



Giant balloons of uncompressed natural gas on buses in China in the 1980s underscore the challenge of using this low energy density fuel for transportation.

STEPPING ON THE GAS

What would it take to put you behind the wheel of a methane-powered vehicle? Researchers are determined to find out

By Robert F. Service, in Los Angeles, California

Dane Boysen is a lousy salesman. Speaking at a conference on natural gas-powered vehicles here this month, Boysen, who heads a natural gas vehicle research program at the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E), says what industry stalwarts don't want to hear. "Honestly, natural gas is not that great of a transportation fuel." In fact, he adds, "it's a stupid fuel."

Some audience members respond with playful boos, but they know what he's talking about: energy density. A liter of gasoline will propel a typical car more than 10 kilometers down the road; a liter of natural gas at ambient temperature and pressure will take it 13 meters. Even when natural gas is chilled to make it liquid or jammed into a high-pressure tank—processes that cost both energy and money—it still can't match gasoline's range.

Nevertheless, Boysen's ARPA-E project, called Methane Opportunities for Vehicular Energy (MOVE), is in the middle of spending \$30 million over 5 years to jump-start the development of natural gas-powered cars and light-duty trucks, a category that makes up nearly 60% of all vehicles on the road.

Why? Because, low energy density aside, natural gas has a lot to offer. It's abundant and cheap. The current fracking boom in the United States is producing so much natural gas that a volume of gas with the energy equivalent of a gallon of gasoline costs roughly half as much. And the United States has known gas reserves to last at least another century. Gas is also relatively clean. Natural gas-powered engines generate up to 30% less climate-warming CO₂ than gasoline engines do, as well as far lower volumes of the nitrogen oxide and sulfur oxide pollutants that contribute to urban smog.

What's more, those engines already exist. With a little tinkering, conventional gasoline or diesel engines can burn natural gas. According to NGV America, an industry trade group in Washington, D.C., 15.2 million natural gas-powered vehicles are on the road worldwide. They include 142,000 in the United States, most of them heavy-duty trucks and transit buses. Some projec-

tions suggest that most trucks in the United States will be natural gas-powered by 2030.

For heavy-duty engines, economics is the driver. Even though trucks with natural gas engines cost tens of thousands of dollars more than their diesel counterparts, trucks use so much fuel—an average of more than 45,000 liters of diesel per year—that fuel savings offset the extra cost in as little as 2 or 3 years, says William Zobel, vice president of market development and strategy

in Sacramento, agrees. "There is only one alternative vehicle technology with an economic advantage, and that's natural gas," he says.

But as Stephen Yborra, who directs market development for NGV America, puts it, "there are an awful lot of hurdles to overcome." Honda, for example, already makes a natural gas version of its Civic sedan. But it has sold only 2000 of them in the United States, compared with more than 1.5 million gasoline-powered cars a year. Major improvements in fuel tanks, pumps, and infrastructure will be needed before natural gas vehicles rule the road.

As Boysen paces a small stage here at a conference center at the Port of Los Angeles, outside the window massive container ships are being unloaded with cars from Japan, TVs from Korea, and furniture from China. Those goods are moved out by some 8000 trucks every day, more and more of them fueled by natural gas to comply with the port's pollution standards. But Boysen is candid about the obstacles to expanding that revolution. He says he's free to speak openly, because he's leaving ARPA-E at the end of this month. One by one, he ticks off formidable technical challenges and the efforts engineers are making to solve them.

GAS TANK MATERIALS. The biggest problem goes back to the meager energy density of natural gas. At ambient temperature and pressure, it's a mere 40,000 joules per liter, slightly more than 1/1000 that of gasoline. To carry enough fuel, a car needs an oversized fuel tank, which eats into its cargo space. As a result, Honda's natural gas Civic has less than half the trunk volume of its gasoline counterpart.

"Drivers hate this because they can't pick up people at the airport," Boysen says.

The fuel tanks also have to be pressurized—another source of headaches. Today's tanks compress gas to 250 bar, about 250 times atmospheric pressure. To handle the stresses, tanks must be made either from thick metal—which makes them heavy—or from lighter but expensive carbon fiber. Current tanks add an average of \$3500 to the cost of natural gas vehicles. Boysen's MOVE project is aiming to reduce this premium to \$2000, a number that in-



“Home refueling and low-pressure tanks would be major game changers for this industry.”

Cherif Youssef, Southern California Gas Company

for Trillium CNG in Escondido, California, which builds compressed natural gas (CNG) fueling stations. Tightening pollution standards for trucks and buses are also driving the shift.

Now, Boysen and others want to see natural gas expand its reach to natural gas-powered light-duty cars and trucks. "It's right here," Boysen says, stretching out a hand to clutch an imaginary prize. "I absolutely believe [the technology] is going to take off," he says. Reynaldo Gonzalez, a transportation researcher at the California Energy Commis-

cludes the costs of any needed refueling equipment. “Two thousand dollars is really a major challenge,” says Cherif Youssef, a technology development manager with Southern California Gas Company here.

One option is to fill storage tanks with porous materials that sponge up methane at modest pressure and release it when the pressure is reduced. That lower pressure would make tanks lighter and cheaper and could also reduce the cost of the compressors needed to refill them. In 2012, the U.S. Department of Energy set the target for methane absorbents at 263 cubic centimeters of volume of methane per volume of absorbent (v/v), equivalent to CNG at 250 bar at 25°C.

Activated carbon is one such sponge that continues to attract plenty of attention, because the material is cheap and is produced by the ton for a wide variety of industrial uses. But its theoretical maximum capacity is only 220 v/v. Materials called metal-organic frameworks (MOFs) have already beaten that number. Unlike activated carbons, which have a randomly oriented internal structure, MOFs are porous crystalline materials that are designed from the atomic scale up, and they can be tailored to grab on to methane molecules.

Researchers have already engineered hundreds of MOFs. The early methane storage leader was a copper-containing MOF known as HKUST-1. When pressurized to 35 bar, it has been reported to store as much as 220 v/v. But not all of that gas is released when the pressure drops. At 5 bar, HKUST-1 still holds on to a third of its methane, reducing its usable capacity to 149 v/v. Earlier this year, researchers led by chemist Omar Yaghi of the University of California, Berkeley, reported in the *Journal of the American Chemical Society* that they could do better. They created a MOF called MOF-519 that has less total volumetric capacity than HKUST-1 but a greater working capacity. Another promising MOF-like material called a porous polymer network, made by researchers at Texas A&M University, tops all other leading materials for total storage capacity but can't yet match their working capacity.

Still, it's one thing to make gram-scale quantities of MOFs in a lab, but another entirely to make it by the train car loads that would be needed to outfit millions of cars with 21st century fuel tanks. Here, too, there has been progress. The chemical company BASF has developed methods to synthesize ton-scale quantities of another MOF contender and is road-testing MOF-equipped delivery vans in Germany. Framergy, a startup company in College Station, Texas, says it can now make grams of other MOFs

How far a car can go on a liter of fuel

In meters, assuming fuel economy of 10.6 km/liter (25 mpg) of gasoline



10,600

Gasoline



7197

Liquefied natural gas



2968

Compressed natural gas (CNG) at 250 bar

2968

CNG with adsorbent at 35 bar (DOE goal)

2257

CNG with MOF-519 adsorbent (theoretical capacity)

13

Unpressurized natural gas

for just pennies, within sight of the ARPA-E target of less than \$10 per kilogram.

That's all good news, Boysen says. But other “large challenges” remain before MOF-based storage will be practical—among them reaching DOE's target of a 263 v/v working capacity. “So there's still work to do here,” he says.

GAS TANK SHAPES. Spongelike fuel storage at modest pressures might free engineers to build tanks in shapes other than the now-standard high-pressure cylinder. That's critical, notes Ellen Sun, who heads a next-generation tank project at the United Technologies Research Center (UTRC) in East Hartford, Connecticut, because in a car, a cylinder occupies a box as big as its largest dimension, wasting a lot of space. For heavy-duty trucks and buses, which don't have tight space constraints, an awkward tank shape is less of a problem. But it's a killer for passenger cars. A MOF-based tank could be shaped like a traditional—though large—gas tank.

UTRC and other companies are also using more conventional approaches to re-engineer high-pressure tanks to ease the stresses on the tank material so it can be made to fit any desired shape. A company called REL Inc., for example, has created a tank prototype with two interpenetrating networks of channels to hold methane. Because it uses the full rectangular volume, it is 30% more space-efficient than a cylindrical tank of the same capacity. UTRC and a company called Otherlab in San Francisco, California, meanwhile, are developing technologies to create networks of small interconnected cylinders that can conform to any shape.

GASSING UP. Whatever sort of tanks wind up on the road, they will have to be refilled. Engineers are working to improve that technology, too. One challenge is the time it takes to fill up. Gasoline pumps can supply as much as 10 gallons (38 liters) of fuel per minute, an energy transfer rate equivalent to 20 megawatts of power. Today's CNG systems can fill the equivalent of a 15-gallon (57-liter) tank in 5 minutes. But they are expensive and primarily service trucks and specialized fleets.

Many advocates of natural gas cars dream of a low-pressure compressor that could be used for home refueling, as roughly half of U.S. homes—some 60 million—already have a natural gas line. If cars could be refueled at home, consumers would tolerate slower filling rates, as they do with electric vehicles. “Home refueling and low-pressure tanks would be major game changers for this industry,” says Southern California Gas



Crystalline metal-organic framework (MOF) materials under development at BASF. The company is working to scale up the production of MOFs to store natural gas.

Company's Youssef. One such compressor is already on the market, Boysen notes. But it costs \$5500, a number the MOVE project is hoping to drop by more than 90%.

At the natural gas-powered vehicles conference, researchers reported a few steps in that direction. A group at Oregon State University, Corvallis, said it had designed a natural gas-burning engine that, at the flip of a switch, can turn one of its cylinders into a compressor and act as its tank's own pump. Meanwhile, researchers at the University of Texas, Austin, have created a simplified compressor with only one moving part: a piston that slides back and forth. They think it could be manufactured for \$1500, not far from the MOVE target.

Like the MOFs, those prototypes still have a way to go to make it to market. Among the many challenges they'll have to deal with is filtering out water and other impurities from low-pressure gas lines so they don't accumulate in gas tanks. But with so few vehicles on the road, compressor manufacturers have been unwilling to invest in new technologies. As a result, says Bradley Zigler, a combustion researcher at the National Renewable Energy Laboratory in Golden, Colorado, "right now there is a valley of death between research progress and commercially available technologies."

INFRASTRUCTURE, INFRASTRUCTURE, INFRASTRUCTURE. Even if engineers do it all—come up with a cheap space-age crystal to hold gas in a low-pressure tank, a more efficient natural gas-burning engine to reduce the demand for a large tank, and a cheap new compressor—that still might not be enough. For drivers to gamble tens of thousands of dollars on a new kind of car, analysts say, they'll need all of these tech-

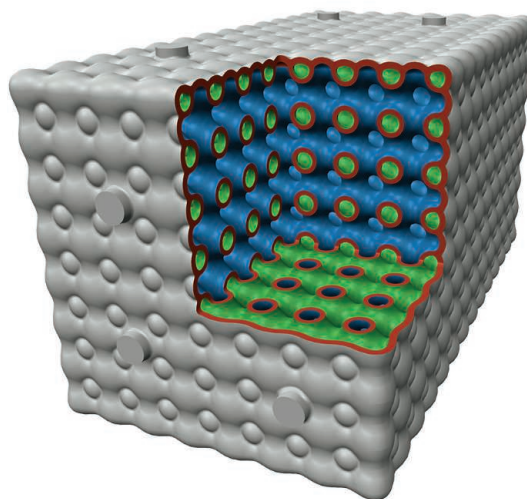
nologies to be widely available at the same time. "It has to be in a box," Youssef says. "To me, that's the biggest hurdle. I'm afraid we're not there yet."

Even then, Boysen notes, natural gas vehicles would face competition from a more-than-viable alternative: the gasoline- and diesel-powered cars that now make up 93% of passenger vehicles on the road. Drivers will need to be convinced that a natural gas car will work at least as well as current cars do. They will need to know they can buy fuel wherever and whenever they want. And they will need a nationwide network of mechanics and parts suppliers to fix things when they break. Gasoline-powered and electric cars already cover the whole menu, but would-be competitors have far to go.

This suite of demands is particularly acute for truly novel technologies, such as hydrogen-powered fuel cell vehicles. The lack of an existing fueling infrastructure for those cars makes it far less likely that drivers will embrace them. But the fact that such challenges are also proving daunting to natural gas-powered cars, with their sizable fuel cost advantage, underscores just how difficult it is to transform the way we drive. For Boysen and his colleagues, the allure of natural gas is stronger than ever. But they know reality can be unkind to even the most appealing technologies. ■

Weaving a new gas tank

Crisscrossing voids (false color) could enable engineers to build high-pressure tanks in any shape needed.



IMAGES: (TOP) BASF CORPORATION (2); (BOTTOM) REL INC.