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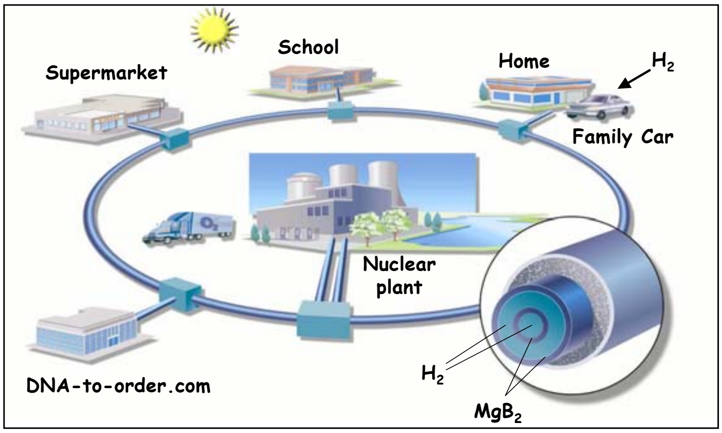
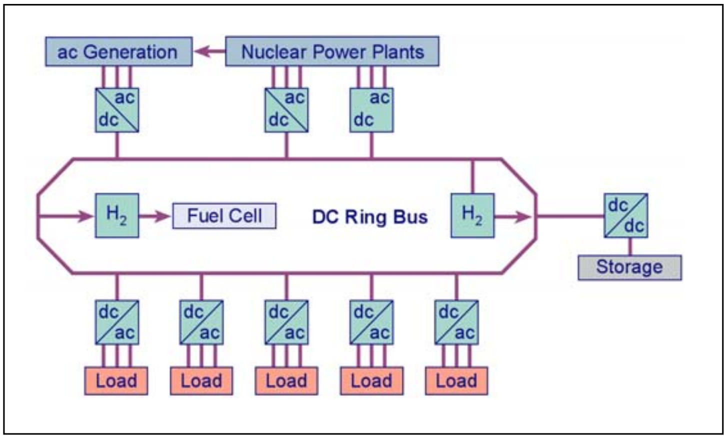
Energy for the Society of the Future

A Symbiosis of Nuclear/Hydrogen/Superconductivity Technologies for Carbon-free, Non-Intrusive Energy for an Industrialized Planet Earth

Based on Articles and Letters Published in Recent Issues of The Industrial Physicist



SuperCity



SuperGrid

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- “MgB_2 – Will It Work?” The Industrial Physicist, Oct-Nov 2001, p. 22.
- “Energy for the City of the Future,” The Industrial Physicist, Feb-Mar 2002, p.22.
- “Letters-to-the Editor,” The Industrial Physicist, Apr-Mar 2002, p. 4.
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by Paul M. Grant

Will MgB_2 Work?

In January, Japanese researchers announced the discovery of superconductivity near 40 K in magnesium diboride (MgB_2), a material that has been around since the 1950s (*Nature* **2001**, *410*, 64). The discovery proves the maxim: if you run across a new metal, or an old one, cool it down. You might get a pleasant surprise.

Superconductivity in MgB_2 engendered a special evening session at the March American Physical Society (APS) meeting in Seattle—dubbed Woodstock West by veterans of the 1987 APS session in New York on high-T_c superconductivity. Most indications now suggest that MgB_2 is the ultimate strong-phonon-coupled superconductor. In such a system, the charge carriers (holes or electrons) are paired together by lattice vibrations (phonons), as explained by the Bardeen-Cooper-Schrieffer (BCS) theory proposed in 1956. This pairing is in contrast to the high-T_c (up to 164 K) copper oxide compounds in which many believe excitations of copper d electrons mediate the pairing of charge carriers in a manner not yet understood.

Several talks in Seattle supported the BCS theory as the explanation for MgB_2's superconductivity. The Ames Laboratory–Iowa State University collaboration reported a classic isotope shift of the superconducting transition temperature upward by 1 K on replacement of all boron by the lighter isotope ^{10}B. In the BCS theory, the lattice vibrations, which pair the charge carriers, depend on the mass of the constituent atoms.

The Ames group and the University of Wisconsin–Princeton University collaboration independently reported that MgB_2 appears scalable to inexpensive wire manufacture (Figure 1). Paul Canfield detailed the Ames work on a method for thermally diffusing Mg into commercially available boron fibers. The resulting "wires" yielded encouragingly high critical current densities. David Larbalestier of the University of Wisconsin–Madison revealed that—unlike the superconducting copper oxide perovskites—there was a remarkable absence of "weak-link" behavior in the applied magnetic field. That is, the connectivity between MgB_2 grains is good enough to allow the robust flow of superconductivity in substantial applied magnetic fields.

Initially, work by David Caplin and his co-workers at Imperial College in London indicated that flux creep—the unimpeded motion of vortices in a type II superconductor that results in power dissipation and loss—was quite large in pristine MgB_2, even substantially below its transition temperature. However, they reported new data in Seattle, which indicated that flux creep essentially stabilizes by 25 K when irradiated with "atomic particles." The Imperial College group has since revealed that it used proton bombardment of up to 2 MeV in kinetic energy.

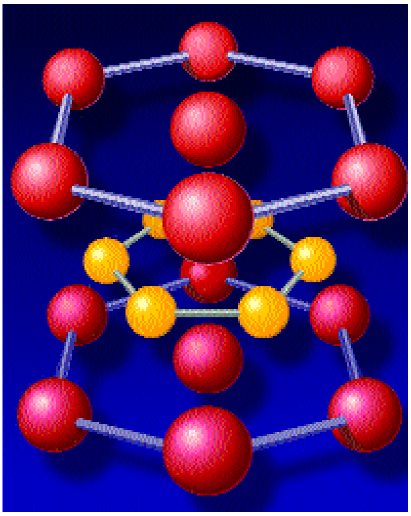

Ian Warpole

Figure 1. Will the crystal structure of magnesium (red) diboride (yellow) lend itself to the production of superconducting electric cables?

It has been known for some time that bombardment of ^{11}B by protons results in a "light fission" reaction yielding three energetic alpha particles. I would suggest that the particles' kinetic energy "rips up" the MgB_2 crystal lattice and produces pinning centers—lattice defects that help stabilize the dissipative flow of vortices.

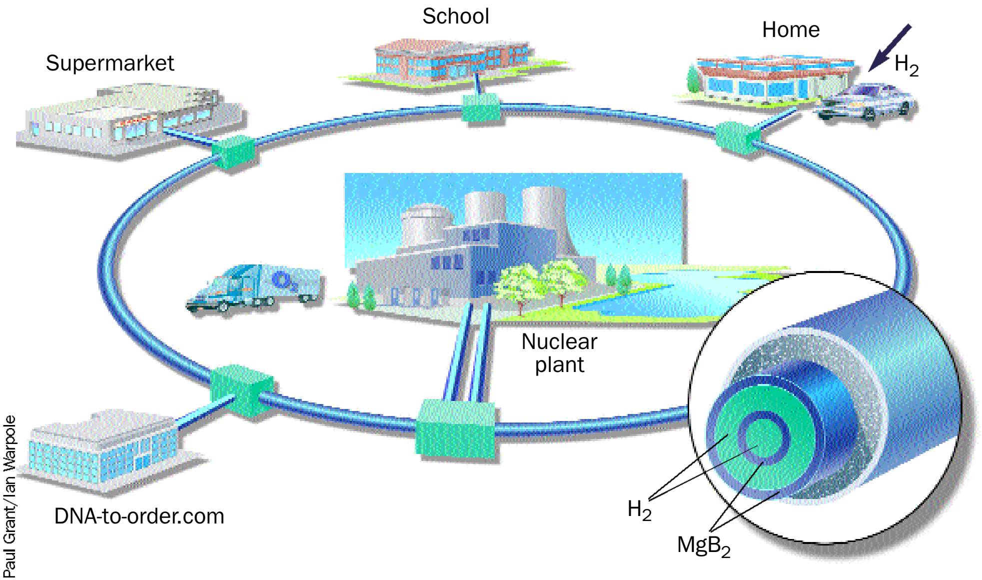
The boiling point of liquid nitrogen, 77 K, is not a necessary operating temperature for many power applications, electric cables excepted (maybe). The reason: at the high magnetic fields that the noncable applications encounter, neither current Generation I bismuth–strontium–calcium–copper oxide/silver oxide-powder-in-tube superconductors nor projected Generation II superconductors coated with yttrium–barium–copper oxide can conduct much current at 77 K.

However, power cables require a liquid cryogen for heat removal because of the long distance (1–2 km) they span without direct refrigeration support, the low magnetic fields involved, and especially their inherent power losses under ac operation.

Superconductors are only "perfect conductors" at dc; under ac operation, there are hysteretic losses similar to those in the iron cores of transformers. Thus, the situation could be radically different for dc transmission cables. It is hard to pick an "average operating point," but for an early evaluation of MgB_2's promise for power usage, I chose a temperature of 25 K and a magnetic flux density of 1 T. This combination is close to the operating range targeted for Generation I high-T_c tape for transformers and rotating machinery.

The figure of merit for superconducting wire, the cost/performance (C/P), is in units of currency per kiloampere of critical current per meter, or \$/kA·m, stated at a particular operating temperature, typically 2/3 of its transition temperature and operating magnetic field. For comparison, the C/P of niobium–titanium (NbTi) is roughly \$1/kA·m at 4.2 K and 2 T, and that of niobium–tin (Nb_3Sn) is about \$10/kA·m at 4.2 K and 10 T. The present C/P of Generation I high-T_c tape is \$200/kA·m at 77 K at 0.005 T, and is expected to drop to \$50/kA·m as production capacity and sales increase. By scaling this last number to 25 K and 1 T for comparison with MgB_2, we obtain a C/P of \$20/kA·m. Thus, the engineering economics involved in designing a particular superconducting power device is a trade-off between the wire C/P at a desired operating point and the cost of cryogenics.

For MgB_2, materials costs are relatively easy to estimate using metal commodity-



Paul Grant/Ian Warpole

Figure 2. An emissions-free, light industrial/residential community of the future uses nuclear power, with hydrogen and dc electric energy supplied via a cryo/superconducting delivery system.

exchange data for magnesium and borax, the ore for metallic boron. It is more difficult to gauge nonmaterials production costs. MgB_2 is an intermetallic, and although it is brittle, a recent paper (*Nature* 2001, *411*, 53) suggests that it may be amenable to swaging, drawing, and postprocessing methods much like those used for NbTi and Nb_3Sn, the workhorse low-T_c wires used in magnetic resonance imaging (MRI) magnets and research applications.

I took the nonmaterials cost of NbTi at $0.225/m as a ballpark figure for MgB_2 because the manufacturing techniques for MgB_2 will likely be similar. I also assumed a wire center-core cross-sectional area of 2 mm^2, all of which is superconducting. What is more problematic is the critical current density, because it is changing (upward) almost weekly. For now, I will use the number 100,000 A/cm^2, 25 K, 1 T, as reported in July by a University of Geneva team at a cryogenics meeting in Madison, Wisconsin.

The materials costs of Mg and B will not play as big a role as Nb in NbTi and Ag in other high-temperature superconductors. In arriving at a total C/P of $0.45/kA·m, I have assumed an extraction cost of $10/kg ($0.01/g) to chemically reduce raw boron pentahydrate to metallic boron, and a similar amount to subsequently react Mg and B for wire processing. Admittedly, these numbers are wet-fingers-in-the-wind estimates and could wind up substantially in error, but let's say they represent a lower limit. As an upper limit, I estimate the purchase price of commercially prepared MgB_2, presently $750/kg, to drop to $300/kg with future volume demand. This yields a C/P for MgB_2 wire in the range of 0.16 to $0.88/kA·m, 25 K, 1 T. When we compare this result with $20/kA·m for Generation I tape, we see that MgB_2 wire would be competitive for power devices such as transformers and rotating machinery, in which high-T_c superconductors would need to be cooled to operate properly. Furthermore, MgB_2 wire could potentially replace NbTi in future MRI magnets.

But what about something "far out" that MgB_2 might enable? The boiling point of hydrogen at atmospheric pressure is 20.13 K. Thus, one might envision liquid hydrogen or cold hydrogen gas as a cryogen for an MgB_2-based dc cable system delivering both electrical and chemical energy to an end user—a hydrogen–superconductivity symbiosis to enable an emissions-free energy economy in the future.

This year, at a peer-review panel meeting of the U.S. Department of Energy's Superconducting Program for Electric Power, I presented a vision of a community powered by a system based on a symbiosis of nuclear, hydrogen, and superconducting technologies (Figure 2). I placed it in a remote part of Mexico, off the power grid, and called it Laguna Genome, a greensited, biotech-industrial and residential development of 50,000 people.

The community derives its power from a 1,500-MW, pebble-bed-reactor, Generation 4 nuclear plant, one-third of whose output is used to manufacture liquid hydrogen through electrolysis of water. One could imagine an MgB_2 transmission cable loop cooled by liquid hydrogen with distribution taps to end users employing shorter high-T_c copper oxide cables using gaseous hydrogen in the 60 to 70 K range. The transition from transmission to distribution voltages, and liquid to gaseous hydrogen, would occur at substations, which would also store gaseous hydrogen at room temperature and high pressure to power substation-sited fuel cells for load peaking. Residential and industrial customers would have a choice of energy source, perhaps using electricity for its usual purposes and cold hydrogen for space conditioning (cooling and heating), cooking, and hot water, as well as in fuel-cell-powered personal and business vehicles. Additionally, hydrogen or electricity would power commuter transportation.

Several reporters present in Seattle asked how I would compare the MgB_2 discovery and the attendant commotion of 2001 with the 1987 APS session on high-T_c superconductivity. There were some similarities, including the overcrowded ballroom in Seattle and a few altercations in the foyer between latecomers and hotel security barring them from entry. There were 70 speakers, each allotted 2 minutes with 1 minute for questions (in 1987, we had 5 minutes plus another minute for questions). By the time my turn came to speak at 11:30 p.m., I jokingly remarked that I thought the field was now old enough to deserve a review talk.

Although "Woodstock West" was indeed exciting, the meeting in New York was the experience of a lifetime—until room-temperature superconductivity finally arrives.

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Energy for the City of the Future

World energy consumption is expected to grow from about 400 quads per year to more than 600 quads by 2020, a 50% increase. How to supply and configure the energy economy and infrastructure for such a world is one of the principal challenges facing civilization today. In a Forum column describing the new superconductor magnesium diboride, I hinted at a future society whose energy supply might rely on a symbiosis of nuclear, hydrogen, and superconductivity technologies (*The Industrial Physicist*, October/November 2001, pp. 22–23). SuperCity, a visionary future energy community, expands on this concept. It is based on emerging societal boundaries and constraints that can be addressed by foreseeable advances in energy science and technology. No new discoveries are assumed or needed.

Hydrogen will play a crucial role in SuperCity. Imagine a city that is approximately the size and population (about 600,000) of Seattle with roughly an equal mix of urban, suburban–residential, and light-industrial buildings—one that requires a baseline power supply from electrical and chemical sources of 1,500 MW—envisioned for existence by 2020. Hydrogen is not only a way to store electricity, but it also can function as an alternative to fossil fuels as thermal energy and aid in delivering electricity almost without loss.

Not everyone will agree with my projected World or share my selection of social constraints or my idea of the ideal, but the exercise should spotlight some of the issues and solutions for future analysis by scientists and policymakers.

Assumptions

By 2020, we will live in a world where:

- a high degree of international cooperation exists, especially with regard to weapons of mass destruction, and organized terrorism has been contained. Such a world will be necessary to provide the greatest freedom of choice among energy options with maximum security and sustainable fuel supplies.
- worldwide electricity use has soared. Today's industrialized societies consume about 215 quads per year and the rest of the world around 185 quads. By 2020, the split is expected to be 270 to 330 quads, respectively. (A quad equals 10^{15} Btu, or 3×10^{11} kW•h—enough electricity to power three cities the size of New York for a year.)
- either greenhouse-gas-driven global climate change is a confirmed scientific fact or the world's nations have adopted policies to eliminate its possibility, despite whatever uncertainties may remain.

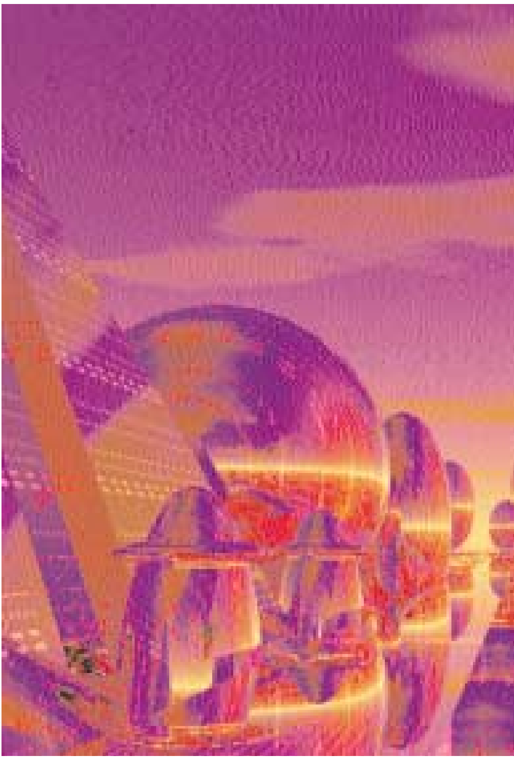
Society will only accept technology solutions that have:

- the least environmental impact, defined as minimizing or perhaps essentially eliminating pollution of the earth's land, air, and water.
- the most benign and minimal intrusion into the eco-structure possible, defined as preserving, and perhaps increasing, Earth's remaining wilderness and land reserves. I also include visual protection of SuperCity's countryside.
- the highest achievable reliability and security of energy generation, delivery, storage, and end use.

By 2020, I envision much of urban and suburban humanity living in communities modeled on various aspects of SuperCity, with energy efficiency being the common thread in all future technology deployment.

Baseline generation

Baseline power is that which is constantly available to the community. It can range from 70 to almost 100% of maximum demand, depending on importable or alternative sources. What technologies will not qualify under our guidelines as baseline supply? Unless an unanticipated breakthrough occurs in carbon dioxide sequestration, energy production by combustion of fossil fuels—oil, gas, and coal—are off the agenda. Implementing biomass—considered "zero emission" on the 1- to 25-year time scale of a chlorophyll-driven photolytic cycle—would inevitably increase land use beyond that necessary for food production. And, like coal, biomass requires continual harvesting and transport to generation centers. As we shall see, most conventional renewables do not have a place at the table either.


T's Studio

The use of hydropower for energy generation and storage involves extensive violation of the ecosystem. One would, in fact, hope that many existing reservoirs could be returned to their natural state. Wind power requires more than 75 square miles to accommodate our target baseline (at a per wind unit capacity of 1 MW spaced 1,000 ft apart). Anyone who has driven through California's Altamont Pass has observed the obfuscation of the landscape that windmills can create and the adverse implications for migratory birds. Solar farms are equally land-use intensive and esthetically unattractive. Economically accessible geothermal sources are usually found near natural geologic formations better put aside as wilderness or parks.

In terms of energy–power density—and thus, minimizing the ecological footprint, maximizing safety and security, and achieving zero greenhouse-gas emissions—nuclear fission power has no peer. In terms of sustainable fuel supply, depending on the choice of radioactinide cycle and reprocessing technology, there exist 300 to 800 years of reserves.

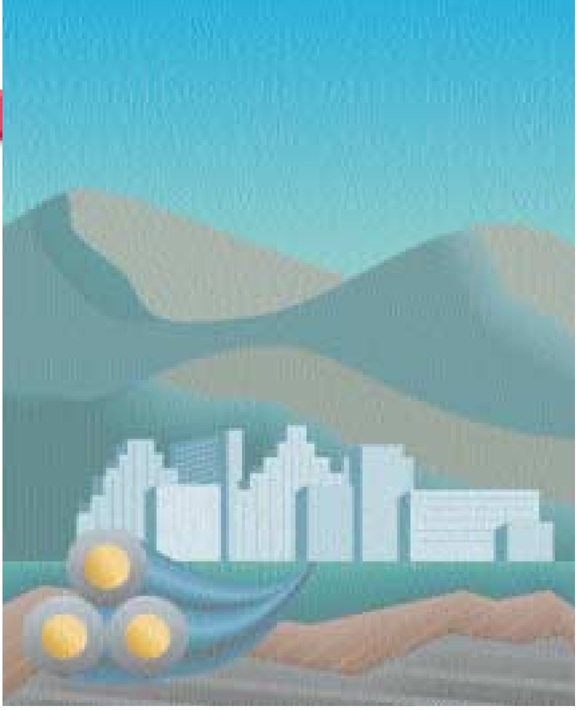
Nuclear-reactor designs based on high-temperature, helium-gas-cooled reactors are now being developed in several countries, notably South Africa, China, Germany, Great Britain, Japan, and Russia, with partial financial support from several U.S. utilities. These reactors use hot (900 °C), high-pressure helium gas derived from passage through the fissile core to drive a turbine connected to an electric generator. Unlike currently employed light water reactors, gas-cooled reactors cannot melt down if the coolant gas is lost. They are designed to dissipate excess heat by passive convection and conduction to their surroundings, and a pyrolytic graphite and silicon carbide shell protects the fuel elements to temperatures of up to 2,000 °C.

The pebble-bed variant of the gas-cooled reactor design, in which baseball-sized spheres of fuel continually flow, has received considerable attention. Spent-fuel pebbles are separated and replaced with fresh fuel in the process, eliminating downtime for refueling. I envision six modular 250-MW (electric) pebble-bed, gas-turbine helium reactors providing an optimal baseline-energy supply for SuperCity and heat for industrial use.

Renewing the nuclear option requires addressing four critical issues—accidents, attacks, disposal, and diversion. First, accidents like those at Chernobyl and Three Mile Island cannot happen with thermally passive, gas-cooled reactors. Also, such reactors do not need massive amounts of water or cooling towers, and they can be placed underground, an essential requirement since September 11, 2001. Most scientists who have studied the problem of high-level waste disposal in depth have concluded there is a vanishingly small risk of leakage and dispersal from carefully chosen repositories on any time scale human beings can intelligently comprehend. Moreover, the volume of waste requiring internment can be vastly reduced through increased deployment of breeding and reprocessing technologies. The last concern—the diversion of reactor fuel and subsidiary materials to producing weapons of mass destruction—is, in my opinion, the most serious remaining obstacle to the widespread return of nuclear power. This is why the boundary condition that world tranquility prevails is vital to the realization of SuperCity. It is absolutely necessary to control and account for every gram of actinide material used for peaceful power production, from tailings to tomb.

Supplemental generation

Baseline generation targets the power supply that must always be available. How much supplemental, or peaking, power an urban area may require depends on many variables, including weather, latitude, diurnal needs, and access to outside sources. Two potential peaking-generation options



are solar roofs and combustion of waste biomass. A large portion of the SuperCity habitat will naturally consist of buildings—industrial, commercial, and residential—whose accumulated roof area lies outside the constraint of minimizing eco-invasion of land for energy production. Assuming SuperCity contains 5,000 buildings with an average roof area of 2,000 ft^2, an installed average dc yield of crystalline silicon of 10 peak W/ft^2 will produce 100 MWe of peaking power at brightest sunlight, or about 7% of baseline. Let's also say that its inhabitants produce an average of 1.5 lb (0.7 kg) of combustible food, paper, and other organic waste daily with an energy density of 10 MJ/kg, or about 40% that of coal. For a population of 600,000, SuperCity can recover a supplemental generation capacity of around 50 MW from a resource that is in accord with both my constraints on greenhouse-gas emissions (net zero in the short term) and restrictions on land use (garbage disposal is necessary).

So by combining solar roofs with communally derived biofuels, we might expect to add a total supplemental power resource of 150 MWe to the electrical baseline. However, there will be times when the sum of the baseline and intermittent supplemental generation is either under or over demand. Clearly, a way to store electricity is needed.

It is often remarked that the Achilles' heel of electric energy is that there are few convenient ways to store it. Electricity is practically the purest form of kinetic energy, but to convert it to potential energy usually means pumping water uphill into storage reservoirs or using batteries.

Of the chemical-storage choices, hydrogen is perhaps optimum because it is readily produced from and returned to electrical kinetic energy. Both paths are necessary because hydrogen must be made from something, and the simplest source is water, H_2O. Under SuperCity's boundary conditions and constraints, hydrogen recovery from biomass or fossil sources is cheating because CO_2 would result by chemical necessity. Present hydrolysis technology is capable of 80% efficiency in converting electricity into hydrogen. I envision transforming the power output of the six modular pebble-bed reactors into hydrogen or direct electricity as needed, with the resulting ancillary oxygen released to the atmosphere or sold for industrial processes.

Energy pipeline

From the date of its discovery in 1911, physicists dreamed of using superconductivity to transmit electricity without loss. However, the current-carrying capacity of the early materials was far below the levels of conventional metallic conductors. By the late 1980s, many Type II superconductors, ranging in temperature operation between the boiling point of liquid helium and above the boiling point of liquid nitrogen, had been discovered that could transport much higher current densities. These developments led to the construction and testing of several superconducting-cable demonstrations that continue today.

Direct current is the preferred method for transmitting electricity through a superconducting cable because ac losses inherent in the physics of Type II materials can cause serious thermal heating and power dissipation. The use of high-temperature superconductors (HTSs) allows a range of possible cooling cryogens, among them liquid and cold gaseous hydrogen. The concept of SuperCity includes a combined electrical–chemical energy transmission–distribution system based on copper oxide or magnesium diboride superconducting wire and liquid hydrogen produced by baseline electricity generation for fuel delivery and as a cryogen. The hydrogen will flow through an underground transmission loop delivering 1,000 MW of electrical power and 200 MWt of hydrogen (700 MBtu/h).

Substations

In the current electric grid, a hierarchy of substations functions to reduce voltage and redistribute power on a local scale. In SuperCity, the function of the substation is expanded and modified to include the storage and generation of hydrogen by reversible fuel cells. To the storage of centrally generated hydrogen and its delivery through the energy pipeline, we add surplus power obtained from SuperCity's solar-roof and waste-biomass sources converted to hydrogen at such substations, which would then regenerate electricity to serve peak-load demands. Redistribution of electricity and hydrogen takes place at lower voltages, down-stepped by solid-state dc transformers over a local network of energy pipelines carrying gaseous hydrogen at 60 to 70 K. Hydrogen would again act as an energy delivery agent and as a cryogen for HTS cables. For security and esthetics, substations would be situated underground.

Perhaps the most unique feature of SuperCity is the consumer's choice between chemical and electric power. For example, cold hydrogen could be passed through heat exchangers to provide air conditioning before undergoing combustion for water heating and cooking. When weather conditions require space heating rather than cooling, the difference between the ambient temperature and that of delivered hydrogen would be thermoelectrically converted to electricity.

Transportation in SuperCity will fully exploit electric–hydrogen concepts. Underground rail transit will be electrically driven, while large surface vehicles will use hydrogen-based fuel cells. Personal vehicles would employ balanced hybrid battery–hydrogen technology. For commuting and local travel, ample battery capacity will sustain short hops between rechargings. For longer travel, fuel cells powered by hydrogen from on-board tanks—initially filled from the household supply and then at fueling stations en route—will get the family to distant destinations.

Energy future

SuperCity is one model of an energy-structured metropolis, from which parts can be drawn for actual application. It is a quiltlike blend of separate, relatively well-understood technologies, although cost–performance challenges remain. The concept should nonetheless prove most useful for gaining some insight into how to stitch these patches together.

Building a SuperCity would be a huge financial and engineering undertaking. Even the independent deployment of its various elements may be beyond the resources of private investment and would likely require government participation. Implementing the technologies represented in SuperCity, collectively or independently, would, I believe, require rethinking present trends in deregulating and restructuring of the electric-energy industry—its re-socialization, if you will—to ensure the timely development and use of advanced technologies in the long-term public interest.

Further reading

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Future energy

Paul Grant's article "Energy for the City of the Future," in the February/March 2002 issue of *The Industrial Physicist*, was great. It should win a prize for maximizing information per page. Even if someone wanted to disagree with the author on a point here or there (which is, after all, what makes a horse race), the article clearly defines issues that might be debated.

When I teach physics majors, I usually have the honors students do an informal energy study of the Washington, DC, metropolitan area, starting with Fermi estimates of supply and demand, then finding the actual numbers, and finally asking them questions about alternatives—what would it take to get all of the energy from hydro, solar, geothermal, and so on? Grant's article is now on the top of the reading list.

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I read "Energy for the City of the Future" with great interest. I have always been concerned about energy sources, their impact on the environment, and their long-term potentials. If the writer's assumptions are met, then he may well have a technically plausible solution for energy production and consumption. But what I do not see in his solution is any allowance for the "human factor" in a SuperCity world.

Is this city just for wage earners who can afford the energy? Where are the slums? Does industry not compete in SuperCity? Where do new office buildings and manufacturing sites go? What happens to the old ones? If people go bankrupt, are they still responsible for maintaining the thermal collectors on their rooftops, or does the energy department own and maintain those? If those are owned and maintained by the government, how does one go about expanding an existing structure? Humans and, in particular, capitalistic humans, don't fit very well into this scheme.

But the most difficult obstacle (to which the author does allude) requires us to answer yes to the famous question, "Can't we all just get along?" Unfortunately, the answer is no. So, I'm back to wondering what we are going to do about energy.

Kurt Erickson
Pendleton, South Carolina

[*Author replies*: Contrary to Mr. Erickson's view, I maintain that SuperCity is all about the "human factor." The "emerging societal boundaries and constraints" I refer to in the introduction are directly related to the human desire for sufficient energy, a protected environment, and an uncluttered ecology. Let me address a few of his points more directly.

Slums. I'm not aware of any city planner who sets aside urban plots for "slum development." In the past, such areas have resulted from a combination of social inequities and less than cost-of-living income, situations we are smart enough to eliminate with continued economic development and growth.

"Where do new office buildings and manufacturing sites go?" Where they go at present, and when local resources become saturated and further growth uneconomic, to other, new developing urban areas or SuperCities.

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T's Studio

"Ownership of rooftop energy production." Let the voters of SuperCity decide between public and private ownership. I suspect that most people would choose the latter, with the energy so produced partially offsetting the cost of grid-supplied electricity, and the capital plant being part of the structure itself (like house plumbing and wiring and many appliances), and thus transferable under conditions of sale…or bankruptcy.

"Can't we all just get along?" In a world possessing enormous numbers of weapons of mass destruction, threatened by their proliferation, with terrorism yet to be contained, the answer is simple. We'd better.

Paul Grant]

While I agree with Paul Grant's utopian concept of a future world with a nuclear–solar–wind–hydrogen energy base, I wish to make a few comments.

First, the change from fossil fuels by the United States should be based on the fight against terrorism, since current payments for oil fund terrorists who are dedicated to the destruction of the United States. Furthermore, our huge foreign trade imbalance and the increasing percentage of national debt owed to foreign interests may well constitute a greater danger to the stability of the United States than terrorists' bombs.

In the area of technology, I see that fusion energy is too far off for current planning, but we should consider the use of decentralized, but still large-sized, nuclear reactors accompanied by fuel recycling. Based on France's approach of having 85% of electricity from nuclear power, this should be the first line of energy production, supplemented by solar and wind energy. Facilities for producing the latter should be located not where usage is highest but where efficiency is greatest, that is, in deserts for solar and in the Midwest for wind—to provide hydrogen for mobile requirements and electricity to supplement the power grids.

Finally, I do not share one of the author's concerns—the "diversion" of nuclear fuel for terrorist uses. New fuel rods contain very long lived isotopes of uranium and/or plutonium that produce little radioactivity and which are chemically relatively inert. Thus, misuse of new fuel rods represents little threat unless there are facilites to remove the ^{238}U and increase the ^{235}U to more than 90%, which is difficult without very high cost and sophisticated facilities.

Spent fuel rods, which contain less of the uranium and/or plutonium, are so highly radioactive when first removed that they would be difficult to steal, transport, and work with to create the so-called dirty nuclear bomb (a chemical explosion that spreads radioactivity over broad areas).

A major concern that is often mentioned is the threat that recycling fuel would create ^{239}Pu, which could be accumulated to make a nuclear weapon. However, numerous scientists claim that recycling produces a slight amount of ^{240}Pu, which has little effect on the use of the ^{239}Pu in a nuclear reactor but is sufficient to "poison" the mixure so that it cannot be used as a nuclear bomb unless the terrorists have a highly sophisticated isotope separation facility to remove the ^{240}Pu and concentrate the ^{239}Pu.

One point with which I disagree with Dr. Grant is on the possible use of superconductivity for long, more-efficient transmission lines. I believe that the efficiency is already high, and I would be concerned about the total amount of coolant (liquid hydrogen, helium, or nitrogen) required and, even more, the risk of severe destruction from a sudden loss of high-temperature superconductivity (HTS) somewhere along the line. Thus, I suggest restriction of HTS use to generators, transformers, and other localized mechanisms.

Fred Schaff
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[*Author replies*: I agree that terrorism today is likely significantly funded by Middle East oil revenues, which is another cogent reason for reducing oil consumption.

On fusion and renewables, I agree… mostly. Fusion is way off and would probably not be based on deuterium–tritium or deuterium–deuterium, because of the huge scale necessary to boil water with 14-MeV neutrons. Exploitation of lunar ^{3}He reserves, whose fusion reaction produces charged alpha particles for direct electricity generation, may be possible.

On wind and solar power, I think that many environmentalists and conservationists (including me) would have some difficulty with obliterating "useless" desert and Midwest land areas.

On diversion of nuclear fuel: Although difficult technological challenges do keep reprocessing out of the hands of the bad guys, we need international control of the actinide cycle for electric power production from mine to grave, as I allude to in my article.

On redundancy of superconducting lines: All power delivery infrastructure requires redundancy and security, and superconductivity presents no special problem. Undergrounding is the best approach, but nothing is bulletproof against a prepared and determined aggressor. At present, the thousands of miles of conventional aboveground pipeline and overhead electrical transmission networks are overwhelmingly vulnerable to attack. I invite Mr. Schaff to invent his own scenarios for their straightforward destruction, as I have done. Since September 11th, preventing such attacks is, in my opinion, the most pressing home security challenge.

Paul Grant]

It's a little deceptive of Paul Grant to describe a passive cooled nuclear reactor, then state that we have nuclear fuel for 300 to 800 years. The relatively safe reactors he describes have enough fuel for only 25 years of world energy production. The only way to extend the available fuel would be to use much more dangerous and commercially unproven breeder reactors.

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[*Author replies*: I'm somewhat at a loss as to where Mr. Donovan obtains his number, "…enough fuel for only 25 years of world energy production." The most pessimistic figure I've seen is 35 years—if the entire present electricity production of the United States were suddenly converted to nuclear energy, fueled only by domestic uranium reserves, without any reprocessing (this does not include the huge net amount of uranium salts in seawater, albeit recoverable at higher cost than land ore deposits). Should we continue at present levels (20% of U.S. electricity supplied by nuclear), known domestic reserves would suffice for about 170 years, again without reprocessing. With reprocessing, we obtain my worldwide figure of 300 to 800 years, depending on the mix of nuclear with other generation methods.

These numbers, which can be found in several textbooks and reviews of nuclear power, do not include the considerable amount of energy that can and will be recovered from the dismantling of the nuclear arsenals of the U.S. and Russia, perhaps tripling "reserves" worldwide. With respect to fast breeder technology, which is neither unsafe nor unproven—simply undeveloped at present because of the low price and availability of uranium ore—some people have estimated that we have planetary capability for 15,000 years.

Paul Grant]

Mail letters to The Editor, The Industrial Physicist, One Physics Ellipse, College Park, MD 20740-3842; fax (301-209-0842); e-mail (tip@aip.org); or respond from our Web site (www.tipmagazine.com, click "Write to the Editor").

City of the future

When windmills are used to generate power, they extract power from the wind. I assume this means that the wind has lost some energy. This suggests that if there were enough windmills, then the wind could cease to exist, which would create weather havoc around the world. At what point would there be too many windmills?

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[*Author replies*: Not being an expert on extracting energy from the wind, I brought your question to one of my colleagues at the Electric Power Research Institute, Chuck McGowin, who runs our wind program. Here is his answer:

The maximum theoretical fraction of the power in the wind that can be extracted (called the Betz limit) is about 59%, based on an energy balance between the air stream flowing in front of, and behind, the rotor. In practice, the collection efficiency is usually 30–45%. To significantly affect the local wind flow at ground level, it would be necessary to cover the entire area exposed to the wind from ground level to an elevation of, say, 200 m with spinning turbine rotors, which is, of course, impractical. In fact, wind turbines are purposely designed with rotors elevated above the ground, and the typical wind turbine site layout is designed to minimize the energy losses resulting from wake turbulence created by upwind turbines affecting the efficiency of downwind turbines. For that reason, the wind turbines are deliberately separated by at least 1.5 to 8 rotor diameters.

The energy extracted by wind turbines from the wind is thus a negligible fraction of the available energy.

These and other interesting wind energy topics are addressed by the Guided Tour at the Danish Wind Energy Association site at www.windpower.dk.

Paul Grant]

In your recent article “Energy for the City of the Future” (*The Industrial Physicist*, February/March 2002, pp. 22–25), the efficiency factor for hydrolysis is quoted as 80%. What about the energy needed to produce electricity for the hydrolysis and to transport liquid hydrogen through the network? What would the resultant efficiency rating look like after taking account of these factors? How does it compare with fossil fuel energy efficiency?

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[*Author replies*: A quantitative answer depends on various end-user choices, societal and policy pressures, and, of course, economics. Some advocates of the hydrogen economy believe that central generation, transmission, and distribution of electricity will no longer be required—that we should generate and distribute hydrogen and make whatever electricity is needed via fuel cells at the end point.

On the other side, the “electricians” maintain that the stability, reliability, and universality of centrally generated electricity will always be needed. In fact, history tells us that the dual generation and delivery of potential (chemical) and kinetic (electric) energy together are essential, as witnessed by the cohabitation of the gas and electricity industries for the past 60 years.

The principal argument for hydrogen is to mitigate carbon emissions from coal, methane, and gasoline in the face of the enormous cost of adapting to global warming. However, hydrogen must be manufactured by either electrolysis or thermal "cracking" of water, both, preferably, using nuclear power. My preference is electrolysis because of its higher efficiency and use of a single modular reactor-generator design that easily can be switched between making hydrogen and grid-delivered electricity.

According to estimates I've seen from a hydrogen industry association, at an electricity cost of \$0.025/kW•h, liquid hydrogen produced by the electrolysis of water would run \$1.80/gal, compared with \$0.60/gal for diesel fuel out of the refinery. Keep in mind that the future cost of fossil fuel has nowhere to go but up as reserves fall, and way up if Kyoto-type protocols are imposed. Extrapolating all transport losses from a previous study we did for a liquid-nitrogen-cooled dc cable transporting 5 GWe with a cryogen flow of 8 L/s (the liquid-hydrogen power equivalent of 60 MW), gives a loss of 3 MW/1,000 km—about twice that suffered if the same amount of power were transported by a high-voltage dc transmission line.

Paul Grant]

Thanks for a clear article on energy policy for the future. However, if nuclear energy is so safe, why is the nuclear power system hiding behind the Price–Anderson Act, which essentially waives its liability to damages caused by accidents? Until this is eliminated, I know these plants are not really safe or economically competitive.

David Rubin
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[*Author replies*: The Price–Anderson Act covers many liabilities and issues in applied nuclear technology, of which the nuclear power industry is only one component. With due respect to Mr. Rubin's comments, Price–Anderson does not "waive" that industry's liability for nuclear plant accidents. In fact, it guarantees it. The act provides a self-funding insurance framework totaling more than $9 billion. The companies pool resources to cover liability incurred by any one of them. Each nuclear power company pays premiums to either the American Nuclear Insurers or the Mutual Atomic Energy Reinsurance Pool, must meet rigorous standards of safety in operation and design, and must undergo periodic review to qualify as a policy holder. I believe that such qualification is also required by the Nuclear Regulatory Commission for both initial and continued plant licensing and relicensing. Since the inception of Price–Anderson in 1957, as far as I know, no public funds have been expended to reimburse commercial nuclear plant liability claims, including those arising from the incident at Three Mile Island, all costs having been paid by the insurers and the utilities.

In the event of a serious accident, Price–Anderson affords the individual nuclear utility some protection from a concerted "tort attack" that might drive it into bankruptcy by spreading the liability throughout the entire industry. All claims must be presented to one of the nuclear insurers, a one-stop shop for claimants, if you will.

The Price–Anderson Act has been renewed three times since 1957 and, in March of this year, the Senate approved its next renewal by an overwhelming majority. The House is expected to follow suit this summer. In fact, since the events of September 11, 2001, Price–Anderson is now beginning to be considered by many legislators as a model for other industries—such as the airlines—that encounter rare events with considerable public consequences.

Although I am not a lawyer, my opinion is that there's nothing wrong with the section of the act related to nuclear power utilities.

Paul Grant]

Lunar solar power

[The article "Solar Power via the Moon" (*The Industrial Physicist*, April/May 2002, p. 12–15) received widespread attention in the media, including ABCNews.com, United Press International, National Geographic Online, *The Ottawa Citizen*, *Die Welt* (Germany), *Repubblica* and *Macchina del Tempo* (Italy), *Business A.M.* (Scotland), *The Straits Times* (Singapore), German Sat.1 TV, BBC-Scotland, ScienceDaily.com, Spaceflightnow.com, Slashdot.org, Green nature.com, Edie.net, Spacedaily.com, AviationNow.com, Astronomer.com, Cos miverse.com, and National Science Teachers Association online—*Ed*.]

"Solar Power via the Moon" (*The Industrial Physicist*, April/May 2002, pp. 12–15) describes another option of power from space systems that are envisaged to come into reality in this century. Central to these schemes is microwave power transmission from space to Earth. Criswell chooses the 2.45-GHz industrial, scientific, and medical (ISM) band as optimum and then assumes that wireless communications systems that operate at this frequency or its harmonics will vacate these bands and relocate to other frequencies. Before this happens, however, there must be a momentous shift in political power from wireless industries to a fledgling energy industry. The scenario of radio-frequency interference (RFI) between wireless and ISM will be played out between owners of more than 300 million microwave ovens in the world and the expanding wireless systems.

Although a prime technical problem is that of RFI, public acceptance of ambient microwaves will require a diminution of the electrophobia that has hindered the deployment of microwave technology, as in the current controversy over cell phones.

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[*Author replies*: Global prosperity requires a new source of clean and lower-cost commercial electric power. The annual net revenue from 20 TW of electrical power, sold at $0.01/kW•h, would be about $1,500 billion per year, which far exceeds the net revenues of the global wireless industry. Gross world product could increase by a factor of 10 or more with this electrical input.

The electromagnetic spectrum is a common benefit of the terrestrial biosphere. In principle, the spectrum is open to reallocation for the greatest good of humanity. In practice, each nation has control over the use of the electromagnetic fields above its boundaries. Poor nations are free to place a higher premium on access to clean, abundant, and low-cost power than on retention of existing spectrum allocations.

Some groups, especially in the rich nations, express fears of microwaves, magnetic fields of power lines, and emissions of cell phones. The controversy over cell phones and power lines is abating in the United States. Lawsuits over power lines have been unsuccessful. Solar power from space or the moon would be delivered to industrially zoned rectennas from which the general public is excluded. Stray power could be far below the Institute of Electrical and Electronic Engineers' standards for continuous exposure of the general population.

The Lunar Solar Power (LSP) System can be implemented at 2.45 GHz, 5.8 GHz, or other frequencies. Beams at 2.45 GHz suffer less attenuation in passing through the moisture of the atmosphere. Beams operated at other frequencies may require more costly combinations of more rectennas, long-distance power transmission, power storage, and power conditioning.

David Criswell]

In transporting any kind of power from the moon to Earth, efficiency is the problem. Propagation loss is proportional to the squared inverse of distance and to wavelength. At 12 cm, the propagation loss for the 384,000-km path from the moon to Earth will be ~ 212 dB, or 1.6×10^{21}. Thus, you would recover one part in 10^{21} on the surface of Earth. Some advantage would be gained by using geostationary satellites. They are about 10 times closer than the moon, but you gain only ~ 20 dB, or 100 times more. This amount of energy is worthless, a fact that ought to end all similar microwave power transmission dreams.

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[*Author replies*: Mr. Polivka provides a unique interpretation of the concept of wireless power transmission (WPT). His calculation assumes that all the power is radiated from one small aperture located at the distance of the moon from the Earth. The radiating power expands spherically over the moon–Earth distance and is of negligible intensity at Earth. Neither his model nor his calculation has any relation to WPT or to the LSP System described in the April/May issue of TIP.

WPT systems are not exotic. They are essentially specialized forms of radar. In the simplest radar system, the microwave source

[David Criswell gives a longer response to readers in "Return to the moon" on page TK.—*Ed*.]

Geothermal energy

In the article by Paul Grant, "Energy for the city of the future" (*The Industrial Physicist*, February/March 2002, pp. 22–25) and in the responses by your readers, nobody mentioned in an appropriate manner an energy resource that is safe, environmentally clean, reliable, and virtually unlimited—geothermal energy. Is it too easy to convert clean water into steam and generate electricity and heating for industry and homes at every location on mother Earth? Instead, we waste valuable fossil resources by burning coal and oil. All the other future energy options discussed involve impressive dangers, limits, and restrictions, as well as the spending of immense amounts of taxpayer money on R&D. As long as narrow minded leaders, politicians, and lobbyists offer only a tunnel vision for the taxpayer, it seems nothing will change.

The technology is available to pulse-drill inexpensive and fast holes 16 miles down into the crust of the Earth, using pulse-mixing to create strong and heat-resistant epoxy-ceramic pipes to protect the underground watertable, and create an underground cavern big enough to heat and store the water–steam medium to supply energy to every city. The turbines generating the required electricity and hot water could be used for many heating purposes, as is already done on a small scale in some volcanic areas. Hypersonic pulse energy has the potential to open an unlimited energy window for mankind. The technology has been proven for many years in testbenches, heavy-duty construction equipment, and many other applications.

Where are the visionaries, the investors, the managers, and others to understand these simple concepts and participate in this much brighter energy future ?

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[*Author replies* Helmut Sieke takes me (and the previous respondents to my "SuperCity" *TIP* article) to task for not appropriately mentioning the potential of geothermal technology as a renewable energy source of the future.

His letter affords me an opportunity to expand my brief remark that tapping the most readily available, and therefore most economic, near-surface hydrothermal sources would be ecologically invasive. I am familiar with three such existing facilities—one in Napa County, California, called "The Geysers"; the second in Mexico near Mexicali, Cerro Prieto; and the third, also in Mexico, Los Azulfres, in the pine-forested hills south of the city of Morelia, capital of the state of Michoacan. All three occupy vast tracts of land. The Cerro Prieto location, comprising four generation plants, takes 30 minutes to drive across at freeway speed, and it has a total general capacity of about 750 MW, less than three-quarters the capacity of a single one-acre nuclear reactor unit at Diablo Canyon on the California coast. The construction of Los Azulfres required the clear-cutting of a portion of the forests providing the home of the monarch butterfly. Most estimates I have seen put the potential at no more than 1% of future energy requirements for hydrothermal exchange of "geyser" liquid or gas thermal energy with secondary water to make steam for electricity generation. That is, if it were allowed and could overcome serious corrosion problems in the heat exchange piping.

However, the geothermal source I believe Mr. Sieke refers to principally relates to "deep well" or "hot dry rock" geothermal formations located adjacent to the earth's mantle. Surface water would be heated at these extreme depths and returned to the surface for electricity production or stored, as Mr. Sieke suggests, at the subterranean thermal source. Several attempts have been made to exploit such sources. The project I have been most aware of, thanks to input from my Electric Power Research Institute and Department of Energy colleagues familiar with a spectrum of geothermal technologies, was the effort near Los Alamos National Laboratory that terminated in 1997. The study concluded that the cost for a 4-km well would run around \$3.5 million, and would "increase substantially" and nonlinearly with depth. Such a well located over a near-surface "hot dry rock" formation could generate possibly 2 MW of electric power.

Mr. Sieke proposes wells as deep as 16 miles (~ 26 km). Let's make the conservative assumption that about \$20 million would be expended in drilling it. To produce 1,350 MW (the capacity of a single modern advanced boiling water reactor (ABWR) nuclear unit) would require 675 wells at a total drilling cost of \$13.5 billion. The newest 1,350 MW ABWR unit in operation in Japan cost around \$2,000/kW or \$2.7 billion *for everything* Thus, even if it were possible to drill to the depths Mr. Sieke suggests at present costs for more shallow wells, the wells alone would cost five times as much as a finished nuclear plant for a given potential power output.

If Mr. Sieke does indeed have a unique approach to boring and drilling, I would imagine there would be many interested parties who would like to know more.

Corrections

The following corrections have been made to the June/July issue of *The Industrial Physicist online*

In "Polymer LEDs," (Briefs) by Eric Lerner, p. 14, the final sentence should read, "We also expect to increase the wavelength to 1.5 μm, the best wavelength for telecommunications," says Tesslar.

In "Silicon–Germanium Gives Semiconductors the Edge," by Jennifer Ouellette, p. 24, under "Characterizing Silicon–Germanium," Rudolph Technologies is located in Flanders, New Jersey.

LETTERS TO THE EDITOR

Mail letters to The Editor, The Industrial Physicist, One Physics Ellipse, College Park, MD 20740-3842; fax (301-209-0842); e-mail (tip@aip.org); or respond from our Web site (www.tipmagazine.com, click "Write to the Editor").