Advanced Chemical Propulsion for Science Missions

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Prepared for the
2008 Aerospace Conference
cosponsored by the IEEE and AIAA
Big Sky, Montana, March 1–8, 2008

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March 2008
Acknowledgments

Author wishes to gratefully acknowledge the following individuals for their substantial technical input—analytical and informational—and programmatic support. Their effort helps advance the state of the art of in-space chemical propulsion, and they either directly or indirectly contribute to the content of this paper. John Dankanich, Gray Research, Inc., NASA Glenn Research Center; Leslie Alexander, Jr., NASA Marshall Space Flight Center; Scott Miller, Scott Henderson, and Kimberly Wilson, Aerojet General Corporation; Thomas Delay, Anthony Kelly, Robert Hickman, and Jack Chapman, NASA Marshall Space Flight Center; Christopher England, Joseph Lewis, and Lorie Grimes-Ledesma, NASA Jet Propulsion Laboratory; and Michael P.J. Benfield, and Matthew Turner, University of Alabama in Huntsville.
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Abstract

The advanced chemical propulsion technology area of NASA’s In-Space Technology Project is investing in systems and components for increased performance and reduced cost of chemical propulsion technologies applicable to near-term science missions. Presently the primary investment in the advanced chemical propulsion technology area is in the AMBR high temperature storable bipropellant rocket engine. Scheduled to be available for flight development starting in year 2008, AMBR engine shows a 60 kg payload gain in an analysis for the Titan-Enceladus orbiter mission and a 33 percent manufacturing cost reduction over its baseline, state-of-the-art counterpart. Other technologies invested include the reliable lightweight tanks for propellant and the precision propellant management and mixture ratio control. Both technologies show significant mission benefit, can be applied to any liquid propulsion system, and upon completion of the efforts described in this paper, are at least in parts ready for flight infusion. Details of the technologies are discussed.

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1. Nomenclature

AMBR Advanced Materials Bipropellant Rocket
BFM Balanced Flow Meter
COPV Composite Overwrapped Pressure Vessel
CVD Chemical Vapor Deposition
ΔV Delta Velocity
E-Beam Electronic Beam (welding)
GEO Geosynchronous Earth Orbit
GRC NASA Glenn Research Center
GTO Geosynchronous Transfer Orbit
HiPAT Trade name for Aerojet R-4D-15 engine
Ir/Re Iridium lined Rhenium material system
Isp Specific Impulse
ISPT NASA In-Space Propulsion Technology Project
JPL NASA Jet Propulsion Laboratory
kg Kilogram
MER Mars Exploration Rover
MDP Maximum Design Pressure
MMH Monomethylhydrazine, N₂H₃CH₃
MR Mixture Ratio, propellant (synonymous With OF)
MSFC NASA Marshall Space Flight Center
NDE Non-Destructive Evaluation
N₂H₄ Hydrazine, N₂H₄
NRA NASA Research Announcement
NTO Nitrogen Tetroxide, N₂O₄
OMG Optical Mass Gauging
OF Oxidizer to Fuel ratio
Pc Chamber pressure
PMD Propellant Management Device
psia Pounds per square inch absolute
Re Rhenium
TLVI Tank Liquid Volume Instrument
T-E Titan-Enceladus

2. Introduction

Chemical propulsion has provided the basis for rocket system transportation for decades. As NASA prepares for future space exploration, the Agency continues to improve and develop new chemical propulsion systems. The effort ultimately focuses on providing greater capability for space science missions by reducing the launched mass, and cost of spacecraft and operation. Currently, the advanced chemical propulsion projects aim at increasing payload capacity and improving reliability for scientific missions.

Seeking to fulfill these goals, the ISPT Program, which is managed NASA’s Science Mission Directorate in Washington D.C. and implemented by the ISPT Project Office located at NASA John H. Glenn Research Center, Cleveland, Ohio, is investing in systems and components for increased performance and reduced cost of chemical propulsion technologies applicable to near-term science missions. Presently the primary investment in the advanced chemical propulsion technology area is in the AMBR high temperature storable bipropellant rocket engine. The other two technologies also invested include the reliable lightweight tank
All three efforts are discussed in terms of their mission application, mission benefit, and date of availability for flight mission, present status, and technical description.

Not discussed here are the previously invested technologies such as gel propellants, advanced monopropellants, foam core shielding for spacecraft, etc. (refs. 1 and 2).

### 3. High Temperature, Storable, Bi-Propellant Rocket Engine (AMBR Engine)

This task effort is of evolutionary nature and its approach is to improve the present state-of-the-art workhorse engines in order to gain further payload benefit. AMBR engine is the result of such an effort, designed to yield improved performance such as Isp and thrust, and reduced manufacturing cost. AMBR is a new engine based on Aerojet’s R-4D-15, dual mode, apogee thruster (ref. 3). This newly designed Ir/Re, NTO/N2H4 and NTO/MMH engine can be ready for science mission development as early as year 2009.

#### Mission Application

AMBR engine, shown in figure 1, can be used as a main or secondary propulsion system for a wide range of NASA science missions from Discovery, New Frontiers, to the Flag Ship class. In addition, it can be utilized for orbital maneuvers for a satellite or upper stage rocket.

#### Mission Benefit

With increased performance (Isp, specific impulse), AMBR engine can reduce the propellant mass required to perform spacecraft maneuvers. See table 1 and figure 2 which follow for the mass benefit figure associated with various missions. This propellant mass saving can directly translate to an increase in scientific payload and thus data gathering capability of the spacecraft.

![Figure 1.—A rendered image of the AMBR Engine in Development.](image)

| Total Propulsion System Mass Reduction (Kg) |
|-------------------------------------------|
| Isp (sec) | 320 | 325 | 330 | 332.5 | 335 |
| GTO to GEO | 0 | 16 | 30 | 37 | 45 |
| Europa Orbiter | N/A | 0 | 12 | 16 | 24 |
| Mars Orbiter | N/A | 0 | 14 | 22 | 29 |
| T - E Orbiter | N/A | 0 | 29 | 45 | 60 |

The bar chart, figure 2, highlights the payload, or mass benefit at the target Isp of 335 sec for NTO/N2H4 propellant combination.

In addition, because of AMBR’s higher thrust, for a mission such as Cassini, the number of thrusters can be reduced, which further reduces the system mass and complexity. The following table 2 lists the AMBR engine characteristics as compared to the state-of-the-art baseline HiPAT engine.

#### Availability Date

AMBR engine is scheduled to be ready for mission development beginning year 2009. At that time the engine can be prepared for flight qualification.

#### Status

Baseline hotfire testing has been completed which yielded data for designing the new AMBR engine. More information related to the hotfire testing is given under the following subheading Technical Description.

New engine design is currently underway which includes injector optimization, chamber/nozzle contour optimization, chamber emissivity reduction, and thermal resistance increase between the injector and chamber.

![Figure 2.—Mass benefits for various science missions of the AMBR engine at Isp of 335 sec.](image)
TABLE 2.—AMBR ENGINE COMPARED WITH STATE-OF-THE-ART HIPAT DUAL MODE ENGINE (NTO,N2H4)

| Design characteristics | AMBR | HiPAT DM |
|------------------------|------|----------|
| Thrust (lbf)           | 200  | 100      |
| Specific impulse (sec) | 335  | 329      |
| Inlet pressure (psia)  | 400  | 310-220  |
| Chamber pressure (psia)| 275  | 137      |
| Oxidizer/Fuel ratio    | 1.2  | 1.0      |
| Expansion ratio        | 400:1| 375:1    |
| Physical envelope      | Within existing HiPAT envelope |
| Propellant valves      | Existing R-4D Valves |

Alternate chamber fabrication processes are being investigated for further cost reduction and performance advantages.

Option I engine for NTO/N2H4 is to undergo testing in May 2008.

Technical Description

AMBR engine developmental goal is to increase the Isp of the pressure-fed, earth-storable bipropellant, apogee rocket engine to at least 330 sec with NTO/MMH propellants and at least 335 sec with NTO/N2H4 propellants. State of the art Isp are approximately 323 and 328 sec for the respective propellant combinations.

Increasing engine Isp lengthens the run time of a given amount of propellant, or, inversely, it reduces the amount of propellant required to perform a given spacecraft maneuver. This propellant reduction can be applied to increasing the life or capability of spacecrafts. These gains are discussed in more detail under the subheading Mission Benefit of this section.

The maximum theoretical Isp of the propellant combination NTO/N2H4 has never been reached in a flight engine partially due to the temperature limitation of the rocket chamber material. Therefore, if improvements are made such that propellants are allowed to combust at a higher temperature and pressure, then better engine performance would occur. Certainly, this increase in operating temperature needs to stay within safety margins critical to mission integrity.

On the other hand, although routinely used in space flight, the Ir/Re engine chambers are yet to be operated at temperatures high enough to fully exploit the materials’ capability of 4,000 °F. Higher operating temperature would require further optimization of Ir/Re engine materials, design, and manufacturing—tasks that are the content of this project. This ISPT project aims to push the bi-propellant engine operating temperature higher and thus increase the engine’s performance. This is to be achieved by expanding the operating envelope of Aerojet Corporation’s flight-proven, Ir/Re, liquid apogee engine R-4D-15—an example of which during hotfire testing is shown in figure 3.

Expansion of the operating envelope is accompanied with design changes made to the baseline engine which are shown in figure 4. Changes include injector and chamber/nozzle contour optimization, reduced chamber emissivity, and increased thermal resistance between the injector and chamber. Engine operating conditions are also be modified to produce higher combustion gas temperatures. These include higher feed pressure/lower internal pressure drop and higher/optimized mixture ratio.

Again, shown previously in table 2 is a comparison of the AMBR engine characteristics to those of the Aerojet Corporation’s HiPAT engine which is the trade name for the R-4D-15 engine.

As mentioned in the Status section, baseline testing was successfully done using the HiPAT engine. The purpose of the baseline test was to increase knowledge base prior to design and test the new, high performance engine for this program. And indeed, data collected from the baseline test has been used for the thermal analysis and as design reference for the new engine which was to be built and tested by first half of 2008.
The baseline test covered a range of chamber pressures and mixture ratios, which are plotted as “NASA NRA” points in figure 5 along with other tested conditions for the HiPAT engine. During the 26 hot fire runs totaling 2,909 sec and consuming more than a thousand pound of NTO/N2H4 propellant, the engine was run purposely both “harder” and “softer” than the design conditions. “Harder” means higher propellant feed pressure or hotter mixture ratio and “softer” means the opposite.

A secondary project goal is to investigate the viability of alternate Ir/Re fabrication processes and other related material systems to determine whether alternate processes offer cost, producibility, or performance advantages over the baseline CVD fabrication process. If one of these alternate processes is found to be of sufficient value and level of development, it would be incorporated into the engine design (ref. 3).

Specifically, the effort investigates better iridium liner forming and rhenium deposition methods, e.g., engineered electroform (EL-Form) with increased allowable tensile stress limits, to further strengthen the chamber materials system for operation at higher temperature and pressure and to reduce production cost (ref. 4). EL-Form process has been demonstrated for fabricating high density rhenium components, and has been applied to fabricate thrust chambers. The process produces high purity material with stable and reproducible properties, but it also decreases the room temperature yield strength. To improve from there, the “engineered” EL-Form process is investigated which deposits multiple layers of rhenium that impede grain growth during deposition and annealing. Figure 6 shows micrographs of the engineered EL-Form Re samples.

Presently, the engineered EL-Form process has shown to improve the rhenium room temperature yield strength by 150 percent. However, the post process, elevated temperature and thermophysical properties of Re were yet to be investigated. More general process development and repeatability demonstration must be performed prior to consistent commercial application.

Figure 5.—Baseline test points (NASA NRA) plotted along with other previously tested conditions for the HiPAT engine.

Figure 6.—Micrographs of Engineered EL-Form Re in as-deposited (left) and annealed conditions.
4. Light Weight Tanks for Propellant

On a spacecraft, propellant tanks are often the single largest dry mass component, and thus making them light in weight while maintaining reliability and safety can bring immediate payload benefit. Presently, state-of-the-art light weight tanks are either all-metal or metal-lined and composite-overwrapped—an example for the latter is shown in figure 7. Further improvement can make the tanks even lighter in weight—such is the goal of our present effort.

Mission Application

Light weight tanks can be used in all liquid propulsion systems using either storable or cryogenic propellants. They can be applied to reduce propulsion system dry mass for all classes of science missions.

Mission Benefit

Improvements in the light weight tanks could result in substantial reduction of the overall propulsion systems weight and allow for more payload and scientific instrumentation, resulting in greater scientific return.

According to an analysis (ref. 5), a mass saving of 20 kg, or payload increase, can be realized by using a lightweight, aluminum lined tank with liner thickness of 0.005 in. (assuming a tank for 500 kg of NTO). And for a larger mission such as the Titan-Enceladus orbiter mission (assuming 1500 kg of NTO), a payload gain of 50 kg can be achieved (ref. 6).

Availability Date

Availability date of the light weight tanks is beyond year 2009, but the component technologies and manufacturing processes and inspection techniques developed for liner welding and for composite overwrapping and bonding to the liner may be available sooner depending on the nature of application.

Status

Present effort focuses on improving the constituent technologies including the Electronic-Beam (E-Beam) welding of the metallic liner and overwrapping and bonding of the composite fibers to the metallic liner. The approach consists of coupon testing and flight-like tank fabrication and testing. Task results are to be documented and reported by end of the task in 2008. Encouragingly, preliminary results indicate strong E-Beam welds with ultimate tensile strength 60 percent of the parent aluminum material. Also, interim result shows the promising bonding strength of the tested adhesive exceeding 7,000 psi of tensile stress.

Technical Description

A state-of-the-art propellant tank is usually made from titanium alloy—a high strength, low weight metal alloy that is 40 percent lighter than steel and has high resistance to corrosive environments, such as salt air. However, new light weight tanks could offer not only the same level of strength and corrosion resistance, but further reduce propellant tank mass by as much as 50 percent as compared to all-titanium tank (ref. 7). Light weight tanks can consist of metallic liners with thickness of 0.01 in. or less, over wrapped with composite material, and the reduced liner thickness coupled with optimized design yields “lightweight” COPV. Taken from (ref. 7), Figure 8 shows the dependence of tank mass (normalized to 0.03 in. thickness) to the liner thickness. In the figure one can see that for an aluminum lined tank, reducing the liner thickness to 0.005 in. can reduce the tank mass by 50 percent. This mass reduction translates to tens of kilograms of payload gain for science missions.

At time of this writing, funding for this task is interrupted and there is no plan for continuing development of the technology with the ISPT program beyond March 2008.

Figure 7.—An example of metallic lined propellant tank overwrapped with composite fibers.
TABLE 3.—MER PROPELLANT TANK DESIGN REQUIREMENTS

| Parameter                     | Requirements                                      |
|-------------------------------|---------------------------------------------------|
| MDP                           | 378 psig                                          |
| Proof pressure                | 501 psig (MDP×1.25)                               |
| Burst pressure                | 624 psig                                          |
| Pressure cycle                | 5 Proof, 1 MDP×1.1, and 7 MDP cycles              |
| Operating temperature         | –20 to 40 °C                                      |
| Non-operating temperature     | –40 to 55 °C                                      |
| Propellant load               | 35 kg max.                                        |
| Leakage                       | 1×10⁻⁵ scc/s He at MDP                            |
| Diameter at MDP               | 16.4 in. max.                                    |
| Overall length at MDP         | 18.9 in. max.                                    |
| Minimum internal volume       | 2600 in.³                                         |
| Maximum weight (with PMD)     | 5.10 lb                                           |
| Mounting configuration        | Boss mounted                                      |

Reference 8 gives a detailed account of the modeling, analyses, design, fabrication, and testing of MER tanks. Only the validation testing is highlighted here. The test sequence was:

1. Proof test after end-cap welding
2. Helium leak test
3. Volume measurement
4. 4X Pressure Cycle Life Test
5. Post-cycle Test Proof Test
6. Post-cycle Test Helium Leak Test
7. Random Vibration 3 Axes
8. Quasi Static Acceleration (Sine Burst) 2 Axes
9. Post-dynamic Proof Test
10. Post-dynamic Helium Leak Test
11. PMD Bubble-point Test
12. Burst (pressure) Test

Thus far, three (3) tanks have been subject to the above test, but during the Step 6 Post-cycle Test Helium Leak Test, one tank was found to have a leak. The leak was believed to be in the location of the central girth weld of the aluminum liner.

The subsequent task presently is a one-year effort to push forward state-of-the-art of the constituent technologies: liner forming, welding, fiber overwrapping and bonding, and testing. The goal is to develop consistent manufacturing processes that yield reliable tanks with a maximum liner thickness of 0.010 in. and a high degree of manufacturing repeatability with reduced dropout rates.

The liners, which provide a hermetic seal for propellants while offering attractive mechanical properties desirable for manufacturing, are flow formed using 1100-series aluminum instead of the 6061-series aluminum used on the MER tanks. The 1100-series aluminum offers more superior weld quality and other properties that minimize crack growth from flaws. To provide a more consistent weld, E-Beam welding is being investigated for the metallic liners and components. Also, to improve overwrap load bearing capacity, a bonding study is underway to explore alternative adhesives and resins to increase bond strength and decrease the potential for debonds.

By providing this multi-pronged risk mitigation approach, the program aims to standardize manufacturing processes and increase confidence in lightweight and ultra-lightweight COPVs for infusion into future missions for science and human exploration.
5. Precision Propellant Management and Mixture Ratio Control

Researchers are developing ways to measure and utilize liquid propellants in propulsion systems with higher quantity-precision, in order to ultimately gain payload mass, better engine performance targeting, and improved system safety. This task focuses on testing components and algorithms using mainly a laboratory simulated propellant feed system. Example component technologies are Balanced Flow Meter (BFM), Optical Mass Gauging (OMG), and Tank Liquid Volume Instrument (TLVI). These technologies plus an improved pressurization scheme can help reduce uncertainties and the need for excessive amounts of propellant reserve of which the mass fraction can otherwise be used for science payload. They allow better control of the engine oxidizer-fuel mixture ratio and hence better engine performance targeting. They can also allow detection of small leaks to improve system safety.

Mission Application

This technology is applicable to all liquid propulsion systems, storable or cryogenic, for planetary spacecraft, Earth orbiting satellite, and launch vehicle applications.

Mission Benefit

Study results (ref. 9) indicate that science payload mass could be increased by 10 to 50 percent by accurately controlling propellant flow. This accurate flow control and measurement can be achieved with a combination of the Balanced Flow Meter (BFM), other advanced sensor technologies, and improved pressurization methods. Figure 9 shows an image of the BFM.

Availability Date

In part or as whole, variation of the precision propellant management system may become available beginning in year 2010 which can, incrementally through time, offer increasing benefits over state-of-the-art equipment.

Status

At this writing, the task effort investigates a number of component technologies that can be used for precision and active propellant pressurization and mixture ratio control. Accuracy is verified via statistical testing for components such as balanced flow meter (BFM), tank liquid volume instrument (TLVI), and optical mass gauging (OMG).

Using a simulated propellant feed system and benign fluids, new pressurization and flow control schemes are tested. The simulated propellant feed system is shown in figure 10.

Figure 9.—Balanced Flow Meter (BFM) enables precision propellant flow measurement.

Figure 10.—Photograph of simulated propellant feed system.

Unfortunately, at time of this writing, the funding for this task is interrupted and there is no plan for continuing development of the technology with the ISPT Program beyond March 2008.

Technical Description

The objective of this task is to achieve substantial payload gains by reducing the 4 to 6 percent propellant reserves typically carried by spacecraft (ref. 10). It is the desire of this task to minimize the propellant reserves which in turn reduces the vehicle mass. The reserves are provided to protect against propellant mixture ratio variations and gauging inaccuracies which occur in propellant loading, mass gauging, and variations in engine throttle rates in both oxidizers and fuels.
Optimizing propellant usage and reducing reserves drive the need for an accurate control of propellant tank ullage pressure and mixture ratio. When propellant amount and consumption are controlled and measured accurately, propellant residuals can be reduced.

The motivation for this work is to reduce the amount of propellant reserve for in-flight consumption variance. Precisely controlling the propellant amount in loading and in usage by means of precision tanking and flow rate control and measurement (also known as “mixture ratio control”) can reduce excessive onboard propellant reserve. If this propellant reserve could be cut in half, the mass savings would be significant: It would be equivalent to a 10 percent reduction in propulsion hardware mass, and this mass reduction translates to a 15 to 50 percent scientific payload gain. For example, according to a NASA ISPT study performed to determine the potential benefits of implementing an active mixture ratio control system for existing and future missions, payload gain for the Jupiter Polar Orbiter with Probes (JPOP) mission can be 40 kg, representing a 13 percent increase; and for the Mars Sample Return (MSR) mission the payload gain can be 60 kg, representing a 48 percent increase. Propulsion hardware mass reduction of this magnitude, performance-wise, is similar to the highest payoffs in hardware technology for space propulsion mass reduction.

Initial project tasks are to assess the potential of active propellant mixture ratio control to determine whether this is a promising area for technology investment. Propellant pressurization feed system control algorithms are also studied using advanced statistical method to assess their performance and impact on reduction of in-flight propellant reserves.

So far, several technologies have been reviewed, and some now under development, which could potentially achieve precision mixture ratio control. Present components in development are the advanced flow meters and new tank liquid mass gauging techniques. Effort has been put forth towards advancing the state of the art for the Balanced Flow Meter (BFM) and tank liquid volume instruments. The former can potentially minimize the error in propellant flow measurement down to 0.15 percent, and the latter can minimize the volume measurement down to less than 0.5 percent.

Quoted from (ref. 11), “The balanced flow meter (BFM) is a thin, multi-hole orifice plate…” shown in figure 9, “…with holes sized and placed per a unique set of equations. It meets all NASA flow meter requirements, and allows measurements where none were possible before, such as LOX lines upstream of turbopumps. It can condition as well as measure flow while improving velocity, momentum, energy or other profiles. It provides flow measurement, flow conditioning, and controlled flow restriction. It functions with minimal straight pipe run; it simultaneously measures mass flow rate, fluid volumetric flow rate and fluid density. In commercial industry, it is at TRL 6 (Chevron, Texaco, Sloss Industries, etc.) For NASA use it is estimated to be at TRL 2.5…” Figure 11 is a schematic comparison with of it with a conventional orifice flow meter.

“…The balanced flow meter has 10X better accuracy, 2X faster pressure recovery (shorter distance), 15X noise reduction, and 2.5X less permanent pressure loss.”

Further, according reference 10, BFM has been successfully applied to liquid oxygen (with repeatable accuracy of ~0.3 percent), nitrogen, and methane, gaseous nitrogen, methane, and air; in many other industrial fluids in commercial and harsh military applications.

In order to apply BFM to precision propellant mixture ratio control, present effort statistically characterizes it in a standard spacecraft pressurization system and further compares its performance to that of turbine, venturi, and cavitating venturi flow meters.

Present effort uses a simulated propellant feed system and benign fluids such as water to test variety of commonly used and novel pressurization and flow control schemes. The system is dubbed as the “demonstration rig” for developing the mixture ratio control technology, see figure 10 for a photograph of it in operation and figure 12 for it during the assembly phase.
Strategically instrumented for the purpose, the rig will be used to statistically evaluate system and component accuracies, operational issues, equipment capability envelop, etc. Propellant pressurization feed system control algorithms are also to be studied.

Presently, the demonstration system has become operational and has tested 4 BFM’s, 2 standard orifices, and calibrated magnetic flow meters in 1.5 and 0.75 in. lines. It has demonstrated both the tank pressure- and the ratio valve based- flow control to set mixture ratio within approximately 0.5 percent of the intended value.

The mixture ratio demonstrator is performing within planned tolerances and, in the future, new techniques and components such as pressurization methods, tank level instrument, flow meters, control algorithms, etc., can be rapidly applied and statistically tested to help improve spacecraft precision propellant flow control and measurement.

6. Conclusions

NASA’s In-Space Propulsion Technology Program invests in several technology areas including advanced chemical propulsion. The objective is to enable and enhance the science capabilities in science missions through development of and improvements to the chemical propulsion systems and components with system level benefits. Presently three tasks are ongoing: (1) High temperature thruster, also known as AMBR engine; (2) light weight tanks for propellant; and (3) precision propellant management and mixture ratio control. All three technologies show potential for significant payload benefit for science missions large or small. For example, AMBR engine can offer a payload gain of 60 kg in a Titan-Enceladus orbiter mission. For the same class of mission, light weight tanks can offer an additional 50 kg of mass advantage. Precisely controlling the propellant amount in loading and in usage by means of precision tanking and flowrate control and measurement (also known as “mixture ratio control”) can reduce excessive onboard propellant reserve. For example, payload gain can be 40 kg as result of the propellant reserve reduction for the Jupiter Polar Orbiter with Probes (JPOP) mission. In general, for the technologies discussed here, payload gains are larger for missions requiring larger ΔV. To be incorporated into flight missions, the technology availability dates are year 2009 for the AMBR engine but later for the light weight tank and mixture ratio control. Finally, AMBR engine is scheduled to undergo testing starting May 2008 while light weight tanks and mixture ratio control tasks are to conclude by midyear 2008 due to interruption in funding.

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### 1. REPORT DATE
01-03-2008

### 2. REPORT TYPE
Technical Memorandum

### 3. DATES COVERED (From - To)

### 4. TITLE AND SUBTITLE
Advanced Chemical Propulsion for Science Missions

### 6. AUTHOR(S)
Liou, Larry, C.

### 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

### 8. PERFORMING ORGANIZATION REPORT NUMBER
E-16298

### 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

### 10. SPONSORING/MONITORING ACRONYM(S)
NASA

### 11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2008-215069

### 12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
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### 13. SUPPLEMENTARY NOTES

### 14. ABSTRACT
The advanced chemical propulsion technology area of NASA’s In-Space Technology Project is investing in systems and components for increased performance and reduced cost of chemical propulsion technologies applicable to near-term science missions. Presently the primary investment in the advanced chemical propulsion technology area is in the AMBR high temperature storable bipropellant rocket engine. Scheduled to be available for flight development starting in year 2008, AMBR engine shows a 60 kg payload gain in an analysis for the Titan-Enceladus orbiter mission and a 33 percent manufacturing cost reduction over its baseline, state-of-the-art counterpart. Other technologies invested include the reliable lightweight tanks for propellant and the precision propellant management and mixture ratio control. Both technologies show significant mission benefit, can be applied to any liquid propulsion system, and upon completion of the efforts described in this paper, are at least in parts ready for flight infusion. Details of the technologies are discussed.

### 15. SUBJECT TERMS
Chemical propulsion; Rocket; Rocket engine; Storable; In-space propulsion; Propulsion system; Propulsion system components; High temperature thruster; Light weight propellant tanks

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| a. REPORT | b. ABSTRACT | c. THIS PAGE |
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### 17. LIMITATION OF ABSTRACT
UU

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15

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