Paraffin-fueled rockets: Let's light this candle

ONE SPRING DAY BACK IN 1990, President George H.W. Bush's domestic and economic policy staff received an urgent call from NASA's legislative affairs office. They needed the White House to send a signal to House and Senate negotiators that a major clean air bill should exempt NASA and other agency rocket launchers from regulation. The White House staff, working with Congress, agreed to shield rocket launches from the bill's restrictions, recognizing that while rockets do pollute the atmosphere, their impact is minimal compared to sources such as automobiles and power plants.

Hybrid rockets grow greener

Today, conversations about the 'greening of aerospace' usually focus on aviation fuels, with little attention paid to rockets. Yet promising research may eventually help reduce rocket launch environmental impacts, as well as increasing rocket safety—based on a hybrid rocket design that stores the oxidizer as a liquid and the fuel as a solid that is immune to chemical explosion.

Within just two years, Peregrine, a sounding rocket powered by paraffin-wax-based fuel, is slated to launch on a suborbital flight from NASA's Wallops Flight Facility in Virginia. The rocket was developed in northern California by teams from NASA Ames, Stanford University, and Space Propulsion Group.

If successful, Peregrine will further prove the utility of environmentally friendly hybrid rocket engines for a variety of space launch uses.

Hybrid rockets, first demonstrated in 1933 by Soviet rocket pioneers Sergei Korolev and Mikhail Tikhonravov, are the short leg of a three-legged rocket propulsion stool dominated throughout the space age by the more mature technologies of liquid and solid rocket systems.

In the past two decades, hybrid rocket technology developed in fits and starts. American Rocket (AMROC) and the NASA/industry hybrid propulsion demonstrator program showed interesting results but were not sustainable. In 2004, however, success came with the flight of SpaceShipOne, the first private manned spacecraft, powered by a hybrid rocket burning HTPB (hydroxyl-terminated polybutadiene) with nitrous oxide. SpaceShipTwo, the suborbital passenger-carrying vehicle that will likely be launched this year, is also hybrid powered.

The utility of cheap, clean-burning paraffin to fuel Peregrine is the brainchild of aerospace engineer Arif Karabeyoglu, who studied hybrid rocket stability for his Stanford Ph.D. dissertation. In 1995 Karabeyoglu and Dave Altman, a retired founder of United Technologies' Chemical Systems Division and an advisor to Stanford Ph.D. students, were intrigued by an Air Force Research Laboratory (AFRL) test using frozen pentane in a hybrid rocket motor. The test obtained a burn rate, or regression rate (the speed at which the fuel surface is turned into combustible material) three to five times higher than expected.

A faster burn

NASA Ames research scientist Gregory Zilliac observes that Karabeyoglu "started analyzing those results, and he predicted that the fuel was burning in a different way than traditionally is done in hybrids. Instead of vaporizing and combusting, it was forming a melt layer on the surface, and that melt layer was getting entrained in the port flow, in forms of little droplets. That process was causing the fuel to burn three times faster. That was a very significant result, because the problem with hybrids has always been that the fuel burns too slow to get high thrust."

To stay frozen, a pentane fuel would require a refrigeration system that maintains the pentane at around 200 C below the freezing point of water. "You don't want to take your rocket and put it in a deep freeze before launch," notes Brian Cantwell, Karabeyoglu's Stanford dissertation

This July 2008 firing of the Peregrine motor occurred before the one that resulted in a burst from overpressure. Motor diameter is 11 in.; thrust about 3,000 lb; oxidizer is nitrous oxide.

With this issue, Aerospace America *introduces a recurring column that will examine new developments in green technologies and engineering.*

advisor and former chairman of the Dept. of Aeronautics and Astronautics. "It's not practical."

Together, Karabeyoglu and Cantwell searched for other fuels that might burn rapidly but would be easier to handle than frozen pentane. They discovered that a range of paraffins (especially those of higher molecular weight, with carbon numbers around 32) such as those used in hurricane candles were good candidates.

"Arif's analysis led us to the idea that most paraffin waxes should have a high rate of burning, just like pentane. And they have the advantage, of course, that you don't have to freeze them," says Cantwell. "They are room-temperature solids."

Growing confidence

Prior to 1998, testing with a 50-lb-thrust motor in Cantwell's lab, says Karabeyoglu, "We predicted that paraffin waxes would burn three to five times faster than certain polymeric materials like Plexiglas. The testing showed that the factor of three to five was really there."

In 1999, Karabeyoglu, Cantwell, Altman, and a fourth partner based in Washington, D.C., started a small company, Space Propulsion Group (SPG). Their goal was to develop, through NASA and Air Force contracts, "some practical hybrid rocket systems using paraffin-based fuels by improving the fuel formulation such that we retain the regression rate of these materials, while increasing the structural and mechanical properties," says Karabeyoglu. His group has refined the paraffin with a dye to give the wax the opacity needed to control melting, and with structural additives that increase the wax's strength "by a factor of two to three, and toughness by a factor of six to nine" compared to the baseline paraffin material. "These are essential to making this work."

The following year Karabeyoglu and Cantwell took their findings to Jim Ross, director of the NASA Ames Fluid Mechanics Lab. Soon after that the center's director, Harry McDonald, authorized Zilliac to start up a research program using a 7.5-in. test motor called the Ames Hybrid Combustion Facility. The Ames tests confirmed Karabeyoglu's regression rate theory at increasingly larger scales.

"The other thing we confirmed with the testing was the lack of pressure effects," says Karabeyoglu. They realized that "if you changed the pressure from 100 psi to 1,000 psi, there was no effect on the regression rate. So that was incredibly useful, because it opened up a lot of possibilities for the design of these hybrid systems. Finally, these tests gave us a lot of confidence in terms of the paraffin wax's structural capability."

Parallel efforts fall short

By contrast, says Cantwell, AMROC had been trying in the 1990s to compensate for the low burning rate in existing hybrid fuels such as HTPB "by increasing the surface area of burning. That led people to multiport grains, where you get a large enough surface area that you get enough fuel generation and produce a halfway decent amount of thrust."

But Cantwell adds, "There are several problems with multiple ports. One is that you have a more complex fuel grain design. The other is that you don't have the same volumetric efficiency. In a given volume of motor, you can't put in quite as much fuel, because you have to have all these ports where you are burning fuel. The third thing is that as the ports burn, they don't all burn at the same rate. It's very difficult to distribute the oxidizer perfectly evenly from port to port. They will tend to burn outward toward the case at a different rate, and the first port to reach the case basically shuts down the combustion sequence. The advantage of the high regression rate that paraffin gives is that now you can design a large hybrid with a single circular port. And that effectively makes hybrids practical."

Indeed, because paraffin-based fuels use just a circular port, the fuel sliver weight is lower and the internal fuel shape is simpler and more robust structurally.

Achieving practicality

Following 40 successful tests at NASA Ames, current center director Pete Worden encouraged the paraffin team to mount an actual mission, dubbed Peregrine, that would launch from NASA's Wallops Flight Facility to an altitude of 100 km. After the program's initiation in October 2006, the team faced a setback in 2008 when a test motor using nitrous oxide as an oxidizing agent for the propellant burst at Ames because of pressure oscillations, which were a factor of two over the motor's normal operating pressure. Cantwell says the team has worked to stabilize the motor so that it "doesn't have low-frequency, high-amplitude pressure oscillations."

As ground testing continues, notes Zilliac, the team hopes to "achieve above 95% combustion efficiency, with combustion stability—in other words, peak-to-peak pressure fluctuations of less than ±5% of the mean chamber pressure," leading to "good combustion efficiency and stability" during Peregrine's maiden flight.

Karabeyoglu says because of the single circular port motors used in the hybrid design, Peregrine should demonstrate "up to 99% fuel utilization. As a result of that and the high efficiencies we have shown in our testing at SPG with liquid oxygen motors, we can actually get delivered vacuum specific impulse values around 340 sec. With that kind of performance, combined with the advantages of hybrids—which are safety, incredible simplicity, and the eventual costs advantages—you can have a game-changing propulsion system."

In January, SPG also started testing a 24-in. paraffin-based/LOX hybrid rocket motor that produces approximately 35,000 lb of thrust. If successful, this AFRL-funded testing effort will be a "critical milestone for paraffin-based hybrids and hybrid rockets in general," according to Karabeyoglu.

He sees potential for the future use of hybrid rockets in "niche markets such as suborbital space tourism. For heavy boosters, obviously hybrids are viable," he adds, "but I think the development or the maturation of the technology at that level will take longer. One area where we think the hybrids can be incredibly useful is in the area of upper-stage systems or motors. There are also cost advantages associated with hybrids, plus their simplicity makes them very favorable for upper stages. Once the technology is proven and matures, I think then we can start talking about much larger propulsion systems."

Environmental and cost benefits

Turning to paraffin's environmental advantages, Karabeyoglu notes that unlike with solid rocket propulsion, "we do not have any chlorine-based compounds in these propellants. The paraffin liquid-oxygen system byproducts are essentially water and carbon dioxide, and the percentages of CO_2 produced by hybrid rocket propulsion is incredibly low compared to the other sources, such as power generation or ground transportation."

"When it comes to the environment, the only really viable high-performance oxidizer for solid rockets today is ammonium perchlorate, and ammonium perchlorate is a known endrocrine blocker. For a number of years there's been a lot of concerns about perchlorate contamination of ground water. Hybrids do not use perchlorates so there's no issue," Cantwell continues.

Looking back on their work, Cantwell observes, "Usually when you do basic research in the lab, your prospects of seeing it in practical applications might be a long way off. It has been a while since the late 1990s. This has been a 10-year development. But I think in the next five years we might see these motors really begin to have an impact. They are going to lower the cost of a whole variety of systems. They are not just suited for replacement of boosters. I think with the very high efficiencies that Space Propulsion Group has been getting recently, they are suitable for building an upper stage. There are a wide range of applications, and the net effect will be lower costs, a much safer system, and a much more environmentally benign system."

Fifty years ago, to begin this nation's era of human spaceflight, Mercury astronaut Alan Shepard memorably told his launch crew to "light this candle." Perhaps the past is prelude to a new era with a new kind of candle to propel America's rocket fleets.

Edward Goldstein
edgold18@comcast.net