"It might be that at least at that size they're ready for industry to develop into commercial launchers," Lyles said. "If that's the case we may not need to be doing a lot of technology work on hybrids. We

ca504

can pick them up and use them when we get ready to develop the next-generation launch system."

While liquid oxygen was the oxidizer used on the SOAREX-2 flight and on the

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.

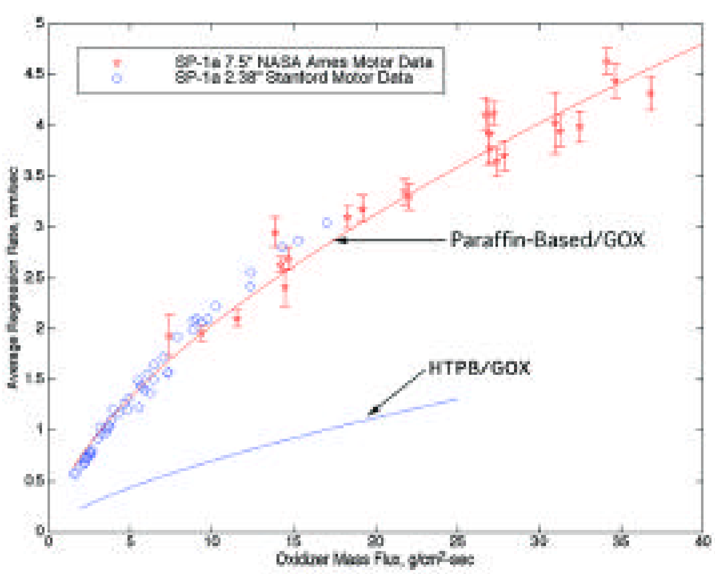
"The downfall of hybrids has been the burn rate," said Gregory G. Zilliac, NASA Ames Research Center chief test engineer for the Ames Hybrid Combustion Facility, part of a joint research program between Stanford and Ames. A 220,000-plus-lbf. motor built by the defunct hybrid company Amroc had 15 ports. "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."

With wax requiring only 1-2 ports, the motor diameter is smaller, the weight is lower, and the internal fuel shape is simpler and more robust. Wax is cheaper than HTPB. Standard hybrids are big, heavy, low-performance motors, but a wax hybrid should be close to a standard solid.

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.

These tests show that wax's desirable characteristics are so far not affected by scale, said Brian J. Cantwell, chairman of the Stanford Aero/Astro Dept. who was Karabeyoglu's thesis adviser. He wants further tests at scales of 2 ft., 4 ft. and 6 ft. dia. to check things like pressure fluctuations and fuel structural characteristics. Altman would later like 8-10-ft. and 14-15-ft. versions. Zilliac would like to see a 2-ft.-dia. motor tested at Stennis Space Center in two years, and a third-generation sounding rocket with 150-mi. altitude capability.

If tests continue to go well, an operational hybrid



Tests show the burning rate of paraffin is about three times higher than standard HTPB hybrid fuel over a wide range of conditions.

four ground tests of the bigger motor at Stennis, other oxidizers have been tried as well. Beginning in the 1980s, a commercial startup called American Rocket Company (Amroc) spent some $20 million on hybrid technology, including motors that used nitrous oxide and hydrogen peroxide as well as LOX.

Over time the company conducted some 300 hybrid motor tests using a variety of fuels, oxidizers and configurations. One motor, the DM-1, generated thrust levels above 220,000 lb. in tests at Edwards AFB, Calif., that also demonstrated thrust vector control. But the company's planned hybrid commercial space launch vehicle never got off the ground.

Amroceventually failed. But Lockheed Martin continued to work on the hybrid technology it developed for them, according to Tassin. SpaceDev, a startup based in Poway, Calif., also acquired technical rights, proprietary data and patents from Amroc and is continuing to develop commercial hybrid products.

The company has put together a concept for a series of orbital "Maneuvering and Transfer Vehicles" (MTVs) that would transfer payloads between Earth orbits using hybrid propulsion systems. The National Reconnaissance Office and the California Technology, Trade and Commerce Agency have supported some of the work with grants and motor contracts, and the Air Force Research Laboratory has awarded SpaceDev a Phase I contract to develop a hybrid propulsion module that can be qualified to fly in the space shuttle to boost payloads to higher orbits.

While Lockheed Martin has studied using hybrids to replace existing rockets, Tassin concedes it is more likely the technology will have to find new applications like the Hybrid Sounding Rocket.

"One of the things you must overcome, of course, is that a lot of the existing systems already have rockets that support them, so you really need a new program or . . . the ability that your non-recurring costs would be more than offset by the advantages of changing. So, [we think] you re-

---

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 is this atomization effect that is key to the burn rate, not the vaporization caused by combustion heat. This conclusion was supported by the Air Force'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.

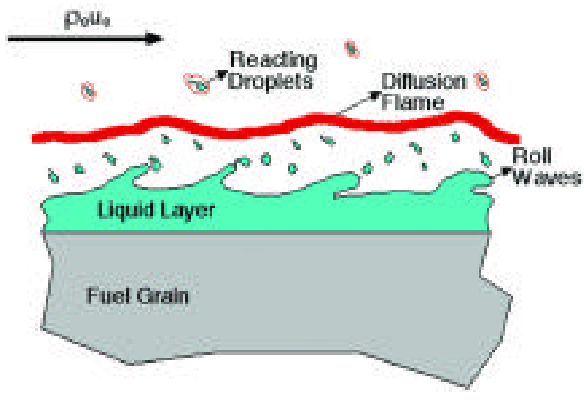
A dye gives the proper opacity to control melting, creating a 0.004-in.-thick liquid layer for atomization. Wax is a good insulator. Other additives are for strength—they double shear strength and increase toughness sixfold. The additives total to about 1% of the wax and make it appear black. The fuel 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 payload bay, 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.

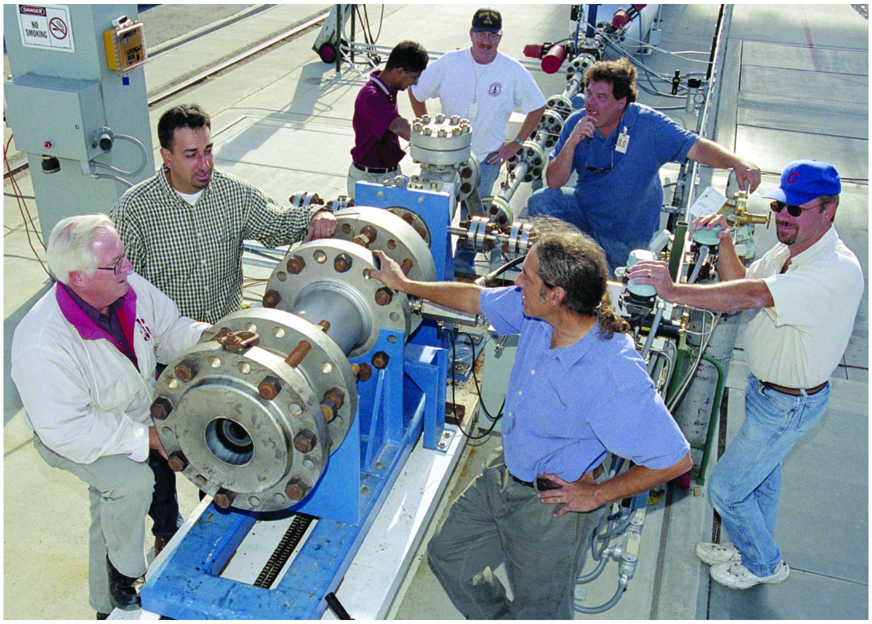
Hybrids could be used as first-stage boosters, a job now done by strap-on solids or liquids. Altman is studying the ultimate expression of this—replacing the solid rocket boosters (SRBs) on the space shuttle. He estimates that the 12-ft.-dia. 150-ft.-tall SRBs could be replaced with wax hybrids that 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



Paraffin has a high burn rate because its low molten viscosity promotes unstable waves that atomize the fuel. More viscous fuels rely on heat of vaporization.



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.

sec. versus 267 sec.

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 Amroc and can cut the amount of helium in half, Altman said. He consulted with Amroc for five years (*AW&ST* Mar. 1, 1993, p. 51). Small rockets work best with cold helium pressurant, he said.

All the motors fired so far have a single cylindrical port. They are made by filling a tube completely with molten wax, capping the ends, laying the tube on its side and spinning it about the longitudinal axis at about 2,500 rpm. The wax shrinks 17% as it solidifies, and the centrifugal force forms the central port with a glass-smooth finish, Cantwell said. Other casting techniques will likely be needed for large motors, but have not been worked out yet. Very big motors may have the wax inserted via thick disks that are stacked, Cantwell said.

One factor in solid rocket design is the "b/a ratio," where "b" is the grain outside diameter and "a" is the diameter of the port. When a rocket ignites, the case pressure makes it expand, creating high tensile stress trying to rip cracks in the port surface. Higher b/a ratios create higher stresses on the port. Wax is more prone to cracking than rubbery HTPB. But because wax is stiffer, it helps to resist and reduce the outward deflection, while HTPB just transmits the loads like jelly. The 7.5-in. motors have been successfully fired at Ames with b/a=2.5 and a chamber pressure of 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.

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 immeasurable effect.

The theoretical vacuum specific impulse (I_{sp}) for wax with oxygen is 369 sec., assuming 500 psi. chamber pressure and a 70:1 expansion nozzle, Zilliac said. HTPB with oxygen is about 360 sec. In practice, Altman hopes to achieve 92% efficiency with wax, or 339 sec. The measured efficiency so far is about 85-90%, and it should improve with size. Because combustion may not be complete within the wax port itself, a post-combustion chamber 10-15% of the length of the grain is added to let the unreacted gases combine. Amroc achieved 92%, Altman said.

Tests at Ames with the 7.5-in.-dia. 43-in.-long motors have used port sizes from under 3 in. to about 5 in., and gaseous oxygen (GOX) flow rates of 2-6 kg./sec. (4.4-13.2 lb./sec.). Most tests are with GOX, but LOX and nitrous oxide have also been used. The GOX/wax mass ratio for best I_{sp} is 2.5, but the tests have been run over a wide range, up to a ratio of 4. Hybrid combustion naturally shifts toward oxidizer-rich as the motor burns, but wax does this less than HTPB, which is good.

The Ames motors produce about 2,500 lbf. and take 10 sec. to burn empty. One has been shut off at 5 sec., then restarted. One also has been throttled back to 50%, then pushed back to maximum. Motors are ignited with an initial GOX/methane flow and a spark plug. "In 40 runs it has always ignited," Zilliac said. "It's not afraid to ignite."

Hybrids have their own design methodology that is different from other rocket motors, Cantwell noted. The length of the motor has to be matched to the oxygen flow rate. If it is too long, too much fuel is produced and the motor will run fuel-rich, and too short results in oxygen-rich conditions.

Since the amount of available oxygen decreases along the length, one would expect more burning up front, but there are self-regulating effects. The gas flow speed is higher toward the end because it has been heated and fuel mass has been added, and the higher speed creates more heat transfer and fuel entrainment. Similarly, a less-burned area will be narrower, increasing gas velocity and burn rate until the diameter is more even. Tests of the 7.5-in. motors running for 10 sec. showed only a few percent variation in burn rate along the bore, Cantwell said. Even when throttled, the burning is even, Karabeyoglu said. Nonetheless, the Lockheed Martin Hybrid Sounding Rocket has a second LOX injector halfway down the bore to mitigate typical hybrid low-frequency combustion instability at startup.

The California Rocket Society tested a form of wax in 1938, but it was not successful, Cantwell said. Now wax has another chance.