IN-SPACE CHEMICAL PROPULSION SYSTEMS AT NASA'S MARSHALL SPACE FLIGHT CENTER: HERITAGE AND CAPABILITIES

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ABSTRACT

NASA's Marshall Space Flight Center (MSFC) is well known for its contributions to large ascent propulsion systems such as the Saturn V rocket and the Space Shuttle external tank, solid rocket boosters, and main engines. This paper highlights a lesser known but very rich side of MSFC—its heritage in the development of in-space chemical propulsion systems and its current capabilities for spacecraft propulsion system development and chemical propulsion research. The historical narrative describes the flight development activities associated with upper stage main propulsion systems such as the Saturn S-IVB as well as orbital maneuvering and reaction control systems such as the S-IVB auxiliary propulsion system, the Skylab thruster attitude control system, and many more recent activities such as Chandra, the Demonstration of Automated Rendezvous Technology (DART), X-37, the X-38 de-orbit propulsion system, the Interim Control Module, the US Propulsion Module, and multiple technology development activities. This paper also highlights MSFC's advanced chemical propulsion research capabilities, including an overview of the center's Propulsion Systems Department and ongoing activities. The authors highlight near-term and long-term technology challenges to which MSFC research and system development competencies are relevant. This paper concludes by assessing the value of the full range of aforementioned activities, strengths, and capabilities in light of NASA's exploration missions.

INTRODUCTION

In the days following the launch of Sputnik I on October 4, 1957, the world and, to a greater extent, the American citizenry eagerly awaited the successful launch of an American rocket. Weeks later, on December 6, 1957, the US Navy's Vanguard rocket exploded on its launch pad at Cape Canaveral. Attention shifted toward the United States' backup rocket program, based on the Army's Jupiter-C rocket developed by the Army Ballistic Missile Agency (ABMA) at Redstone Arsenal in Huntsville, Alabama under the direction of Dr. Wernher von Braun. The Jupiter-C, a descendent of the German V-2 rocket and the ABMA Redstone rocket, successfully launched the Explorer I satellite on January 31, 1958, catapulting Dr. von Braun and the rocket scientists in the quiet southern town of Huntsville to celebrity status.

The US Congress responded to public outcry in the wake of the Sputnik successes and American launch failures, enacting the National Aeronautics and Space Act of 1958. The space act called for the creation of the National Aeronautics and Space Administration, incorporating the National Advisory Committee on Aeronautics (NACA) laboratories—Langley, Ames, and Lewis. The new agency also acquired the Jet Propulsion Laboratory at the California Institute of Technology and personnel from the Navy Research Lab (NRL) who would form the Goddard Space Flight Center. In 1960, NASA also absorbed the ABMA rocket team at Redstone Arsenal, renaming the organization as the George C. Marshall Space Flight Center (MSFC), in honor of the five-star general and Secretary of State who had overseen the rebuilding of Europe following World War II. Dr. von Braun served as the center director for the next decade with his seasoned team of German and American rocket analysts, designers, technicians, and operators. When NASA received direction to send humans to the moon, it was MSFC who led the charge to develop the gigantic Saturn vehicles. In the 1970s, as NASA undertook the development of a reusable space vehicle, MSFC furthered its propulsion legacy, developing the Space Shuttle main engines, the solid rocket boosters, and the external tank. MSFC is indeed well-known for its contributions to US launch vehicles; however, its thundering moon rockets and Shuttle propulsion elements have often diverted attention away from the Center's rich heritage involving in-space chemical propulsion systems. This paper therefore illustrates the richness of MSFC's in-space propulsion history, pointing out its role in developing both human-rated and robotic in-space systems and highlighting the Center's significant value for present and planned missions involving spacecraft propulsion.

Just as "No man is an island entire of itself," the NASA centers of today are truly interdependent. The spacecraft propulsion community at MSFC recognizes its interdependency and values its relationships with industry, academia, government organizations, and other NASA centers. Most areas of experience and expertise at MSFC reported herein are the result of meaningful and often extensive partnerships. Since mergers, acquisitions, and reorganizations make acknowledgements quite cumbersome in a paper and since the identity of contractors responsible for developing the various spacecraft mentioned here are well documented in the literature, the authors have generally avoided the temptation to identify each partner while making cursory references to projects and programs, except for those cases where their identity helps clarify the context.

MSFC'S IN-SPACE PROPULSION HERITAGE

One of MSFC's most significant and earliest in-space propulsion systems was the human-rated Saturn S-IV-B upper stage (see Figure 1), which provided orbit insertion for both the Saturn I and Saturn V vehicles. Developed in the early 1960s, the S-IVB stage included a single J-2 engine burning liquid oxygen and liquid hydrogen while the on-board auxiliary propulsion system provided 3-axis reaction control capability using 150-lbf thrusters burning monomethylhydrazine and nitrogen tetroxide. The S-IVB stage was central to an early MSFC flight experiment, AS-203, launched on July 5, 1966 (see Figure 2). This landmark flight test provided extremely rare video footage documenting the movement of cryogenic liquid hydrogen inside the common-bulkhead tank during unaccelerated flight and subsequent propellant settling. This flight experiment validated analytical predictions and assured proper propellant orientation before restarting of the J-2 engine (a critical operation for later Apollo missions).[1]

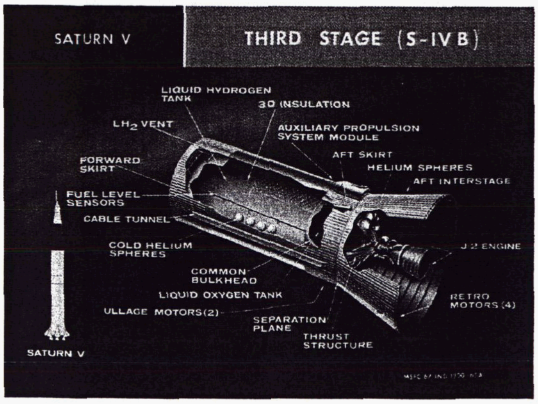


Figure 1. The S-IVB Stage, including the auxiliary propulsion system module.

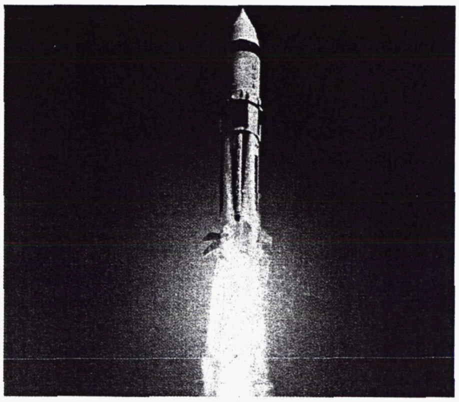


Figure 2. Lift-off of the AS-203 Flight Experiment on July 5, 1966.

The S-IVB experience aptly foreshadowed MSFC's continued contributions for spacecraft propulsion. Experience gained in the development of the S-IVB stage is still active at MSFC. Film of the AS-203 flight experiment is reviewed even today as a guide for intuition and an anchor point for predictive analysis. Storage and acquisition of cryogenic propellants, particularly now for longer-duration missions and omni-directional acceleration environments, continues to be a very active area at MSFC as well as its long-time partner, the Glenn Research Center (GRC). Recent cryogenic storage tests at MSFC have included 45-day zero-boil-off demonstration of liquid hydrogen[2] storage and a 21-day thermodynamic vent system test using liquid nitrogen as a simulant for liquid oxygen.[3] Experience gained in the development of the S-IVB auxiliary propulsion system has also been repeated many times at MSFC. The Center maintains a significant and constantly utilized competency in the development of orbital maneuvering and reaction control systems.

MSFC further expanded its spacecraft propulsion heritage through the development of the Thruster Attitude Control System (TACS) for Skylab (see Figure 3). The enormous lift capability of the Saturn V launch vehicle enabled the TACS to exploit the safety and simplicity of cold-gas nitrogen without concern for the inherent mass of this system. Using six thrusters, each capable of delivering 50 lbf thrust, the TACS performed reliably, although unforeseen levels of TACS usage depleted the nitrogen propellant during the final human-tended period of Skylab's flight.[4]

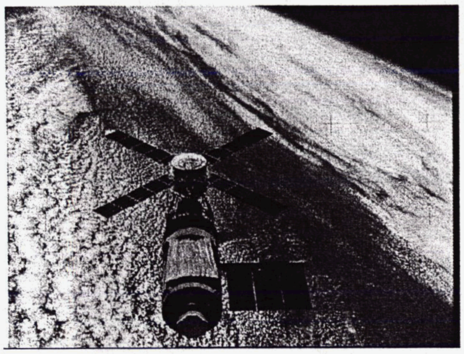


Figure 3. The Skylab Spacecraft

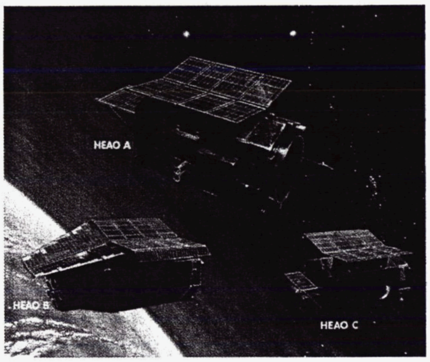


Figure 4. The High-Energy Astrophysics Observatory (HEAO) Series of Spacecraft

The three High Energy Astronomy Observatory (HEAO) spacecraft represent another MSFC contribution to the development of in-space chemical propulsion systems. HEAO-1 launched in August 1977, followed by HEAO-2 in November, 1978 and HEAO-3 in September, 1979. These highly successful spacecraft, propelled by 1.1lb_f (5-Newton) monopropellant hydrazine thrusters, helped establish and maintain monopropellant hydrazine expertise at the Center which continues to the present day. Other NASA MSFC monopropellant hydrazine systems include the Combined Release and Radiation Effects Satellite (CRRES), launched in July, 1990 (see Figure 5), as well as the reaction control systems for both the Inertial Upper Stage (IUS), depicted in Figure 6, and the Transfer Orbit Stage (TOS).

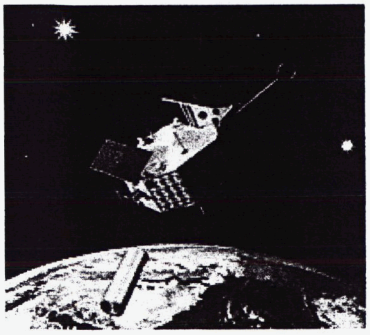


Figure 5. The Combined Release and Radiation Effects Satellite (CRRES)

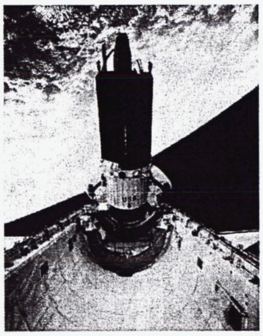


Figure 6. The Inertial Upper Stage (IUS)

Ironically, the unfortunate series of program cancellations over the last several years has also contributed significantly to MSFC's continued competency in spacecraft propulsion. Multiple high-profile spacecraft have kept MSFC propulsion analysis, development, testing, and technical oversight skills well-maintained. The Space Station Program, for example, tapped MSFC engineering resources on numerous occasions. First, in the 1980s, MSFC collaborated with JSC, GRC, and industry demonstrating the vacuum operation of a gaseous-oxygen/gaseous-hydrogen thruster in a system which used water electrolysis to generate the gaseous propellants. Years later, when Station redesign activities had shifted Station reboost and attitude control functions to the Russian on-orbit segment, NASA drew upon MSFC project management and propulsion engineering skills to develop the Interim Control Module (ICM), a modified version of the Navy Research Lab Bus, to provide emergency propulsion services for the Station. Although completed, certified, and delivered to Kennedy Space Center (KSC), the ICM spacecraft was never launched. As a more permanent US contribution to Station propulsion needs, NASA also assigned MSFC to develop the US Propulsion Module, which was to have included a human-rated storable bipropellant propulsion system to be resupplied by propellant transfer from the Shuttle orbital maneuvering and reaction control systems. During this project, MSFC engineering made strides in addressing the challenges of long-life human-rated storable propulsion systems, on-orbit propellant transfer, and reduced-cost propulsion system certification testing. The ICM and US Propulsion Module projects also helped forge renewed and strengthened partnerships between MSFC and JSC engineering and safety personnel.

There are other terminated activities that also contributed to MSFC skills. The Aero-assist Flight Experiment (AFE), for example, began as an in-house activity that culminated in a detailed design featuring a monopropellant hydrazine propulsion system with 25-lbf and 125-lbf thrusters to assist in aero-capture. The Orbital Maneuvering Vehicle (OMV) project also engaged MSFC's spacecraft propulsion engineers, providing experience in the conceptualization and development of high delta-V systems and on-orbit propellant transfer systems.

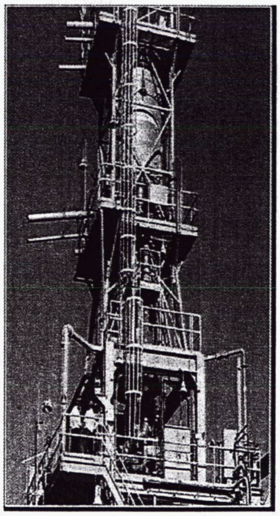


Figure 7. The MSFC-designed Bantam Propulsion Test Article at Stennis Space Center

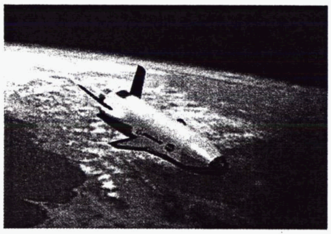


Figure 8. Artist's concept of the X-37 spacecraft

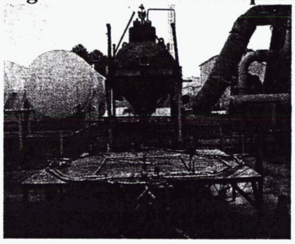


Figure 9. Cold Flow Testing of the X-38 Deorbit Propulsion System at MSFC

The 1990s presented an upsurge in the number of "X vehicles" being developed through NASA contracts and partnerships. Through its industry partnerships during this period, MSFC gained insight into the development of oxygen-hydrogen propulsion for DC-XA and the oxygen-methane reaction control system to be flown aboard the X-33 vehicle. Aerojet completed and delivered the X-33 RCS, but the hardware did not fly due to program termination. X-34 included in-house analysis and design of pressurization and propellant storage and delivery systems as well as in-house development of the FASTRAC engine. Development of the Bantam Propulsion Test Article (PTA) at Stennis Space Center (SSC) also exercised MSFC propulsion analysis, design, and test skills relevant to in-space chemical propulsion (see Figure 7). Various iterations on the design of X-37 (Figure 8), in partnership with Boeing Seal Beach and Boeing Huntington Beach, heightened MSFC experience in the development of hydrogen peroxide systems and storable bipropellant systems for robotic missions. Likewise, MSFC oversight of the X-38 deorbit propulsion stage and in-house cold-flow testing in MSFC's west test area (Figure 9), helped maintain current skills in monopropellant hydrazine systems.

MSFC's leadership of high-profile and human-rated spacecraft propulsion systems has also included the recently terminated Orbital Space Plane (OSP) program, for which MSFC provided engineering leadership reporting directly to the OSP spacecraft project office at JSC. Although short-lived, this program illustrated MSFC's propensity to work across Center boundaries, as the propulsion team included representatives from MSFC, JSC, GRC, and KSC.

Fortunately, MSFC's propulsion skills base also includes successfully completed spacecraft development activities. The Chandra spacecraft (see Figure 10) stands as one of MSFC's proud contributions to NASA's system of great observatories. Launched in July, 1999 and still flying, Chandra incorporated MSFC's first dual-mode propulsion system (i.e. bipropellant nitrogen-tetroxide/hydrazine apogee engines and monopropellant hydrazine RCS and momentum unloading thrusters). Another recent example is the Demonstration of Automated Rendezvous Technology (DART) spacecraft (Figure 11) launched on April 15, 2005. In addition to recertifying the mission duration capability of the Pegasus and Hydrazine Auxiliary Propulsion System (HAPS), the DART project included the development of a new cold-gas nitrogen reaction control system used for proximity operations.

Figure 10. The Chandra Spacecraft as Viewed from the Space Shuttle

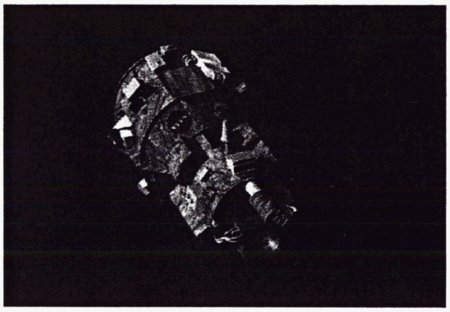


Figure 11. The DART Spacecraft

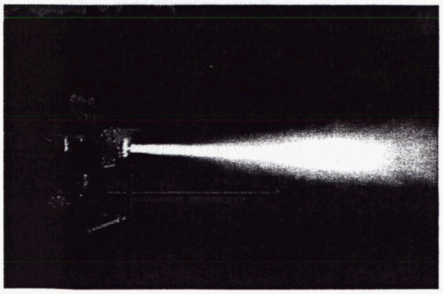


Figure 12. Testing of Northrup-Grumman 1000 lb_f O_2/H_2 Thruster at MSFC TS500

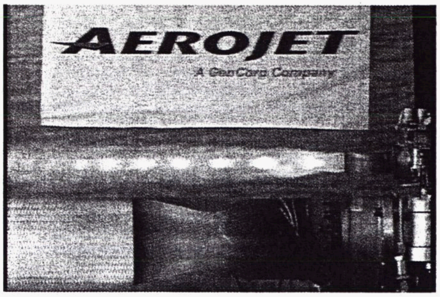


Figure 13. Testing of the Aerojet O_2-Ethanol thruster at Aerojet-Sacramento

Technology programs have also contributed significantly to MSFC's in-space propulsion competency. A very significant example is the Next-Generation Launch Technology (NGLT) Non-Toxic Auxiliary Propulsion System project, which has included the maturation of liquid-oxygen/liquid-hydrogen[5] and liquid-oxygen/ethanol[6] reaction control engine technologies under detailed MSFC technical oversight (see Figure 12 and Figure 13). This same MSFC project office has managed the Auxiliary Propulsion System Test Bed designed and built by the Johnson Space Center (JSC) at NASA's White Sands Test Facility (WSTF). In late 2005, the MSFC-managed oxygen-ethanol engines have been coupled with the JSC-designed feed system. Cold flow tests are underway at the time of this writing, with altitude hot fire testing scheduled to be completed by the end of 2005.

Inter-center personnel transfers have also enhanced MSFC skill and competency, including personnel with in-depth experience in the development of human-rated monopropellant hydrazine systems, i.e. the Space Station Freedom propulsion module, and personnel with experience in Shuttle OMS and RCS ground operations.

Recently, MSFC has undertaken the in-house development of a scalable 25-lbf oxygen/methane thruster. Cold flow testing has been completed on the first-generation prototype with plans for hot fire testing currently underway. Cold flow testing has been completed, and hot fire testing is set to begin in the late winter of 2005-2006.

Although recent years have seen numerous program cancellations and redirections, good experience has been gained and propulsion skills have remained sharp through successful development and operation activities such as Chandra, DART, and NGLT Auxiliary Propulsion.

Table 1 highlights MSFC's heritage in in-space chemical propulsion systems, which are sorted in order of recent activity (i.e. most recent activities are listed first). The table illustrates MSFC's extensive experience with both conventional and low-toxicity propellants as well as advanced technologies such as cryogenic reaction control systems. It is noteworthy that a broad range of propellants and applications (human-rated vs. robotic spacecraft) are in active use and very recent experiences at MSFC.

Table 1. Highlights of MSFC In-Space Chemical Propulsion Heritage and Active Skills

Spacecraft or Project	**Most Recent Activity***	**Human Rated****	**Storable Bipropellant*****	**Monopropellant Hydrazine**	**Oxygen/ Methane**	**Hydrogen Peroxide, JP-8**	**Dual Mode**	**Cold Gas**	**Non-Toxic**	**Cryogenic**
Chandra *(Hydrazine, N_2O_4)*	2005	No	●	●			●			
Demonstration of Automated Rendezvous Technology (DART)	2005	No		●				●		
In-House 25-lbf O_2/CH_4 Thruster	2005	No			●				●	●
NGLT LO_2-Ethanol thruster	2005	No							●	●
Orbital Space Plane	2004	**Yes**	●	●						
X-37 Orbital Vehicle	2003	No	●							
NGLT LO_2-LH_2 Thruster	2002	No							●	●
X-38 Deorbit Propulsion	2002	No		●						
X-37 (Original)	2001	No				●	●		●	
US Prop Module *(for International Space Station (ISS))*	2000	**Yes**	●							
X-33 Reaction Control System *(gaseous oxygen/methane)*	2000	No			●				●	
Interim Control Module (ICM) for ISS	1998	**Yes**	●							
Aero-assist Flight Experiment	1994	No		●						
Combined Radiation and Release Effects Satellite	1991	No		●						
Inertial Upper Stage (IUS) RCS Transfer Orbit Stage (TOS) RCS	1990	No		●						
Orbital Maneuvering Vehicle (OMV)	1990	No	●	●						
HEAO *(3 spacecraft)*	1981	No		●						
Skylab	1977	**Yes**						●	●	
Saturn S-IVB Auxiliary Propulsion System	1973	**Yes**	●							

* Dates are approximate.

** Note that MSFC provided propulsion engineering leadership for development of NASA's human-rated propulsion systems from the Zero-Based Review of the mid-1990s until the Exploration work assignments of 2005, with the exception of upgrades of the Shuttle orbital maneuvering and reaction control system led by JSC).

*** All systems identified in this column utilize monomethylhydrazine and nitrogen tetroxide, except Chandra, which uses hydrazine and nitrogen tetroxide.

PRESENT CAPABILITIES

Built upon this heritage, MSFC's expertise and facilities provide insight into its present capabilities for developing both state-of-the-art and advanced chemical propulsion systems.

PROPULSION SYSTEMS DEPARTMENT

The Propulsion Systems Department at MSFC houses not only the propulsion systems integration expertise but also entire branches that are focused on specialized areas such as valves, lines, and ducts; combustion devices (chambers, injectors, and igniters); turbomachinery; detailed thermal analysis of propulsion systems; detailed structural analysis of propulsion systems and components; detailed design; computational fluid dynamics; etc. These specialized organizations provide cross-cutting expertise to support both launch vehicle and spacecraft propulsion applications. This department houses the Component Development Area (CDA), partially depicted in Figure 14 and Figure 15. The CDA offers very-low-cost development testing of fluid system components, including valves, lines, and ducts for hydraulic systems as well as valves (see Figure 15), regulators, feed systems, and small thrusters or igniters for non-toxic propulsion systems. The Propulsion Systems Department reaches across the entire Center to coordinate support from organizations such as materials and processes, test facilities, and avionics.

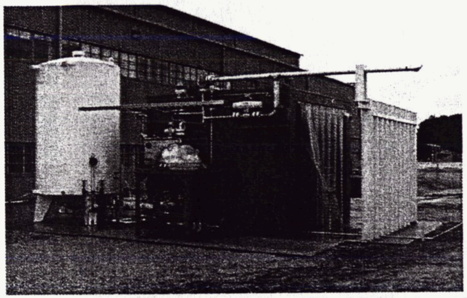


Figure 14. High-Pressure Fluid System Test Cell at CDA

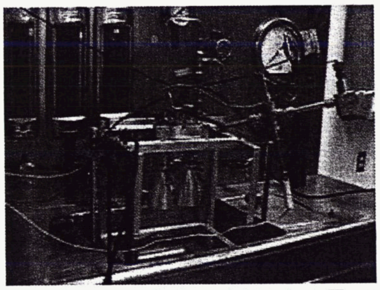
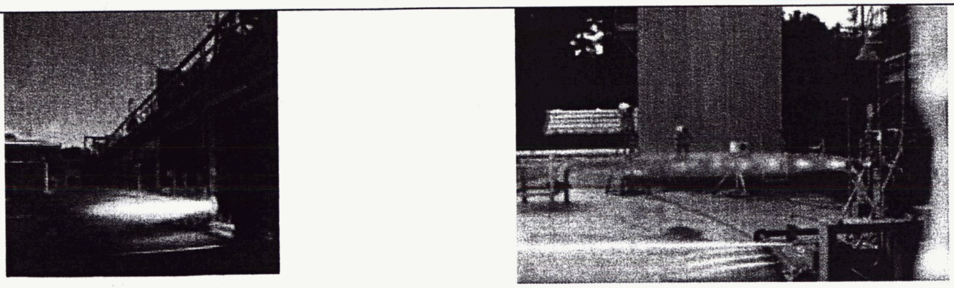


Figure 15. Thruster Solenoid Valve Test at CDA

PROPULSION RESEARCH AND TEST FACILITIES

The MSFC Test Laboratory maintains a well-utilized set of propulsion test facilities (shown in Figure 16) that have served frequently in the development of non-toxic reaction control thrusters and the demonstration of in-space cryogenic propellant storage systems. These facilities offer near-sea-level test capabilities for propulsion system components using non-toxic propellants and vacuum testing for cryogenic fluid management systems.[7]



(a) Test Cells 100 through 110

(b) Test Stand 115 Combustion Test Facility

(c) Test Stand 116 Component Test Facility

(d) Test Stand 300 Thermal Vacuum Test Facility

Figure 16. A Sampling of MSFC Test Facilities Capable of Non-Toxic In-Space Chemical Propulsion Testing

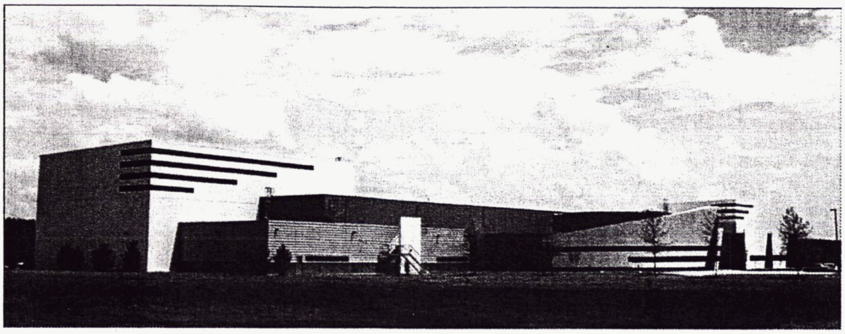


Figure 17. MSFC's Propulsion Research Laboratory

MSFC's Propulsion Research Laboratory (Figure 17) adds fundamental research capabilities to augment the Center's development and operations competencies. This laboratory enables an environment of "technology pull" and allows more seamless collaboration between technologists and users.

PARTNERSHIPS

The spacecraft propulsion development community at MSFC collaborates frequently with other NASA centers and facilities. MSFC's Spacecraft Propulsion Systems Branch personnel, for example, maintain frequent informal contact with fellow propulsion experts at Goddard Space Flight Center (GSFC), GRC, the Jet Propulsion Laboratory (JPL), JSC, KSC, and the White Sands Test Facility (WSTF) as well as experts at other government facilities, such as the US Army propulsion laboratory collocated with MSFC on Redstone Arsenal.

THE ROAD AHEAD

MSFC's in-space chemical propulsion community, along with its partners across NASA, government, industry, and academia, is mobilizing to enable the Vision for Space Exploration announced by President George W. Bush on January 14, 2004.

First, MSFC's spacecraft propulsion engineers are initiating the development of auxiliary propulsion systems for the Crew Launch Vehicle (CLV) shown in Figure 18, including a roll control system for the booster and a reaction control system for the upper stage. MSFC will also be a key participant in the Robotic Lunar Exploration (RLEP) program, although precise details are still being defined at the time of this writing.

Further, MSFC is providing key support to JSC and GRC by leading the advanced development of an oxygen-methane rocket engine to be used on the Crew Exploration Vehicle (CEV) Service Module (shown conceptually in Figure 19) and supporting JSC in the development of the hypergolic backup version of the reaction control system. Through use of the multipurpose hydrogen test bed (MHTB) at TS300 (see Figure 20) and deployment of MSFC's long-duration cryogenic fluid management experts, the Center is also supporting GRC and JSC by providing critical cryogenic testing and cryogenic mass gauge development to enable the use of oxygen-methane for the CEV Service Module.

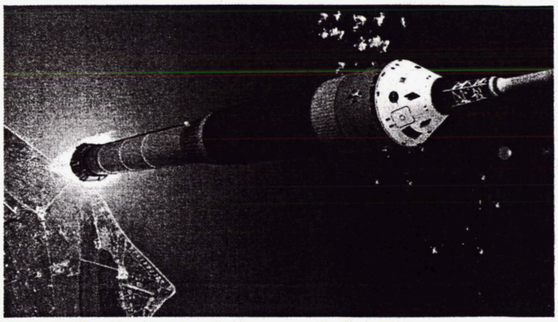


Figure 18. Artist's Concept of the Crew Launch Vehicle, including MSFC-developed booster roll control and upper stage reaction control systems.

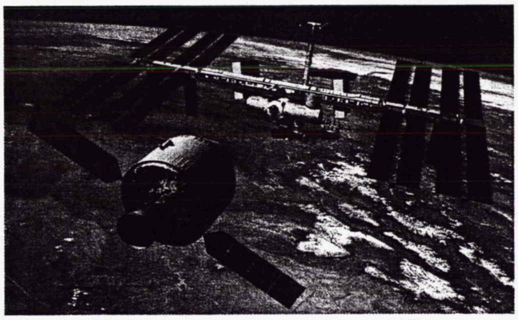


Figure 19. Artist's Concept of the Crew Exploration Vehicle (CEV) Approaching the International Space Station. MSFC is leading advanced development of the oxygen-methane main engine for CEV Service Module.

In addition to these development activities, MSFC will continue technology development focused on the needs of future science and exploration missions. One example of an ongoing task in this area is MSFC's work with advanced liquid monopropellants. The MSFC Liquid Monopropellant Strand Burner (LMSB), shown in Figure 21, is presently being used in a joint program with the Air Force Research Laboratory (AFRL) at Edwards Air Force Base. This test program is seeking to determine burn rate as a function of pressure and propellant temperature for various AFRL-developed monopropellants. Future studies may include more emphasis on combustion method evaluation using the LMSB. Another example of focused technology work is MSFC's ongoing testing[8] of vacuum-plasma spray (VPS) coatings to increase the life of chambers and injectors, illustrated in Figure 22 and Figure 23.

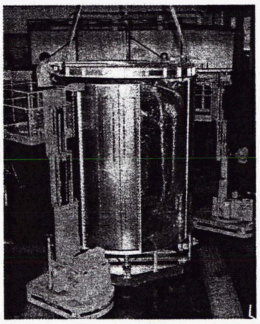


Figure 20. The Multipurpose Hydrogen Test Bed (MHTB) at MSFC, also capable of testing other cryogens such as nitrogen and methane.

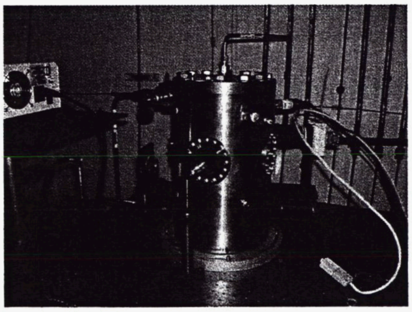


Figure 21. MSFC's Liquid Monopropellant Strand Burner

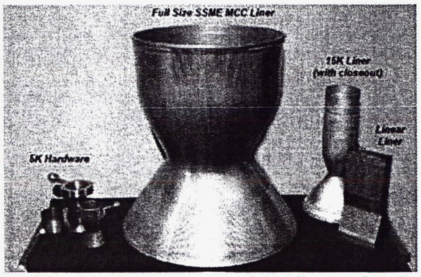


Figure 22. An Assortment of VPS and GRCop-84 Chambers and Chamber Liners

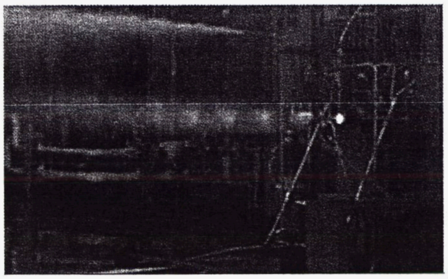


Figure 23. Hot Fire Test of a GRCop-84 Chamber Liner at MSFC.

MSFC's heritage and expertise bear strong relevance to the Vision for Space Exploration. The Vision's need for high-performance in-space propulsion systems and systems that utilize in-situ propellant production will benefit from MSFC's long history in the development and operation of cryogenic propulsion systems and MSFC's extensive experience in testing oxygen-methane combustion devices beginning in the 1980s and continuing to the present.

SUMMARY AND CONCLUSIONS

As illustrated earlier, the Spacecraft propulsion community within MSFC draws on a long and rich heritage of in-space chemical propulsion systems developed by MSFC and its partners. As a result of decades of corporate knowledge and sustained activity in recent years, MSFC offers a well-seasoned cadre of engineers including Apollo-era propulsion and cryogenic fluid management specialists as well as senior-level engineers with multiple in-depth development experiences. Despite the frequent redirection and cancellations of the last decade, MSFC's analysis, test, and development skills have continued to grow. The steady stream of development activities and in-house analysis and testing tasks have assured that nearly every spacecraft propulsion engineer at MSFC has experience analyzing and troubleshooting actual hardware. MSFC's active skill set includes experience with a full range of conventional and next-generation propellant selections for both human-rated and robotic systems.

The Propulsion Research Laboratory augments these capabilities by enabling MSFC engineers to assess and overcome the technology challenges inherent in next-generation propulsion systems and the Vision for Space Exploration. Together, these capabilities represent a vital, though less famous, aspect of MSFC which offers significant value for the Agency and for industrial and academic partners as NASA begins to implement the Vision for Space Exploration.

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