Ergonomics Research: Impact on Injuries

NO tool has characterized the modern workplace like the personal computer. An estimated 60 million PCs adorn desks in virtually every work environment today, achieving remarkable increases in productivity while virtually transforming entire industries. At the same time, however, an increasing number of employees are heavy computer users who suffer painful and sometimes debilitating (and occasionally career-ending) injuries called work-related musculoskeletal disorders (WRMSDs) involving their hands and arms.

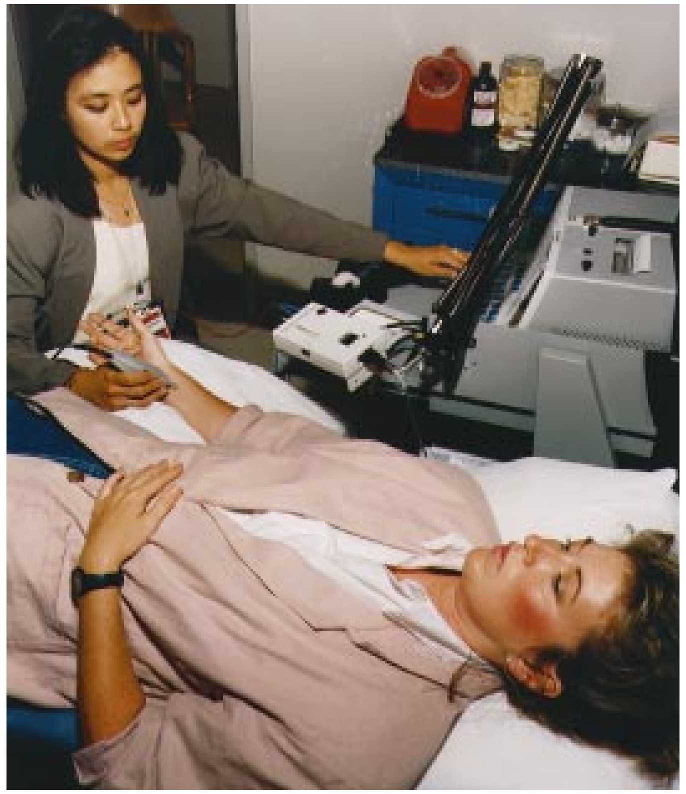
According to Dr. Steve Burastero, director of Lawrence Livermore's Interdisciplinary Ergonomics Research Program and a physician in the Health Services Department, the mounting numbers of injuries should not come as a surprise. After all, someone typing 60 words per minute for 6 hours a day will keystroke a half-million keys every week, often in an awkward position or under stress.

Burastero says the number of cases of WRMSDs has increased dramatically to near-epidemic proportions in the U.S. workforce, from about 20% of occupational illnesses nationwide in 1981 to more than 60% of all occupational illnesses today, according to U.S. Bureau of Labor statistics. Within computer-intensive occupations, the incidence of injury has doubled every year for the past four years.

These disorders cost the nation over $40 billion per year in medical costs alone. When productivity losses and disability and retraining costs are included, the total bill may top $80 billion per year. A common injury is tendonitis—inflammation of tendons, which connect muscle to bone. Another well-publicized injury, carpal tunnel syndrome, involves damage to the median nerve that travels through a tight space in the wrist called the carpal tunnel.

Burastero notes that in the past, safety at most work sites, including Lawrence Livermore, traditionally focused on avoiding accidental injuries caused by hazardous materials or industrial equipment. As a result, procedures and instruments were developed that can detect, for example, toxic solvents at extremely low levels.

"We have technology that is very good for detecting the most minute amounts of hazardous materials," says Burastero. "The technology for measuring musculoskeletal risk is very crude in comparison. At Lawrence Livermore, we rarely see people inhaling toxic materials, but, as at worksites everywhere, we see musculoskeletal injuries among computer users."



Clinical tests are done with Livermore subjects. Ergonomist Pat Tittiranonda shows Nancy Johnson how a nerve conduction test would be performed to assess the symptoms of carpal-tunnel syndrome. Probes on the finger and wrist measure the nerve conduction velocity across the wrist joint.

Experts say preventing WRMSDs begins with ergonomics, a relatively new field concerned with studying the interaction between individuals and their working environment to ensure that tasks are performed safely and efficiently. Burastero contends, however, that all too often, products labeled ergonomic are not backed by data gained from rigorous research or extensive field trials. As a result, there's a surprising lack of knowledge on how injuries can be prevented.

In response to the lack of scientific data, Lawrence Livermore's Interdisciplinary Ergonomics Research Program is addressing comprehensively the problem of WRMSDs plaguing U.S. industry. The program uses a multidisciplinary research team that taps LLNL's strengths in human factors design and engineering, computational modeling, biomechanical engineering, sensors, industrial hygiene, and occupational medicine.

These strengths make it appropriate for Lawrence Livermore to tackle a pressing national problem such as WRMSDs, says Burastero. The LLNL work is funded by Livermore's Laboratory Directed Research and Development, the Department of Energy, and the computer industry. The research projects have attracted collaborators from the University of California's San Francisco School of Medicine, UC Berkeley, the National Institute of Occupational Health in Sweden, and the University of Michigan.

The research is also closely aligned with the Laboratory's Center for Healthcare Technologies and an internal ergonomics program. The latter is an employee-oriented research program that aims to reduce the severity of ergonomic injuries and illnesses at the Laboratory and to reduce the lost and restricted time attributed to these injuries.

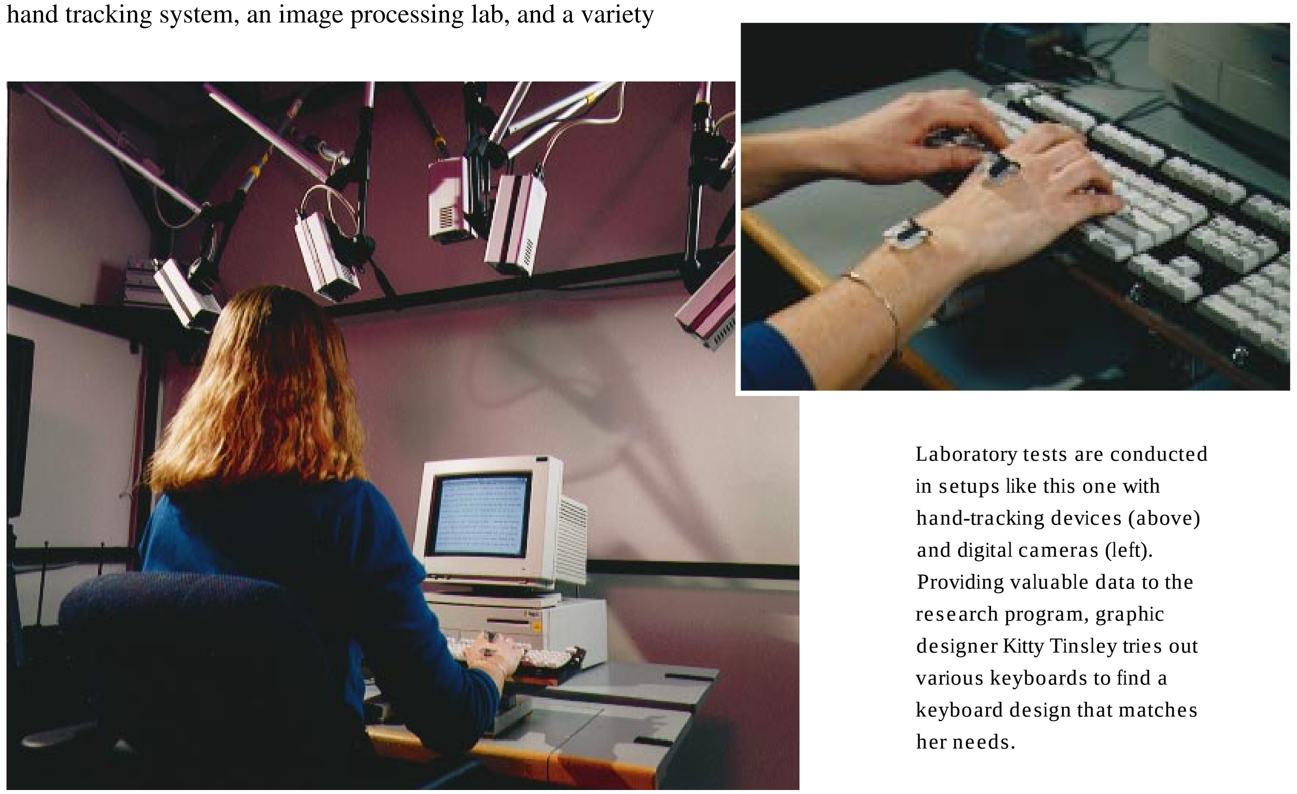
Unique Resources at LLNL

Livermore's ergonomics research program draws upon a combination of four resources, which together exist nowhere else in the national laboratory family. The first is an ergonomics laboratory (see photo below) that is outfitted with state-of-the-art three-dimensional motion-analysis equipment that is used to study dynamic wrist motion, a sensor-based hand tracking system, an image processing lab, and a variety of ergonomic assessment equipment. Much of the equipment can be transported to an employee's worksite for "real-world" analysis of how people interact with their computers.

The ergonomics lab works closely with computational modeling experts in LLNL's Institute for Scientific Computing Research. This modeling capability, the program's second significant resource, is being applied to the study of human–machine interactions. For example, ergonomics laboratory data help validate the work of LLNL bioengineer Karin Hollerbach, who is developing a dynamic computational model of the bones and joints that are often associated with these injuries. (See September 1996 *S&TR*, pp. 19–21).

Biomedical engineer Robert Van Vorhis, who coordinates the ergonomics lab, also heads the technical aspects of a project to enhance a physician's visualization during endoscopic surgery for carpal tunnel syndrome. Improvements in endoscopic surgery could improve the cure rate of this minimally invasive surgical procedure such that, when it is successful, employees return to work in two weeks instead of six. This project is also leveraging Livermore's capabilities in optics and digital imaging with spinoff applications in advanced manufacturing.

The ergonomics research program's third major resource is Health Services' occupational health clinic (see photo on



Laboratory tests are conducted in setups like this one with hand-tracking devices (above) and digital cameras (left). Providing valuable data to the research program, graphic designer Kitty Tinsley tries out various keyboards to find a keyboard design that matches her needs.

previous page), which has expertise in the diagnosis, treatment, and rehabilitation of WRMSDs. Livermore physicians and nurse practitioners diagnose and manage problems while physical therapists administer on-site treatment.

Finally, LLNL's large, stable, and innovative workforce provides excellent subjects for testing new products in the workplace and for providing valuable feedback. "We are a mini-town, with every profession represented, including editors, administrators, accountants, computer scientists, physicists, technicians, and engineers," says Burastero. All use computers differently, and most, he adds, are not shy about voicing their ideas and problems concerning computer usage.

With these four resources—laboratory, computer modeling, clinic, and employees—Livermore is providing a better picture of how these injuries are initiated and prevented and the role that computer accessories play in prevention and cure. Burastero says combining data from laboratory studies, workplace observation, long-term subject feedback, and expert medical monitoring is much preferable to other methods that consist solely of testing people in a controlled setting for a few hours or lending them a product to try.

Much of the research program's focus has been studying recent alternatives to standard computer keyboards. Conventional keyboards have been suspected of causing or exacerbating WRMSDs because their design can encourage use with wrists bent into awkward postures. Burastero notes that keyboards really have not changed much during the past 30 years—witness the host of "vestigial keys" such as "scroll lock" that date from the PC's earliest days.

Pat Tittiranonda, an ergonomist with the program, recently completed the most comprehensive computer-keyboard study ever performed. The three-year study involved 80 participants representing a broad range of occupations at Livermore. All had suffered WRMSDs such as carpal-tunnel syndrome or tendonitis. The volunteers were given one of four alternate keyboards to use for six months. The keyboards had been developed and marketed by different companies with the goals of increasing user comfort and reducing the risks of awkward wrist postures.

Over a period of six months, the research team closely analyzed how the subjects used their keyboards, including how much force they exerted on the keys with their fingers. The team also did video and three-dimensional motion analysis of the volunteers working at their computers. The results showed for the first time that keyboards specifically designed to lessen pressure on wrists can relieve the symptoms of WRMSDs and promote recovery. What's more, many of the alternative keyboards did not impair productivity and were relatively easy to learn.

The test subjects also completed a questionnaire on supervisor and coworker support and conflict. The data affirmed preliminary findings that the effectiveness of ergonomic interventions can be reduced in a stressful working situation.

The study, says Burastero, should have a "significant impact" by changing the way keyboards are designed and providing safety and health professionals with a greater understanding of the role of keyboards in WRMSDs. "There had been a lot of anecdotal evidence, but until now no one had systematically looked at how people actually work with keyboards or at the long-term effects," he says.

Livermore ergonomics experts caution that keyboards are only one factor associated with WRMSDs. For example, chairs, desks, terminals, and lighting conditions also play roles. So do pointing devices such as mice and trackballs, which the research team is planning to investigate in depth. At the very least, says Burastero, Lawrence Livermore can provide a knowledgeable perspective to manufacturers, clinicians, and workers everywhere.

—Arnie Heller

Key Words: carpal tunnel syndrome, ergonomics, industrial health, work-related musculoskeletal disorders (WRMSDs).

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The Linear Electric Motor: Instability at 1,000 g's

WHAT do salad dressing and nuclear fusion have in common, and how can an electric motor further our understanding of both? More than one might suspect.

In both salad dressing and nuclear fusion, materials of different density will mix, which has a great bearing on such things as the uniformity of the dressing or how much energy will be achieved from an inertial confinement fusion (ICF) capsule.[1] To investigate this mixing process, Lawrence Livermore has built a linear electric motor (LEM) that can provide selected acceleration profiles up to 1,000 times Earth's gravity.

"When friends ask what I do, I like to tell them that I'm particularly concerned with what happens when you turn a bottle of salad dressing upside down," quips Guy Dimonte, the Lawrence Livermore physicist who is leading the project to study instabilities in liquids of different densities when they are accelerated by a linear electric motor. "Actually, I'm only half joking, because the principle is the same, whether it's oil mixing with vinegar or a plastic shell mixing with thermonuclear fuel in inertial confinement fusion. We need to understand how hydrodynamic instabilities enhance the mixing of different materials because this information is very important to Lawrence Livermore's stockpile stewardship work," he says.

Perturbations Grow

When fluid of high density is supported against gravity by a less dense liquid, the system is unstable, and microscopic perturbations grow at the interface between the fluids. This phenomenon, called the Rayleigh–Taylor instability, also occurs when a bottle of oil-and-vinegar salad dressing is turned upside down. The instability causes spikes of the dense fluid to penetrate the light fluid, while bubbles of the lighter fluid rise into the dense fluid. The same phenomenon occurs when a light fluid is used to accelerate a dense fluid, causing the two fluids to mix at a very high rate. For example, during the

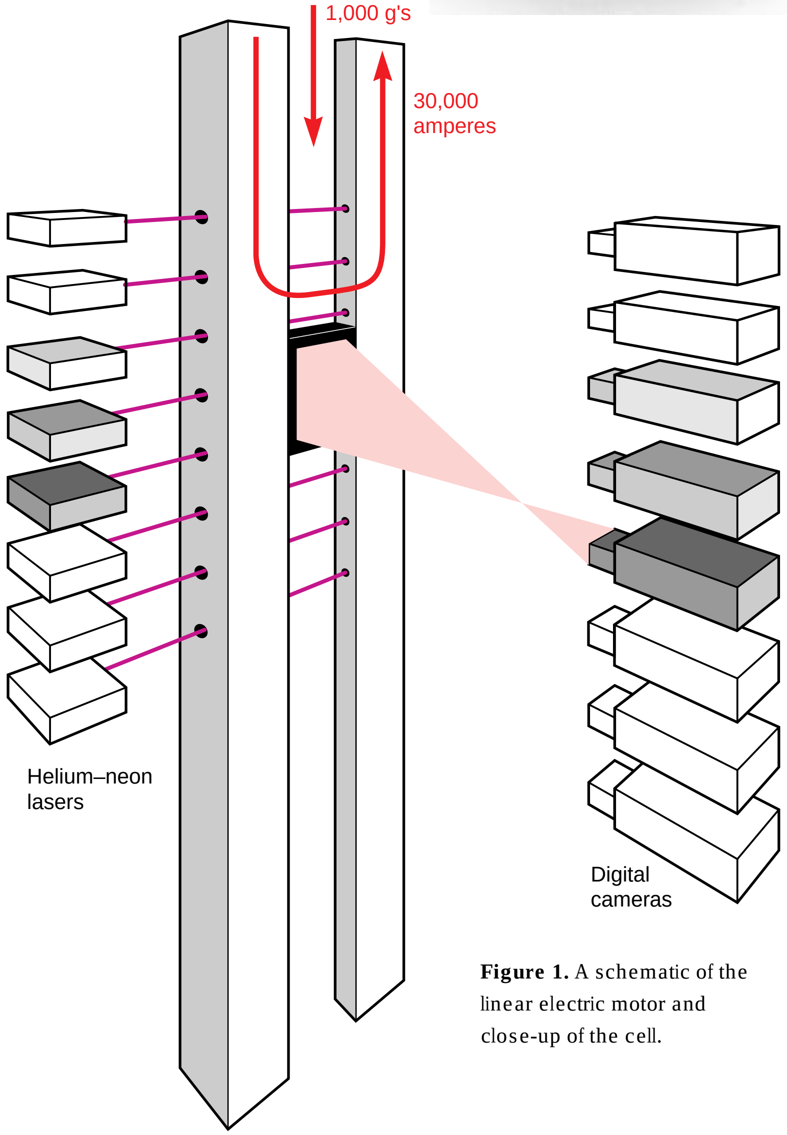

Figure 1. A schematic of the linear electric motor and close-up of the cell.

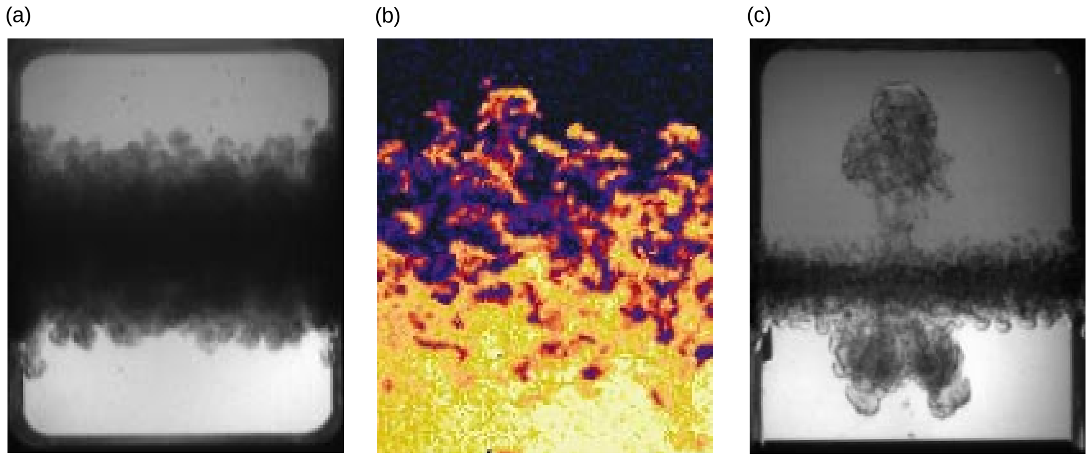

Figure 2. Sample images using (a and c) a flash backlighter and (b) a laser sheet. Images (a) and (b) have a smooth initial interface; (c) has a localized initial disturbance.

implosion of an ICF capsule, this instability can cause enough mixing to contaminate, cool, and degrade the yield of the thermonuclear fuel.

The LEM is an excellent tool for studying this instability, but what is it? Think of a miniature high-speed electric train (the container) hurtling down a track (the electrodes) while diagnostic equipment (optical and laser) photographs it. The configuration is shown in Figure 1.[2]

The LEM, configured by Dimonte and his colleague, physicist Marilyn Schneider, consists of four linear electrodes, or rails, that carry an electrical current to a pair of sliding armatures on the container. A magnetic field is produced that works in concert with the rail–armature current to accelerate the container—just as in an electric motor, but in a linear fashion rather than in rotation. The magnetic field is augmented with elongated coils just as in a conventional electric motor. This configuration also helps hold the armatures against the electrodes to prevent arcing. The electrical energy (0.6 megajoules) is provided by 16 capacitor banks that can be triggered independently to produce different acceleration profiles (i.e., how the acceleration varies with time).

The container that holds the fluid is machined from a block of Delrin, a material that is corrosion-resistant, strong, and nonconducting. The container is 9 × 9 × 12 centimeters (about 4 inches on a side) and has 0.5-cm-thick Lexan windows in the front and back so the liquids can be backlit and imaged. High-resolution optical imaging diagnostics record the inter-fluid mixing. The optical source is either a flash backlighter for photography or a laser sheet for laser-induced fluorescence (Figure 2).

The container trajectory is measured with a laser position detector (LAPD) consisting of eight transverse, 1-milliwatt beams at different positions along the trajectory. When the container intersects these beams, photo diodes send electrical signals that are recorded by digitizers and then trigger the optical diagnostic system. The images are captured electronically using charge-coupled device (CCD) cameras and a desk-top computer using a LABVIEW program. Higher resolution images are taken with remote-controlled 35-millimeter cameras, and the images are digitized later with a photodensitometer. Electrical signals from the LAPD, current monitors, magnetic field loops, and crystal accelerometers are acquired on digitizing oscilloscopes and archived on another desk-top computer. Finally, the container is stopped by a mechanical brake with spring-loaded aluminum drums.

The key to successful operation of the LEM is the sliding armature because it must carry as much as 30,000 amperes of current without arcing. "When we first started, our armatures were flawed, and we melted a lot of copper electrodes with spectacular arcs. After several modifications, we developed an armature that is very reliable, capable of several hundred arc-free shots before the electrodes need to be replaced. The system now works great, but without the exciting fireworks of the early days," Dimonte says.

In a typical experiment, the container is filled with two fluids (such as freon and water) and inserted between the rail.[3] The diagnostic equipment is activated, and the laboratory is then closed and interlocked. From an adjoining control room, the capacitors are charged and fired, sending the container down the rails with a final velocity of about 30 meters per second, depending on the needs of the experiment. Higher velocities are attainable with the energy available in the banks, but they are not required for most experiments. As the container intersects the laser beams, the imaging diagnostics are triggered and electrical signals are acquired. The container then enters the brake region and stops smoothly. "When we are in high gear, technicians Don Nelson and Sam Weaver can fire a shot as quickly as every 10 minutes," Dimonte explains.

Wide Range of Acceleration

"The beauty of using the LEM for these experiments is that we can take very high resolution images of the instabilities over a wide range of acceleration profiles," Dimonte says. "Most alternative drivers like compressed gas or rocket motors do not provide this flexibility. Mixing experiments are performed on Livermore's Nova laser under realistic conditions, but with less relative detail than on the LEM. The LEM is complementary to Nova and a very reliable and cost-effective tool for investigating the fine details of turbulent mixing."

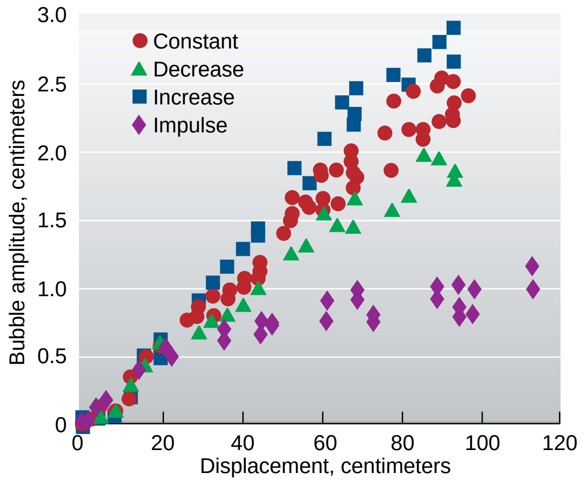

Figure 3. The bubble penetration distance versus the distance traveled by the fluids in a LEM.

In the example of Figure 2, the fluids have very little viscosity and the mixing is fast and turbulent. Here, scientists are interested in how the random bubbles of light fluid (on top) penetrate the heavy fluid (on bottom) and how the corresponding spikes of heavy fluid penetrate the light fluid. (Remember, gravity has been turned upside down because of the downward acceleration.) The amount of fluid mixing is indicated in Figure 3, which shows the bubble amplitude versus the distance traveled by the container for different acceleration profiles. From these data, Dimonte and Schneider can test turbulent mixing models and full hydrodynamic computer simulations.[3]

In another set of experiments, Dimonte and Schneider are investigating the mixing when the "fluids" have material strength. For example, when an aluminum plate is accelerated by high explosives, the driving pressure is comparable to the yield strength, or the point at which the material would become plastic. In this case, a smooth surface is expected to remain stable indefinitely, whereas a very rough surface would be unstable. They are testing this hypothesis by doing experiments using yogurt because it has enough yield strength to show the effect at the reduced g-forces of the LEM.

Figure 4. Yogurt perturbations after being accelerated by 30 g's. Initial undulations at the interface were 1 millimeter; here they grew to 40 millimeters.

Figure 4 shows an image of yogurt accelerated in the LEM when the initial undulations at the interface were about 1 millimeter in amplitude. The perturbations became very large because of the instability. When the experiment was repeated with a smooth interface, the instability was inhibited by the material strength.

Many more experiments are possible on the LEM with different fluids, diagnostics, and acceleration profiles. "Our strategy is to use small-scale experiments like the LEM, with high-quality optical diagnostics, to investigate the micro-physics of turbulent mixing. Over the next five years, we will test the mixing models with data of unprecedented resolution. When the National Ignition Facility becomes available, the mixing models can then be applied to more realistic conditions in an integrated sense, that is, including the other issues relevant to stockpile stewardship, such as radiation flow and material equation of state," Dimonte says.

—Sam Hunter

Key Words: acceleration, linear electric motor (LEM), Rayleigh–Taylor instability.

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