Nuclear and future flight propulsion

by **Ivana Hrbud**

This year has seen exciting research aimed at the development of new propulsion technologies. Industry, academia, and government agencies are working on a number of projects encompassing nuclear, electric, and propellantless propulsion concepts.

University activities

The Polytechnic Institute of Turin and the University of Rome "La Sapienza" evaluated performance of the fission fragment heated engine, a high-performance nuclear thermal rocket (NTR) based on concepts formulated by Carlo Rubbia. The reactor core consists of thin-walled porous propellant flow passages coated with a thin layer of americium 242. Propellant is injected radially into the passages and heated directly from fission fragments from the liner. This approach allows much higher bulk temperatures in the propellant than a conventional NTR, while keeping fluid in contact with the walls within material temperature limits. This concept theoretically warrants a specific impulse (I_{sp}) of 2,000-4,000 sec and thrust comparable to conventional NTR concepts. The two universities researched phenomena associated with plasma expansion and thermal heating due to gas/plasma interactions and developed a gas injection system.

The University of Michigan (UM) made significant progress in the development of laser accelerated plasma propulsion systems. To generate thrust, this concept utilizes lasers with ultrashort pulse lengths to accelerate charged particle to relativistic energies. Confirmed by theoretical studies, proton velocities are proportional to the intensity, wavelength, conversion efficiency, and focal spot radius of the laser. Recent experiments, where the UM terrawatt research laser impinged on a thin aluminum target, demonstrated that energies of the ejected particle scale to the square roots of intensity and wavelength. In addition, target thickness of approximately 10 wavelengths produced maximum proton energies independent of the target material. Current experimental work aims to demonstrate the dependence of the other two parameters.

Pioneered by the University of Washington, the mini-magnetospheric plasma propulsion, or M2P2, concept has inspired scenarios of great potential due to its favorable performance characteristics. The sail-type concept inflates a magnetically confined plasma bubble about 10-30 km in diameter. The interaction of this magnetic field with flowing charged particles in the solar wind generates thrust. Marking a considerable improvement this year, experiments were conducted in a larger vacuum chamber, more closely reproducing space conditions. For these experiments, plasma temperatures reached 25 eV (290,000 K) for about 1 kWe, while achieving gas utilization of nearly 100%. Dipole configuration providing magnetically closed geometry is mainly responsible for these operational characteristics. Magnetic field perturbations were measured; however, wall contact of the plasma affects field expansion. Current efforts concentrate on developing a unit of several tens of kilowatts, which might someday have potential applications for human exploration.

The Innovative Nuclear Space Power and Propulsion Institute at the University of Florida continues to lead advanced nuclear fuel development and innovative fabrication and processing techniques for high-performance space nuclear reactors. Recent efforts concentrated on enhanced manufacturing methods for tricarbide, such as (U, Zr, Nb)C, nuclear fuels. Powder metallurgical techniques and liquid-phase sintering of uranium carbide produced high-quality samples, which are exposed to flowing hot hydrogen at 2,600 K (4 hr) and 3,000 K. Long-duration tests at these temperatures are crucial to verifying stability, long lifetime, and burn-up rates. Future work includes testing of other tri-carbide and carbonitride based fuels.

Government and industry efforts

Aerojet recently completed nonnuclear demonstration tests of the LO_X-Augmented Nuclear Thermal Rocket (LANTR) concept. Pioneered by Aerojet and NASA-Glenn, this concept could substantially increase the thrust-to-weight ratio of an NTR by injection and supersonic combustion of oxygen in the nozzle. A highly fuel-rich conventional hydrogen/oxygen rocket simulates the hot hydrogen exhaust of an NTR, while Aerojet's Cascade scramjet injectors introduce oxygen into the supersonic nozzle. Latest tests show a thrust increase of 53% and an oxygen combustion efficiency of 73%. Plans for future hot, dry hydrogen tests of the

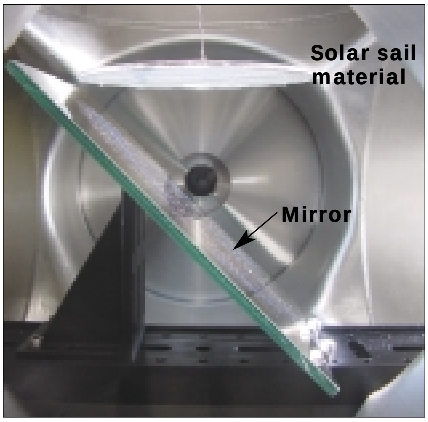
LANTR concept anticipate a thrust augmentation from the current 30% up to 100%.

The need for R&D to support new propulsion technologies and ground testing spun off significant research programs. NASA-Johnson continued work on the variable specific impulse magnetoplasma rocket (VaSIMR) concept for high-power nuclear electric propulsion (NEP) missions within the solar system. Experiments demonstrated the operation of a flight-like high-temperature superconducting magnet, while proving innovative magnet technology that reduces weight by a factor of 30. Plasma source development resulted in increasing plasma production rate and column diameter. Experiments verified that ion cylcotron resonance heating (ICRH) adds energy to the plasma. Continuing R&D focuses on the three primary sections of VaSIMR: plasma source, plasma booster ICRH, and magnetic nozzle.

NASA-Glenn continues developing revolutionary aerospace fuels that promise to increase I_{sp} by 50-150% for hydrogen/oxygen rockets. Trapping/storing atomic hydrogen, boron, or carbon within solid hydrogen may greatly boost the performance and combustion efficiency of rockets and combined-cycle engines using LH_2/LO_X propellants. Major efforts concentrate on identifying progression mechanisms to form millimeter-sized solid hydrogen particles in liquid helium. Experiments measuring temperature, pressures, and flow rate of the liquid and gas characterize the solid hydrogen formation, while video imaging documents growth rate.

Glenn is also involved in evaluating MW-class magnetoplasmadynamic (MPD) thrusters for future interplanetary missions. MPD thrusters are electromagnetic plasma accelerators providing moderate thrust and I_{sp} approaching 10,000 sec. A new pulsed MPD thruster (30 MW during 2 msec pulse) establishes quasisteady plasma flow conditions simulating steady-state thruster operation. The primary goal of pulsed MPD testing is to evaluate new, more efficient designs before embarking on more expensive steady-state high-power engine tests. MACH2 code provides new insights into high-power MPD thruster physics and performance.

NASA-Marshall developed a thrust stand accurately measuring the photon force on solar sail materials. A solar simulator exposed candidate materials to the light intensity of three Suns, while measuring photon force with this stand. The measurement and the theoretical values agreed within a few percent. The force on the sail depends on the sail's size, distance from the Sun, angle to the Sun, and reflection properties. The group is also investigating the impact of space environment exposure on optical and mechanical properties of solar sail materials. Preliminary data indicate mechanical properties are more likely to degrade before a noticeable degradation of optical properties. These are crucial milestones leading to technology development and eventually to solar (photon) propulsion techniques.



In testing, a solar simulator exposed solar sail material to extremely high intensity light.

Over the past year, Marshall achieved another important operating point with the High-Performance Antiproton Trap (HiPAT). Researchers successfully demonstrated dynamic capture of positive hydrogen ions injected by a radio frequency ion source. HiPAT is an electromagnetic containment system developed to store and transport up to 1 trillion antiprotons. The "trapping" region contains a cylindrical electrode structure capable of 20,000-V operation and is surrounded by a 4-Tesla liquid-helium-cooled superconductor. An ultrahigh-vacuum system encloses the entire trap assembly while removing background gases detrimental to ion storage lifetimes. "Normal matter" beams simulate antiprotons, significantly simplifying development of experiment hardware and techniques. The HiPAT will provide a test bed for basic low-energy antiproton research and serve as a supply for experimentally demonstrating the theory behind several high-performance antiproton-driven propulsion concepts.

NASA-Marshall and various DOE labs including Los Alamos and Sandia, along with industry, continued development of NEP systems, focusing on refractory metal cores, high-temperature resistance heaters, advanced heat exchanger concepts, and innovative ground testing techniques. Marshall's High-Power Propulsion Thermal System program investigates, but is not limited to, test articles based on heat pipe, direct-drive gas, and liquid metal heat transfer methods. Recent experiments with JPL show the full operating range and importance of ground testing fully integrated systems. Hardware work continues in the areas of SAFE heat pipe and direct-drive gas reactors where the liquid metal reactor concept entered the design phase.