Spacecraft Chemical Propulsion Systems at NASA Marshall Space Flight Center: Heritage and Capabilities

Patrick S. McRight*, Jeffrey A. Sheehy†, and John A. Blevins‡
NASA George C. Marshall Space Flight Center, Huntsville, AL 35812

NASA Marshall Space Flight Center (MSFC) is well known for its contributions to large ascent propulsion systems such as the Saturn V and the Space Shuttle. This paper highlights a lesser known but equally rich side of MSFC – its heritage in spacecraft chemical propulsion systems and its current capabilities for in-space propulsion system development and chemical propulsion research. The historical narrative describes the efforts associated with developing 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, X-37, the X-38 de-orbit propulsion system, the Interim Control Module, the US Propulsion Module, and several technology development activities. Also discussed are MSFC chemical propulsion research capabilities, along with near- and long-term technology challenges to which MSFC research and system development competencies are relevant.

I. Introduction

IN the days following the launch of Sputnik I on 4 October 1957, the American public eagerly awaited the successful launch of an American rocket. Weeks later, on 6 December 1957, the US Navy Vanguard rocket exploded on its launch pad at Cape Canaveral. Attention shifted toward the United States backup rocket program, based on the Army 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 31 January 1958, catapulting von Braun and his team of 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 creation of the National Aeronautics and Space Administration, incorporating the National Advisory Committee on Aeronautics laboratories: Langley, Ames, and Lewis. The new agency also acquired the Jet Propulsion Laboratory (JPL) at the California Institute of Technology, and personnel from the Naval Research Laboratory who would form the Goddard Space Flight Center. In 1960, NASA also absorbed the ABMA rocket team at Redstone Arsenal, forming the George C. Marshall Space Flight Center (MSFC), in honor of the General of the Army, Secretary of State, and champion of the European Recovery Plan (which came to be called the Marshall Plan) in the wake of World War II.

Dr. von Braun served as MSFC director for the next decade, leading a seasoned team of German and American rocket analysts, designers, technicians, and operators. When NASA received direction to send humans to the moon, MSFC led the charge to develop the gigantic Saturn launch vehicles. In the 1970s, as NASA undertook the development of a reusable space vehicle, MSFC developed the Space Shuttle main engines, solid rocket boosters, and external tank. Whereas MSFC is well-known for its contributions to US launch vehicles, its thundering moon rockets and Shuttle propulsion elements have often obscured its rich heritage in spacecraft chemical propulsion systems. This paper highlights MSFC spacecraft propulsion history, reviewing its role in developing both human-rated and robotic propulsion systems and indicating the Center's significant value to present and planned missions involving spacecraft propulsion.

---

[*] Deputy Chief, Spacecraft Propulsion Systems Branch, Mail Stop ER23, AIAA Member.
[†] Physical Scientist, Propulsion Systems Design and Development Division, Mail Stop ER20, AIAA Member.
[‡] Research Engineer, Propulsion Research Laboratory, Mail Stop XD22, AIAA Senior Member.

Most areas of experience and expertise at MSFC discussed here are the result of meaningful and often extensive partnerships. The spacecraft propulsion community at MSFC recognizes its interdependency and values its relationships with other NASA centers, industry, academia, and other government organizations. Because the identity of contractors responsible for developing the various spacecraft mentioned here are well documented in the literature, and mergers, acquisitions, and reorganizations make full acknowledgements cumbersome, the authors have generally resisted the desire to identify each partner except where it helps clarify the context.

II. MSFC Contributions to Spacecraft Propulsion

One of the most significant and earliest spacecraft propulsion system developed at MSFC was the human-rated Saturn S-IV-B upper stage, which provided orbit insertion for both the Saturn I and Saturn V launch vehicles. The S-IVB stage included a single J-2 engine burning liquid oxygen (LOX) and liquid hydrogen (LH_2) while the on-board auxiliary propulsion system provided three-axis reaction control capability using 670 N thrusters burning monomethylhydrazine (MMH) and dinitrogen tetroxide (N_2O_4). The S-IVB stage was central to an early MSFC flight experiment, AS-203, launched in July 1966. This landmark flight test provided rare video footage documenting the movement of cryogenic liquid hydrogen inside the common-bulkhead tank during unaccelerated flight and subsequent propellant settling, validating analytical predictions and assuring proper propellant orientation for J-2 engine restarts.[1]

Storage and acquisition of cryogenic propellants, particularly now for longer-duration missions and omnidirectional acceleration environments, continues to be an active area of research and development at MSFC and its long-time partner, NASA Glenn Research Center (GRC); film of the AS-203 flight experiment is still used today as a guide for intuition and a touchstone for predictive analysis. Recent cryogenic storage tests at MSFC have included a 45-day zero-boil-off demonstration of liquid hydrogen storage[2] 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 called upon many times in recent decades at MSFC; the center maintains a significant and constantly utilized competency in the development of orbital maneuvering systems (OMS) and reaction control systems (RCS).

MSFC further expanded its spacecraft propulsion heritage through development of the Skylab thruster attitude control system (TACS). 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 a thrust force of 225 N, the TACS performed reliably, although unforeseen levels of TACS usage depleted the nitrogen propellant during the final human-tended period of Skylab flight.[4]

The three High Energy Astronomy Observatory (HEAO) spacecraft launched in 1977-1979 represent another MSFC contribution to the development of in-space chemical propulsion systems. These highly successful spacecraft, propelled by 5 N monopropellant hydrazine thrusters, helped establish 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 1990 and the RCS for both the Inertial Upper Stage and the Transfer Orbit Stage.

Ironically, the unfortunate string of program cancellations over the last several years has also contributed significantly to the expertise in spacecraft propulsion at MSFC; several high-profile spacecraft have kept propulsion analysis, development, testing, and technical oversight skills well-honed. The International Space Station program, for example, tapped MSFC engineering resources on numerous occasions. In the 1980s, MSFC collaborated with JSC, GRC, and industry to demonstrate the vacuum operation of a gaseous oxygen (GOX)/gaseous hydrogen thruster in a system that used water electrolysis to generate the 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 Naval Research Laboratory 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 contribution to Station propulsion needs, MSFC also developed 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 OMS and RCS. 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 Johnson Space Center (JSC) engineering and safety personnel. The Aeroassist Flight Experiment began as an in-house activity that culminated in a detailed design featuring a monopropellant hydrazine propulsion system with 110 and 550 N thrusters to assist in aerocapture. The Orbital Maneuvering Vehicle project provided experience in the conceptualization and development of high delta-V systems and on-orbit propellant transfer systems.

Table 1. Highlights of MSFC Spacecraft Chemical Propulsion Heritage and Capabilities

Spacecraft or Project	**Most Recent Work**	**Human Rated**	**Storable Biprop**	**Mono-prop**	**O_2 / CH_4**	**H_2O_2 / JP-8**	**Dual Mode**	**Cold Gas**	**Non-Toxic**	**Cryo**
Chandra	2005		●	●			●			
DART	2005			●				●		
In-House 110 N LOX/CH_4 thruster	2005				●				●	●
NGLT LOX/Ethanol Thruster	2005								●	●
Orbital Space Plane	2004	●	●	●						
X-37 Orbital Vehicle	2003		●							
NGLT LOX/LH_2 Thruster	2002								●	●
X-38 De-orbit Propulsion	2002			●						
X-37 (Original)	2001					●	●		●	
US Propulsion Module for ISS	2000	●	●							
X-33 RCS (GOX/CH_4)	2000				●				●	
Interim Control Module for ISS	1998	●								
Aeroassist Flight Experiment	1994			●						
CRRES	1991			●						
Inertial Upper Stage RCS Transfer Orbit Stage RCS	1990			●						
Orbital Maneuvering Vehicle	1990		●	●						
HEAO (three spacecraft)	1981			●						
Skylab	1977	●						●	●	
Saturn S-IVB auxiliary propulsion	1973	●	●							

The 1990s presented an upsurge in the number of "X vehicles" being developed through NASA contracts and collaborations. Through its industry partnerships during this period, MSFC gained insight into the development of LOX/LH_2 propulsion for DC-XA and the GOX/methane (CH_4) RCS 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 LOX/kerosene 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 spacecraft chemical propulsion. Various iterations on the design of X-37, in partnership with Boeing Seal Beach and Boeing Huntington Beach, heightened MSFC experience in the development of hydrogen peroxide (H_2O_2) systems and storable hypergolic propulsion systems for robotic missions. Likewise, MSFC oversight of the X-38 de-orbit propulsion stage and in-house cold-flow testing helped maintain skills in monopropellant hydrazine systems.

Launched in 1999 and still flying, Chandra X-Ray Observatory propulsion system incorporates the first dual-mode propulsion system developed by MSFC, consisting of bipropellant N_2O_4/hydrazine apogee engines and monopropellant hydrazine RCS and momentum unloading thrusters. For the Demonstration of Automated Rendezvous Technology (DART) spacecraft launched in April 2005, MSFC was involved in certifying the mission duration capability of the Pegasus and Hydrazine Auxiliary Propulsion System (HAPS), and developing a new cold-gas nitrogen RCS for proximity operations.

Technology programs have contributed significantly to the MSFC spacecraft propulsion competency. A significant example is the Next-Generation Launch Technology (NGLT) Non-Toxic Auxiliary Propulsion System project, which included the maturation of LOX/LH_2[5] and LOX/ethanol[6] reaction control engine technologies under detailed MSFC technical oversight. MSFC has also managed the Auxiliary Propulsion System Test Bed designed and built by JSC at NASA White Sands Test Facility (WSTF). In August 2005, the MSFC-managed LOX/ethanol engines are to be coupled with the JSC-designed feed system for altitude testing. Recently, MSFC has undertaken the in-house development of a scalable 110 N LOX/CH_4 thruster. Cold-flow testing has been completed on the first-generation prototype with plans for hot-fire testing currently underway. Testing of the second-generation prototype is set to begin in the late summer of 2005.

Table 1 highlights the MSFC heritage in chemical spacecraft propulsion systems, sorted in order of activity, with the most recent programs listed first). The table illustrates extensive experience with both conventional and low-toxicity propellants as well as advanced technologies such as cryogenic RCS. It is noteworthy that a broad range of propellants and applications are in active and recent use at MSFC.

III. MSFC Research and Development Capabilities

The preceding summary of the spacecraft propulsion heritage at MSFC emphasizes the center's role in the development of *systems*. The propulsion system capabilities at MSFC, however, rest upon a significantly more specialized set of research and development competencies. For example, the Propulsion Systems Department houses not only the propulsion systems integration engineers but also entire branches focused on specialized areas such as valves, lines, and ducts; combustion devices, including chambers, injectors, and igniters; turbomachinery; detailed thermal analysis of propulsion systems; detailed structural analysis of propulsion systems and components; detailed design; and computational fluid dynamics. These specialized organizations provide cross-cutting expertise to support both launch vehicle and spacecraft propulsion applications. Additionally, the Propulsion Research Center adds applications-oriented research efforts to augment these development competencies, with ongoing activities in new propellants and ingredients, as well as propellant combustion and ignition.

Hydrazine derivatives such as MMH or unsymmetrical dimethylhydrazine (UDMH), and mixtures of these have been fuels and monopropellants of choice for chemical spacecraft propulsion since the inception of the space age. Notwithstanding their success as propellants, the hydrazines do have several noteworthy limitations and drawbacks in the areas of performance, density, and handling. Monopropellant research and development in recent years has been dominated by formulations based on various fuel-rich compounds mixed with the oxygen-rich ionic liquid hydroxylammonium nitrate (HAN). Many candidate monopropellant formulations have been made with this oxidizer, but most are difficult to ignite and have significant safety and handling concerns, usually due to the large amounts of HAN required to achieve the desired oxygen balance. Getting away from HAN altogether is a difficult challenge because most ionic liquids are fuel rich. However, MSFC is working to synthesize and characterize new energetic ionic liquids that require significantly reduced quantities of HAN to achieve a balanced monopropellant formulation.

Of particular importance for liquid rocket engine development, especially for manned missions, is reliable ignition. There is a renewed interest in bipropellant engines that require forced ignition to replace the current hypergolic propellants to improve performance and mitigate the handling concerns associated with toxic propellants. This effort will require intelligent design and rigorous testing to assure safety and mission assurance before replacement is feasible. To address these concerns, research efforts are aimed at new hypergolic propellant combinations[7] and investigations of ignition methods that do not require hypergolic igniter propellants.[8]

IV. Future Prospects

Predicting the future, which calls for an untidy mixture of fact, conjecture, and opinion, is fraught with opportunities for error. In recent years there have been several programs that were announced with great fanfare, only to be cast aside before fabricating even a single part or component. The Space Launch Initiative, which spawned the Orbital Space Plane and Next-Generation Launch Technology programs, is only the most recent example. Nevertheless, it is perhaps worthwhile to briefly review where the technology and the programmatics stand at present, with an eye toward extracting prospects for the way forward.

The Vision for Space Exploration, first put forward by President George W. Bush on 14 January 2004, is focusing NASA on robotic and human exploration of the Moon and Mars. One of the more immediate concerns is developing an architecture that is capable of transporting people beyond low-Earth orbit, and to and from the surface of the moon. For piloted missions in the Apollo program, the guiding principles were simplicity and redundancy, which added up to reliability:

> Nothing exemplified this better than the Service Propulsion System (SPS) rocket engine ... The beauty of the SPS was its simplicity: It was a no-frills rocket engine. There were no fuel pumps because pumps have moving parts that could break down ... It had no ignition system; none was required because the SPS burned hypergols ... As long as the valves opened, that engine would fire.
>
> The (lunar) ascent engine ... was another of Apollo's engineering marvels, for it was even simpler in design than the Service Propulsion System engine. Like the SPS it burned hypergols that ignite on contact, eliminating the need for an ignition system ... And (Neil) Armstrong knew there were several redundant ways to fire the engine ..."[9]

These same concerns will be paramount in the design of spacecraft propulsion systems for missions designed to return humans to the moon. Moreover, the current timetable for developing a key element of the Vision, a Crew Exploration Vehicle that will carry up to six astronauts beyond low-Earth orbit, calls for it to be available as soon as possible after 2010, when the Space Shuttle fleet is scheduled for retirement. Such an aggressive schedule is not likely to be compatible with the research, development, and injection of new spacecraft propulsion technologies into the vehicle design process; off-the-shelf or otherwise technologically mature components and subsystems will be required.

These considerations have several consequences. First, chemical propulsion will continue to be the workhorse for the foreseeable future; no other means of propulsion is sufficiently mature, reliable, or capable of delivering crews and cargo to the moon in a timely manner. Electric propulsion (EP) systems based on Hall-effect or gridded-ion thrusters may eventually play a role in delivering large cargos to the moon once bases of operation have been established there. EP power processing units and thrusters capable of handling as much as a few hundred kilowatts of electric power are the subject of active research and development at GRC, JPL, and elsewhere, but to date the technology readiness level of high-power EP is relatively low.

Higher-energy-density fuels and monopropellants based around ionic liquids such as hydroxylammonium nitrate have been a focus of research and development by the Air Force Research Laboratory, NASA, and others for about a decade, and may be ready for flight in the next several years.[10] There remain, however, issues that must be resolved related to initiating and maintaining the decomposition of these new monopropellants; their high decomposition temperatures tend to rapidly degrade hydrazine catalysts such as Shell 405, and alternative decomposition methods have not yet been thoroughly tested. Additionally, chamber and nozzle materials may need to be fortified or replaced to withstand the high exhaust temperatures of the new monopropellant formulations. For bipropellant applications, it is surmised that hypergolic ignition is such a reliability advantage that any candidate propellants would have to exhibit that characteristic. In the final analysis, monopropellant thrusters using hydrazine, and bipropellant engines burning hydrazines hypergolically with N_2O_4, are tried and tested technologies that will likely be difficult to supplant with new ionic liquid fuels and monopropellants.

With respect to oxidizers, there has been in recent years a moderate revival of interest in H_2O_2, although it may have storage problems due to autocatalytic decomposition, and its specific impulse with most fuels suffers slightly by comparison with N_2O_4. Setting aside fluorine and a few fluorine-containing compounds, LOX is the highest-performing oxidizer, and, as indicated earlier, engineers at MSFC and GRC have been examining the use of zero-boil-off and other technologies to overcome LOX storage constraints and increase its prospects for spacecraft propulsion. If one is willing to go to the trouble of storing LOX for spacecraft propulsion, of course, that opens up the playing field to soft-cryogenic fuels such as CH_4.

The possibility of producing CH_4 *in situ* on Mars, as well as its performance and perceived packaging advantages, heightens its attractiveness for the long-term NASA exploration program. The selection of a LOX/CH_4 propulsion system will depend significantly on the outcome of accurate trade studies to determine whether its raw performance advantage overcomes the added complexity and mass associated with storage, acquisition, in-flight mass gauging, feed system thermal management, and ignition of these propellants. Many notable challenges exist for methane thrusters, such as large changes in ignition energy required with relatively small changes in local concentrations of methane and slow flame speed[11]. Also, flammability limits of methane are slightly tighter than other candidate fuels, indicating the need for a good understanding of local mixing to ensure reliable ignition.

Although it may be difficult to incorporating new technologies into aggressively scheduled development programs, MSFC engineers and researchers recognize the potential value of new technologies to the long-term operability and evolvability of subsequent phases of the Exploration program. Ongoing activities at MSFC and GRC are already addressing the long-duration storage, acquisition, and mass gauging of cryogenic liquids. The experience to be gained later this year using the JSC Auxiliary Propulsion System Test Bed at WSTF will begin to address the feed system thermal management challenges and may offer an initial test capability for demonstrating CH_4 behavior in lengthy, small-diameter feed lines. The subtleties of CH_4 ignition are expected to be a subject of future investigation at MSFC.

In thinking about the way forward, one approach is to look back at the Apollo program and ask, "If we had it to do over again, what would we do differently?" The Vision for Space Exploration is providing the opportunity to do it over again, to once mount a renewed human exploration program to the moon. It is not yet known how much the new spacecraft will resemble those of the Apollo program, although it is evident that the options for propulsion systems that significantly depart from those used previously are somewhat limited. This is partly due to the relative lack of research and development funding in propulsion over the past few decades, but it is also a manifestation of the fact that the Apollo-era engineers were expert at distilling the knowledge of the 1950s and '60s into working systems. What is clear, however, is that the breadth and depth of MSFC chemical spacecraft propulsion expertise offers significant value for the development of in-space propulsion systems that will make the Vision a reality.

V. Conclusion

The spacecraft propulsion community at MSFC draws on a long and rich heritage of in-space chemical propulsion systems developed by MSFC and its partners. Decades of corporate knowledge and sustained activity in recent years have resulted in a seasoned cadre of engineers at MSFC, including Apollo-era propulsion and cryogenic fluid management specialists as well as senior-level engineers with many in-depth development experiences. Despite the frequent program redirections and cancellations of the last decade, MSFC analysis, test, and development skills have continued to grow. The steady stream of development activities and in-house analysis and testing tasks have ensured that nearly every spacecraft propulsion engineer at MSFC has experience analyzing and troubleshooting actual hardware. The active skill set at MSFC includes experience with a full range of conventional and next-generation propellant selections for both human-rated and robotic systems, as well as targeted research efforts aimed at assessing and overcoming the technology challenges inherent in next-generation propulsion. Together, these capabilities represent a vital, although perhaps poorly publicized, aspect of MSFC that offers significant value for the agency and for industrial and academic partners as NASA begins to implement the Vision for Space Exploration.

References

---

[1] "Evaluation of Saturn 2B vehicle AS-203 low gravity liquid hydrogen orbital experiment," NASA-CR-94045, 1967.

[2] Hastings, L. J., Hedayat, A., Bryant, C., and Flachbart, R. H., "Liquid Hydrogen Zero Boil-Off Testing and Analysis for Long-Term Orbital Storage," Advances in Cryogenic Engineering; Vol. 49B, pp. 1163-1170.

[3] Flachbart, R. H., Hastings, L. J., Hedayat, A. Nelson, S. L. and Tucker, S. P., "Testing of a Spray-Bar Thermodynamic Vent System in Liquid Nitrogen," Cryogenic Engineering Conference, Keystone, CO; August 29-September 2, 2005 (to be published).

[4] Belew, Leland F. *Skylab: Our First Space Station*, NASA SP-400, NASA, Washington, DC, 1977, pp. 130-131.

[5] Calvignac, J., Dang, L., Tramel, T. L., and Paseur, L. "Design and Testing of Non-Toxic RCS Thrusters for Second Generation Reusable Launch Vehicle," AIAA 2003-4922, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 20-23, 2003.

[6] Robinson, P. and Veith, E., "Non Toxic Dual Thrust Reaction Control Engine Development for On Orbit APS Applications," AIAA-2003-4925, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 20-23, 2003.

[7] Blevins, J.A., Gostowski, R., and Chianese, S., "An Experimental Investigation of Hypergolic Ignition Delay of Hydrogen Peroxide with Fuel Mixtures," AIAA paper 2004-1335.

[8] Osborne, R.J., Wehrmeyer, J.A., Cooper, R.A., Trinh, H.P., and Early, J.W., "Technology Development of Laser-Induced Spark Ignition for Rocket Engines," JANNAF Propulsion Meeting, Las Vegas, NV, May 10-13, 2004.

[9] Chaikin, A., *A Man on the Moon*, Penguin Books, 1998, pp.74-75, 222-223.

[10] Hawkins, T. Brand, A., Drake, G., McKay, M., and Ismail, I. "Characterization of Reduced Toxicity, High Performance Monopropellants at AFRL," 4th International Conference on Green Propellants for Space Propulsion, Noordwijk, Netherlands, June 2001.

[11] Lewis, B. and von Elbe, G., Combustion, Flames and Explosions of Gases, 3rd ed., Academic Press, 1987, pp.339-354.