

Clean Power

On the voyage home to Ithaca, Odysseus and his sailors had to navigate between Scylla and Charybdis—dangerous rocks and a whirlpool. Maneuver to avoid one peril and you risk the other. Researchers at the National Energy Technology Laboratory in Morgantown, West Virginia know the feeling. Their job is to steer the course of environmental stewardship in the face of accelerating demands for electrical power around the globe.

“America is running short of electricity,” said a front-page story in the Wall Street Journal a few months ago (May 11, 2000). The information age—temperature controlled machine rooms and offices—and surging appliance purchases have juiced power consumption. Summertime U.S. peak demand is now about 700,000 megawatts, up from 525,000 in 1989, a rise that threatens to outstrip capacity, now about 780,000 megawatts. Complicating things is that deregulation of the electric utility indus-

try has spawned uncertainty about the return on investment in new plants.

Adding fuel to the fire, literally, developing countries are a burgeoning market for energy. One recent projection holds that over the next few years 300 megawatts of new electric generating capacity will be installed somewhere in the world each day!

What about acid rain? What about greenhouse gases? These and other environmental imperatives drive research that will provide clean power options for the world’s energy. At present, 85 percent of U.S. consumption and 90 percent of the world’s comes from fossil fuel, and as the president’s commission of science and technology advisors reported last year, the current best opportunity for environmental progress in power generation is high-efficiency, low-emission combustion.

“The challenge is to convert fuel to energy without creating pollutants,” says George Richards, who leads NETL’s com-

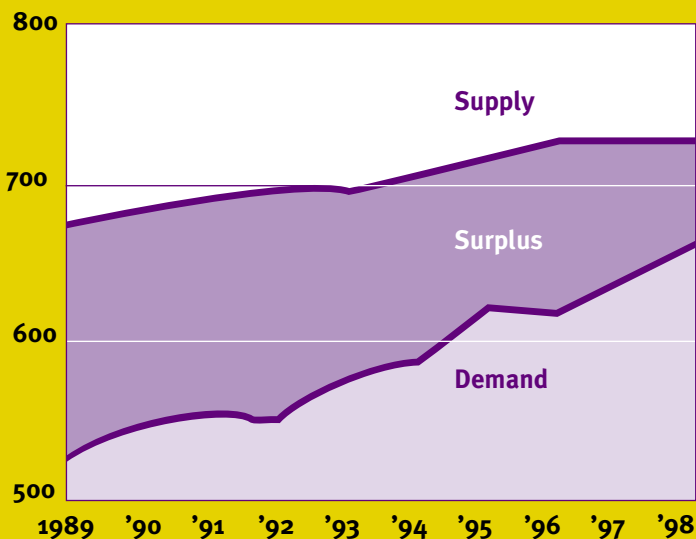
bustion dynamics team. The workhorses of electrical-power generation are the jet-engine-like gas turbines that convert fossil fuel into megawatts of electricity, and the mission of Richards’ team is to help develop the engineering knowledge to make 21st century turbines more efficient, cleaner and cheaper to operate. In a recent series of simulations at the Pittsburgh Supercomputing Center, they’ve made progress toward this goal.

Lean, Pre-Mixed Combustion

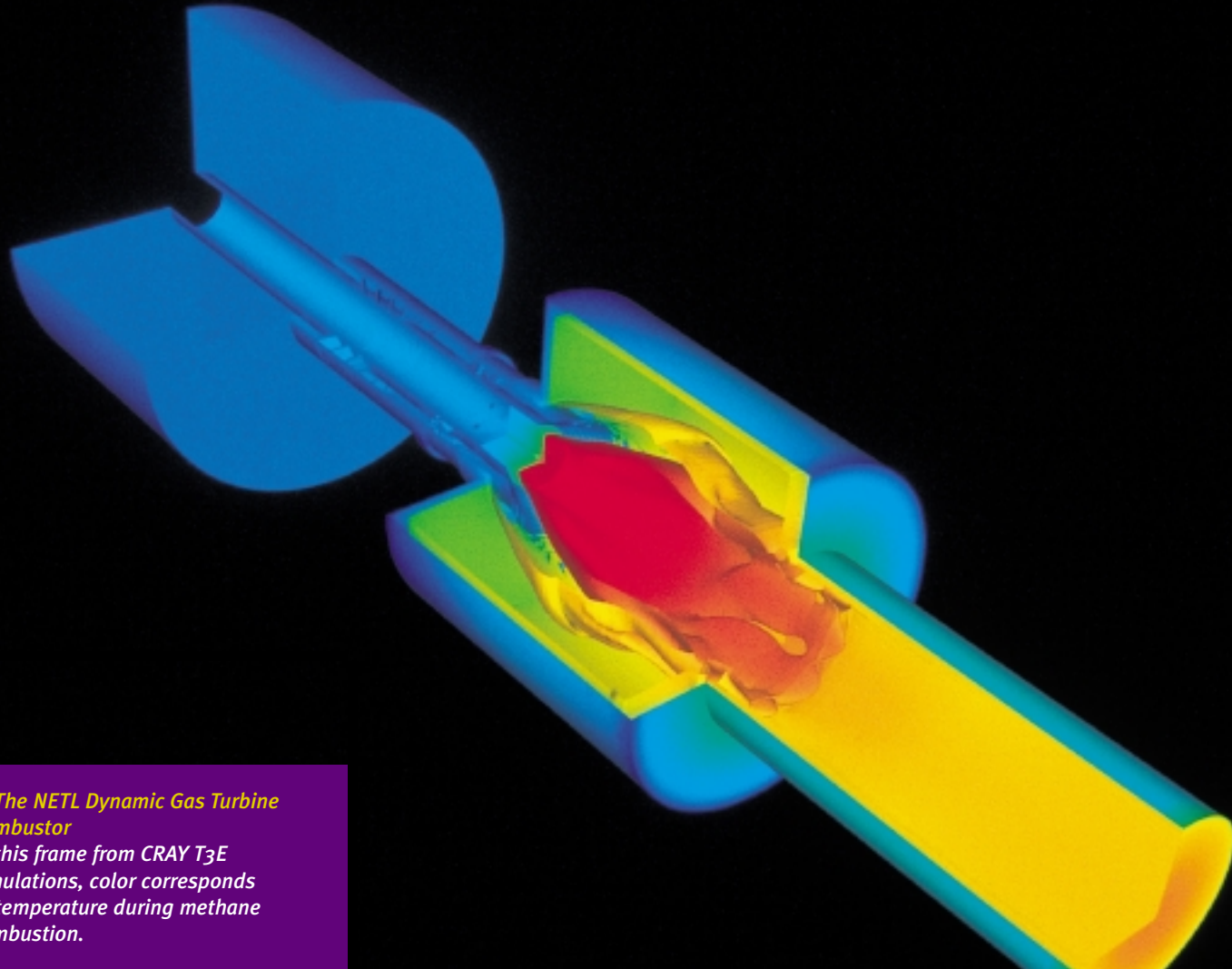
The power industry began to shift its new installations toward low-emission technology about 10 years ago, says Richards, and many new power plants employ low-emission turbines. The key to these advanced systems is “lean, pre-mixed combustion”—mixing the fuel, typically natural gas, with a relatively high proportion of air prior to burning. This substantially reduces nitrogen oxide pollutants (known as NOx) while allowing high-efficiency operation. The high efficiency reduces carbon dioxide, a major greenhouse gas, and lowered NOx alleviates smog and decreases other byproducts that affect air quality.

But a nasty problem bedevils these systems. With a lean-fuel mix, the combustor flame burns on the thin edge of not having enough fuel to keep burning, and a phenomenon analogous to a flickering candle sets up pressure oscillations—like a series of very rapid small explosions rather than a steadily burning flame. These oscillations can resonate with the vibration modes of the combustion unit and, literally, shake it to pieces.

Summertime Blues
U.S. summer electricity demand, supply and surplus, in thousands of megawatts.



Source: U.S. Department of Energy



▲ *The NETL Dynamic Gas Turbine Combustor*

In this frame from CRAY T3E simulations, color corresponds to temperature during methane combustion.

“This instability is a major issue that every turbine developer using pre-mix combustion has to face,” says Richards. “It comes up in every conceivable stage—in development, during engine commissioning, in engine-fielding applications. It comes up in permitting these engines and in keeping them operating. It’s a very tricky problem. I’m happy to say that there’s been a lot of progress, and we can now see fielded engines using these incredibly clean combustors. But we also know that avoiding instability places very tight restrictions on how the engine can operate. Adding desirable features, like fuel flexibility, or a wider operating range, can lead to the same old problem.”

To zero-in on the problem, NETL researchers conducted extensive experiments with their Dynamic Gas Turbine Combustor. This state-of-the-art test facility makes it possible to adjust parameters involved in turbine-combustor design—such as location of the fuel injector relative to the flame—and to observe and measure what happens.

The experiments revealed an unexpected result. Changing the location of a nozzle component called the “swirl vane” affected the pressure oscillations. The swirl vane—so-called because it swirls the air flow to create aerodynamics that mix the fuel and air—sits upstream of the fuel injector. In experiments comparing two swirl-vane locations, with other parameters unchanged, when the swirl vane was moved two inches farther upstream the pressure oscillations virtually disappeared. Why?

What to Measure?

The objective, stresses Richards, is to understand the physics behind the observed data, so it can be incorporated rationally into turbine design. Moving the swirl vane gave better performance in one set of conditions, but the data was inconclusive when it came to explaining the results. Prior research suggested that the time lag between when fuel is injected and when it burns is a key factor for the oscillations, but presumably, since the fuel-injector didn’t

move, the swirl-vane would have little or no effect on this.

“You can place the swirl vane either closer to the flame or farther away,” says Richards, “and it makes a difference. But we didn’t know why. We had some conjectures, and we tested those, but we still couldn’t prove what was going on. There’re subtle effects, like decay of turbulence and swirling flow, that impact the important time scales—multiple, simultaneous processes, and you can’t interpret the experimental data without quantifying the contributions from these simultaneous events.”

To sort out the details, Richards and his colleagues turned to simulations on PSC’s CRAY T3E. In recent years, the NETL team worked with consultants for FLUENT, commercial fluid-dynamics software, to develop 3D modeling that realistically simulates experiments in the experimental combustor. In summer 1999, with help from PSC scientists, they adapted FLUENT to the CRAY T3E and ran a series of simulations replicating the experiments.

Each computation—one for each experiment—required about a week of computing on 20 T3E processors to simulate 30 milliseconds of combustion. Each produced 20 gigabytes of compressed data, an enormous amount of information, which itself created a huge post-processing task.

When the results were in, they told an interesting story: The aerodynamics in the nozzle are such that moving the swirl vane, with no change to the fuel injector, significantly affects the time lag between injection and burning. In the two cases of interest, moving the swirl vane two inches upstream slows this lag time by a millisecond, and that millisecond makes a big difference in combustion stability.

“We looked at the simulations,” says Richards, “and said ‘ah-ha.’ It was obvious. The change in this time lag from

the point of injection is what we need to measure. That’s a whole different universe to work in from where we were, a definite conclusion. It helped us set up the next set of experiments in which we’ve been trying to make a verifiable measurement of those time scales. And we’ve made some progress on that.”

Flame Volume & Reaction Rate

Along with focusing their analysis of the swirl-vane results, the CRAY T3E simulations also provide the NETL team with a way to look deeper yet at the physics of turbine combustion. A key factor in combustor stability is the flame’s reaction rate, the speed of burning, which varies with time. The NETL group would like to know what drives this variable. Does the volume of the flame change, such as when a candle-flame flickers, or does the flame volume stay constant as the burning-rate varies?

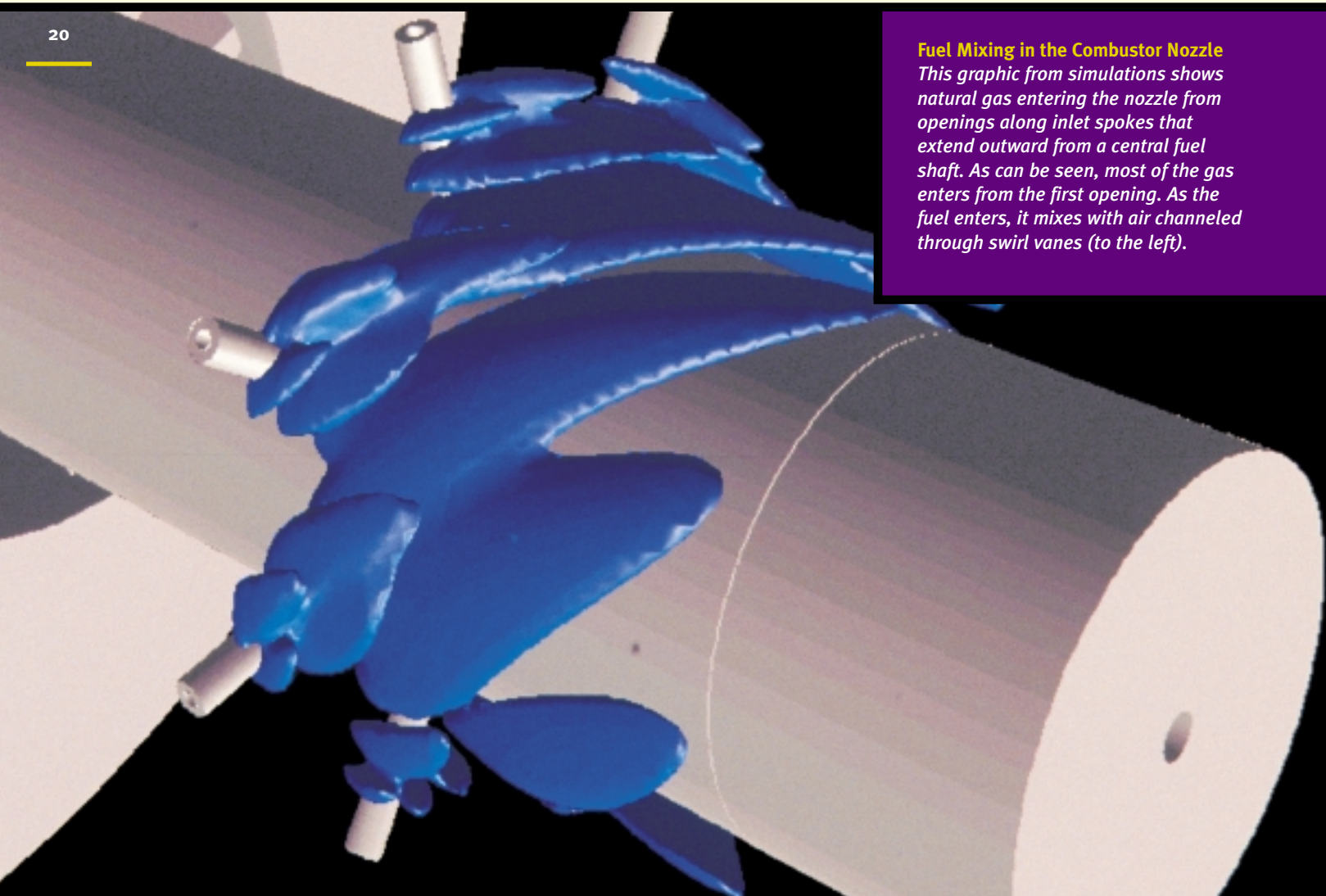
“We don’t know which occurs in practical systems,” says Richards. “We want to use these simulations and identify



▲ *William Rogers, consulting engineer, Fluent, Inc. (left) and George Richards, team leader for unsteady combustion research, National Energy Technology Laboratory.*

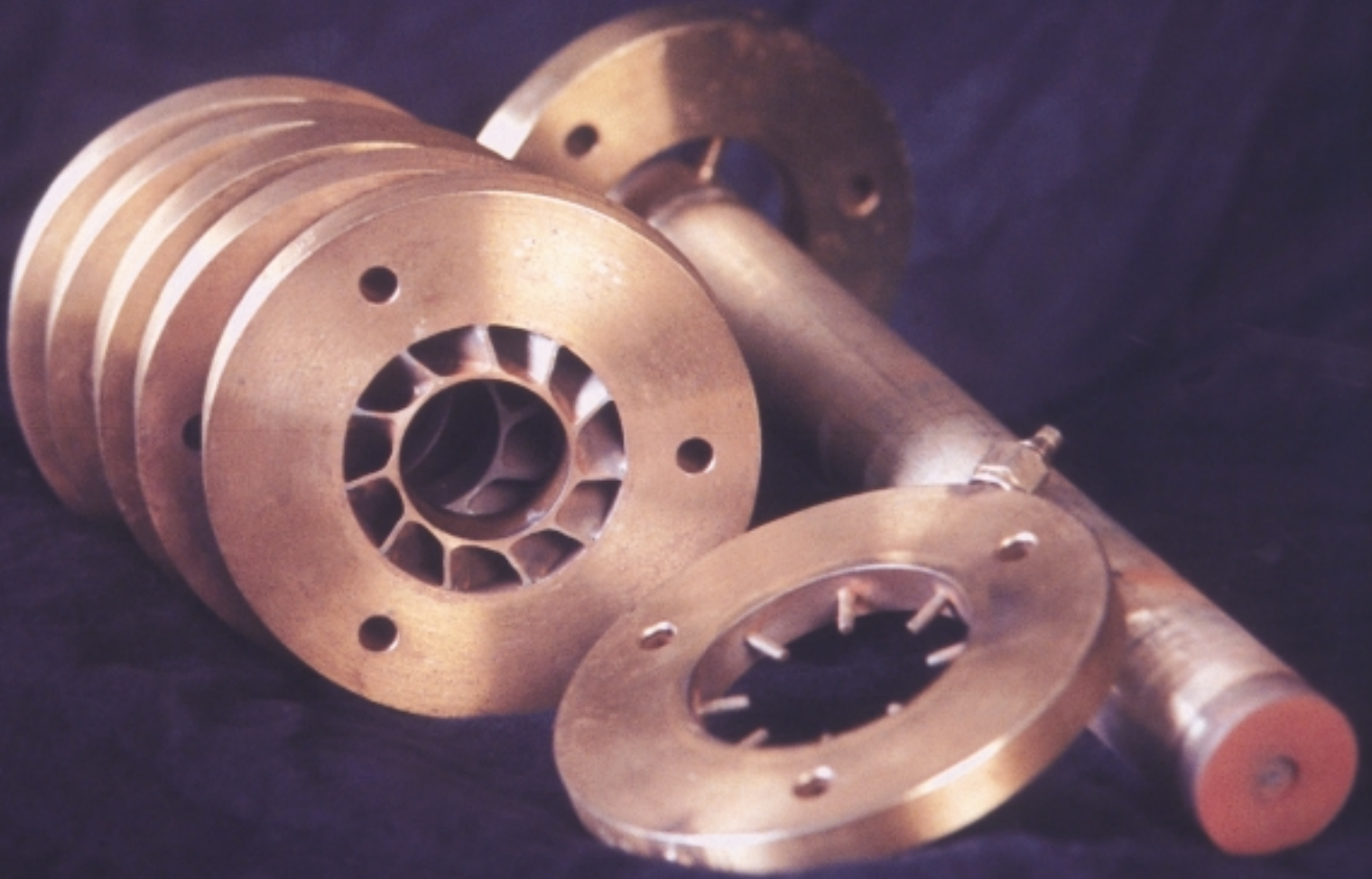
the dominant mechanism. It’s probably some of each, but is it 90/10, 50/50 or 20/80? We may find that it’s different under different conditions. That’s where the simulations really help. If we show that you go from one mechanism to the other in the same combustor, depending on operating conditions, you’d have to do different things to make the system quiet. With simulations, and going back and forth iteratively with the experiments, we’re learning a lot about fundamental physics.”

[Engineering Knowledge for 21st Century Turbines]



Fuel Mixing in the Combustor Nozzle

This graphic from simulations shows natural gas entering the nozzle from openings along inlet spokes that extend outward from a central fuel shaft. As can be seen, most of the gas enters from the first opening. As the fuel enters, it mixes with air channeled through swirl vanes (to the left).



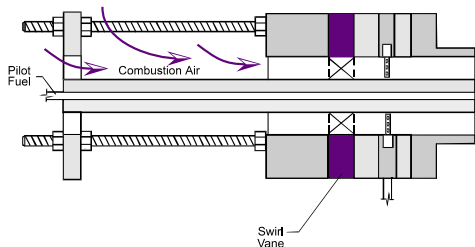
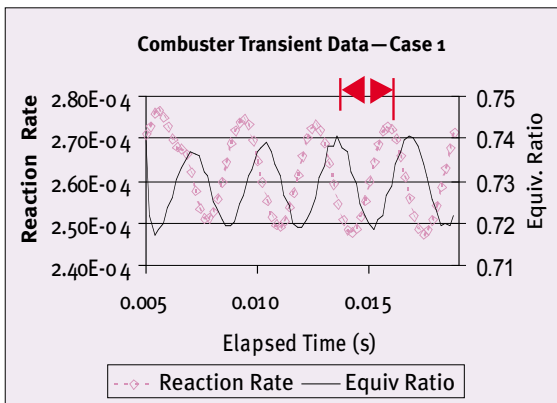
▼ Time Lag with Change in Swirl-Vane Location

Plots of reaction rate, the speed at which the fuel burns, versus equivalence ratio, which represents the amount of fuel in the air-fuel mix. In the stable case (lower right), the fuel-mix peaks correspond with reaction-rate peaks. Here the time lag between fuel injection and burning is 3.2 milliseconds, versus 2.2 milliseconds in the unstable case.

More information:

<http://www.psc.edu/science/richards.html>

Case 1 Time-lag: 2.2 ms



Case 2 Time-lag: 3.2 ms

