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## Paper Session III-A - Space Transportation Options for the 21st Century

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# Space Transportation Options for the 21<sup>st</sup> Century

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## **Abstract**

As NASA's designated Center of Excellence in Space Propulsion, Marshall Space Flight Center (MSFC) recently established the Propulsion Research and Technology Division (PRTD), an organization responsible for the theoretical and experimental study of advanced propulsion concepts and technologies. Although the scope of the division is broad, the mission is quite focused - *to demonstrate the critical propulsion functions and technologies underpinning the transportation systems and spacecraft needed to achieve NASA's Grand Vision for exploration, commercial development and ultimately human settlement of space.* The division is intended to serve as a bridge that takes promising technologies from the conceptual or early experimental stage to proof-of-concept. The aim is to address the key issues associated with promising high-payoff technologies, some of which were conceived decades ago, to where they can be seriously considered for advanced development. This paper describes the division's research strategy and summarizes its current activities.

## **Introduction**

Propulsion systems come in many shapes and sizes. From the standpoint of station-keeping and attitude control, propulsion is on a par with the other subsystems, which support the operation of a particular spacecraft. However when it comes to vehicles in which the primary purpose is transportation from one location to another, the propulsion system is unique and is the main delimiter on how far and how fast one can travel in space. It is the lack of advanced, truly high-performance propulsion systems that has and continues to restrict the extent of human efforts in space. In addition for almost all space transportation systems, especially launch vehicles, the propulsion system is the heaviest element of the spacecraft, and because of its redundancy and complexity it is usually a major factor in a vehicle's development and life cycle cost.

Since just before World War II, most of the resources expended on improving propulsion capability have been directed towards development. Most launch vehicles in the U.S. can trace their heritage back to the V-2 and early ICBM's of the 1950's. Not many new engines have been developed since that time and those that have utilize the same chemical sources of energy pioneered by Robert Goddard and the early rocket scientists. Apart from the electric thrusters currently making their way onto satellites and deep-space probes, most propulsion today is part of a lineage that was established by the fundamental research done in the first part of this century.

Chemical propulsion has been tremendously successful in enabling mankind to take its first tentative steps into the Frontier. Unfortunately, this success has made us lose sight of the need for continued research of new and radically different propulsion technologies in order to open up space to ambitious exploration, commercial development and human settlement. We have reached the upper limits of chemical rocket performance, and further improvements in this technology will be incremental and decreasingly cost effective, at best.

The following paper outlines the activities of MSFC's PRTD. This recently established organization embodies the broadening of MSFC's interests to cover not only its traditional role as a propulsion development center, but also research of new technologies which promise to greatly improve transportation capabilities into the next century. The PRTD's mission is intended to complement the research activities of other NASA centers, such as NASA LeRC, NASA LaRC and JPL. However, with all of NASA becoming structured along the lines of designated centers of excellence, MSFC cannot avoid assuming an active role in propulsion research. Besides, MSFC brings a unique perspective from its development background that emphasizes the need for significant demonstrations in order to mature technologies to a point where they can be seriously considered for flight applications.

## **The Grand Vision**

In the days of Apollo, the objective of the U.S. space program was very clear - *to send a human to the Moon and safely return him to Earth*. Since that time, NASA has struggled with how to define itself within a continually changing political, economic and social environment. It has also been very difficult to define specific goals for propulsion research that would be immune from changes in national priorities and political interests. However, there are general themes which characterize nearly all activities in space, whether they are commercially or politically-driven. These are embodied in the four elements constituting The Grand Vision:

- Human colonization and settlement of other planets and ultimately star systems,
- Exploration to expand understanding of the universe and its fundamental processes,
- Commercial development and utilization of extraterrestrial resources,
- Betterment of human life on Earth.

Assuming no unanticipated crises (e.g., asteroid collision, Apollo-type national competition), these goals are overarching and fairly immutable to changes in the social, political and economic environment. Hand-in-hand with these goals is the very important and oftentimes unstated assumption that the Grand Vision will provide tremendous benefits to mankind. Hence most that have a strong interest in space and embrace the Grand Vision feel that it should be prosecuted as quickly as possible within the constraints imposed by available resources.

All elements of the Grand Vision require transportation systems that will enable low-cost travel between Earth and orbit, affordable transfer of payloads between various orbits and efficient transport to locations throughout the solar system and deep space. All of these types of missions can be better accomplished (i.e., reduced costs, extended distances and reduced mission times) with the advanced propulsion technologies coming from a strong, focused research program. The overall goal of this research program is to enable rapid, affordable access to any point in the solar system.

## **PRTD Research Description**

The PRTD research program represents a consolidation of on-going and new MSFC projects, and are divided into five main areas, namely (1) Rocket Components and Processes, (2) Advanced Launch Systems, (3) Propellant Storage and Feed Systems, (4) Electromagnetic and Photonic Technology, and (5) Nuclear Technology. There are also several other activities that focus on requirements for future missions and the new physics required to enable revolutionary "breakthrough" advancements in propulsion capability. This paper will focus on the last three areas of the PRTD research program.

### **Propellant Storage & Feed Systems**

Propellant storage and feed technology encompasses all the subsystems associated with thermal control, pressure control, liquid acquisition, pressurization and propellant transfer for launch vehicles and spacecraft. It is a critical crosscutting technology that pertains to many spacecraft applications. PRTD activities in this area have been primarily focused on low-gravity cryogenic fluid management, but there are several efforts that relate to storable propellant systems as well.

One of the most important technologies in enabling long-duration space missions is high-performance thermal control. The PRTD has recently completed an extensive experimental evaluation of a combined foam and multilayer insulation (MLI) concept that could significantly improve the thermal performance of cryogenic upper stages and space transfer vehicles. The MLI was unique in that it (1) incorporated a variable density MLI to minimize insulation weight, (2) had larger vent holes to reduce radiation heat loads, and (3) was virtually seamless to reduce installation time and improve performance. Simulated on-orbit

tests in MSFC's Multipurpose Hydrogen Test Bed (MHTB), shown in Fig. 1, yielded boiloff rates significantly lower than current systems. Also, the foam insulation eliminated the requirement for an MLI helium purge bag, and the new roll/wrap MLI installation method saved nearly 1 man-year of fabrication time.

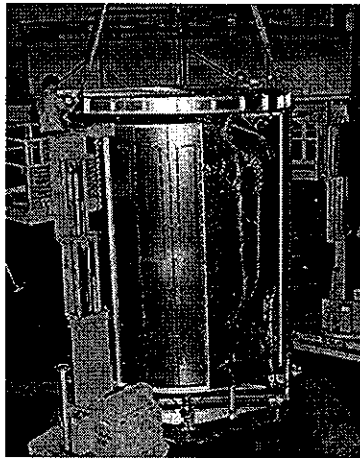


Fig. 1: Multipurpose Hydrogen Test Bed (MHTB)

The MHTB was also used to test a radial flow "spray bar" thermodynamic vent system (TVS) consisting of a recirculation pump and a parallel flow/concentric tube heat exchanger spray bar positioned close to the longitudinal axis of the tank. Testing demonstrated that the radial TVS was effective in providing tank pressure control for various fill levels and applied heat loads. In addition, the new concept appears to be ideal for other upper stage applications such as chill and fill operations.

MSFC is also participating in a consortium that is demonstrating various critical cryogenic fluid technologies for solar thermal propulsion systems. The PRTD's role in the performance testing of liquid hydrogen storage and feed systems includes aero-gravity venting, capillary screen liquid acquisition, pressurization and expulsion, and multilayer insulation. Testing will first be conducted to establish the baseline thermal performance (heat leak/LH2 boiloff for the MLI). The LH2 feed system will then be operated to simulate a 30-day mission with 140 vent cycles (simulated engine burns).

A ground test program has also been established to develop a cryogenic LAD screen performance database. Thermodynamic and heat transfer phenomena such as wicking, evaporation, condensation, pressurant absorption, localized heating and heat entrapment are technology issues that will be addressed. The initial phase will focus on validating test apparatus/procedures and screen bubble point confidence limits using storable test fluids. The second phase will involve the evaluation of bubble point, heat entrapment, pressure drop, and pressurant solubility effects using LN2 (LO2 simulant) as the test fluid. The third phase will perform the same evaluations using LO2.

An alternative or supplement to LADs is to employ magnets to exploit the inherent magnetic properties of fluids such as liquid oxygen (LO2). Since LO2 is strongly attracted to regions of higher magnetic field flux densities, it will tend to accumulate around a magnet and thereby be accessible for fill, drain and settling operations. Liquid hydrogen is also influenced by magnetic fields but in a very weak diamagnetic or "repulsive" manner.

A research effort is being conducted to demonstrate use of magnetically-actuated propellant orientation (MAPO) and obtain experimental data for validation of computational fluid dynamic (CFD) models that account for weakly magnetized fluid behavior. Experiments using the test package shown in Fig. 2 were conducted aboard the KC-135 low-gravity aircraft and confirmed the ability of magnets to control a water-based ferromagnetic fluid used to simulate the behavior of LO2. The opacity of the test fluid limited the

utility of recorded observations. However, several CFD simulations have been performed and show promising results.

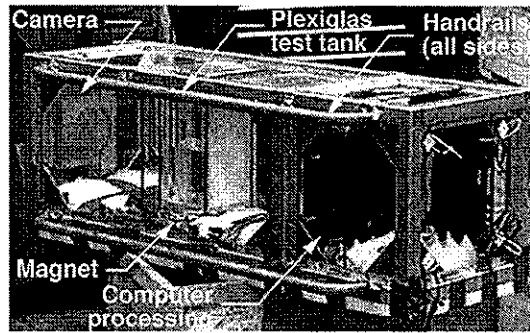


Fig. 2: KC-135 MAPO Experiment Package

Other activities in cryogenic fluid management include demonstration of a hybrid thermal control concept using the MHTB with its current foam/MLI thermal control system (TCS), the radial flow spray bar, and off-the-shelf cryocoolers. Advanced versions of the hybrid concept will then be demonstrated with flight-type cryocoolers and optimized TCS's in subsequent years. Zero-g mass gauging concepts utilizing both compression and optical techniques are being pursued for large scale cryogenic testing in the MHTB.

### **Electromagnetic & Photonic Technology**

The demand for deployment of small commercial and scientific payloads is expected to rise significantly over the next 20 years. Although chemical, electric, or nuclear propulsion systems could meet this requirement, each of these technologies has several drawbacks that suggest a need for a concept that bridges gaps in their performance capabilities. A promising alternative is solar thermal propulsion (STP).

The propulsion system of a solar thermal-powered spacecraft consists of three basic elements: a concentrator, a thruster/absorber and a propellant storage/feed system. Considerable research is being conducted in these three areas for several different NASA, Air Force and industry-led activities. All three have their own unique and challenging issues.

Central to MSFC's efforts in solar thermal propulsion is the installation of an engine test facility in MSFC's East Test Area (Fig. 3). Complementing the Air Force's unique facility at Edwards AFB, the MSFC facility will enable the test of full-scale engines in a simulated space environment.

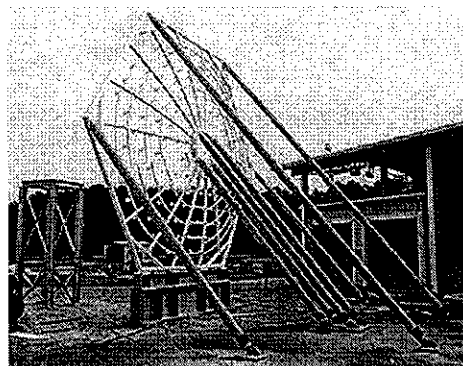


Fig. 3: Solar Thermal Test Facility

The facility will be used primarily to test engines for MSFC's solar thermal technology projects. It will also serve as a resource for commercial technology efforts, and will be available for testing of other thermal

rocket concepts, such as arcjets, resistojets, microwave thrusters, laser propulsion and simulation of nuclear thermal engine flow passages.

The PRTD's principal research project in this area was initiated to assess fabrication techniques for solar thermal absorber/thrusters and evaluate their performance in MSFC's Solar Thermal Test Facility. The first part of the effort involved fabricating several subscale tungsten absorber/thrusters via a vacuum spray process using MSFC manufacturing facilities. The second part entails experimental evaluation of the absorber/thrusters in a small vacuum chamber that is aligned with the solar facility primary concentrator. The tests planned for this project will provide the data needed to examine several simultaneously occurring effects, namely (1) actual versus ideal Isp, (2) exit flow characteristics, (3) solar energy collection efficiency, and (4) materials durability.

Another project is the Shooting Star Experiment, which was originally planned to be the first flight demonstration of a solar thermal propulsion system. The project has now been rescoped into a technology program which will (1) quantify the effectiveness of the engine as a heat exchanger and rocket, (2) verify the structural integrity of the engine module assembly in a launch configuration, and (3) demonstrate the flight worthiness of the materials, design configuration, structure and instrumentation. Two engine module assemblies have been designed, fabricated and assembled. The module assemblies will each test a different support structure design. This is important because these structures must carry substantial launch loads while withstanding high variations in temperature.

### **Nuclear Technology**

Nuclear fission-based propulsion has considerable potential for both ambitious robotic and manned missions to other planets and the outer solar system. Compact fission power supplies could be used to power electric propulsion systems and provide power to other spacecraft subsystems. These power supplies could also be vital to propellant production on planetary surfaces. Fission propulsion systems could be used to provide high thrust at specific impulses double that of the most advanced chemical systems. The US flew a space fission power system in 1965, and the Former Soviet Union (FSU) flew over 30 such systems. Both the US and the FSU have made significant progress toward developing high-thrust fission propulsion systems. Current commercial interest in space fission systems lies primarily with FSU power-only systems. A significant advantage of fission systems is that they are virtually non-radioactive at launch and contain no plutonium.

In conjunction with Los Alamos National Lab, MSFC is developing a Heatpipe Bimodal System (HBS) - a near-term, low-cost, electric power and thermal propulsion device that can provide moderate levels of thrust and power. As currently conceived, the HBS should be able to deliver up to 65 lbf of thrust at an Isp greater than 800 secs. The HBS uses only demonstrated technologies, and may be an attractive first-generation fission system. A primary objective of this project is to fabricate and test a tungsten HBS module, including the Mo/Li heatpipe. All testing will be done using electrical resistance heaters in a vacuum chamber. Fig. 4 shows a Mo/Li heatpipe operating against gravity at a temperature of 1400 K.



Fig. 4 Molybdenum/Lithium Heatpipe Operating Against Gravity at 1400 K.

To enable rapid, affordable development of fission systems, non-nuclear testing must be utilized wherever practical. For systems with thermal power levels on the order of 1 MW or less, it is often possible to use resistance heaters to closely simulate the thermal-hydraulic environment of an actual fissioning system. If the system is designed such that in-core components operate well within the nuclear database, the system can be almost completely developed and demonstrated with relatively simple tests. The PRTD is in the process of establishing a thermal-hydraulic test facility for fission systems.

For ambitious missions to Mars and beyond, nuclear electric propulsion (NEP) may currently be the most viable propulsion option. In this approach, a high specific power (power per unit mass) fission system is used to power a lightweight electric propulsion subsystem. The PRTD is initiating research related to high specific power fission systems and high power electric propulsion subsystems.

Nuclear reactions involving the fusion of low-atomic number nuclei produce up to four times more energy per unit mass than nuclear fission, and seven orders of magnitude more than combustion. For that reason, fusion may be especially attractive for space propulsion on extremely ambitious missions.

Fusion for commercial power has been researched extensively over the last 40 years. Although much progress has been made, the goal of economically viable power has been elusive. Fusion propulsion systems have different constraints than those associated with commercial power production. For example, to be used in space a fusion propulsion system would not have to be "commercially viable", it would simply have to be the best way to accomplish a desired mission.

Current PRTD fusion research is aimed at understanding the basic plasma behavior associated with approaches that could lead to viable propulsion systems. A combination of analyses and experiments will determine whether ignition conditions can be sustained and used to generate thrust. The eventual goal is subscale, proof-of-concept experiments that demonstrate the production of thrust with exhaust power ratios (i.e., jet/input power) high enough to create an attractive propulsion system (typically the ratio must exceed 5).

Several concepts are being pursued as part of the MSFC program. The PRTD is focusing on fusion approaches that could lead to systems that do not require the use of tritium fuel. Thermal management issues associated with tritium-based systems limit their performance potential to roughly that achievable by NEP systems today. One concept that could achieve the higher temperatures needed to sustain fusion reactions that do not involve tritium uses the magnetic field compression of a field reversed plasma configuration (FRC). The Colliding Merging Toroid Experiment (CMTX), shown in Fig. 5, will form FRCs via the collision of two counter-rotating toroids of plasma (i.e., spheromaks) and achieve ignition with pulsed application of a surrounding mirror magnetic field. This promising method draws off the heritage of the TRISOPS experiment that was performed from 1960 to 1981. TRISOPS was not only the first colliding spheromak experiment to achieve near-ignition temperatures, but it also employed a relatively simple test apparatus.

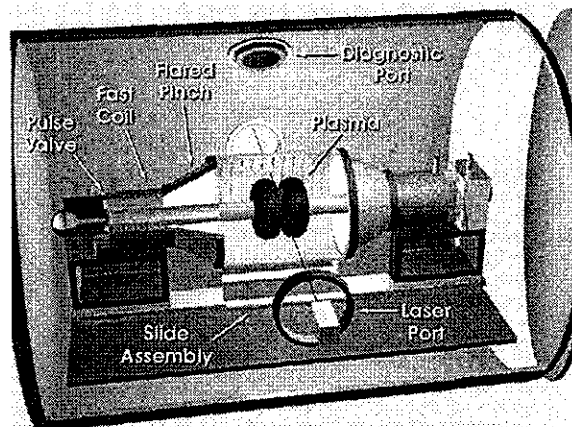


Fig. 5: Compact Merging Toroid Fusion Experiment

Another promising technique, which is under investigation, employs the same FRC formation method as CMTX but utilizes an imploding plasma liner to achieve final ignition conditions. This form of Magnetized Target Fusion (MTF) looks very appealing from a propulsion standpoint because the imploding liner formed by the spherically arranged pulsed plasma jets also serves as the thrust producing reaction mass of the system.

The annihilation of particles and their antimatter counterparts is the most energetic reaction known in physics. Although exploitation of antimatter could hold the key to ambitious exploration of the solar system and nearest stars, there are several challenges that must be overcome before such a system is developed. One is the extremely low worldwide production rates, which are currently limited to nanograms per year. Another is the difficulty of storage that must be accomplished using very low capacity, cryogenically cooled magnetic bottles. Thirdly, the conversion of reaction energy into propulsive thrust is complicated by the unwieldy nature of the reaction products that decay quickly into gamma rays and neutrinos.

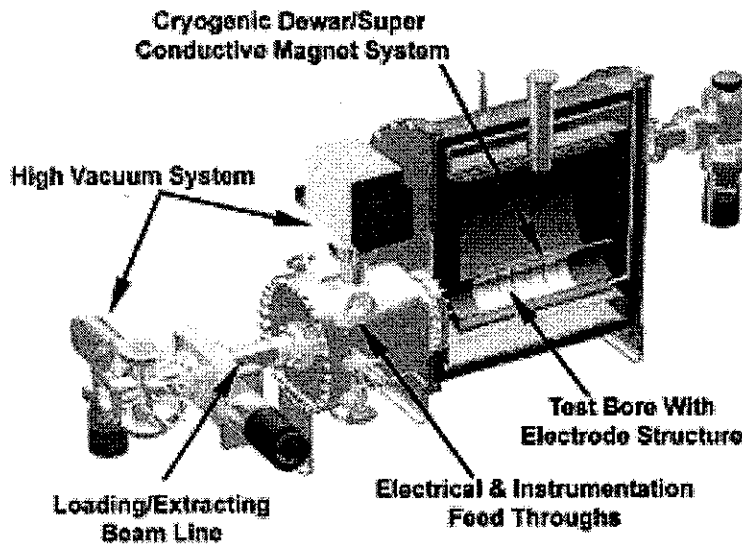


Fig. 6: High Performance Antimatter Trap (HiPAT)

The focus of PRTD efforts in this area is the design, construction and experimental evaluation of an improved antimatter storage device. The High Performance Antiproton Trap (HiPAT), shown in Fig. 6, should lower annihilation losses with container walls, increase space charge density, expand total containment volume over the current state-of-the-art represented by Penn State's PT Mark I Penning Trap. Specific objectives include (1) demonstrating storage capabilities up to  $10^{12}$  antiprotons, (2) storage of

antiprotons for periods extending to 1 to 2 weeks which will make thruster-oriented tests more practicable, and (3) demonstrating transfer of charged particles from HiPAT to Penn State's PT Mark I trap which would be the first exchange of charged particles between two magnetic traps.

A different project with Horizon Technologies addresses the daunting problem of producing antimatter economically and at significant quantities. Current production techniques rely on high energy collisions between beam particles and target nuclei in large particle accelerators. Low production and capture efficiencies make these methods inadequate for cost-effective production of antimatter for space propulsion and other commercial applications. The new technique being evaluated here involves production of particle-antiparticle pairs at a steep electric potential step formed by the suppression of the local, quantum mechanical vacuum field energy. If successful, then a new method of generating antimatter will have been demonstrated that could revolutionize production for scientific, commercial and space applications.

Another project with Synergistic Technologies addresses a critical need in the U.S. for a low-energy source of antiprotons. Although sufficient quantities of antiprotons are produced at the Fermi National Accelerator Laboratory (FANL), the particles are produced at very high energies and are decelerated only to 433 MeV. Reasonable, long-duration storage techniques will require energies less than 20 KeV. This project entails building and demonstrating a proof-of-concept experiment that will use a very simple



degrader system to reduce the energy of the particle beams from several hundred MeV down to a few KeV. Potentially, the cost of the device could be two orders of magnitude less than the current magnetic deceleration methods. The device will be demonstrated using proton micropulses at the Los Alamos Neutron Science Center and then using the antiproton beam at FNAL.

### **Summary**

The Propulsion Research & Technology Division (PRTD) has been established at MSFC to develop a broad range of technologies that address the requirements for an ambitious future in space. The technology areas of Rocket Components & Processes, and Propellant Storage & Feed Systems are focused on improving and lowering the costs of current and near-term systems. The areas of Advanced Chemical Systems and Electromagnetic & Photonic Technology are intended to provide higher performance technology for anticipated launch, orbit transfer and space exploration missions. The last area of nuclear technology is intended to open up the Frontier to ambitious manned and robotic exploration.

Some of these nuclear technologies also have tremendous potential for commercial applications. In all of these activities, the PRTD seeks to leverage resources inside and outside of MSFC through collaborations with university, government and industrial partners. The division also takes full advantage of visiting researcher programs, such as the NRC post-doctorate fellowship, IPA, summer faculty programs, GSRP's and coops. Furthermore, small, relatively inexpensive research activities that concentrate on TRL 3 (demonstration of critical functions and proof-of-concept) are emphasized.