

## ADVANCED SPACE PROPULSION CONCEPTS

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### INTRODUCTION

In the early part of the 20th century, Konstantin Tsiolkovsky and Robert Goddard laid the theoretical foundations for chemical propulsion systems which would one day land humans on the moon and send robotic emissaries hurtling beyond the confines of the solar system. Over the past few decades, a variety of missions have been performed with propulsion systems based upon the combustion of chemical fuels. Chemical propulsion has been sufficient during this preliminary epoch of exploration, but a continued reliance on chemical fuels carries the penalty of large, expensive, and often impractical propellant-to-payload mass ratios for several missions of interest. Advancements in spacecraft propulsion are required to sustain an ambitious near-term program of space commercialization, and to support the permanent expansion of mankind into the solar system. Toward this goal, the NASA Lewis Research Center has evaluated a variety of advanced space propulsion technologies. Recent efforts have focused on advanced chemical, plasma, and laser propulsion concepts, which are outlined below.

### HIGH ENERGY DENSITY PROPELLANTS

The performance of conventional chemical rockets is constrained by the energy available in chemical combustion to specific impulse values near 500 s. High energy density propellants, which use the recombination energy of free-radicals to supplement the release of chemical bond energy during combustion, have been investigated by a variety of researchers<sup>1,2</sup>. The Lewis Research Center has focused on the use of atomic hydrogen propellants, which can potentially deliver up to three times the specific impulse of conventional chemical propulsion systems to provide a revolutionary launch vehicle capability<sup>3</sup>. Fundamental issues to be resolved in the development of atomic hydrogen propellants include the production, storage, and controlled release of free-radical hydrogen in a propellant mixture. To increase the performance over conventional O<sub>2</sub>/H<sub>2</sub> launch vehicles, the storage mass density of atomic hydrogen in molecular H<sub>2</sub> must exceed 10-15%<sup>3</sup>. Current theoretical estimates place an upper bound of approximately 5% on the mass storage density of atomic hydrogen in a solid H<sub>2</sub> matrix, while recent experiments using energetic tritium decay to create free-radical hydrogen have only achieved a few atom percent storage density of H in H<sub>2</sub>.<sup>4</sup> Producing hydrogen atoms in a solid hydrogen matrix at the storage densities required for propulsion may not be feasible using tritium decay schemes, and alternative production methods such as radiofrequency excitation or high energy particle beams may be necessary for the large scale production of atomic hydrogen. Futuristic possibilities include the use of nanotechnology to manipulate and store the hydrogen atoms in an appropriate propellant matrix, or microlasers to selectively locate and split stored hydrogen molecules into atoms. Long term storage possibilities include the use of high field superconducting magnets to stabilize spin-polarized hydrogen atoms within a solid H<sub>2</sub> matrix, delaying the transition to ground state and postponing atom recombination. The magnets and their associated support structure would be an integral part of the launch facility, placed around the propellant tanks to keep the atomic hydrogen from recombining until the vehicle was ready for launch. Because the atomic hydrogen and solid H<sub>2</sub> matrix must remain at cryogenic temperatures, a suitable method for transporting a solid cryogenic H/H<sub>2</sub> matrix from the propellant storage tank to the rocket engine must be designed. Significant breakthroughs in production, storage, and transfer technologies are clearly required before atomic hydrogen becomes a useful rocket propellant, but the potential improvement in launch vehicle performance warrants a continued investigation of this high energy density propellant.

### ELECTRODELESS THRUSTER CONCEPTS

The specific impulse values associated with current chemical propulsion systems are limited by the chemical bond energy associated with the combustion of the propellant. An increase in specific impulse can be realized by decoupling the energy source from the propellant, an approach utilized in electric propulsion devices such as the ion engine<sup>5</sup> and magnetoplasmadynamic (MPD) thruster.<sup>6</sup> These devices supply electrical energy to ionize and accelerate a gaseous propellant, with maximum specific impulse values approaching 5000 s for the MPD thruster and 10,000

s for the ion engine. Both devices are designed to provide continuous low thrust, and must operate for several thousand hours to provide total impulse values of interest for orbit maneuvering or planetary mission applications. Efforts have focused on mitigating the electrode erosion associated with the accelerating grids in ion thrusters and the arc-sustaining cathodes in MPD thrusters, which significantly limit the useful life of the devices. To achieve the benefits of high specific impulse while avoiding the life-limiting erosion of electrode materials, the Lewis Research Center has been actively involved in the development of electrodeless electric propulsion concepts. Three concepts, the microwave electrothermal thruster, the helicon or whistler wave thruster, and the pulsed inductive thruster, are discussed below.

Microwave Electrothermal Thruster. The LeRC microwave electrothermal thruster (MET) test assembly, depicted schematically in Figure 1, consists of a resonant microwave cavity traversed by a longitudinal propellant discharge tube. A commercially available magnetron converts electric power to 915 MHz cw microwave radiation, which is coupled to the tuned resonant cavity. The resulting electromagnetic fields transfer energy to the propellant electrons, which in turn collisionally transfer their energy to ignite and sustain a free-floating plasma discharge. Propellant flowing around the plasma discharge is heated and expanded through a nozzle to provide thrust. A phase shifter-tuner is used to regulate the amount of microwave power delivered to the resonant cavity, from zero to a maximum deliverable power of 30 kW. Stable plasmas have been created and maintained in an open channel configuration with helium, nitrogen, and hydrogen in both the  $TM_{011}$  and  $TM_{012}$  resonant modes at discharge pressures from 10 Pa to 69 kPa<sup>7</sup>. Vortical propellant injection is used to form a stable (spike) plasma along the centerline of the discharge tube, enabling maximum power absorption with minimum heating of the discharge tube walls. A maximum applied power level of 11.2 kW has been achieved with 54% coupling efficiency for nitrogen in the spike condition<sup>7</sup>. Microwave coupling efficiencies above 90% have routinely been obtained for the various propellants at absorbed power levels up to 2 kW. Thrust and specific impulse have not been measured, but numerical simulations predict specific impulse values approaching 2000 s may be achieved with hydrogen<sup>8</sup>. A superconducting magnet, capable of producing 5.7 T field strengths, has been used for preliminary investigations of magnetic nozzling effects. In addition to advanced propulsion research, the microwave plasma test facility provides a unique capability for plasma processing and materials applications.

Helicon (Whistler-Wave) Thruster. In collaboration with the Lawrence Livermore National Laboratory (LLNL), LeRC is investigating the use of helicon waves to ignite and sustain a hydrogen plasma discharge in a thruster-relevant geometry. The helicon wave thruster is an electrodeless device, similar in nature to other electron cyclotron resonance heating (ECRH) devices, but operated at a much higher plasma density. Increasing the plasma density allows an increase in the power and thrust density, yielding improved thruster efficiencies and anticipated specific impulse values of several thousand seconds. Typically, an increase in the plasma density would require operating the device at high microwave frequencies for efficient power coupling and the use of strong magnetic fields to mitigate plasma losses, stressing available microwave and magnet technology. Instead, plasma generation and heating in the helicon thruster uses a helicon (whistler) wave, which propagates at frequencies below both the electron cyclotron frequency and the electron plasma frequency. Injecting the microwave power at frequencies below the electron cyclotron frequency allows the use of a magnetic mirror to separate the hot plasma from the thruster backplate, and propagation at frequencies below the electron plasma frequency permits operation at the desired high plasma densities. In the current thruster configuration (Figure 2), a microwave antenna surrounds the plasma region, coupling the whistler waves to the plasma across the magnetic field lines. As the wave propagates into the plasma, energy is efficiently transferred to the plasma electrons to collisionally sustain the plasma discharge. An initial experiment has been designed and fabricated by LLNL, and preliminary tests are currently underway in the microwave plasma test facility at the Lewis Research Center<sup>9</sup>.

Pulsed Inductive Thruster. The pulsed inductive thruster (PIT), developed by TRW with recent funding provided by LeRC, is an electrodeless plasma accelerator which can operate with a variety of gaseous propellants. The PIT, shown schematically in Figure 3, consists of a flat spiral induction coil powered by a set of capacitors. A puff of propellant gas is injected through a fast acting valve, and spreads across the insulated surface of the coil. The capacitor bank is simultaneously discharged to provide a fast rising current pulse within the coil. The current pulse induces a transient magnetic field, which in turn creates a strong azimuthal electric field via Faraday's law. The azimuthal electric field breaks down the propellant gas, and the resulting plasma is pushed away from the surface of the coil via the mutual repulsion between the induced plasma current and the primary coil current. There is

minimal direct contact between the plasma and the insulating surfaces of the coil and propellant injector, mitigating thruster erosion. The current PIT MkVa design consists of a 1 m diameter coil and a 36 microfarad capacitor bank, chargeable to 16 kV<sup>10</sup>. Recent experiments with ammonia propellant<sup>10</sup> have produced specific impulse values in the range of 4000 to 8000 s, with thruster efficiencies slightly exceeding 50%. Operation at a lower specific impulse value of approximately 2000 s lowered the thruster efficiency to around 43%. Operation with a simulated hydrazine propellant<sup>10</sup> produced specific impulse values of 4000 s with thruster efficiencies of around 45%. The PIT is capable of operating over a power range from kilowatts to multimewatts, and the performance may be tailored for specific missions of interest. The PIT has demonstrated efficient operation with specific impulse values of interest for orbital transfer and interplanetary missions applications. Pending additional funding, research efforts will focus on quantifying insulator erosion, wear-testing thruster components, and evaluating the effect of radiated EMI on communications and data links.

## LASER POWERED PROPULSION

While the electrodeless thruster concepts discussed above seek to decouple the energy source from the propellant, laser powered propulsion concepts seek to decouple the energy source from both the propellant and the spacecraft. Both near-term electric propulsion, and the more far-term advanced electrodeless concepts outlined above, must carry along a power supply which adds mass to the spacecraft and reduces the available payload fraction. Laser powered propulsion concepts seek to keep the power supply on the ground, and beam the required energy to the spacecraft. The efficiency of solar cells are nearly doubled under laser illumination of the proper frequency<sup>11</sup>, allowing a significant reduction in the size and mass of the photovoltaic arrays required for electric powered propulsion. Alternatively, ground-based laser energy might be absorbed directly to heat a propellant for laser thermal propulsion<sup>12</sup>. Near-term applications of ground-based laser beaming include supplemental power for satellites with degraded solar arrays or dead storage batteries, while future applications include laser propelled transfer vehicles and earth-based laser power to sustain a lunar base during the 14-day lunar night<sup>13</sup>. A disadvantage of ground-based laser power is the necessity to propagate through the Earth's atmosphere, where turbulence and temperature induced changes in refractive index can significantly distort and broaden the beam profile. Adaptive optics have been used to sense the distortion of the beam and provide the necessary corrections to propagate a nearly-diffraction limited beam through the atmosphere. LeRC has investigated the use of reportedly nondiffracting beams in conjunction with phase conjugation methods to achieve similar results. Based on theoretical and experimental results, LeRC has shown that nondiffracting wave experiments published in the literature instead conform to standard diffraction theory, and the reports of nondiffracting wave propagation misinterpreted the role of the optical systems used to generate the beams<sup>14</sup>. The use of optical phase conjugation methods to propagate a beam through a distorting media was verified at low powers. In addition, an analysis was performed to evaluate the use of current technology for ground-based, low power laser illumination for satellite propulsion applications in low earth orbit (LEO)<sup>15</sup>. Preliminary results indicate that the short illumination periods associated with LEO systems make ground-based laser propulsion concepts impractical compared with current chemical and solar electric propulsion systems. High power laser propulsion systems continue to look promising for the variety of applications noted above, but await the development of reliable, high power laser systems to bring the technology to fruition.

## CONCLUDING REMARKS

The NASA Lewis Research Center has been actively involved in the evaluation and development of advanced spacecraft propulsion. Recent program elements have included high energy density propellants, electrodeless plasma thruster concepts, and low power laser propulsion technology. A robust advanced technology program is necessary to develop new, cost-effective methods of spacecraft propulsion, and to continue to push the boundaries of human knowledge and technology.

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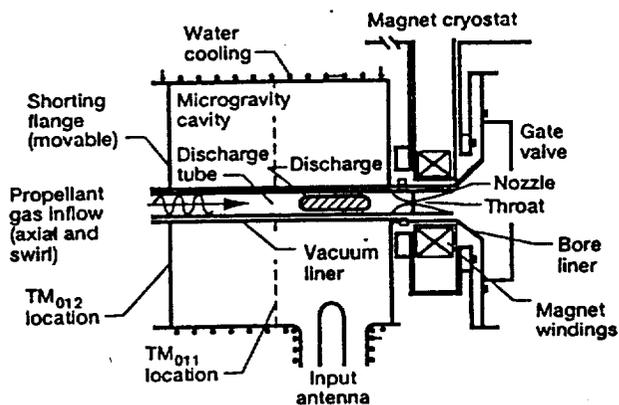


Figure 1. Microwave Electrothermal Thruster.

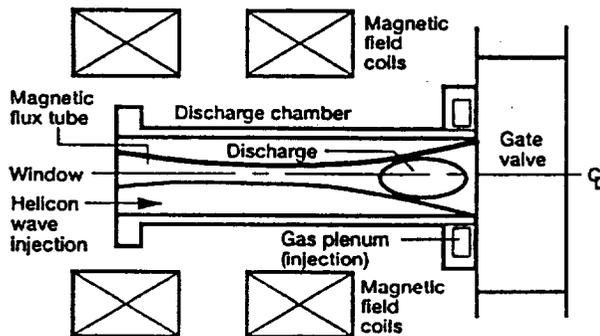


Figure 2. Helicon Wave Thruster.

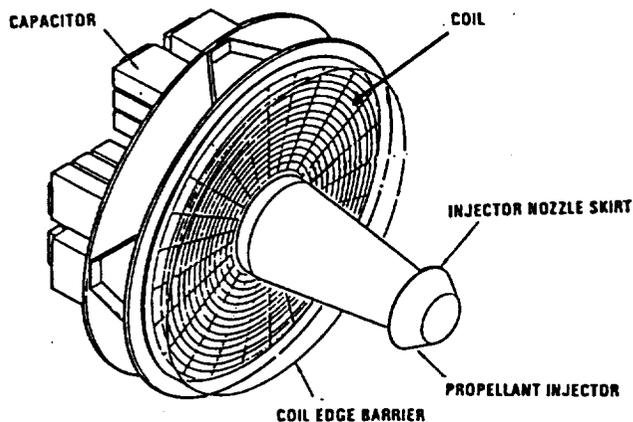


Figure 3. Pulsed Inductive Thruster.