

# Cold War computers, California supercars, and THE PURSUIT OF LITHIUM-ION POWER

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**The electric vehicle's history offers a lesson to the wise: Harvesting the fruits of basic science requires industrial foresight, investment, and a healthy dose of realpolitik.**

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**B**y 2004 the all-electric vehicle seemed destined for the dustbin of history. General Motors (GM) was recalling and destroying all copies of the EV1, its first-generation electric car, after company officials convinced themselves and regulators that fuel cells, not batteries, were the ultimate power source of the future electric car.

Meanwhile, hybrid electrics had begun to proliferate as a more economically viable alternative in the short run. Most batteries were then considered simply too expensive, too heavy, and too weak to power cars on their own.

Then came the lithium-ion battery. (See the article by Héctor Abruña, Yasuyuki Kiyu, and Jay Henderson, *PHYSICS TODAY*, December 2008, page 43.) With higher energy density than older rechargeables—and with the ability to release that energy quickly on demand—the battery is widely viewed as having led a revival of the electric vehicle. Tesla Motors pioneered its use in automobiles with the Roadster, and today most all-electric vehicles have batteries that use some sort of lithium chemistry. Although concerns about safety, cost, and durability linger, few would dispute that the lithium-ion battery has been the chief technological enabler of the renaissance of the all-electric vehicle.

The emergence of the lithium-ion battery did not happen overnight. It was shaped for decades by the influence of materials scientists. It was the product not of a singular eureka moment but of many strands of research tracing back to the rise of the US national security state at the dawn of the Cold War. That's when John Goodenough, a physicist by training, found himself helping to build a sophisticated air-defense computer for the US military. Although he couldn't have imagined it at the time, he was about to embark on research that would help found solid-state ionics—the science of inserting and storing ions inside solids without changing their fundamental structures—and contribute to revolutionizing automobile transport.

The many twists and turns that ensued illustrate the unpredictability and contingency of innovation. The story of the long road to lithium-ion power shows how changing social, economic, and environmental conditions after World War II altered the R&D priorities of government and industry. It affords insight into how trends in the energy economy shaped science and engineering over time. And it reveals a hidden history of the shifting fortunes of physics, a discipline that has traditionally relied on state patronage.

### The Lincoln years

Solid-state ionics, the science underpinning lithium-ion technology, can be interpreted as a byproduct of Project Lincoln,

the US Air Force's effort to develop the Semi-Automatic Ground Environment, America's first air-defense system. In 1952, at the age of 30, Goodenough joined MIT's Lincoln Laboratory, an institution then at the leading edge of engineering research in radar, telecommunications, and digital computers.

Possessing a doctorate in theoretical solid-state physics from the University of Chicago, Goodenough worked in the unit responsible for the memory of the Whirlwind computer, the brains of the air-defense system. There, under the leadership of superstar researcher Jay Forrester, he explored the electronic properties of ceramics and metal oxides.

Over the course of Project Lincoln, Goodenough became an expert in those materials and, in particular, oxide minerals known as spinels, which have the form  $A^{2+}B_2^{3+}O_4^{2-}$ . He developed an interdisciplinary research agenda and a style of work that straddled basic and applied sciences. Motivated by fundamental questions of solid-state science and materials design, Goodenough was guided by what he referred to as engineering targets, or theoretical problems arising from devices. After identifying a target, he would design experiments for chemists to execute.

Occasionally, Goodenough's research brought him into conversation with battery technologists, who in the late 1960s were experiencing something of a resurgence. For most of the 20th century, battery makers had stuck to proven and profitable chemistries—namely, lead-acid batteries, invented in 1859 by French physicist Gaston Planté, and nickel-cadmium batteries, invented in 1899 by Swedish engineer Waldemar Jungner.

For a brief period in the late 19th and early 20th centuries, electric vehicles powered by lead-acid batteries were an important component of the light-duty automobile fleet. Such vehicles had relatively short range, but in densely populated, compact eastern cities with good electrical infrastructure, that wasn't necessarily a handicap. Many urbanites viewed the electric "city car" as superior to the noisy, smelly, and fragile internal combustion vehicle of the day.

The comparative advantage rapidly disappeared as industry, led by the Ford Motor Co, developed reliable gasoline vehicles and began producing them on a massive scale in the late 1910s and especially after World War I. The lead-acid battery was relegated to the secondary role of starting the motors and powering the lights of gasoline vehicles. Automobile engineers,

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as historian Richard Schallenberg observed, stopped thinking in terms of electrochemistry.<sup>1</sup>

### The rise of solid-state ionics

For decades afterwards, battery technoscience languished. In the Cold War era, only US federal institutions were willing to procure powerful advanced batteries, mainly for highly specialized military applications. Industry's economic interest in advanced batteries was marginal. Nevertheless, the emergence of the conjoined energy and environmental crises in the last quarter of the 20th century created justifications for corporations to dabble in power-source research.

One such program, conducted, ironically, in the research laboratories of Ford—the company that had done perhaps more than any other to sweep the electric automobile from American roads—yielded a battery that would change the course of Goodenough's research and upend the conventional paradigm of power-source technology.

The battery, developed in 1966–67 by Joseph Kummer and Neill Weber, functioned on the same basic principle as every battery before and after it: During discharge, an oxidation reaction at the negative electrode, the anode, liberates electrons from their parent atoms; the electrons and the ions they leave behind then travel separate paths—the electrons through an external circuit to do work, the ions through an electrolyte. They then recombine via a reduction reaction at the positive electrode, the cathode. (See figure 1.) During recharging, the polarity and the process are reversed: The cathode becomes negative, the anode becomes positive, and the anodic materials are reconstituted.

Whereas a conventional battery contains solid electrodes and a liquid electrolyte, Kummer and Weber's battery featured liquid electrodes—a molten sodium anode and a molten sulfur cathode—and a solid ceramic electrolyte known as beta-alumina. Beta-alumina contained spinels and had previously been used mainly as industrial furnace insulation. But the compound also served as an ion conductor when used as an electrolyte. That hitherto unknown property of what had previously been considered a prosaic material would create a scientific sensation.

Because Goodenough had become an authority on spinels during his time at Lincoln Laboratory, he was asked by the Atomic Energy Commission to evaluate the technology. Like all molten-salt batteries, the sodium–sulfur system had serious practical problems issuing from its relatively high 350 °C operating temperature. One of the chief issues was corrosion. Moreover, if the molten electrodes breached containment, the battery would almost certainly trigger a fire or, worse, an explosion. Ford made no plans to commercialize the technology.

Still, historians Hervé Arribart and Bernadette Bensaude-Vincent credit the technology with stimulating study of the reversible insertion of ions into solids, a major shift in thinking at a time when electrochemists believed that reactions occurred primarily at the electrode surface.<sup>2</sup>

### Opportunities in crises

The late 1960s and early 1970s brought energy and environmental crises that renewed US interest in nonnuclear power sources and shifted the R&D priorities of government and industry. For Goodenough, that meant new engineering targets.

At the time, he had been exploring zirconia-based solids as

possible electrolytes for solid oxide fuel cells (SOFCs), then regarded in some quarters as the ultimate power source. Whereas a battery's energy is stored in its electrodes, a fuel cell converts the energy in externally stored fuels by electro-oxidizing their hydrogen. Researchers were excited by the possibility that the technology could directly use the H<sub>2</sub> bound up in cheap and dirty carbonaceous substances such as diesel, kerosene, and gasoline. (See the article by Joan Ogden, *PHYSICS TODAY*, April 2002, page 69.)

In practice, most fuel cells worked well only on costly clean fuels—usually pure H<sub>2</sub> or, in some variants, natural gas. But the SOFC, first developed in the late 1930s, was, in principle, capable of directly using the dirtiest fuels. The SOFC also obviated the limitations of water-based electrolytes. Water decomposes into oxygen and hydrogen at 1.23 V, which constrains batteries with aqueous electrolytes to operating at relatively low power. The trade-off was that the SOFC operated at 1000 °C. Like all high-temperature power sources, it was slow to start and prone to corrosion.

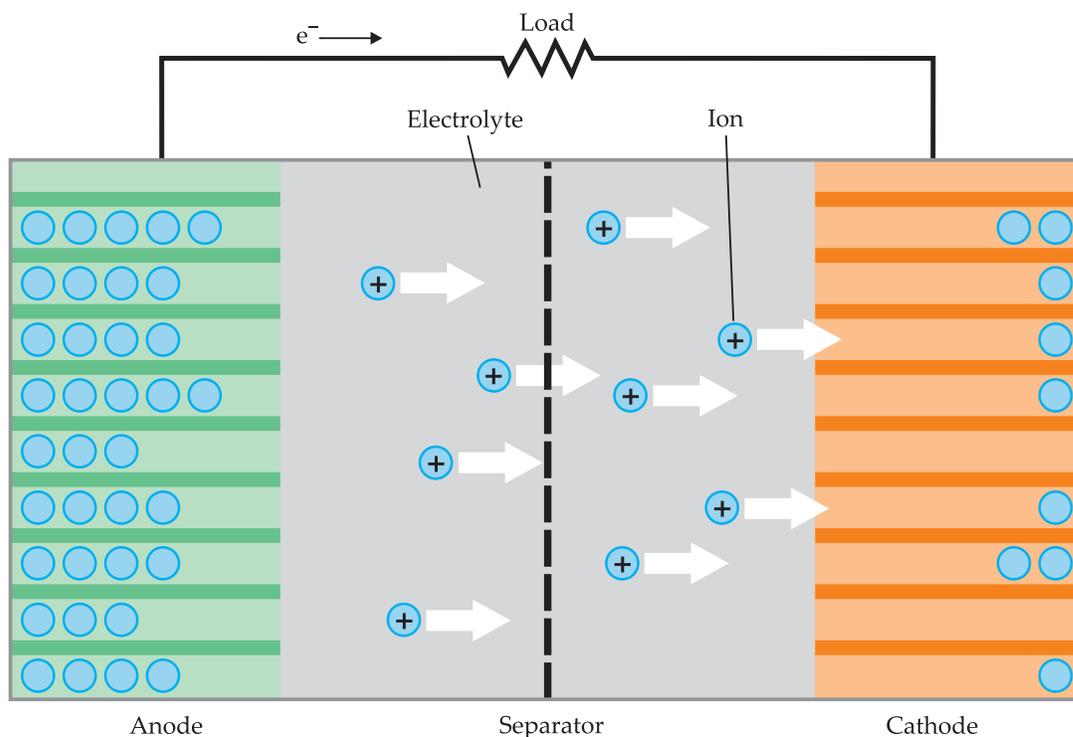
Enter M. Stanley Whittingham, then a chemist at Exxon's research and engineering division. In the wake of the OPEC embargo of October 1973 and the accompanying spike in oil prices, the company synonymous with the fossil-fuel order had to consider the possibility that automakers might be forced to build electric vehicles. It was in that context that Whittingham, aware of the problems of SOFCs, began to consider the virtues of low-temperature, nonaqueous electrolytes. In 1976 he invented the lithium titanium disulfide battery, which employed a liquid organic electrolyte, lithium hexafluorophosphate dissolved in propylene carbonate, at ambient temperature.<sup>3</sup> Whittingham definitively demonstrated that lithium ions could be reversibly inserted into the spaces between the sheet-like layers of the titanium disulfide cathode. The reversible storage of ions in a layered structure, known as intercalation, is the fundamental operating principle of a rechargeable lithium battery.

Whittingham's achievement marked a major advance in power-source technoscience. At the time, Whittingham suggested that he had developed a practical battery, but that was not quite the case. After focusing his efforts on developing the titanium disulfide cathode, Whittingham paired the cathode with a metallic lithium anode for his proof-of-concept tests. It was a dangerous combination. When such a cell was repeatedly recharged, lithium ions plated unevenly on the anode, forming tree-like growths called dendrites (see figure 2) that could bridge the electrodes and cause a short circuit. In such circumstances, the organic electrolyte can ignite and the battery effectively becomes an incendiary.

### Building a better cathode

Whittingham's lithium titanium disulfide battery would nevertheless inspire perhaps the most important engineering target of Goodenough's career—one that would be instrumental in the creation of the first practical lithium-ion rechargeable battery.

Goodenough pondered the problems of lithium titanium disulfide at Oxford University, where he had accepted an offer to chair the school's inorganic chemistry laboratory in 1976. Like Whittingham, Goodenough favored power as the chief metric of battery performance. He realized that a layered sulfide cathode mated to a metallic lithium anode could not



**FIGURE 1. A DISCHARGING BATTERY** converts chemical potential into electric potential. At the anode, an oxidation reaction frees electrons ( $e^-$ ) from their parent atoms. The electrons pass through an external circuit, where they do work on a load, while the ions they leave behind diffuse through an electrolyte and separator to the cathode. There, the electrons and ions recombine via a reduction reaction. During recharging, the process is reversed, and the anode is restored. In lithium-ion batteries, the electrode materials are typically layered structures, with lithium stored in the gaps between layers.

yield much more than 2.5 V. Paired with a safer anode, he held, the cathode's yield would drop further still, to the point that the device would not be able to compete with existing rechargeables that used nonflammable aqueous electrolytes. Because he had no intention of designing a complete battery for a specific application, he thought about the problem in abstract terms and privileged power over safety, cost, and durability.

Aware of the power limitations of sulfides, Goodenough looked to metal oxides as potential cathode materials. He worked with Japanese physicist Koichi Mizushima to determine how much lithium could be reversibly extracted from various transition metal oxides.

Generally speaking, the more ions that can be extracted from a cathode, the greater the voltage it can deliver. In protracted experiments, Goodenough, Mizushima, and their colleagues showed that when a cobalt oxide cathode was paired with a metallic lithium anode, they could extract about 60% of the cathode's lithium—enough to generate 4 V. They extracted even more, 80%, from a nickel compound, but that material was unstable and difficult to prepare.<sup>4</sup>

Despite his professed interest in basic research, Goodenough wanted to sell the new cathode. But battery manufacturers were not interested, because they lacked a suitable safe anode. Moreover, lithium cobalt oxide was too expensive to be produced in the quantities needed for electric vehicles. As oil prices declined through the 1980s, interest in electric vehicles waned. Low on money, Goodenough patented his cathode through the UK's Atomic Energy Research Establishment and relinquished all of his rights.

That arrangement came back to haunt him when the formula turned out to be well suited to consumer electronics. In 1985 Sony's Energytec division began working to integrate the lithium cobalt oxide cathode with a graphite anode developed

in large part through the contributions of Akira Yoshino and Asahi Kasei Corp. The resulting lithium cobalt oxide rechargeable batteries supplanted the nickel-cadmium battery and became widely used in consumer electronics in the 1990s and 2000s. The patent licensing generated billions of dollars in royalties, of which Goodenough received nothing.

Still, he had become perhaps the world's foremost expert on spinels and lithium-insertion compounds. In the early 1980s, he attracted the attention of Michael Thackeray, a young South African chemist for whom the search for a better electric automobile battery would become a life's work.

### An era of energy plenitude

For most of the developed world, the 1980s spelled the return of cheap oil and the end of the energy crisis. As oil prices declined, the auto industry's interest in electric vehicles waned. In oil-poor South Africa, however, the crisis continued, due to increasing international isolation and a trade embargo provoked by the country's apartheid policies. South African policymakers responded by linking science with a semiautarkic industrial policy emphasizing energy and transportation. In 1977 the country's Council for Scientific and Industrial Research (CSIR) initiated work to develop electric-vehicle (EV) batteries, a project that became known as ZEBRA.

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Like Whittingham, Thackeray began his career considering the materials problems of high-temperature batteries. In the mid 1970s he was a doctoral student of Johan Coetzer at the CSIR's main laboratory in Pretoria. Coetzer had initially sought to build a safer sodium-sulfur battery by immobilizing its molten cathode in a porous zeolite matrix. When that configuration turned out to be too heavy, he instead mated the sodium anode with an iron chloride cathode, a component he'd developed as an alternative to the iron sulfide cathode of a hot lithium battery invented by Argonne National Laboratory. His work led the CSIR to focus on high temperature (250–350 °C) sodium-metal chloride chemistries.

As Coetzer worked, Thackeray contemplated metal oxides, a less corrosive alternative to iron sulfide and iron chloride cathodes in high-temperature lithium cells. He noted the potential of certain spinels to absorb and release lithium ions, and he contacted Goodenough and arranged to work with him at Oxford as a postdoctoral fellow. Supported by the CSIR, its affiliated South African Inventions Development Corp, and mining giant Anglo American, Thackeray demonstrated the insertion of lithium into two different spinels, magnetite ( $\text{Fe}_3\text{O}_4$ ) and hausmannite ( $\text{Mn}_3\text{O}_4$ ), between the fall of 1981 and the end of 1982.

That research informed Thackeray's subsequent demonstration of lithium insertion into a manganese oxide cathode. In 1985 Goodenough and Thackeray patented their research on the use of spinel frameworks as battery components. (The patent was assigned to the South African Inventions Development Corp.)

Meanwhile, the CSIR had cast its lot with high-temperature sodium-metal chloride technology. In 1986, with basic research on those materials complete, the council transferred most of its staff to Anglo American. Shortly thereafter, the mining firm partnered with Daimler-Benz, which would begin testing sodium-nickel chloride batteries in electric vehicles in the early 1990s.

But interest in electric vehicles remained tepid in the 1980s. Undeterred, Thackeray and coworkers made a series of improvements to manganese oxide cathodes in the early 1990s with practical applications in mind, even as their support from the South African government dried up. Their 4 V manganese oxide cathode tended to distort and dissolve under conditions of deep discharge, but Thackeray and company found they could stabilize it by doping it with various metals. They also developed a spinel anode, made of lithium titanium oxide, suitable for pairing with the stabilized cathode. In 1993 the CSIR left battery research entirely, and in January 1994 Thackeray accepted a position in Argonne's chemical technology division, where he continued his work with lithium manganese oxides.<sup>5</sup>

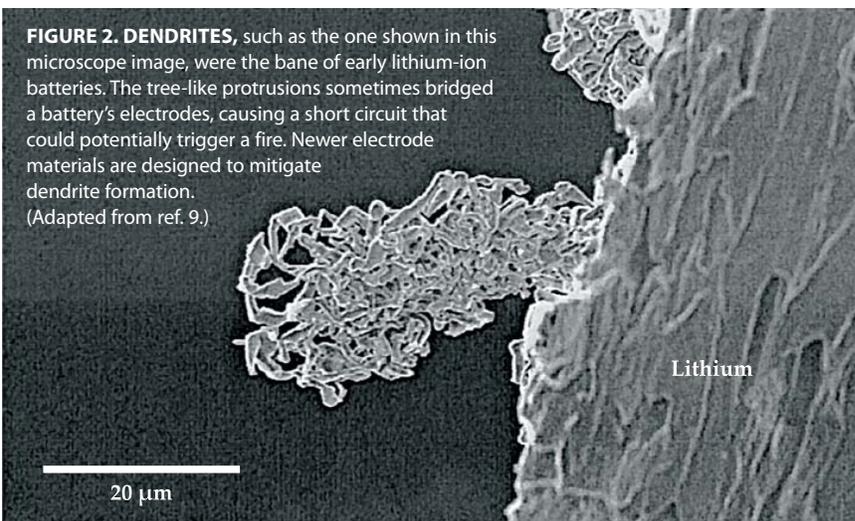
### The politicians and the automakers

Just as political conditions for electric vehicles were diminishing in South Africa, they were ripening in the US. Air-quality politics in California gave rise in 1990 to the Zero Emission Vehicle (ZEV) mandate. As drafted by the California Air Re-

sources Board (CARB), the legislation compelled the big automakers to produce a rolling quota of ZEVs as a percentage of overall sales.

The unprecedented technological mandate provoked fierce resistance from automakers, who exploited a loophole in the law: The CARB did not specify the technology by which the air-quality outcomes were to be achieved, so the auto industry was able to negotiate the definition of a ZEV.

At that time, the only practical ZEV was the all-battery electric car, a technology that automakers adamantly opposed. They argued consumers would reject it because existing batteries had low energy density and gave short range. The car companies favored fuel cells, under the logic that the technology would allow electric vehicles to use common liquid fuels, which would in turn provide more convenience and longer range than all-battery electrics.



**FIGURE 2. DENDRITES**, such as the one shown in this microscope image, were the bane of early lithium-ion batteries. The tree-like protrusions sometimes bridged a battery's electrodes, causing a short circuit that could potentially trigger a fire. Newer electrode materials are designed to mitigate dendrite formation. (Adapted from ref. 9.)

Auto executives knew, however, that a practical fuel-cell-powered electric car was still years, if not decades, away. Packaging fuel cells in electric drive trains and getting them to run on alcohol and gasoline posed severe engineering challenges. Still, air-quality regulators recognized the fuel-cell electric as a kind of ZEV and rolled back mandate deadlines in exchange for an industry promise to commercialize it.

Another option was the hybrid electric. True, the hybrid was no ZEV, but it posed fewer economic risks than all-battery electric vehicles. Used day in and day out, even the best batteries will wear out before the electric motors they serve, and that represents a hefty replacement cost that consumers may not realize. The hybrid was attractive in part because it used a smaller battery and buffered it from hard use with a gasoline motor. In short, the hybrid was a compromise between environmental politics and industrial-technological exigencies.

The Japanese manufacturers embraced that compromise. For power, Honda and Toyota looked to the nickel-metal hydride (NiMH) battery, a technology developed by a team at Energy Conversion Devices, the laboratory founded by independent American inventor Stanford Ovshinsky. The NiMH battery used relatively cheap and safe materials, including a nonflammable aqueous electrolyte, to achieve energy densities



**FIGURE 3. GENERAL MOTORS EXECUTIVES** and US government officials commemorate the first assembled battery for the 2011 Chevrolet Volt. The lithium-ion battery uses manganese oxide electrodes developed in part by Argonne National Laboratory chemist Michael Thackeray. Weighing almost 200 kg, it can propel an idle car to 97 km/h in 9.2 seconds. (Photo by Jeffrey Sauger/General Motors.)

of up to 80 Wh/kg, considerably higher than the 30–40 Wh/kg provided by the best lead–acid EV batteries of the day.<sup>6</sup>

Toyota adopted the technology in a remarkably short time. Like all automakers, it had no expertise with sophisticated batteries, so it teamed with a Japanese electronics company, Matsushita Electric Industrial, to create the joint venture Panasonic EV Energy in 1996. One year later the partnership produced a cylindrical NiMH battery for the Prius passenger automobile. It infringed on Ovshinsky’s patents in the process, however, and Matsushita was later forced to pay considerable compensation and licensing fees to Energy Conversion Devices.

### Super hybrids and fuel-cell futurism

The American hybrid, on the other hand, was conceived as a high-performance vehicle—a kind of supercar. Its development was crucially shaped by the Partnership for a New Generation of Vehicles (PNGV), an industry–government collaboration launched by the Clinton administration in 1993 as the equivalent of the Apollo moon project for advanced automobiles. Led by the US Department of Commerce, the PNGV included several federal agencies, the most important being the US Department of Energy, which provided more than half of the annual \$250 million federal commitment. For its part, the auto industry contributed a further \$800 million per year.

The PNGV’s planners insisted that the hybrid battery have dual operating modes: power assist and pure electric. The power-assist mode required high power but not necessarily high energy, since the battery’s average depth of discharge would be relatively shallow—especially when coupled to internal combustion engines. (Coupled to a fuel cell, which responds sluggishly to demands for power, a power-assist battery would be expected to discharge more deeply.) But the pure electric mode called for both high power and high energy. In other words, a dual-mode battery had to be robust enough to withstand repeated, deep discharges.

By opting for dual-mode hybrids, the PNGV planners rejected the premise of the hybrid electric as a compromise technology. In essence, they were asking the US industry to build what was essentially a battery electric vehicle—a second-generation hybrid requiring precisely the sort of super battery that automobile industry executives insisted they could not quickly develop—at a time when Japanese manufacturers were well on their way to commercializing a first-generation hybrid electric.

The PNGV identified two candidate chemistries for the dual-mode hybrid: NiMH and lithium ion. The French company Saft was the sole contractor for the latter. For the cathode material, Saft selected lithium nickel oxide, believing that the compound could deliver high power and energy and withstand the rigors of repeated recharging, all at low cost.

Predictably enough, perhaps, given Goodenough’s early experiments with nickel oxides, Saft’s cathodes didn’t hold up in long-term tests of charge–discharge cycling. They became dangerously unstable as they aged, which sometimes resulted in combustion. Researchers had essentially rediscovered the perils of pairing the electrode with a flammable organic electrolyte: Overcharge, overdischarge, vibration, and other relatively minor abuses could lead to catastrophe.

With the PNGV’s hybrid EV battery program in trouble, DOE intervened to help manufacturers understand and address lithium nickel oxide’s failure modes. In 1998 it launched the Advanced Technology Development Program, which funded research on various so-called ordering elements, introduced to help prevent nickel ions from escaping the nickel layer. Candidates included cobalt, cobalt and aluminum, manganese and cobalt, and nickel cobalt aluminum. During the 2000s the Advanced Technology Development Program would constitute an important part of the US government’s battery research efforts and influence Panasonic’s work to develop a nickel cobalt aluminum battery, which the company eventually produced for Tesla’s Model S sedan.

In the late 1990s, however, the fuel-cell electric car rapidly stole the spotlight from hybrids in the US. The PNGV’s spending on fuel-cell technology began to grow in 1997, and by mid 1998 fuel cells had supplanted hybrids as DOE’s top priority. Around the turn of the millennium, mounting technical problems—above all the inability of onboard converters to quickly crack gasoline or methanol into hydrogen—led government and industry researchers to focus on pure-H<sub>2</sub> fuel-cell systems. Those technologies became the focus of

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President George W. Bush's FreedomCAR, the successor to the PNGV.

### The lithium electric vehicle

If the idea of the H<sub>2</sub> fuel-cell vehicle helped kill the pure battery electric vehicle, as some critics claimed, it did not stop the proliferation of hybrids powered by NiMH batteries. As the Prius became a familiar sight on US roads, American manufacturers belatedly realized there was indeed a lucrative market for the technology. In 2006 GM initiated the Chevrolet Volt project. Sometimes described as an extended-range EV, the Volt is technically a dual-mode hybrid. In essence, it was the super hybrid that the PNGV had failed to deliver.

Robert Lutz, vice chair of GM, characterized the Volt as a response to both the Prius and the emergence of startup Tesla. For the all-electric Roadster, Tesla cofounder Martin Eberhard designed a battery pack using lithium cobalt oxide commodity electronics cells, the first application of lithium cells in an electric vehicle. By contrast, GM designed a battery employing lithium cells expressly intended for vehicle propulsion.

Two cell chemistries were in the running: one based on manganese oxide developed by LG Chem and a less powerful but safer system based on iron phosphate designed by Massachusetts-based startup A123 Systems. In that competition Thackeray and Goodenough witnessed the culmination of decades of research on lithium-ion insertion compounds: It was Goodenough and his doctoral student Ashoka Padhi who first recognized lithium iron phosphate's promise as a cathode in the early 1990s, and it was Thackeray who laid the groundwork for manganese oxide cathodes.

In the end, GM selected lithium manganese oxide, a decision that also validated US federal science; the Volt pack, pictured in figure 3, used components licensed from Argonne. Unfortunately for Volt fans, however, the quest for a super EV delayed the company's move into hybrids by a crucial decade. Demand for the Volt was low throughout the recessionary late 2000s and early 2010s, and the lithium-battery manufacturing plant built with stimulus funds from President Obama's administration initially operated below capacity.

Lingering questions remain of the social and economic viability of large lithium-ion battery packs such as the Volt's. Today's commercial lithium-ion batteries outperform all other power sources in terms of energy density per weight, with energy densities typically twice that of nickel-cadmium. But the batteries do not age well and have a short shelf life.

They also have well-documented safety problems. Some scientists, including materials scientist Robert Huggins, hold that lithium-ion batteries are inherently dangerous because they use flammable organic electrolytes and they tend to produce O<sub>2</sub> at high voltage.<sup>7</sup> Making such batteries safe requires elaborate measures that increase cost and complexity.

Moreover, the economics of user ownership of EV batteries remain opaque. Currently, most automakers do not produce their own battery cells and depend heavily on federal and state assistance to subsidize the high costs of the electric vehicles they produce. Much of that money, in turn, is captured by battery cell suppliers like Panasonic and LG Chem.

### An electric car for the masses

Nevertheless, it seems safe to say that lithium-ion electric vehicles are here to stay. To be sure, automakers have different

philosophies. Tesla selected the most powerful formula—and the biggest and costliest power packs. The company's largest pack can rocket a driver from 0 km/h to 97 km/h in three seconds. Tesla boss Elon Musk hopes to radically cut costs with a new production facility, the "gigafactory," currently under construction near Reno, Nevada. But the company faces significant challenges in delivering the Model 3, touted as an affordable electric supercar, in times of recession and cheap oil.

Other automakers have been more circumspect. For Toyota, the hybrid is the electric vehicle of the future and, in a sense, already the electric vehicle for the masses.<sup>8</sup> Toyota alone has produced more than 8 million hybrids to date, almost all equipped with NiMH batteries. The company has also invested in lithium-ion batteries, but cautiously. When Toyota encountered technical problems introducing lithium technology in the Prius in 2009–2010, it pragmatically retained NiMH technology for the regular Prius while using costlier lithium packs for the plug-in version. Toyota now offers a choice between NiMH and lithium-ion batteries in the baseline Prius.

The legacy of US public science in the context of electric vehicles is mixed. Without question, the government's environmental regulations and its sponsorship of the materials sciences helped spawn the current revival of electric vehicles. In one way or another, taxpayer dollars contributed to the development of nearly all the major lithium compounds in use today.

But in developing those compounds, materials researchers tended to treat batteries and fuel cells as materials rather than parts of complex technological systems. Indeed, for them, the material largely was the device, and the compounds they and their patrons found most interesting tended to be the most reactive, not necessarily the safest or most durable. Such an approach sometimes prevented materials researchers from appreciating the physical qualities of power sources in real-world use.

The US industry largely failed to exploit knowledge generated by the US physical sciences apparatus. The all-or-nothing approach to EV technology met with mixed success at best. And yet among science policymakers—whose political masters have long been committed to the neoliberal principle of the unfettered movement of people, capital, and ideas—the belief that the benefits of national programs of science must necessarily accrue to domestic manufacturers has unaccountably persisted. If the history of the lithium-ion battery teaches us anything, it is that the fruits of science are unlikely to be harvested in the absence of industrial foresight, investment, and realpolitik.

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