Nuclear and future flight propulsion

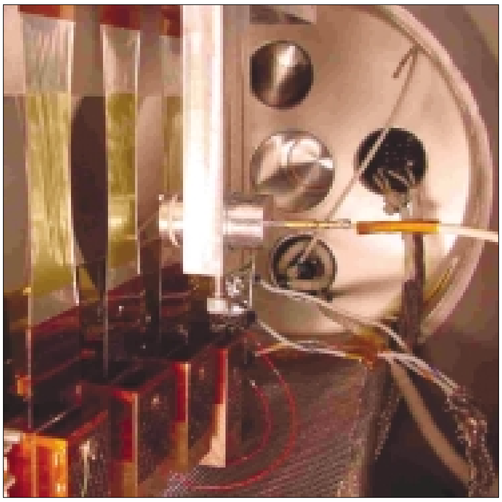
This year, advances in various future flight propulsion methods have been made in industry, both here and abroad; at universities; and at NASA installations.

Corporate and university efforts

For the past two years, Andrewspace has conducted research on improving the original Orion nuclear pulse propulsion concept with funding through NASA's SBIR program and the Dept. of Energy (DOE). The revised approach may hold promise for future terrestrial power generation, which is of interest to the DOE. The Mini-Mag Orion concept is a gigajoule-scale, pulsed nuclear fission device wherein externally initiated electromagnetic compression of individual fission pellets yields low-mass criticality. The resulting fission reaction produces highly energetic plasma, which is then expanded through a magnetic nozzle.

To access concept feasibility, experiments were conducted at Sandia National Laboratory using the Saturn and Z-pinch pulsed-power machines. Results verified the possibility of transmitting the required power discharges through low-mass Mylar transmission lines. In addition, imploding pinch experiments proved the ability to compress cylindrical liners of high-Z material (gold) to very high densities.

European companies ELV, Avio (Italy), and Reaction Engines (U.K.) teamed to advance the development of SKYLON—a single-stage-to-orbit spaceplane. This reusable vehicle employs the synergetic air-breathing and rocket engine (SABRE) concept. Transition between the air-breathing and rocket modes is around Mach 5 at an altitude of 26 km. In the air-breathing mode, precooling and conventional axial flow compression are combined to deliver air at approximately 140 bar to the combustion chamber of a conventional rocket engine. After the transition to the rocket mode, the external air supply is disabled and internal oxygen tanks supply the oxidizer to the rocket engine.



Solar sail materials undergo mechanical stress testing after exposure to space environment radiation.

The fuel of these dual-mode engines during the single-stage ascent is hydrogen, which also serves as a heat sink for cooling the inlet air. During the past two years, Reaction Engines has designed, built, and tested heat exchanger technologies for the engine at their site in Oxfordshire. Supported by QinetiQ in Farnborough, Reaction Engines conducted preliminary wind tunnel tests at Mach 12 to explore shock-shock interactions during reentry.

Researchers at Innovative Nuclear Space Power and Propulsion Institute (University of Florida) are continuing their focus on both near-term nuclear propulsion concepts and revolutionary power generation systems. Encouraged by results from (U, Zr, Nb)C tricarbide fuels that showed improved stability at high temperatures (2,700 K), work was extended to fuels with tantalum carbide, critical for water-submerged, subcritical reactors and for operation at high temperatures (3,000 K). Ultra-clean and efficient glove boxes and vacuum systems allow for enhanced production at greater purity with fewer dissolved interstitials such as oxygen and nitrogen. Future work will focus on gradient coatings of refractory carbides.

A detailed engineering analysis was conducted on a vapor core reactor design with magnetohydrodynamic energy conversion. This study indicated that multi-megawatt-class systems are capable of achieving specific masses of less than 1 kg/kWe. The study focused on the reactor system, shielding, and radiator. Results included the analysis and modeling of a condensing, ultra-high-temperature radiator. The study incorporated advances in molybdenum-based high-temperature material alloys due to their strength and compatibility with liquid/vapor UF_4 at high temperatures.

For researchers at the University of Michigan, this past year saw another significant milestone for the development of the laser accelerated plasma propulsion system. Theoretical predictions and experiments confirmed that the protons received added energy during the expansion phase of the plasma upon leaving the target. In experiments where laser pulse lengths are shorter than the ion acceleration time in the target, the expansion is adiabatic, thus maximizing the velocity of the protons. Furthermore, this velocity scales directly with the dia-

by **Ivana Hrbud**

meter-to-thickness ratio of the target. This result is particularly significant since the energy of the ejected protons increases with increasing spot size. This relationship will have significant impact on thrust enhancement.

NASA efforts

NASA-Marshall continues to explore innovative technologies for solar sail propulsion systems, where a spacecraft gains momentum from incident photons. This past year, researchers concentrated their efforts on characterizing the mechanical properties of candidate solar sail materials exposed to space environments. Sails, when fully deployed, can have biaxial stress states as low as 1 psi, while stress states are expected to be considerably higher at sail suspension points. The objective of the investigation was to determine the radiation dose that would induce material failure for the specific tension load applied to the candidate materials.

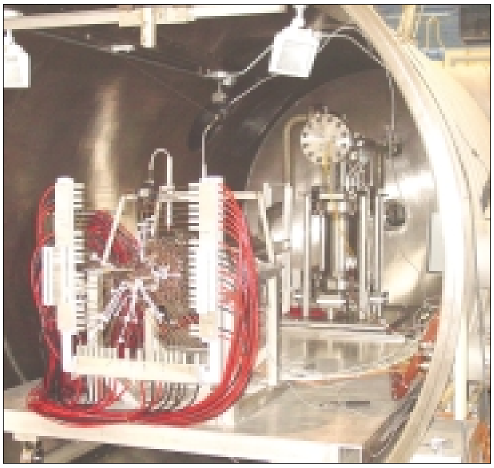
The materials investigated were 2-µm Mylar and Teonex with and without aluminum coating, which were loaded with uniaxial tensioners up to 5,000 psi. Preliminary results show that radiation dose has an effect on the integrity and degrades mechanical properties of these materials. More research is under way to better understand the underlying failure mechanisms and to develop better models for predicting functional lifetimes.

Marshall pursued a range of efforts aimed at identifying and developing new technologies for primary spacecraft propulsion. Research efforts focused on high-power pulsed electromagnetic thruster concepts that use novel methods of plasma formation to address life-limiting erosion issues and other disadvantages of current electric propulsion devices. One such project is the plasmoid thruster experiment, which inductively forms and accelerates compact toroids. Initial tests have demonstrated the ability to efficiently create plasmas propagating at over 20 km/sec into a neutral backfill of gas. The liquid-fed pulsed-plasma thruster is a two-stage electromagnetic device that uses a porous cathode to inject liquid metal propellant. This approach refreshes the cathode surface and significantly alleviates erosion issues.

The center also continues with design, fabrication, and testing of nonnuclear test beds and innovative ground testing techniques. To achieve the maximum benefits of a strong nonnuclear testing program, tangible realistic prototypic hardware milestones must be shown on a yearly basis. In addition, each product must build on the success of its predecessor and must be applicable to the next system.

This approach was used for the Safe Affordable Fission Engine (SAFE) test article development program and accomplished via cooperative efforts with DOE labs, industry, universities, and other NASA centers. Through hardware-based design and testing, the SAFE program investigates component, subsystem, and integrated design and performance. The approach is being adapted for all reactor concepts tested at Marshall. Significant accomplishments of 2003 include demonstrations of an automated control zone on a 183-pin, 100-kW heat pipe reactor concept and a direct-drive gas (DDG) -cooled reactor concept.

This year, NASA's Nuclear Systems Initiative was renamed Project Prometheus, after Greek mythology's famous titan, who gave rise to human civilization with his gift of fire. The project's ultimate goal is to significantly increase available power for spacecraft, which consequently will open up the solar system for more ambitious exploration and much greater scientific return.



SAFE and DDG tests are being conducted at NASA-Marshall.

The most significant attributes of high sustainable power levels would permit agility, longevity, flexibility, and comprehensive scientific exploration to be designed into the new-era missions. Project Prometheus named the Jupiter Icy Moons Orbiter (JIMO) mission as its first endeavor. Nuclear electric power and propulsion uniquely augments this mission and enables the combined exploration of Jupiter's moons Callisto, Ganymede, and Europa. JIMO's project office is located at JPL. Team members include NASA-Glenn, -Kennedy, and -Marshall, as well as the DOE, with its affiliates at Los Alamos and Oak Ridge National Lab.

To date, the program office has awarded three parallel JIMO mission study contracts to explore spacecraft conceptual designs and to conduct technology trade studies. In addition, it awarded, through competitive selection, 15 R&D contracts to teams from industry, academia, and government. The three major contract areas are electric propulsion, space nuclear fission, and radioisotope power system development. The multimission radioisotope thermoelectric generator and the Stirling radioisotope generator are considered candidates to power the 2009 Mars science lab. Over 60 organizations are participating in Project Prometheus.