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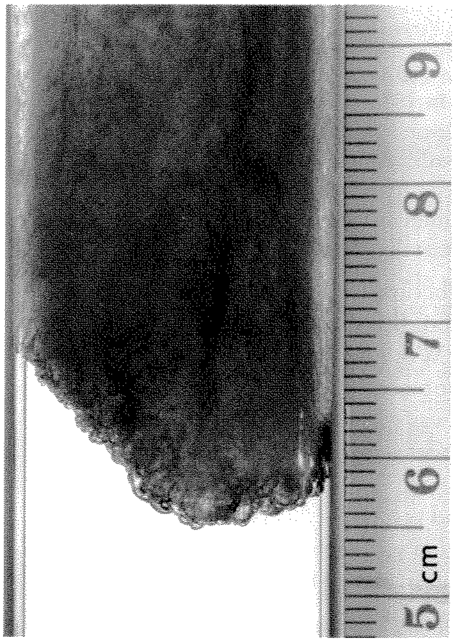
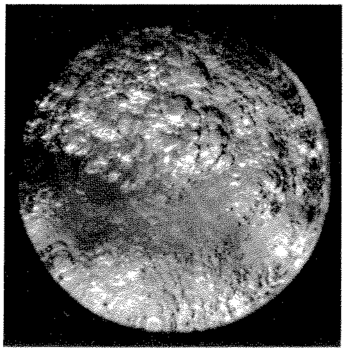




**Top: This column of Freon (lower, light area) is "erupting"—boiling away at .5 meters per second. The mixture of vapor and fine droplets (upper, dark area) is being ejected upward at 35 meters per second.
Bottom: Simultaneous view of the boiling front from below.**

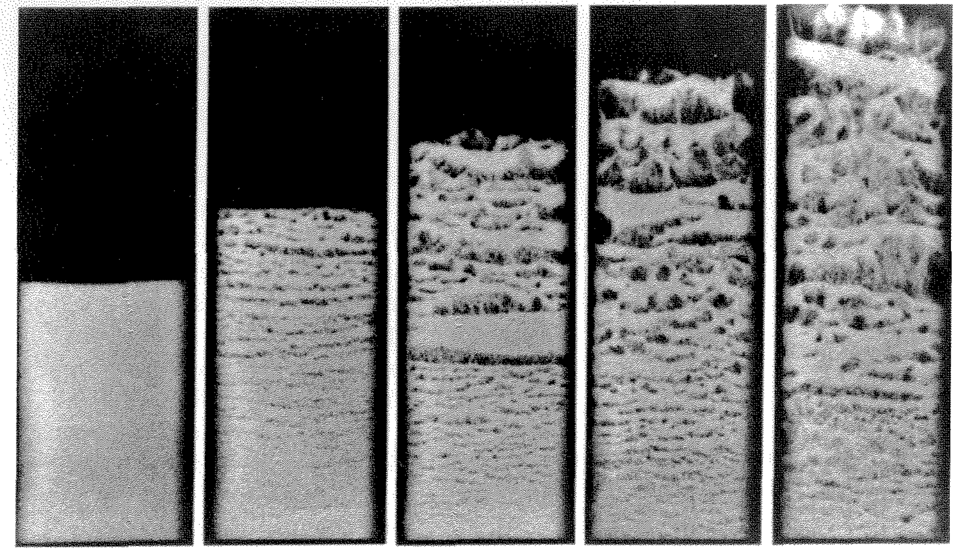
Magma: Champagne of the Gods?

This past summer, Mount Pinatubo devastated Clark Air Force Base. On May 18, 1980, an erupting Mount Saint Helens flattened some 230 square miles of trees and killed 57 people. And on August 24, A.D. 79, Vesuvius buried the Roman city of Pompeii. In each case, the agent of destruction was a pyroclastic flow—a choking cloud of gas and volcanic dust heated to 1,000 degrees Fahrenheit. Such clouds flow down mountainsides like avalanches, knocking loose tons of boulders en route, at speeds that can be supersonic. Professor of Aeronautics Bradford Sturtevant, a specialist in shock waves and explosions, has spent seven years collaborating with volcanologists internationally on the fluid mechanics of explosive volcanoes. "We do classical geological field work—which is pretty rare for engineers—as well as laboratory flow simulations."

One way to generate a pyroclastic flow is a lot like opening a champagne bottle. The champagne—or magma—is surfeited with gas kept in solution by the pressure of the container. When the cork pops—or the mountain blows—the sudden release of pressure allows the dissolved gas to vaporize. Instantaneously, all through the liquid, microscopic bubbles form, merge, and expand, belching the liquid out of the container. The carbon dioxide in a bottle of brut hasn't got much destructive power (errant corks aside), but the superheated steam that drives a pyroclastic flow blasts magma into dust particles, called ash, as small as 10 millionths of a meter in diameter. "It's an incredible process that nobody fully understands," says Sturtevant. "We hope that learning how these flows are generated will allow us to intelligently treat their hazards."

There are certain obvious drawbacks to building a complete, working volcano in the laboratory. "We don't pretend to be able to simulate a 4,000-foot-tall volcano. We abstract certain features to make simple models that perhaps can be understood." As a result, the equipment might appear to owe more to the vintner than to the volcanologist. In 1986, graduate student Larry Hill (MS '84, PhD '91) built an apparatus consisting essentially of a thick-walled, one-inch-diameter test tube whose top could be sealed with a diaphragm of heavy-duty aluminum foil. Hill would evacuate the sealed tube, chill it, then partially fill it with Freon-12, a liquid that boils well below room temperature. Some of the Freon would evaporate as the tube warmed back up, until it finally held liquid that desperately wanted to boil, but couldn't because of the six atmosphere's worth of pressure exerted by the pent-up vapor. Then a knife blade would burst the diaphragm, venting the tube into a vacuum tank while

This series of photos of a column filled with glass beads was taken (left to right) before the "eruption," and at 2.8, 4.0, 5.2, and 6.5 thousandths of a second after it.



Hill watched the "eruption." Says Sturtevant, "We've taken movies at 6,000 frames per second, and stills at exposures of one millionth of a second—the best ever taken of this process—but we still can't write equations describing the dynamics of this behavior." They could see that the bubbles grew only on the liquid's surface—an unexpected finding. Some bubbles developed a rough surface whose texture was too fine to make out. The roughness became wrinkles, which grew into wavelets, whose crests seemed to tear themselves apart into clouds of fragments too small to see—the "ash" particles. They also saw dark clouds of vapor and fine droplets racing over the boiling surface. This rapid motion may mean that the bubbles shatter in a domino effect—shards from one bubble hit its neighbors like a shotgun blast, bursting them into more droplets that tear through *their* neighbors, and so on.

Those first experiments used one substance for both the molten rock and the water vapor dissolved in it. A real eruption is more complicated, because the gas molecules must diffuse through the involatile magma in order to meet their fellows and form bubbles. David Pyle and Youxue Zhang, then postdocs in Leonhard Professor of Geology Edward Stolper's group, heard about the work and decided to borrow Hill's apparatus for a more realistic simulation using two different components, one of which was involatile. This proved to be trickier than anticipated. The liquids had to be clear, in order to photograph what was going on within them; the involatile liquid had to be able to dissolve a lot of its volatile partner; the volatile component had to have a high enough vapor pressure to drive the "eruption," even when present only as a minor component dissolved in the involatile liquid; and finally, the liquid and the vapor had to coexist at room temperature and a pressure the apparatus could sustain. Pyle and Zhang experimented with a variety of mixtures, and finally hit on a water (involatile)-carbon dioxide (volatile) combo that, under sufficient pressure, gave a gratifyingly "volcanic" eruption.

These experiments revealed differences in the eruption styles of the one-component (Freon) and two-component (CO_2-H_2O) systems. The Freon system had a well-defined interface between the liquid and the layer of vapor above it. The eruption began at the interface, and proceeded smoothly at a constant—albeit rapid—rate into the liquid's bulk. But in the CO_2-H_2O system, bubbles grew simultaneously everywhere inside the liquid, and there was no clear interface between the liquid and the vapor. The liquid's entire volume was involved in the eruption, not just its surface.

In another set of experiments with similar apparatus, Sturtevant grad student A. V. Anilkumar (MS '83, PhD '89) used 0.25-millimeter-diameter glass beads as stand-ins to see how the ash particles, once formed, would ride the blast's pressure wave. "We had imagined that things would expand fairly uniformly, and that we'd end up with an even, high-density flow of dusty gas," says Sturtevant. They found instead that the depressurization would loft entire layers of solid-packed beads, a few beads thick, separated by regions of very nearly bead-free air. Traceries of beads would rain off the bottom of each layer, enclosing regions of the void below into "bubbles" that drifted up through the packed layers. "These kinds of buoyant instabilities are seen all the time in industrial processes at normal gravity, but we didn't expect them here, where the average acceleration on the beads is about 200 times that of gravity. All the computer models of pyroclastic flows—and of nuclear blasts—assume a uniform density. But these fluctuations from packed beads to free air mean that something in the flow, like a human being or a missile silo, isn't going to feel a steady whoooosh, but a bam! bam! bam! as these blobs hit it. The effect on the object can be quite different from what we would calculate from a nice, uniform flow. I think the flow-averaged models have to be a bit suspect now." ☐ *—DS*