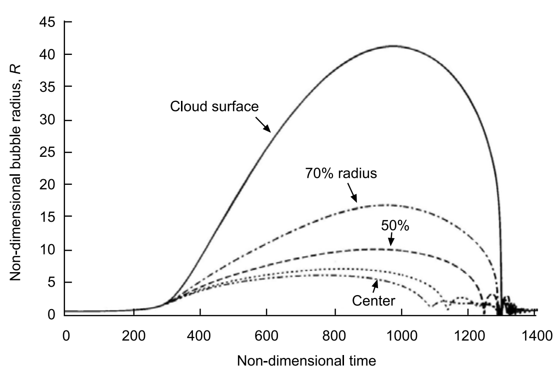
First, let me show you what happens when β is greater than one, which happens when the bubbles are dense enough or the cloud is large enough.



Above: How bubbles grow and collapse at various depths within a cloud that has a β greater than one. The bubbles on the outside collapse first, creating an imploding pressure wave.



The blue plot shows the bubbles' size (again, for β greater than one) versus their distance from the cloud center at the midpoint of the collapse process. The red curve is the pressure spike associated with the collapse.

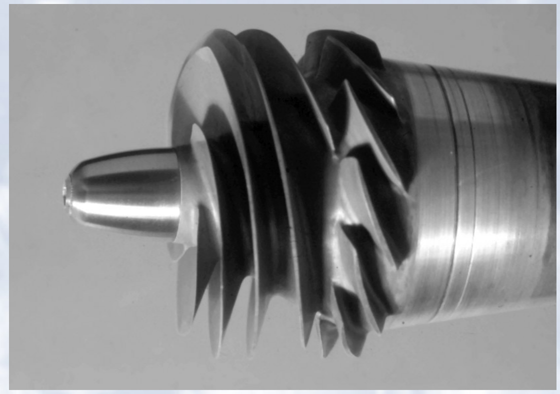


When β is small, the collapse begins at the center and moves outward, causing the pressure front to dissipate.

Above left is a plot of the average radius of the bubbles in various parts of the cloud, from the center all the way out to the surface, against time. The cloud goes through the low-pressure region between time 0 and time 400, and the bubbles everywhere in the cloud grow, but the ones on the surface grow fastest. It's as though the growth of the bubbles inside the cloud is blocked by the growth of the bubbles on the surface. The bubbles on the surface also collapse first, and that collapse front, the collapse process, moves inward toward the cloud's center. That's the key—the collapse moves in from the edges. And associated with that is a huge pressure spike, or shock wave, which Yi-Chun Wang (PhD '96) discovered when he did the first nonlinear analyses of these clouds. So this collapse front becomes a shock wave as it moves in. Moreover, because of the geometry of its inward focus, the magnitude of the shock grows at a great rate so that when that shock wave gets to the center of the cloud, it's a *huge* pressure pulse—a surge of 10 atmospheres is not uncommon. This is why a collapsing cloud packs such a wallop—the focusing shock wave generates much more noise, much more damage, than would happen with single bubbles, and having a β greater than one is the culprit.

If β is less than one, which could happen if the bubble density is small, the surface bubbles again grow faster. But now the collapse begins in the center, instead of on the surface, and all that happens is that the collapse front moves outward in a weakening wave of little or no consequence.

A model of the low-pressure liquid-oxygen pump in the Space Shuttle's main engine.



Rocket Science

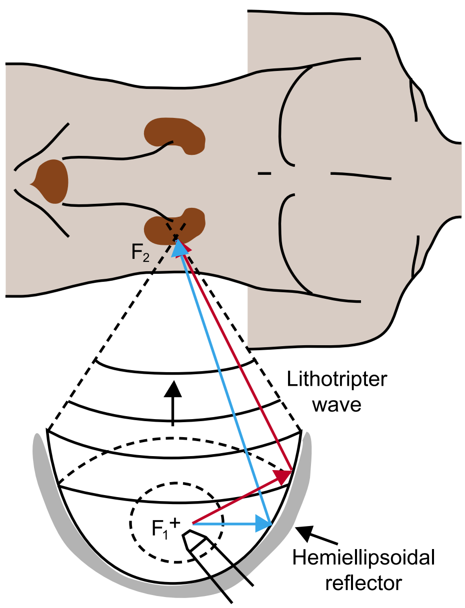
This kind of mathematical analysis has allowed us to analyze complex cavitating flows in devices like the liquid-oxygen pumps in the Space Shuttle's main engines. (For reasons I won't go into, the liquid-hydrogen fuel has very different properties, and the cavitation in it is much more benign.) But the liquid-oxygen pumps cavitate like crazy, because NASA really pushed the design envelope. The high-pressure turbopump runs at 40,000 revolutions per minute, which is almost fast enough to tear itself apart by centrifugal force. The pump is only about eight inches in diameter, and it has to spin that fast in order to move the enormous amount of liquid oxygen the engine consumes. To get the same flow rates at a more reasonable speed would require a pump tens of feet in diameter, and the launch-weight penalty would be prohibitive. Even the more sedate low-pressure transfer pumps, which are a foot across, run at 8,000 rpm. This leads to several problems.

The first and most basic one is a phenomenon called the "pogo instability." A liquid-fueled rocket sitting on the launch pad is essentially two tall, thin tanks of fluid stacked one on top of the other. Now, this structure is very flexible, and after liftoff it may begin to oscillate in a longitudinal mode, a phenomenon first analyzed by Sheldon Rubin (BS '53, MS '54, PhD '56). This causes fluctuations in the pressures going through the pumps, which in turn causes the rocket's thrust to vary, which feeds back into the tanks and makes the oscillations worse. This has been a problem since the early days of the space age, and the first stages of all large rockets have been modified to eliminate it. In 1962, before the role of pump cavitation was recognized, a Titan II rocket had to be destroyed in flight after pogo oscillations of 10 g, or 10 times the force of gravity, led to premature shutdown of the first-stage engines. The second stage of the Saturn V rocket also suffered from pogo instabilities. On Apollo XIII, 33-g oscillations caused one of the five engines in the second stage to shut down prematurely, but the liftoff continued successfully. So when the Shuttle was being designed in the mid-'70s, Allan Acosta (BS '45, MS '49, PhD '52), the Hayman Professor of Mechanical Engineering, Emeritus, and I calculated the dynamic transfer function for the low-pressure liquid-oxygen pumps—that is, we figured out how fluctuations in the flow going into each pump affected fluctuations in the flow coming out. This had never been done before—in fact, the concept of a transfer function for pumps didn't even exist; I borrowed it from electrical engineering. We then verified our calculations experimentally, in an apparatus we built here in the basement of Thomas Lab. NASA used our findings to design an accumulator, a sort of gas-filled reservoir that absorbs the fluctuations, and I am happy to say that the Shuttle has never yet suffered from serious pogo instability.

We revisited the problem several years later, when NASA asked us for help again because the Space Shuttle's main-engine turbopumps weren't operating as expected. Every pump has a critical speed, above which it is whirling so fast that it becomes unstable, like an unbalanced load in the spin cycle of your washing machine. Because the critical speeds on these pumps turned out to be significantly lower than predicted, the engines weren't capable of the designed amount of thrust. We were able to go back and do a more detailed analysis, and discovered that forces within the pump caused by the flow itself affected the critical speed. Once the system's detailed behavior was understood, the engineers found a fix for it. And again, we verified our calculations experimentally. We decommissioned that facility several years ago, since we weren't using it any more, and NASA came in, dismantled it bolt by bolt, and reassembled it at the Marshall Space Flight Center in Huntsville, Alabama, where it is still in use today.

Teeth and Kidneys and Eyes, Oh My!

Now, cavitation and its shock waves aren't always a bad thing. The energy from collapsing bubbles is used to very beneficial effect in a number of medical applications. If you've ever had your teeth cleaned by ultrasound, with that little vibrating probe used by some dental hygienists, you probably think it's the vibration that cleans your teeth. That would be wrong. There's a jet of water surrounding the probe, and it's the collapse of the cavitation bubbles caused by the probe's vibration that cleans your teeth. That's true of any kind of ultrasonic cleaner.

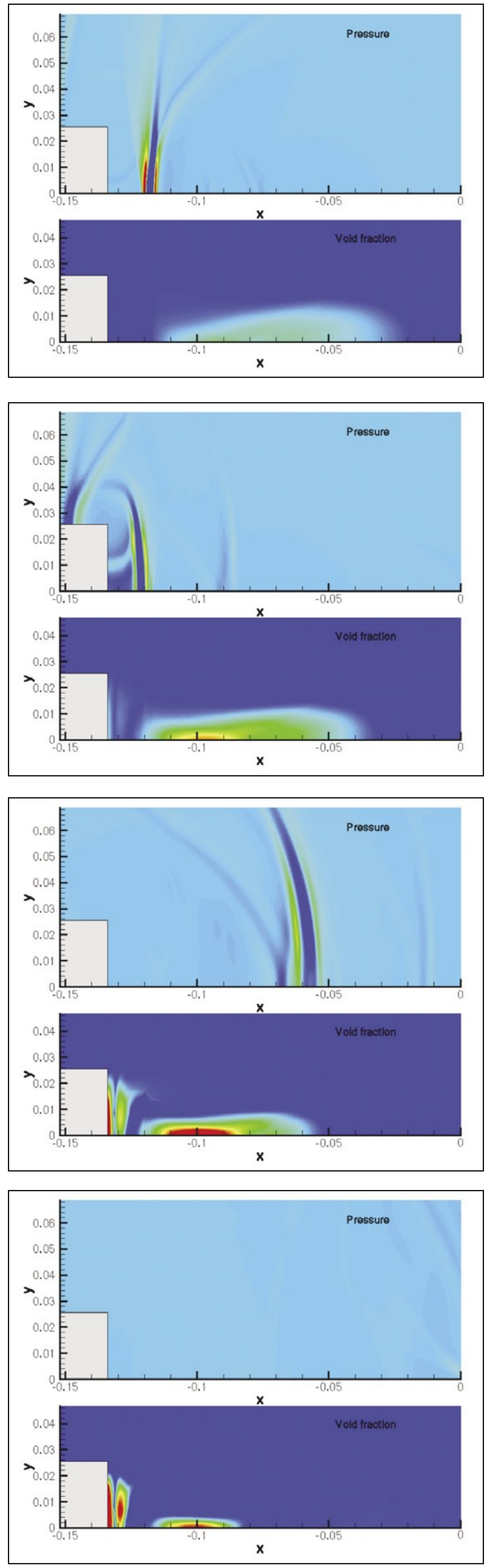


Cavitation is also the active ingredient in lithotripsy, which is a procedure for reducing kidney stones and gallstones inside the body without any surgical intrusion. The patient lies in a tub full of water, which conducts the shock wave, and a big hemiellipsoidal reflector in the tub focuses a shock wave generated at F_1 onto the patient's kidney stone at F_2. Very large pressure oscillations are generated at F_2 that cause cavitation on the surface of the kidney stone, breaking it up into pieces that can be passed out of the body. But it's very difficult to focus shock waves down to a single point, so some of the bubbles don't form quite on the surface. Guess what happens when they collapse—they damage the surrounding tissue.

It would help to be able to predict this behavior, which is a very hard thing to do, but my colleague, Professor of Mechanical Engineering Tim Colonius, and his students have developed a very nice mathematical model. At right is a set of pictures from a simulation of a shock wave hitting a kidney stone, shown as a gray rectangle. The top panels show pressure (red being high), and the panels below them show the void fraction, which is the density of bubbles created. In these panels red means lots of bubbles. So as the red high-pressure wave crashes into the stone, it creates a red zone of high bubble density on the face of the stone. That's good. But notice that at the same time, another zone of high bubble density forms some distance away, which obviously is not good. Just being able to compute the overall flow has been quite an achievement, because of the many different scales of length and time involved, and we're still decades away from being able to model what goes

Above: Lithotripsy is a procedure for destroying kidney stones and gallstones inside the body without having to remove them surgically. A water bath conducts a shock wave generated at F_1 and focused by a hemiellipsoidal reflector onto the patient's kidney stone at F_2.

Far right: This computer simulation of a lithotripsy pressure wave and its associated bubble clouds—one at the kidney stone, and one in the surrounding tissue—was part of Michel Tanguay's 2004 PhD thesis work under Tim Colonius.



on around every individual bubble. Still, these techniques are very helpful in trying to tailor the lithotripter to avoid creating regions of collateral damage.

An alternative way of doing lithotripsy would be to use ultrasound, which can be focused much more tightly. My friend Yoichiro Matsumoto at the University of Tokyo, who has visited Caltech many times and with whom I have worked on many projects, has devised an interesting strategy. He begins by bombarding the stone with fairly weak ultrasound waves, which make a cloud of large bubbles, and then he hits it with a large-amplitude wave, which collapses the bubbles. This would not be so easy to do with shock-wave lithotripsy. And again, the effect of the collapse of the cloud is much greater than the effect of any one single bubble, or of all of them separately. There are still some challenges to be resolved before ultrasound lithotripsy moves out of the lab, but it's an exciting idea.

Cavitation has also led to a better way of doing cataract surgery, which is one of the commonest, most necessary surgical procedures done in the world. Cataracts occur when the lens in your eye turns cloudy with age due to a buildup of opaque proteins in it, and eventually lead to blindness. An eye doctor named Charles Kellman invented a technique called phacoemulsification, in which a small, hollow probe—based on that vibrating dental probe—is inserted into the eye. The probe's tip vibrates, destroying the old, opaque lens, which gets vacuumed away. The new lens is inserted through the same tiny incision that was made to admit the probe, so there's minimal trauma to the eye. Recently, another doctor named Aziz Anis added a clever, literally revolutionary, twist in that he rotates the probe to create a vortex that confines the bubbles to the center of the working surface. This reduces the collateral damage that might be caused by bubbles forming off to the side of the probe.

So the thought I want to leave you with is that cavitation offers a way of focusing energy, noninvasively, from afar. The energies involved can be quite staggeringly large—when that little bit of air inside the bubble gets compressed, it can heat up enough to produce flashes of light, a phenomenon known as sonoluminescence. Experiments by Kenneth Suslick (BS '74) at the University of Illinois at Urbana-Champaign have shown that under some conditions transient temperatures of around 15,000°C can be achieved, more than twice as hot as the surface of the sun. That's the sort of energy you can use to break chemical bonds and do molecular engineering. For example, my colleague Michael Hoffmann, the Irvine Professor of Environmental Science, has been exploring the use of ultrasound and the cavitation it generates to treat polluted water. I could go on, but we're just beginning to understand the positive uses of cavitation, and it's clear that many more lie ahead. □

Although it's generally considered good to immerse oneself in one's subject, this piece of field work on the lower Kern River was a bit too intimate. Brennen was wearing a blue cap and seated in the rear before entering the drink.

Chris Brennen is a Caltech institution. The Hayman Professor of Mechanical Engineering, he came to Caltech as a research fellow on Fulbright scholarship in 1969, and has been here ever since. He has variously been the Master of Student Houses, Dean of Students, Executive Officer for Mechanical Engineering, and Vice President for Student Affairs. Born in Belfast, Northern Ireland, he earned his BA, MA, and DPhil in engineering sciences at Oxford's Balliol College. His professional accolades include the American Society of Mechanical Engineers Fluids Engineering Award, NASA's New Technology Award, and the Feynman Prize, Caltech's highest teaching honor.

An avid outdoorsman, he received the American Canyoneering Society's John Wesley Powell Award for his contributions to the sport, including his online guide, Adventure Hikes and Canyoneering in the San Gabriels.

This article was adapted by Douglas Smith from a Watson lecture given November 6, 2006.

PICTURE CREDITS: 30—Bob Paz; 40—Doug Cummings; 33, 34, 35, 39—Chris Brennen