The Fluids With a Case Of Split Personality

In normal settings they are liquid, but in a strong electric field they turn solid; researchers still aren't sure why

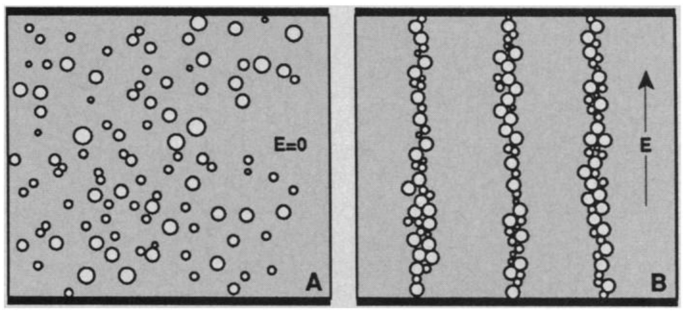
STIR A CUP OF CORNSTARCH into a bowl of vegetable oil and what do you get? A gooey mess. But it is a mess with a startling property. If a strong electric field is applied across it, the oily mixture will suddenly harden. Turn off the electric field, and you've got goo again.

The cornstarch-oil concoction is an example of an electrorheological (ER) fluid—a liquid whose flow properties change when it is exposed to an electrical field. First discovered more than 50 years ago, ER fluids are now getting a great deal of attention primarily because they may offer ways to make mechanical devices that take advantage of the calculational speed of modern computers. Companies hope to use ER fluids in such applications as valves with no moving parts that can open and close in milliseconds, industrial robots that respond more quickly and accurately than any available today, and vibration-control systems for engine mounts or even buildings in earthquake-prone areas (also see box on p. 1181).

Strangely enough, although researchers using trial and error have discovered hundreds of particle-liquid combinations that act as ER fluids, no one has ever explained exactly how they work. Now, in just the past 2 years, scientists have begun to develop quantitative theories to predict how a given fluid will behave, and initial results look promising. But at least one well-respected worker in the field claims these theories are fatally flawed and err in identifying the fundamental cause of the ER effect. The answer in the debate is of more than theoretical interest—it will likely determine just how useful ER fluids can be in commercial applications.

The effect of an electric field on an ER fluid is easily seen through a microscope. The fluid consists of solid particles from 0.1 to 100 micrometers across suspended in an oil or other nonconducting liquid. With no electric field, these grains are distributed evenly throughout the liquid. But if the fluid is placed between two electrodes and a high voltage applied across them, the particles align themselves into fibers that stretch from one electrode to the other. These fibers resist deformation, causing the material's sudden rigidity.

Researchers have found that ER fluids can be based on almost any type of oil imaginable, and the particles can consist of either organic materials, such as starch and cellulose, or inorganics, such as ceramics, glass, and a variety of polymers. No matter what their composition, all ER fluids respond similarly to an electric field, with their viscosity increasing proportionally to the square of the field; several thousand volts per millimeter are usually needed to solidify an ER fluid. For best results, the particles should make up 10 to 40% of the mixture by volume, and water must often be added to obtain a good ER effect or sometimes to get any at all.



High fiber. *An electric field creates fibers in an ER fluid.*

The role of that water is central to the disagreement over what causes the ER effect. A majority of workers think water is probably not essential for the effect. According to this school of thought, the applied voltage polarizes the particles, creating a surplus of negative charge on the ends nearest the positive electrode and extra positive charge on the ends nearest the negative electrode. These polarized particles then line up, positive end to negative end, and form columns stretching between the electrodes. In this model, says Alice Gast, a chemical engineer at Stanford, all that is necessary is for the particles and solvent to have different dielectric constants. The dielectric constant is a measure of how easily a material polarizes in an electric field, and if the liquid polarizes as much as the particles, it would cancel out the effect.

Gast, with her student Paul Adriani, and Charles Zukoski of the University of Illinois at Urbana along with his student, Dan Klingenberg, have developed mathematical models that idealize an ER fluid as a homogeneous liquid containing a suspension of solid particles with a different dielectric constant. Under the influence of an electric field, the models predict, the particles in the fluid form structures similar to those seen experimentally. Gast admits that the models do not predict just how solid the ER fluid becomes—the calculated shear strengths are an order of magnitude lower than those of real fluids. But she suggests that the models could be improved by adding other physical features of the particles—their surface roughness, their nonspherical shapes, and their proper sizes. At least, she says, "The trends are correct."

At Caltech, chemical engineer John Brady has done computer simulations of ER fluids using approximations like Gast's for the electrical properties and adding equations to describe the hydrodynamics of the fluid. "We see all the phenomena that are seen experimentally," he says. The success leads him to predict that the ER effect can be understood primarily as a result of electrical attraction between the particles caused by their polarization.

James Stangroom of ER Fluids Development Ltd. in England disagrees vigorously. In an ER fluid, he says, electrical forces between the polarized particles are far too weak to account for the fluid's rheological properties. According to Stangroom, who has worked in the field longer than nearly all of his colleagues, the amount of water in an ER fluid is the single most important factor, and it is ignored completely in models based on particle polarization. After years of testing which mixtures show the ER effect, he says, he found one consistent pattern: "The ones that worked were capable of absorbing a significant amount of water [into the particles]."

So Stangroom posits a completely different mechanism for the ER effect. He agrees with Gast and Brady that when the electric field is applied, it polarizes the particles, but after that their theories diverge. As a particle is polarized, Stangroom says, mobile ions inside pores in the particle move to one end or the other of the particle. Since water molecules tend to cluster around ions, the moving ions will carry water along with them. At the end of the particle, the collected water molecules will form a "water bridge" to an adjacent particle, causing the two to stick together. When the field is

At Long Last, Will Electrorheological Fluids Compute?

Researchers touting electrorheological fluids for commercial applications find themselves in the same fix as the boy who cried "Wolf." In the late 1940s, after the first publication describing ER fluids, several companies tried to make use of their unique property of hardening when exposed to an electric field to make vibrators and dampers, but gave up because the fluids were then too abrasive and damaged the equipment. Interest revived in the late 1960s, and for the past 20 years a succession of firms has dabbled in the field, but many have become discouraged by the difficulties in making ER devices and quit. There is still no successful ER product on the market.

So why should the 1990s be different? James Stangroom of ER Fluid Developments Ltd. in England has a compelling answer. "The need for ER fluids has only developed over the past 10 years as we have developed the ability to calculate," he says. Today's computers can manipulate tremendous amounts of information at fantastic speeds, but for most applications there is no good way to transform those calculations into action. Industrial robots, for instance, rely on such things as stepper motors and feedback loops which cannot take full advantage of speedy computer decision-making. "We need [mechanical] systems that are computer-compatible," Stangroom says. ER fluids, which can respond to electric signals faster and more precisely than existing technologies, offer that capability.

Theodore Duclos at Lord Corporation in Cary, North Carolina, describes several prototype ER devices that could be controlled by computer. The simplest is a valve with no moving parts. In it, fluid passes between two electrodes; applying a voltage across the electrodes solidifies the fluid and reduces or stops the flow within a millisecond or so. An experimental ER clutch has been constructed out of two plates separated by a thin layer of ER fluid, one plate connected to a rotating drive shaft and the other to an output shaft; varying the intensity of an electric field between the plates controls the viscosity of the fluid, so that the rotation of the output shaft can be adjusted with exquisite accuracy. And ER vibration-control devices could be valuable in engine mounts, Duclos says. Industry rumor has it that a Japanese car maker will have an ER engine mount on a 1991 model, he says, but he suspects that is unlikely. Still, he adds, it would not be too surprising to see such an automotive application by 1995.

Stangroom compares the state of ER fluids now to that of transistors in the 1950s, when they were used mainly by the military and kept in temperature-controlled cabinets. And like transistors, ER fluids offer a unique capability likely to be applied in ways that cannot even be imagined now. The analogy with electronics seems particularly fitting since the future of ER fluids may rest on their ability to ride the coattails of the computer revolution and provide a simple, efficient way for computers to do more than just compute. ■ R.P.

turned off, the water molecules retreat into the particles and the bridges disappear.

These same water bridges are what cause a flour-water mixture to be solid, Stangroom notes. Indeed, he says, if water is added to a slurry of flour and oil, the mixture will solidify even without an electric field.

Stangroom's argument that water is all important is flawed, says Harry Block, a chemist at Cranfield Institute of Technology in England, because some ER fluids function quite well without any water at all. Although Stangroom replies that it is impossible to get all of the water out, Block contends that, "The amount of water [in the nonwater mixtures] is not enough to produce the ER effect."

Block gets backing from Zukoski at Illinois, who has recently completed a careful series of experiments on anhydrous ER fluids. By using particles made out of a polymer that can be doped to give a variety of dielectric constants, Zukoski was able to test how the ER effect changed as the polarizability of the particles was varied and everything else kept constant. The experiments matched up quite well with predictions made from a model based only on electrical effects, he says. In this particular case, Zukoski says, the presence of water was not an important factor.

That still begs the question of exactly what role water does play, since many ER fluids will not function when completely dry and most work much better after water is added. The proponents of the particle polarization model suggest that water increases the polarizability of the particles in the fluid. For instance, water molecules adhering to the surface of particles could greatly increase their dielectric constant since water is easily polarized. And, Zukoski says, it is not impossible that chemical effects such as water bridges might play a role in some ER fluids.

The question of how essential water is for the ER effect is vitally important for commercial applications. Engineers would like to find ER fluids that can endure a wide range of temperatures, and fluids dependent on water do not last long at temperatures much over 100°C.

But the temperature range is just one of the important factors for industrial use, says Theodore Duclos, a researcher at the Lord Corporation in Cary, North Carolina. An ideal ER fluid would have low viscosity in the absence of an electric field but solidify with as low an electric field as possible; the particles should remain in suspension for a long time without settling to the bottom; the fluid should not damage equipment; and it should be nontoxic and nonpolluting.

Right now, the engineers are not waiting for the scientists to explain what is going on. They are proceeding to look for that ideal ER fluid by themselves. ■ ROBERT POOL

Gene Therapy Proposed

NIH scientists R. Michael Blaese and W. French Anderson have submitted the first protocol to test real human gene therapy. The two are asking for permission to insert a working gene in children having a genetic defect that causes a life-threatening immune deficiency.

In another ongoing experiment at NIH, Blaese, Anderson, and cancer surgeon Steven A. Rosenberg are already infusing melanoma patients with potentially therapeutic cells labeled with a foreign gene, but the study is not, strictly speaking, a case of gene *therapy* because the foreign gene is being used only as a marker, not as a drug.

Now, Blaese and Anderson propose administering the gene for adenosine deaminase to children who do not have this enzyme, which is vital to immune functioning. Their protocol will be reviewed on 30 March when the NIH's Recombinant DNA Advisory Committee meets in concert with the human gene therapy subcommittee.

■ BARBARA J. CULLITON