Ideal Hybrid Fuel Is . . . Wax?

MICHAEL A. DORNHEIM / LOS ANGELES

A graduate student at Stanford University has found what promises to be a better hybrid rocket fuel than the usual rubberized polymers like hydroxyl-terminated polybutadiene (HTPB). The new fuel is a broad class of paraffins, imprecisely known as wax, and may make the hybrid rocket a more viable contender.

Wax's main virtue is that it burns three times faster, producing more thrust for the same surface area. Hybrids have advantages over conventional solid and liquid rockets of safety, low cost, throttleability, and simplicity, but with fuels like HTPB the burn rate is so slow that it must be laced with holes for more surface area, making it prone to internal breakup.

With wax's higher burn rate, fewer holes, or ports, are needed. A single port may be enough and no more than two would be required, said Arif Karabeyoglu, the graduate student who is now a research associate at Stanford's Dept. of Aeronautics and Astronautics. This compares with a typical minimum of four ports for smaller HTPB grains and up to 32 for larger grains, said David Altman, a retired founder of UTC Chemical Systems Div., who has been experimenting with hybrids for four decades.

Potential problems with wax include slumping in storage and cracking at large sizes. But cracking in a hybrid is not the catastrophe it is with a solid.

"The downfall of hybrids has been the burn rate," said Gregory G. Zilliac, NASA Ames Research Center chief test engineer for the Ames Hybrid Combustion Facility, part of a joint research program between Stanford and Ames. A 220,000-lb. motor built by the defunct hybrid company Amroc had 15 ports. "Very few multi-port motors have flown successfully, and they have had problems in ground demonstrations. With the high G-loads of flight, many are concerned that the webs will tear out and it will puff chunks of fuel."

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Nice theory, but what is the proof? Stanford, with the support of the Defense Advanced Research Projects Agency (DARPA) and NASA Ames, has made more than 300 firings of wax hybrid motors ranging in scale from 2.0-7.5 in. dia. and producing 50-3,500 lbf. thrust, using both nitrous oxide and oxygen as oxidizers. They flew a 2.0-in. 5.5-ft.-long rocket to 6,000 ft. in 1999 and plan to send a 12-ft.-long, 7-in.-dia. 165-lb. rocket to 80,000 ft. in April or May. Forty tests of the 7.5-in. motors have been conducted at the purpose-built Ames facility.

Tests show the burning rate of paraffin is three times higher than standard HTPB hybrid fuel over a wide range of conditions. With the high G-loads of flight, many are concerned that the webs will tear out and it will puff chunks of fuel. Alternatives include slumping in storage and cracking at large sizes. But cracking in a hybrid is not the catastrophe it is with a solid.

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motor could be a reality in 5-10 years, Cantwell said. Altman has formed a company called Space Propulsion Group to develop paraffin hybrids, and is part of the Stanford team.

The discovery of wax started with Karabeyoglu and Altman attending a 1995 propulsion conference where U.S. Air Force researchers discussed their tests of frozen pentane as a hybrid fuel. The pentane burned about three times faster than expected, which the Air Force researchers attributed to a lower heat of vaporization. Altman and Karabeyoglu recognized the importance of the high burning rate, but knew that cryogenic pentane was not practical. The burn rate, also known as the regression rate, is the speed at which the fuel surface is turned into combustible material.

Karabeyoglu calculated that pentane’s lower heat of vaporization could only account for a small fraction of the burn rate, and realized that another phenomenon must be involved. He found the answer in Alex Craik’s 1960s theory of thin-film instability, which describes how gas flowing over a thin film of liquid can create unstable waves in the liquid. The important phenomenon in frozen pentane is that a thin, low-viscosity film forms unstable waves, and tiny droplets are produced at the tips of the waves and then entrained and combusted in the oxidizer flow (see drawing at right).

It was this atomization effect that is key to the burn rate, not the vaporization caused by combustion heat. This conclusion was supported by the Air Forces’s results with frozen alcohol, which produces a more viscous film that is not prone to Craik instability. The alcohol burned at the usual low rate expected from heat of vaporization alone. Similar results are had with polyethylene and HTPB fuel. When burned, they have a liquid film, but it is too viscous to productively atomize. HTPB burns much faster in conventional solid rockets, where it is intimately mixed with ammonium perchlorate oxidizer.

**The search was on** for a practical room-temperature fuel with the right thin-film characteristics. After several weeks in the chemistry library, Karabeyoglu found that cheap, plentiful wax might be the ticket. More technically, paraffins with carbon numbers averaging 32 that are refined to remove oils. Wax for hurricane candles is the right stuff.

A dye gives the proper opacity to control melting, creating a 0.004-in.-thick liquid layer for atomization. Wax is a good insulator. Other additives are for strength—they double shear strength and increase toughness sixfold. The additives total to about 1% of the wax and make it appear black. The fuel is called “SP-1.” Cantwell said aluminum could be added to improve performance in some cases, such as with hydrogen peroxide oxidizer. Paraffin is not far removed from kerosene, and all the researchers agreed that the wax hybrid is essentially an oxygen/kerosene engine.

Cantwell sees one possible early application as a two-stage upper stage for DARPA’s Rascal program, which uses an aircraft as a first stage to place small payloads into orbit (AW & ST Feb. 25, 2002, p. 19). Other upper stage applications are envisioned, including for the space shuttle payloadbay, as well as the high-impulse main motors for interplanetary spacecraft. A hybrid main motor would reduce the size of the liquid fuel tank, making fuel handling easier.

Hybrids could be used as first-stage boosters, a job now done by strap-on solids or liquids. Altman is studying the ultimate expression of this—replacing the solid rocket boosters (SRBs) on the space shuttle. He estimates that the 12-ft.-dia. 150-ft.-tall SRBs could be replaced with wax hybrids that are 14-15-ft.-dia. and 160-170-ft. long, and increase total liftoff weight by less than 5%. With the ability to throttle and shut off a hybrid, they can be run up and checked on the pad before liftoff, like the liquid main engines are now, and be shut off early for inflight emergencies. They are sized to give more impulse than the SRBs, as a reward for the trouble of implementing new boosters. The increase in performance would translate into more weight to orbit and greater abort options.

Altman has been discussing this scheme with NASA’s Marshall Space Flight Center. Because wax is safer to fabricate and store than solid rocket propellant, costs should be lower.

Wax and liquid oxygen (LOX) have an average specific density of 1.1, similar to HTPB/LOX and lighter than the 1.8 of HTPB solid rocket propellant infused with oxidizer and aluminum. But wax/LOX vacuum specific impulse is about 30 sec. higher than today’s SRBs—about 295-300
NASA has concepts for a flyback SRB, and Zilliac said there are plans to launch a folding oblique wing design next year with a Stanford hybrid.

In such a large motor, the fuel has to be strong enough to support its own weight under gas flow and acceleration without shearing out, and not slump, or creep. The shear strength of paraffin with additives is 2-3 times greater than HTPB, and while Altman has not performed structural calculations, he does not expect this to be a problem. Tests of SP-1 fuel show that slumping should not be a problem if temperature is maintained below 40-45C (104-113F), Cantwell said, though Altman is more comfortable with 35C. The melt temperature is 70C. But they are cautious about these conclusions and look forward to larger scale tests for proof.

An SRB-size hybrid would probably have the liquid oxygen injected by a turbopump because a helium pressurant system would get too large, Altman said. Another idea is to burn a small amount of hydrogen with the oxygen to heat the helium. This technique was planned by Am-roc and can cut the amount of helium in a 45C oven. A large crack in a conventiona solid motor can be catastrophi- cally, because it increases the burning area, but in a hybrid the oxidizer can’t get down the crack. Several of the 7.5-in. motors have been fired with cracks with imper-measurable effect.

If micro-cracking becomes a problem, it might be fixed by annealing the grain in a 45C oven. A large crack in a conventional solid motor can be catastrophic because it increases the burning area, but in a hybrid the oxidizer can’t get down the crack. Several of the 7.5-in. motors have been fired with cracks with imper-measurable effect.

The theoretical vacuum specific impulse (Isp) for wax with oxygen is 369 sec., assuming 960 psi.; a 600 psi. motor with b/a=3 works as well, Cantwell said. Expected b/a is below 3. “Cracks are an issue with larger motors,” and will be watched as the tests grow to larger scale.

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NASA Ames Research Center has tested forty 7.5-in.-dia. wax motors in its Hybrid Combustion Facility. Stanford and Ames have a joint hybrid research program.