THE DAINTIEST DYNAMOS

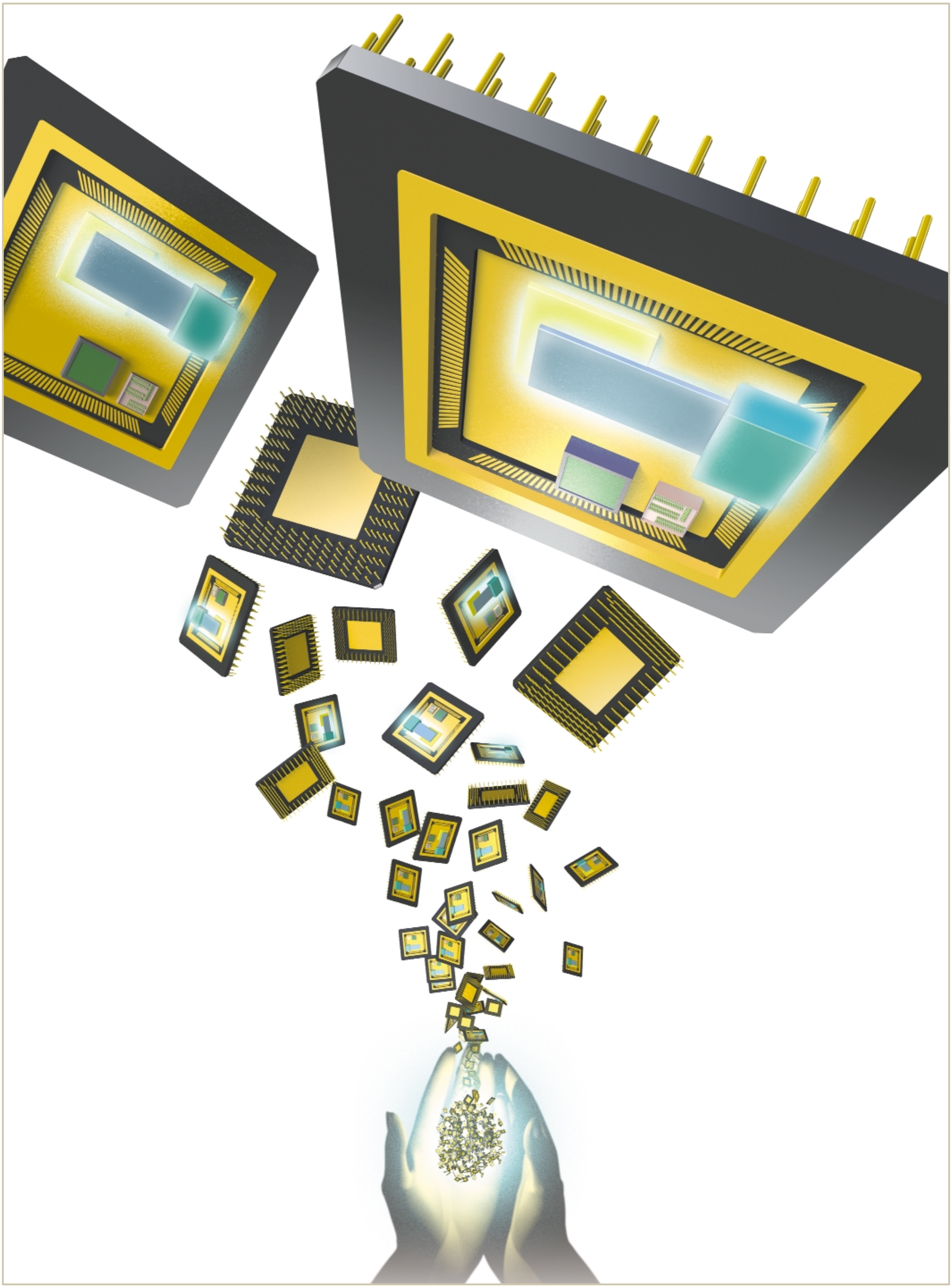
BY HARVESTING ENERGY FROM RADIOACTIVE SPECKS, NUCLEAR MICROBATTERIES COULD POWER TOMORROW'S MICROELECTROMECHANICAL MARVELS—AND MAYBE YOUR CELLPHONE, TOO

BY AMIT LAL & JAMES BLANCHARD

For several decades, electronic circuitry has been shrinking at a famously dizzying pace. Too bad the batteries that typically power those circuits have not managed to get much smaller at all.

In today's wrist-worn GPS receivers, matchbox-size digital cameras, and pocketable personal computers, batteries are a significant portion of the volume. And yet they don't provide nearly enough energy, conking out seemingly at the worst possible moment.

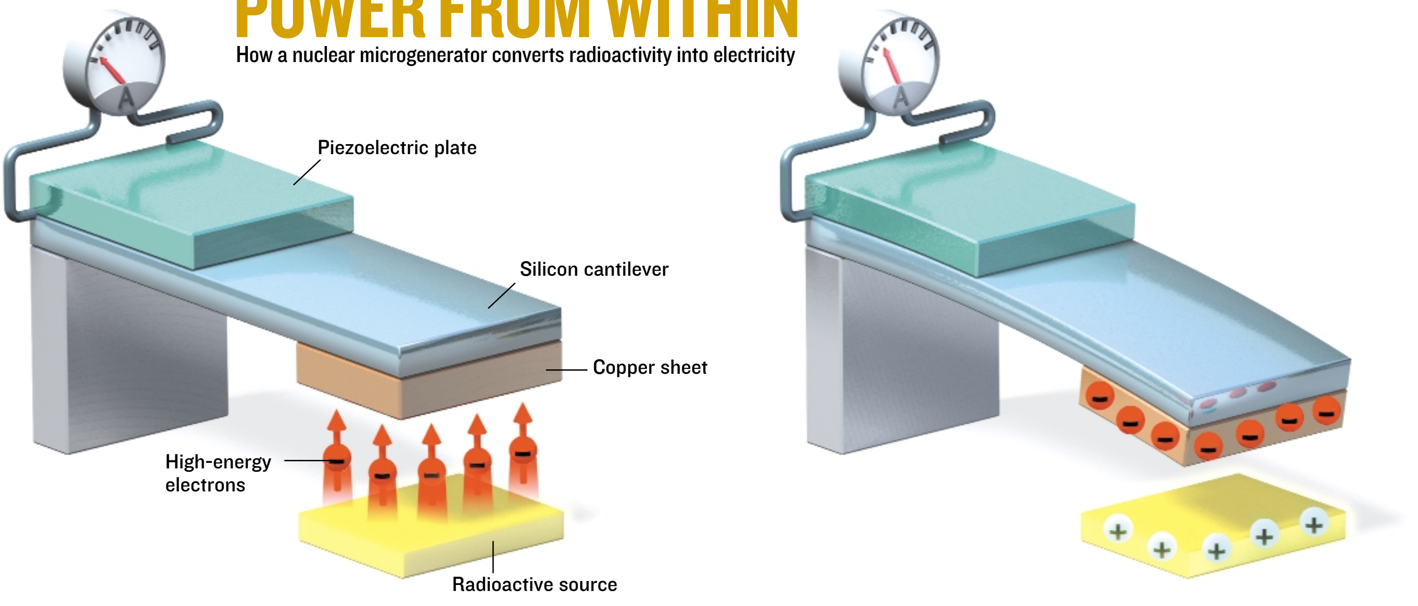
The reason is simple: batteries are still little cans of chemicals. They function in essentially the same way they did two centuries ago, when the Italian



BRYAN CHRISTIE

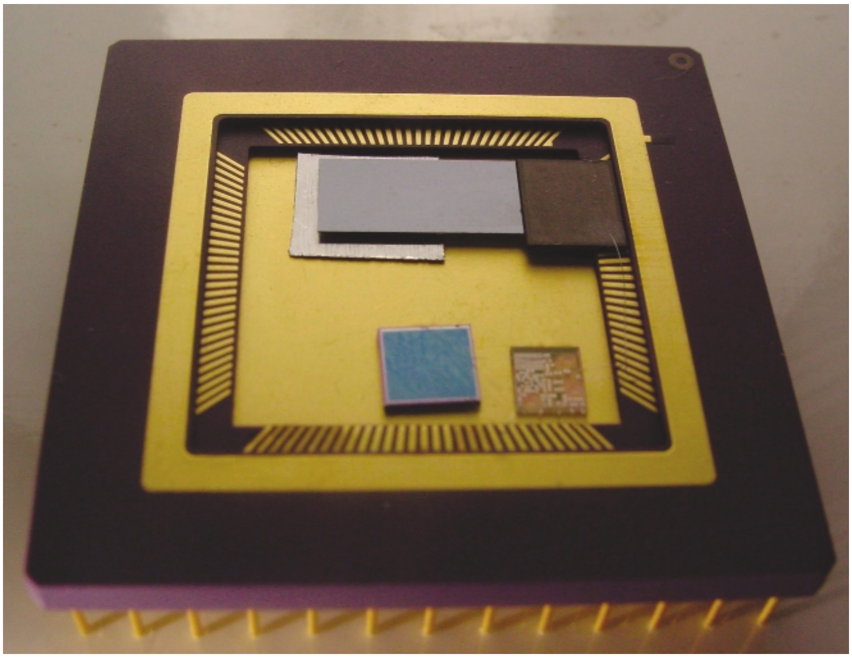
POWER FROM WITHIN

How a nuclear microgenerator converts radioactivity into electricity



1 Beta particles (high-energy electrons) fly spontaneously from the radioactive source and hit the copper sheet, where they accumulate.

2 Electrostatic attraction between the copper sheet and the radioactive source bends the silicon cantilever and the piezoelectric plate on top of it.



IT'S GOT THE POWER: A nuclear microgenerator [gray rectangular pieces] powers a simple processor [blue square] and a photodiode [smaller square]. Packaged as a chip, the device works as a self-powered light sensor for optical communications.

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physicist Alessandro Volta sandwiched zinc and silver disks to create the first chemical battery, which he used to make a frog's leg kick.

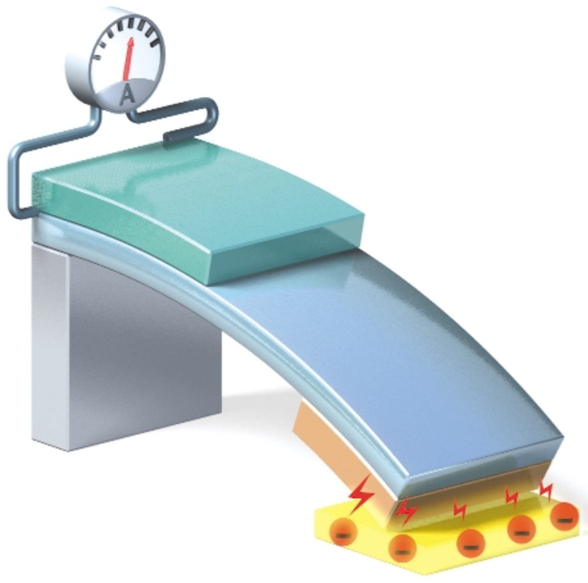
Now, with technologists busily ushering in a new age of miniaturization based on microelectromechanical systems (MEMS), batteries have arrived at a critical juncture. MEMS are finding applications in everything from the sensors in cars that trigger air bags to injectable drug delivery systems to environmental monitoring devices. Many of these systems ideally have to work for long periods, and it is not always easy to replace or recharge their batteries. So to let these miniature machines really hit their stride, we'll need smaller, longer-lasting power sources.

For several years our research groups at Cornell University and the University of Wisconsin—Madison have been working on a way around this power-source roadblock: harvesting the incredible amount of energy released naturally by tiny bits of radioactive material.

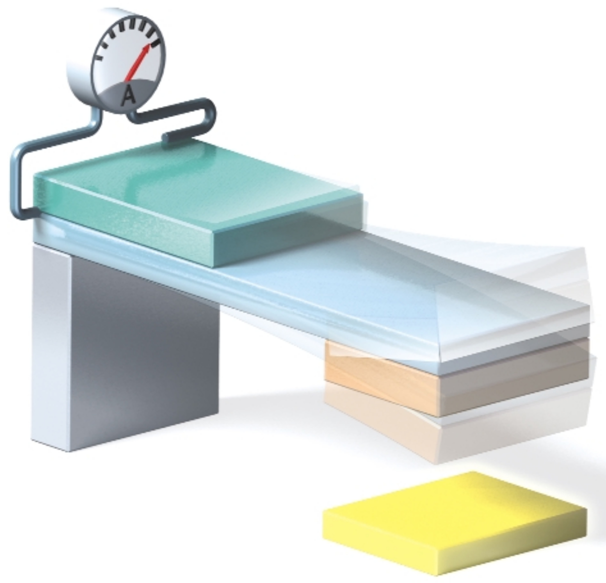
The microscale generators we are developing are not nuclear reactors in miniature, and they don't involve fission or fusion reactions. All energy comes from high-energy particles spontaneously emitted by radioactive elements. These devices, which we call nuclear microbatteries, use thin radioactive films that pack in energy at densities thousands of times greater than those of lithium-ion batteries [see table, "Energy Content"].

A speck of a radioisotope like nickel-63 or tritium, for example, contains enough energy to power a MEMS device for decades, and to do it safely. The particles these isotopes emit, unlike more energetic particles released by other radioactive materials, are blocked by the layer of dead skin that covers our bodies. They penetrate no more than 25 micrometers in most solids or liquids, so in a battery they could safely be contained by a simple plastic package [see sidebar, "Not All Radioisotopes Are Equal."]

Our current prototypes are still relatively big, but like the first transistors they will get smaller, going from macro- to microscale devices. And if the initial applications powering MEMS devices go well, along with the proper packaging and safety considerations, lucrative uses in handheld devices could be next. The small nuclear batteries may not be able to provide enough electric current for a cellphone or a PDA, but our experiments so far suggest that several of these nuclear units could be used to trickle charges into the conventional chemical rechargeable batteries used in handheld devices. Depending on the power consumption of



3 When the cantilever bends to the point where the copper sheet touches the radioactive source, the electrons flow back to it, and the attractive force ceases.



4 The cantilever then oscillates, and the mechanical stress in the piezoelectric plate creates an imbalance in its charge distribution, resulting in an electric current.

these devices, this trickle charging could enable batteries to go for months between recharges, rather than days, or possibly even to avoid recharges altogether.

“IT IS A STAGGERINGLY SMALL WORLD THAT IS BELOW,” said physicist Richard P. Feynman in his famous 1959 talk to the American Physical Society, when he envisioned that physical laws allowed for the fabrication of micro- and nanomachines and that one day we would be able to write the entire *Encyclopaedia Britannica* on the head of a pin.

Feynman’s vision has finally begun to materialize, thanks to ever more sophisticated microelectronics. Micro- and nanoscale machines are poised to become a multibillion-dollar market as they are incorporated in all kinds of electronic devices. Among the revolutionary applications in development are ultradense memories capable of storing hundreds of gigabytes in a fingernail-size device, micromirrors for enhanced displays and optical communications equipment, and highly selective RF filters to reduce cellphone size and improve the quality of calls.

Nuclear batteries can pack in energy at densities THOUSANDS OF TIMES greater than those of lithium-ion batteries

But, again, at very small scales, chemical batteries can’t provide enough juice to power these micromachines. As you reduce the size of such a battery, the amount of stored energy goes down exponentially. Reduce each side of a cubic battery by a factor of 10 and you reduce the volume—and therefore the energy you can store—by a factor of 1000. In fact, researchers developing sensors the size of a grain of sand had to attach them to batteries they couldn’t make smaller than a shirt button.

IN THE QUEST TO BOOST MICROSCALE POWER GENERATION, several groups have turned their efforts to well-known energy sources, namely hydrogen and hydrocarbon fuels such as propane, methane, gasoline, and diesel. Some groups are developing microfuel cells that, like their macroscale counterparts, consume hydrogen to produce electricity. Others are developing on-chip combustion engines, which actually burn a fuel like gasoline to drive a minuscule electric generator.

There are three major challenges for these approaches. One is that these fuels have relatively low energy densities, only about five to 10 times that of the best lithium-ion batteries. Another is the need to keep replenishing the fuel and eliminating byproducts. Finally, the packaging to contain the liquid fuel makes it difficult to significantly scale down these tiny fuel cells and generators.

The nuclear microbatteries we are developing won’t require refueling or recharging and will last as long as the half-life of the radioactive source, at which point the power output will decrease by a factor of two. And even though their efficiency in converting nuclear to electrical energy isn’t high—about 4 percent for one of our prototypes—the extremely high energy density of the radioactive materials makes it possible for these microbatteries to produce relatively significant amounts of power.

For example, with 10 milligrams of polonium-210 (contained in about 1 cubic millimeter), a nuclear microbattery could produce 50 milliwatts of electric power for more than four months (the half-life of polonium-210 is 138 days). With that level of power, it would be possible to run a simple microprocessor and a handful of sensors for all those months.

And the conversion efficiency won’t be stuck at 4 percent forever. Beginning this past July we started working to boost the efficiency to 20 percent, as part of a new Defense Advanced Research Projects Agency program called Radio Isotope Micro-power Sources.

Space agencies such as NASA in the United States have long recognized the extraordinary potential of radioactive materials for

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generating electricity. NASA has been using radioisotope thermoelectric generators, or RTGs, since the 1960s in dozens of missions, like Voyager and, more recently, the Cassini probe, now in orbit around Saturn. Space probes like these travel too far away from the sun to power themselves with photovoltaic arrays.

RTGs convert heat into electricity through a process known as the Seebeck effect: when you heat one end of a metal bar, electrons in this region will have more thermal energy and flow to the other end, producing a voltage across the bar. Most of NASA's washing-machine-size RTGs use plutonium-238, whose high-energy radiation can produce enormous heat.

But as it turns out, RTGs don't scale down well. At the diminutive dimensions of MEMS devices, the ratio between an object's surface and its volume gets very high. This relatively large surface makes it difficult to sufficiently reduce heat losses and maintain the temperatures necessary for RTGs to work. So we had to find other ways of converting nuclear into electric energy.

ENERGY CONTENT

TECHNOLOGY	ENERGY DENSITY (MILLIWATT-HOURS/MILLIGRAM)
Lithium-ion in a chemical battery	0.3
Methanol in a fuel cell*	3
Tritium in a nuclear battery**	850
Polonium-210 in a nuclear battery**	57 000

*Assuming 50 percent efficiency
**Assuming 8 percent efficiency and 4 years of operation

ONE OF THE MICROBATTERIES WE DEVELOPED early last year directly converted the high-energy particles emitted by a radioactive source into an electric current. The device consisted of a small quantity of nickel-63 placed near an ordinary silicon *p*-*n* junction—a diode, basically. As the nickel-63 decayed, it emitted beta particles, which are high-energy electrons that spontaneously fly out of the radioisotope's unstable nucleus. The emitted beta particles ionized the diode's atoms, creating paired electrons and holes that are separated at the vicinity of the *p*-*n* interface. These separated electrons and holes streamed away from the junction, producing the current.

Nickel-63 is ideal for this application because its emitted beta particles travel a maximum of 21 μm in silicon before disintegrating; if the particles were more energetic, they would travel longer distances, thus escaping the battery. The device we built was capable of producing about 3 nanowatts with 0.1 millicurie of nickel-63, a small amount of power but enough for applications such as nanoelectronic memories and the simple processors for environmental and battlefield sensors that some groups are currently developing.

The new types of microbatteries we are working on now can generate substantially more power. These units produce electricity indirectly, like minute generators. Radiation from the sample is converted first to mechanical energy and then to oscillating pulses of electric energy. Even though the energy has to go through the intermediate, mechanical phase, the batteries are no less efficient; they tap a significant fraction of the kinetic energy of the emitted particles for conversion into mechanical energy. By releasing this energy in brief pulses, they provide much more instantaneous power than the direct-conversion approach.

For these batteries, which we call radioactive piezoelectric generators, the radioactive source is a 4-square-millimeter thin film of nickel-63 [see illustration, "Power From Within"]. On top of it, we cantilever a small rectangular piece of silicon, its free end able to move up and down. As the electrons fly from the radioactive source, they travel across the air gap and hit the cantilever, charging it negatively. The source, which is positively charged, then attracts the cantilever, bending it down.

A piece of piezoelectric material bonded to the top of the silicon cantilever bends along with it. The mechanical stress of the bend unbalances the charge distribution inside the piezoelectric crystal structure, producing a voltage in electrodes attached to the top and bottom of the crystal.

After a brief period—whose length depends on the shape and material of the cantilever and the initial size of the gap—the cantilever comes close enough to the source to discharge the accumulated electrons by direct contact. The discharge can also take place through tunneling or gas breakdown. At that moment, electrons flow back to the source, and the electrostatic attractive force vanishes. The cantilever then springs back and oscillates like a diving board after a diver jumps, and the recurring mechanical deformation of the piezoelectric plate produces a series of electric pulses.

The charge-discharge cycle of the cantilever repeats continuously, and the resulting electric pulses can be rectified and smoothed to provide direct-current electricity. Using this cantilever-based power source, we recently built a self-powered light sensor [see photo, "It's Got the Power"]. The device contains a simple processor connected to a photodiode that detects light variations.

Also using the cantilever system, we developed a pressure sensor that works by "sensing" the gas molecules in the gap between the cantilever and the source. The higher the ambient pressure, the more gas molecules in the gap. As a result, it is more difficult for electrons to reach and charge the cantilever. Hence, by tracking changes in the cantilever's charging time, the sensor even detects millipascal variations in a low-pressure environment like a vacuum chamber.

To get the measurements at a distance, we made the cantilever work as an antenna and emit radio signals, which we could receive meters away—in this application the little machine was "radio active" in more ways than one. The cantilever, built from a material with a high dielectric constant, had metal electrodes on its top and bottom. An electric field formed inside the dielectric as the bottom electrode charged. When it discharged, a charge imbalance appeared in the electrodes, making the electric field propagate along the dielectric material. The cantilever thus acted like an antenna that periodically emitted RF pulses, the interval between pulses varying accordingly to the pressure.

What we'd like to do now is add a few transistors and other electronic components to this system so that it can not only send simple pulses but also modulate signals to carry information. That way, we could make MEMS-based sensors that could communicate with each other wirelessly without requiring complex, energy-demanding communications circuitry.

NUCLEAR MICROBATTERIES MAY ULTIMATELY CHANGE the way we power many electronic devices. The prevalent power source paradigm is to have all components in a device's circuitry drain energy from a single battery. Here's another idea: give each component—sensor, actuator, microprocessor—its own nuclear microbattery. In such a scheme, even if a main battery is still necessary for more power-hungry components, it could be considerably smaller, and the multiple nuclear microbatteries could run a device for months or years, rather than days or hours.

One example is the RF filters in cellphones, which now take

NOT ALL RADIOISOTOPES ARE EQUAL

Nuclear microbatteries contain only small amounts of radioactive material, but safety is nonetheless a crucial issue. It is important first to note that not all radioisotopes are alike. The level of radioactivity depends on the type and amount of the radioisotope.

Radioisotopes are unstable atoms that spontaneously emit high-energy particles as they decay to a more stable state. Most emit gamma rays, which are essentially high-energy X-rays that can penetrate most materials, including human flesh. But other radioisotopes emit alpha particles (an aggregate of two protons and two neutrons) and beta particles (high-energy electrons) that can't penetrate as deeply and therefore pose less risk.

The nuclear microbatteries we are developing contain 1 to 10 millicuries of nickel-63 or tritium, whose beta particles have relatively low energy and can be blocked by a layer of 25 to 100 micrometers of plastic, metal, or semiconductor; they are also blocked by the thin dead-skin layer covering our bodies.

Other than shielding considerations, safety concerns also involve the possibility of a release of the radioisotope into the environment and subsequent inhalation or ingestion. Again, by limiting the amount of radioisotope and by using the proper packaging, it is possible to ensure that such nuclear microbatteries offer minimal risk to the public.

In fact, radioisotopes have been used for decades in commercial applications. Many smoke detectors contain 1 to 5 microcuries of americium-241, used to ionize the air between a pair of parallel plates. (The detector measures the degree of ionization between the plates; when smoke enters the gap, it changes the ionization, which activates the alarm.) And some emergency exit signs in public buildings, schools, and auditoriums that have to remain visible during power outages contain 8 to 10 curies of tritium, whose emitted electrons excite phosphor atoms, illuminating the sign.

The amount of radioactive material in the nuclear batteries we are developing falls between those in a smoke detector and in an exit sign. And for whatever amount, any commercial application of such nuclear batteries would have to take into account all required safety measures, including designing safe packaging and following regulations about handling and disposing of the device and its components.

—A.L. & J.B.

TOP: SRB TECHNOLOGIES INC.; BOTTOM: HEMEVA TECHNOLOGIES/ALAMY

up a lot of space in handsets. Researchers are developing MEMS-based RF filters with better frequency selectivity that could improve the quality of calls and make cellphones smaller. These MEMS filters, however, may require relatively high dc voltages, and getting these from the main battery would require complicated electronics. Instead, a nuclear microbattery designed to generate the required voltage—in the range of 10 to 100 volts—could power the filter directly and more efficiently.

Another application might be to forgo the electrical conversion altogether and simply use the mechanical energy. For example, researchers could use the motion of a cantilever-based system to drive MEMS engines, pumps, and other mechanical devices. A self-powered actuator could be used, for instance, to move the legs of a microscopic robot. The actuator's motion—and the robot's tiny steps—would be adjusted according to the charge-discharge period of the cantilever and could vary from hundreds of times every second to once per hour, or even once per day.

THE FUTURE OF NUCLEAR MICROBATTERIES depends on several factors, such as safety, efficiency, and cost. If we keep the amount of radioactive material in the devices small, they emit so little radiation that they can be safe with only simple packaging. At the same time, we have to find ways of increasing the amount of energy that nuclear microbatteries can produce, especially as the conversion efficiency begins approaching our targeted 20 percent. One possibility for improving the cantilever-based system would be to scale up the number of cantilevers by placing several of them horizontally, side by side. In fact, we are already developing an array about the size of a postage stamp containing a million cantilevers. These arrays could then be stacked to achieve even greater integration.

Another major challenge is to have inexpensive radioisotope power supplies that can be easily integrated into electronic devices. For example, in our experimental systems we have been using 1 millicurie of nickel-63, which costs about US $25—too much for use in a mass-produced device. A potentially cheaper alternative would be tritium, which some nuclear reactors produce in huge quantities as a byproduct. There's no reason that the amount of tritium needed for a microbattery couldn't cost just a few cents.

Once these challenges are overcome, a promising use for nuclear microbatteries would be in handheld devices like cellphones and PDAs. As mentioned above, the nuclear units could trickle charge into conventional batteries. Our one-cantilever system generated pulses with a peak power of 100 milliwatts; with many more cantilevers, and by using the energy of pulses over periods of hours, a nuclear battery would be able to inject a significant amount of current into the handheld's battery.

How much that current could increase the device's operation time depends on many factors. For a cellphone used for hours every day or for a power-hungry PDA, the nuclear energy boost won't help much. But for a cellphone used two or three times a day for a few minutes, it could mean the difference between recharging the phone every week or so and recharging it once a month. And for a simple PDA used mainly for checking schedules and phone numbers, the energy boost might keep the batteries perpetually charged for as long as the nuclear material lasts.

Nuclear microbatteries won't replace chemical batteries. But they're going to power a whole new range of gadgetry, from nanorobots to wireless sensors. Feynman's "staggeringly small world" awaits. ■