3 AEROSPACE AMERICA MARCH 2012

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REAL ESTATE IN FREQUENCY SPACE

The ephemeral 'advanced propulsion'

Strategic bombers—relevant again

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AIAA

The ephemeral 'advanced propulsion'

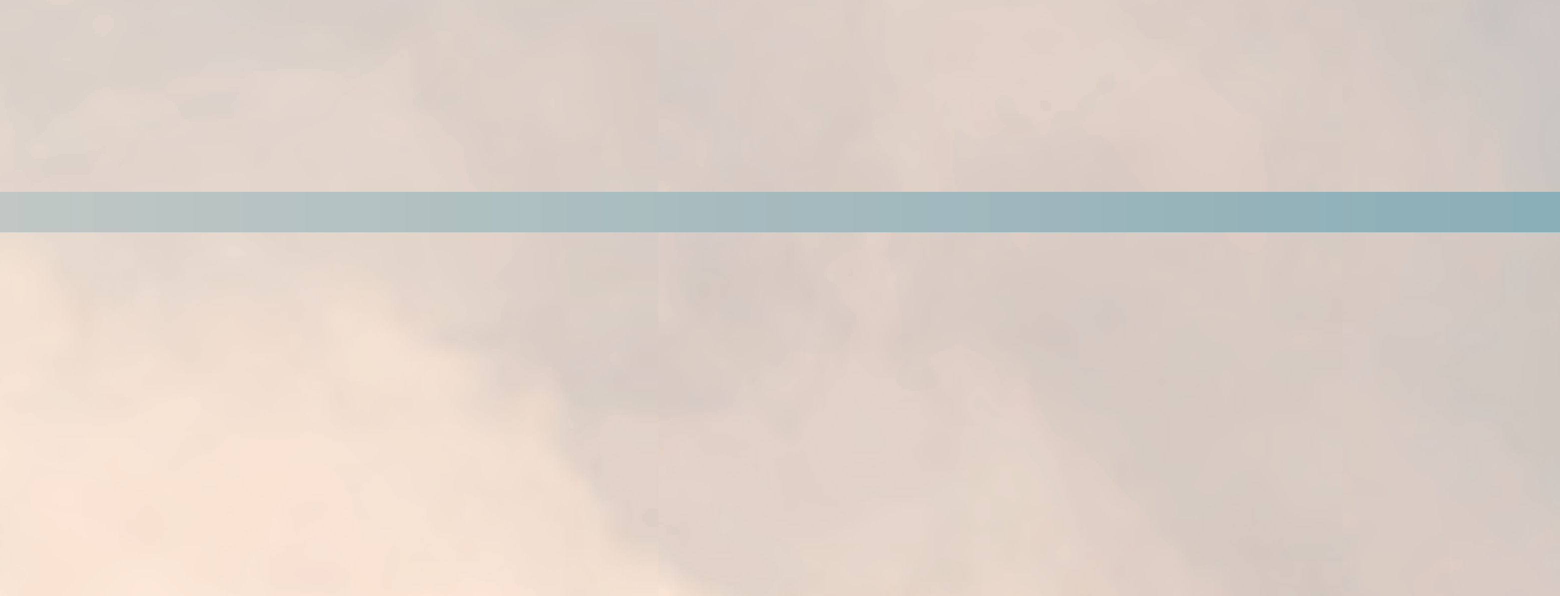
New technologies with the promise of more affordable, more efficient, and safer propulsion for space launch currently seem to be out of reach. That, however, does not mean that we should stop searching.

by **Jerry Grey**
Editor-at-Large

Frequent letters to the editor and commentaries in space journals have decried current and past deep-space mission concepts as being doomed by inefficient propulsion systems. They call upon NASA or DARPA to develop 'advanced propulsion' technologies that will make those difficult missions more efficient, more affordable, more capable, more whatever.

The term 'advanced propulsion,' properly, has been applied primarily to in-space technologies, not those suitable for Earth-based launches. These have included various electric propulsion methods (electrostatic, electromagnetic, electrothermal, magnetoplasmadynamic), nuclear thermal rockets, various forms of catapults (railguns, tether 'slingshots'), laser-heated propellants, photon sails (solar or laser), charged-particle sails, or 'way out' concepts using nuclear fusion or antimatter-based energy sources.

Unfortunately, advanced propulsion with sufficient thrust for Earth-based launchers requires concepts involving esoteric materials (often denoted as 'unobtainium') or other new (or as yet unknown) principles of physics such as antigravity, modifying the structure of space-time, employing electromagnetic zero-point energy, faster-than-light drive, or 'wormholes.' None of these is likely to be operational in the foreseeable future. So, for Earth launch, we are stuck with the few high-thrust technologies available within our current understanding of physics: liquid-propellant and solid-propel-



lant rockets, combined-cycle systems involving air-breathing engines and rockets, guns, and nuclear-thermal rockets.

Neither guns nor nuclear-thermal rockets are suitable for space launch from Earth; guns because of their need to achieve orbital or escape velocity—over 7 km/sec—while still in the high-density atmosphere (even high-altitude launch sites or airborne gun-launch platforms have been studied and found to be eminently impractical and economically disastrous), and nuclear-thermal booster rockets because of valid environmental concerns.

Indeed, the most advanced but still practicable Earth-launch propulsion available to us today or in the foreseeable future remains the one first conceived by rocket pioneer Konstantin Tsiolkovsky in the 19th century—the oxygen-hydrogen rocket. True, we can get slightly better performance from fluorine-hydrogen or ozone-hydrogen, but only with unacceptable cost, hazard, and complexity issues (both have been tried in the past). Other improvements in liquid- and solid-propellant rockets are, of course, possible, and are indeed likely to be pursued, but they are equally likely not to provide game-changing breakthroughs.

Nevertheless, in December 2011 the Air Force announced funding of the first major research phases of a reusable booster system intended to replace its costly expendable launch vehicles, with initial contracts issued to Boeing, Lockheed Martin, and Andrews Space.

THE PROMISE OF THE COMBINED CYCLE

Most past efforts to improve launch performance via air-breathing engines combined with rockets (the so-called combined-cycle systems) have never been able to demonstrate practical, operationally suitable results, although there are still several such concepts currently being pursued—at funding levels too low to possibly produce much in the way of operationally useful systems for years to come. However, there are a few recent developments in this category that appear to be worth following up actively, if sufficient funding can be made available.

Of the many research efforts seeking to demonstrate a practical high-speed air-breathing engine that might be adaptable to space launch, only two have achieved significant flight demonstrations: the third flight of NASA's X-43A in November 2004, whose supersonic combustion ramjet (scramjet) engine operated for 10 sec and boosted the craft to a new world speed record of Mach 9.8, and the first powered flight of Boeing's X-51A Waverider, which reached a Mach number of 4.87 in May 2010 and boasts the longest operating time to date of a scramjet engine: 143 sec. The engine was developed and built by Pratt & Whitney Rocketdyne.

Several other potential combined-cycle approaches are also worthy of note. For example, Aerojet has proposed a three-engine concept, the TriJet, which combines the two classical combined-cycle designs—turbine-based and rocket-based—to achieve a smooth transition from start to over Mach 7. Lockheed Martin's axisymmetric scramjet, based upon a design conceived during DARPA's canceled Blackswift project, has been proposed as the turbine-based combined-cycle powerplant for a new Air Force Research Laboratory prototype of a long-range strike missile, planned for flight testing in 2016. Boeing's successor to the X-51 is another candidate for that mission.

Whereas current U.S. high-speed com-

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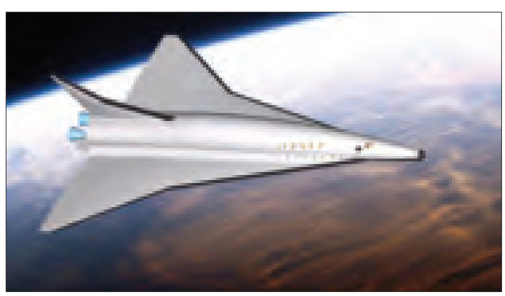
The black X-43A rides on the front of a modified Pegasus booster rocket hung from the special pylon under the wing of NASA's B-52B mother ship.

Lapcat has flight test targets of Mach 5 and Mach 8 using a hydrogen-fueled dual-mode ramjet-scramjet.



SpaceLiner is a two-stage all-rocket-propelled vehicle launched vertically from the ground for ultra-fast long-range flights.

bined-cycle engine concepts are aimed at military applications, Europe has been especially active in research on combined-cycle engines for high-speed transport that could be adaptable to space launch. ESA's Lapcat-II concept, a study conducted under the 4-year Long-Term Advanced Propulsion Concepts and Technologies program, has flight test targets of Mach 5 and Mach 8 using a hydrogen-fueled dual-mode ramjet-scramjet named Scimitar. This engine,designed by the U.K.'s Reaction Engines, employs air cooling and a shaftless air-compression system. One Lapcat-II vehicle design is derived from Reaction Engines' single-stage-to-orbit Skylon concept; another is based on a waverider under study by ESA's Estec and the U.K.'s Gas Dynamics; a third is being explored by France's ONERA and the Universities of Brussels and Rome.

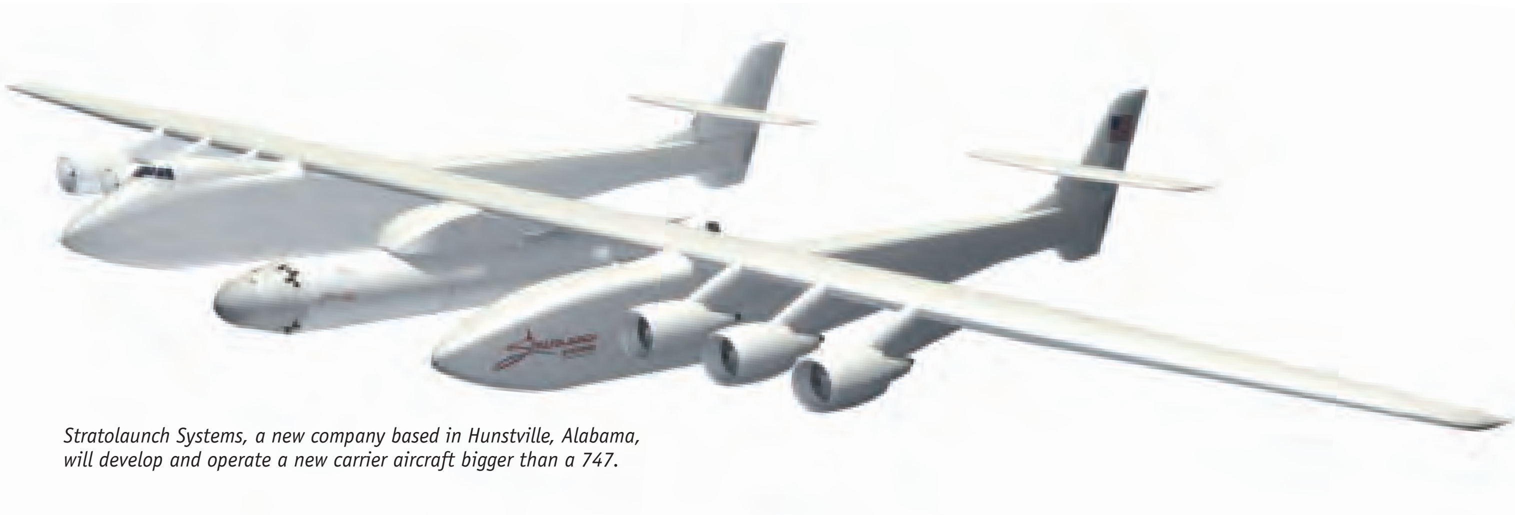
A separate project under Lapcat is the Future High-Altitude High-Speed Transport 20XX (FAST20XX), a two-stage vertical-takeoff SpaceLiner concept by ESA and Germany's DLR. Both of its recoverable stages land horizontally; its upper stage uses a new staged-combustion hydrogen-oxygen rocket. Germany's Sharp Edged Flight Experiment (Shefex-2), whose design speed is Mach 11, is a pathfinder for suborbital reentry tests in 2020, building on the prior Shefex-1 flight at Mach 6 in 2005.

But despite all this activity, it is still far from clear that any of these efforts eventually can produce a practical, low-cost, operational space-launch capability.

Some will ask, "What about the Holy Grail of space transportation: fully reusable single-stage to orbit (SSTO)?" Unfortunately the physics of orbital launch (or at least, our present knowledge of physics) simply does not allow us to attain this ultimate goal. With our highest performance Earth-to-orbit launcher, the hydrogen-oxygen rocket, the rocket equation tells us that we need a mass ratio (propellant mass divided by takeoff mass) of about 0.9; that is, the total mass of engine, tanks, structure, controls, return and landing vehicle, and payload can total only about one-tenth of the launch vehicle's initial mass. For comparison, 0.9 is about the mass ratio of a hen's egg, if we consider the contents to simulate the propellant and the shell to contain everything else.

Past efforts to beat those odds, even with the benefit of an air-breathing boost engine, haven't even come close; for example, the X-30, the X-33, and Lockheed Martin's VentureStar. Britain's Skylon project, another single-stage-to-orbit wannabe, is still in its very early stages and will not be able to prove its worth (if any) for a long, long time.

And if we were to forgo advanced-technology Earth-launch concepts and devote our attention to reducing space transportation costs by using advanced higher thrust in-space propulsion for upper stages and space 'cruise' operations, we would face a nearly insurmountable cost and mass barrier: the need by all such systems (other than nuclear thermal rockets) for high electric power. This requirement, which calls for multikilowatt or even megawatt nuclear (or less practical solar) powerplants, imposes such severe mass penalties on the craft as to make any mission that requires both high performance and high thrust both impractical and much too costly. Several studies have explored the prospect of using beamed power from another satellite serving as a 'power depot,' but this option, although its basic technology is reasonably well advanced, would require considerable, expensive development.



Stratolaunch Systems, a new company based in Hunstville, Alabama, will develop and operate a new carrier aircraft bigger than a 747.

INNOVATION AND RISK

So with what options does this somewhat discouraging picture leave us? For Earth launch in the foreseeable future, there is really only one: Find ways to reduce the cost of space transportation by seeking major improvements in development practices, manufacturing and testing, and perhaps most important, flight operations. Such improvements—in all three areas—require both innovative thinking and, even more important, greater willingness to accept risk.

Innovative development practices have already begun to be pioneered in the U.S. by the new commercial entrepreneurs, most notably SpaceX and Scaled Composites. These companies, in contrast to the other 'new space' wannabes, have demonstrated initial operational success in flight, with development funding that is significantly lower than that of NASA or of the legacy launch-service providers. As cited in *Aviation Week* last August, "…SpaceX is ramping up plans to become the world's largest producer of rocket engines in less than five years, manufacturing more units per year than any other single country."

One of the newly revived operational concepts is airborne launch, which could be significant mainly for the abovementioned combined-cycle propulsion systems. Prior limited use for small payloads carried by rocket-powered orbital launchers, such as the highly successful DARPA/NASA Pegasus launch system developed by Orbital Sciences and ATK, has not demonstrated significant cost reduction. Indeed, two more recent programs for such launches, DARPA's 2003 Responsive Access Small Cargo Affordable Launch and the 2008 DARPA/USAF Quick Reach booster, were both canceled shortly after inception.

Nevertheless, in November 2011 DARPA reinstated the prospective use of airborne launch for small (45-kg) payloads in a new program named Airborne Launch Assist Space Access (ALASA).

Also, operational practices being pioneered by The Spaceship Company, a joint venture of Burt Rutan's Scaled Composites and Richard Branson's Virgin Galactic, along with their innovations in development and testing, could lead to significant cost reductions using airborne launch. Indeed, in December 2011 Paul Allen, cofounder of Microsoft, announced a new Huntsville, Alabama-based launch company named Stratolaunch Systems that will develop and operate a new carrier aircraft bigger than the Boeing 747. The aircraft will be designed and built by Scaled Composites; the rocket launcher it carries, able to orbit payloads up to 6,100 kg, will be designed and built by SpaceX. Although the current plan is to fly only unmanned payloads, the company's future prospects envision a human-rated launcher.

Allen's impressive design team includes Burt Rutan, his collaborator on X-Prize winner SpaceShipOne; Elon Musk, the CEO of SpaceX; former NASA Administrator Mike Griffin; David King, a former director of NASA Marshall; and Stratolaunch Systems' current president and CEO, Gary Wentz, a former NASA chief engineer.

Another interesting operational innovation is orbital refueling, currently being pursued as low-level research by both NASA and DARPA, with a relevant but low-budget

NASA demonstration project ($2.4 million in several study contracts) being considered by the Office of the Chief Technologist for 2016. Several commercial efforts to refuel and refurbish satellites have been abandoned, however, and NASA has recently downplayed orbital refueling as a low-percentage option. For human space missions, human-rating-proven legacy launchers such as Atlas V and Delta IV are another prospect, but one that does not offer much in the way of major cost reduction.

Outside the U.S., improvements in launch effectiveness (although not specifically in propulsion) are being pursued by all the spacefaring countries—Russia, China, Japan, and India—as well as the European Space Agency. ESA is considering the development of an Ariane 6; Russia is developing the Angara and Phoenix families to launch, among other payloads, a new human-carrying space vehicle (to replace the tried-and-true Soyuz launcher and capsule), and a brand-new Siberian launch site, Vostochny. China is designing several new high-payload versions of the venerable Long March family. India is upgrading its Geostationary Satellite Launch Vehicle, and Japan has the new H-2B. Although none of these developments can be categorized as employing 'advanced propulsion,' their improvements in development, test, and operations will contribute to some launch cost reduction and/or capability enhancement.

THE NUCLEAR AND SOLAR-ELECTRIC OPTIONS

Aside from these potential improvements, which are certainly worth pursuing but do not lead to the game-changing dreams of advanced-propulsion proponents, there appear to be only two prospects with any realistic near- to midterm hope of offering significant gains in cost and/or capability: the nuclear thermal rocket and one or more of the solar-electric options. Neither is applicable to Earth launch, the most costly component of space transportation; they are suitable only for upper-stage or in-space operations.

The nuclear thermal rocket, in which a relatively small nuclear fission reactor is used to heat hydrogen propellant to very

December 1, 1967, the first ground experimental nuclear rocket engine is seen in 'cold flow' configuration as it arrives at the Nuclear Rocket Development Station in Jackass Flats, Nevada.

high temperatures, offers reasonably high thrust (on the order of 75,000 lb) and about double the specific impulse of the best chemical rockets. It saw extensive development in the 1950s and 1960s, undergoing a series of quite successful ground tests. Its primary application was seen as a prospective propulsion system for a Mars mission, but when that mission faded from NASA's view in the early 1970s so did the nuclear thermal rocket. However, with renewed recent interest in human flights to Mars, the prospect of using the nuclear thermal rocket in an upper stage has seen some revival. NASA Marshall is currently conducting research on simulated nuclear-thermal rocket configurations, using electric heating to simulate the nuclear reactor's energy. A November 2009 *Aerospace America* commentary ("Nuclear propulsion—the affordable alternative") identified two key points:

• "Planning for human solar system exploration has stubbed its toe, badly, on a simple bit of reality: The performance of chemical rocket propulsion is inadequate. The mass ratio required to deliver something to Mars is over 20 times greater than with nuclear propulsion. The added costs of necessary ferry flights and on-orbit integration are fatal."

• "To resuscitate this option, major decisions must be made, beginning with recovery of the engineering data and equipment still available from remnants of the extensive Rover/NERVA nuclear rocket testing and development programs in the 1950s and 1960s. A fast-track program ranging over six or seven years to flight appears feasible."

Electric propulsion has seen not only extensive development in the past half-century or so, but also a large number of actual mission applications, ranging from comet and asteroid explorers to operational use for station-keeping in commercial communication satellites to orbit-raising of military satellites. Offering proven reliability and specific-impulse performance orders of magnitude higher than chemical or nuclear-thermal propulsion, it nevertheless has the principal drawback of all electric propulsion systems, as noted earlier: very low thrust in the absence of onboard megawatt-level electric powerplants.

However, if flight time is not of the essence, solar-electric propulsion can deliver reasonably high payloads much more efficiently than other propulsion options. For example, as an enabling technology for future human flights to near-Earth objects and Mars after 2020, NASA is now considering the prospects for multi-hundred-kilowatt solar-electric propulsion systems, with projected savings of required mass in low Earth orbit of up to 60% for such missions.

But the engineering obstacles for even the smallest of these prospects (300 kW) are daunting: building an 800-m^2, high-voltage (~300 volt), radiation-protected (glass-covered) solar-cell array that is deployable in space and can withstand the Earth-departure acceleration. Moreover, getting budget approval of the development cost for such systems may be difficult: Even a small 15-30-kW demonstration project, begun by NASA in 2010, had a $1-billion-plus price tag before being cut back to a less ambitious undertaking.

Skylon is a grandchild of the early British single-stage-to-orbit HOTOL concept. Currently being planned by Alan Bond of the U.K.'s Reaction Engines, it uses the Sabre engine,which combines turbomachinery using pre-cooled air with a hydrogen-oxygen rocket to enable flight from standstill to orbital speed.

All in all, the near- to-midterm prospects for applying 'advanced propulsion' to create a new era of space exploration are not very good. Nevertheless, there is every reason to continue seeking breakthrough technologies as an investment in the future, for example, via recently initiated programs such as DARPA's 100-year Starship project and NASA's Innovative Advanced Concepts, an outgrowth of the former highly successful NASA Institute for Advanced Concepts that was terminated in 2007 after 10 years.

But don't expect anything approaching *Star Trek*'s faster-than-light 'warp drive' for many years to come.