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Forefront

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**Pint-Sized Engine
 Packs a Bundle of Energy**
 Carlos Fernandez-Pello's tiny engine uses
 computer chip technology to generate power

The Incredible Shrinking Engine

BY SALLY STEPHENS

Two years ago, when Berkeley mechanical engineering professor Carlos Fernandez-Pello first suggested building an internal combustion engine smaller than a millimeter in size, his colleagues said it could not be done. Now, as Fernandez-Pello tests a working engine the size of a penny — an intermediate step toward the even smaller micro-engine he envisions — his colleagues have admitted how wrong they were. These days, even his critics talk about how best to use a micro-engine in everything from remote sensors to mini-rovers. And they have begun to realize just how much the tiny engines could change the way they think about power, engines, and batteries.

This potential revolution began brewing after a lecture by Berkeley mechanical engineering/electrical and computer sciences professor Albert P. Pisano, then on leave from Berkeley to work as a program manager at DARPA (Defense Advanced Research Projects Agency). Pisano's lecture on the importance of MEMS (microelectromechanical systems) research inspired Fernandez-Pello to begin thinking about using the miniaturized computer chip-making technology to generate power. As electronic and mechanical systems have diminished in size, their energy requirements have been similarly reduced. Batteries meet those power needs, but they tend to be big and bulky. Could micro-engines actually replace batteries and provide the milliwatts of power needed by MEMS-style mini-rovers and sensors?

"Micro-engines are for packing a lot of

energy in a small volume," says Pisano, whose area of expertise on this project is the design and fabrication of the engines, down to the micro-scale. "Their liquid hydrocarbon fuels, like butane, kerosene, or propane, pack at least 10 times more energy, pound for pound, than batteries do, even after taking into account how inefficiently an engine burns fuel," he says. That means, according to Pisano, that an engine could be 10 times smaller than a battery and still deliver the same amount of energy. Or, he adds, it could be the same size as a battery and last 10 times longer.

The micro-engine Fernandez-Pello decided to build was a Wankel engine, a tiny version of the rotary engine Mazda once trumpeted in its cars. At the heart of a Wankel engine is a triangular rotor that both spins and precesses — the point about which it spins also moves in a circle. As the rotor

turns, its three corners stay in constant contact with the walls of the strangely shaped combustion chamber. This causes the pocket between each side of the rotor and the chamber walls to change in volume as the rotor turns, compressing and expanding an air-fuel mixture in the pocket like pistons in a regular piston engine.

"It's very simple," Fernandez-Pello notes, "because it has only one hole in and one hole out — the intake and outtake ports." The Wankel engine has no valves that open or close, and no moving parts beyond the rotor. The revolving rotor acts like both a valve and piston, controlling the pocket's intake, compression, expansion, and exhaust. The Wankel engine is also relatively flat, crucial because MEMS technology is essentially planar. Everything fits on a chip.

But would a micro-Wankel engine work? About two years ago when Fernandez-Pello came up with the notion to give it a try, the smallest internal combustion engines were those used in model airplanes, no more than two inches across. Conventional wisdom held that combustion could not be sustained in anything smaller. The reaction, it was widely believed, would be quickly quenched or put out as the burning gas touched the cool walls of the combustion chamber. Since the ratio of surface area to volume increases as devices shrink, there is proportionately more wall surface to cool the burning gas in smaller engines, and any combustion would therefore be quickly extinguished.

Fernandez-Pello, the project's principal investigator in charge of all aspects of combustion on a micro-scale, argued that if you could somehow warm the walls, quenching would no longer be a problem. "Pello's a brave guy," Pisano says. "He put his neck on the line." Fernandez-Pello was able to show experimentally that there were several ways to warm the walls by stacking engines so they heat each other, or by recycling

exhaust. He proved that sustained combustion was possible on scales 10 to 20 times smaller than the experts had thought.

Teaming up with Pisano (who now holds the prestigious FANUC Chair of Mechanical Systems and is director of the Electronics Research Laboratory), and Berkeley bioengineering/mechanical engineering professor and micro-fluidics expert Dorian Liepmann, the team set out to build a prototype micro-engine.

They decided to split the three-year, DARPA-funded project into two phases. They would begin by building a mini-engine no bigger than a penny. This intermediate step would allow them to learn about and solve the problems sure to arise in shrinking a Wankel engine. Then later, when they knew better what they were dealing with, they would reduce the size of the engine even more. Their eventual goal: to build a micro-engine smaller than a millimeter square.

In building the mini-engine, the team found that they had to design not only the engine, but all the peripheral equipment, from small-scale dynamometers, clutches, and ignition systems, to testing machines. "On the one hand, all this has created more problems that we have to solve," Fernandez-Pello notes. "On the other hand, we are developing a new field."

The penny-sized mini-engine, fabricated out of metal in the mechanical engineering department's machine shop, now runs under its own power. "We're getting some energy out," Pisano says. "And we're working on improving the engine efficiency." Initially, the team used a hydrogen and oxygen fuel mixture because it was easier to ignite. Now they are switching to hydrocarbon fuels, which are easier to handle. And they are tinkering with the ignition timing and rotor sealing, among other things, trying to optimize the workings of the mini-engine.



"We're in the business of shrinking," says Carlos Fernandez-Pello, holding a working model of the mini-combustion engine test bench. Shown here is not only the penny-sized engine (see highlight), but all the peripheral equipment from small-scale clutches and ignition systems to a dynamometer for measuring power output. The mini-engine runs partially under its own power.

BRUCE COOK

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“Fuel efficiently burned still whomps the daylights out of batteries.”

Fernandez-Pello originally saw the mini-engine as just one step toward the smaller MEMS micro-engine. He was surprised to discover industry's apparent interest in the mini-engine on its own as a device capable of generating a few watts of power. “What started out as a scientific tool,” he says, “has become a marketable device.”

The transition from the mini- to the micro-engine, however, has not gone as smoothly as Fernandez-Pello had hoped. Because of its tiny size, the micro-engine requires MEMS fabrication technology similar to that of computer chip manufacturers. In the case of the micro-engine, that means cutting the rotor and combustion chamber from a ceramic silicon carbide wafer. It sounds simple, but is extremely difficult to do with the required high precision.

Unfortunately, the rotors manufactured to date have been slightly uneven and do not turn smoothly enough in the chamber. “I was naive because I thought that MEMS fabrication, which had been around for five or six years, was developed enough to make this,” Fernandez-Pello admits. “I thought all I had to do was solve the thermodynamic, heat transfer, and combustion problems. Turns out,” he says, “the fabrication is the problem that's been the most limiting for us.”

The team continues to struggle through those limitations to make the micro-engine. As they push MEMS fabrication technology to its limits and beyond, they remain confident the problems will be worked out. “We make a little bit of progress each semester,” Pisano says.

And they are not working without competition. A group at Georgia Tech is working on a combustion-driven magnetic free piston; another at Honeywell is at work on

a tiny piston engine; and a team at MIT is pursuing a mini-turbine engine. To date, none of them have successfully built a fully functioning system.

All four teams remain committed to developing tiny internal combustion engines they believe will eventually replace batteries as an energy source for many low-power needs from laptops to cellular phones. This is a distinct possibility, because by using hydrocarbon fuels, these engines could produce at least 10 times more energy per pound than standard batteries can generate. One cubic millimeter of kerosene, about the same volume as four dandelion seed pods, can generate a milliwatt of power for one hour. And that assumes that no more than 10 percent of the fuel's energy is actually converted to power, a figure that is small

for standard internal combustion engines. Pisano notes that just one fluid ounce of kerosene, some 29,000 cubic millimeters – the size of a small, hotel-sized bottle of shampoo – could generate enough power to run a digital wristwatch for 1,466 years.

“If you're talking about power per pound of fuel,” he says, “fuel inefficiently burned still whomps the daylights out

of batteries.” Because of this, micro-engines should prove particularly effective anywhere you need small, long-lasting power sources, such as in satellites, or for remote or autonomous systems or sensors.

In addition to their miniature size and huge energy potential, micro-engines should be relatively inexpensive. “MEMS is based on the fabrication techniques of the computer chip industry,” Fernandez-Pello explains. “The idea is to have a sensor, engine, and a controlling microprocessor manufactured simultaneously on the same chip,” he says. If micro-engines could be

mass-produced like computer chips, their costs should remain relatively low, according to Fernandez-Pello. And that, in turn, could influence the way micro-engines are used.

The military already has an eye on using micro-engines to power mini-sensors able to sniff out biological weapons in battle zones. If the micro-engine-powered mini-sensors are relatively cheap, the military could drop large numbers onto an area before troops arrive. The sheer numbers of sensors dropped would ensure that enough survive to send back useful, and potentially life-saving, information.

Other applications involve using the torque generated by the micro-engine's moving rotor to turn the wheels or engine blades of micro-rovers or mini-airplanes. Perhaps one day, says Fernandez-Pello, every soldier will carry a small personal reconnaissance device (a mini-rover or mini-airplane), packed with sensors and powered by micro-engines.

Beyond a wide range of military applications are those that would affect most anyone's daily life. Pisano imagines a day when micro-engines could replace batteries in devices like laptop computers or cellular phones. “What if my laptop needed recharging only once every 45 days?” he asks. “The long life of hydrocarbon-fueled micro-engines makes that a possibility. Plus a micro-engine power pack would probably be much cheaper and lighter than today's batteries. This game is all about price and power-per-pound,” says Pisano. “And that's the micro-Wankel game.”

Ultimately, says Pisano, micro-engines could affect how we think about power. Today, an enormous electrical infrastructure is already in place, able to power household appliances from lamps to thermostats. At the same time, ongoing innovations in electronics mean these devices require less and less energy. “Much of the cost of these appliances goes into supporting the heavy-duty infrastructure required to bring energy to them. But as their energy consumption comes down, that infrastructure becomes unnecessarily expensive,” Pisano notes. “That's when a portable, self-contained energy source suddenly makes financial sense.” That is just the kind of low-power energy source micro-engines could provide.

Pisano envisions a world where every light bulb has its own micro-engine as a power source, making power cords a thing of the past. “If I want lights in my back-

yard,” says Pisano, “I'll just stick a few light bulbs on stakes wherever I need them and turn them on.” Cheap, micro-engine-powered thermostats could be taped to the wall, communicating via radio with the furnace. “When their fuel runs low, the entire thermostat could be replaced,” says Pisano. “These are the sorts of changes you'll start seeing if micro power sources are there.”

But the first order of business is to get a micro-engine up and running, an accomplishment the team thinks could happen within the next five years. “Even then,” says Liepmann, “a huge amount of research and development remains to be done before the micro-engine is ready to go to market.” One remaining concern is the exhaust. The by-products of combustion are water and carbon dioxide. “But our engine is so small,” says Fernandez-Pello. “And there is so little being burned that very little comes out, even less carbon dioxide than we exhale.”

Other problems still to be addressed include poor seals, something Wankel engines are notorious for, and one of the reasons they never caught on in automobiles. And then the additional questions remain about friction, the ignition system, and engine efficiency – concerns the team is just beginning to tackle.

Despite these unresolved issues, the team has come a long way in a remarkably short time. “Two years ago this whole thing was nothing but a twinkle in Pello's eye,” says Pisano. “He's broken ground in some really fundamental science, shattering a lot of the old rules about what the minimum size is for combustion. My gut feeling is this engine is going to work. With the results we have so far, we think we have a chance of revolutionizing the way the world works.” ■



Using a high-powered microscope hooked up to a VCR, Dorian Liepmann (rear) and Al Pisano, in clean suits and safety glasses, examine the silicon carbide micro-rotor on the monitor, checking for manufacturing tolerances and changes they could make to refine the rotor's fabrication.



Detail of the penny-sized MEMS mini-engine. On the right, the mini-engine is assembled; center and left, it is pulled apart showing the triangular rotor (center foreground), output shaft, gear, and housings.

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