New Frontiers AO
Advanced Materials Bi-propellant Rocket (AMBR) Engine Information Summary
August 2008

Summary: The Advanced Material Bi-propellant Rocket (AMBR) engine is a high performance (I_{sp}), higher thrust, radiation cooled, storable bi-propellant space engine of the same physical envelope as the High Performance Apogee Thruster (HiPAT[TM]). To provide further information about the AMBR engine, this document provides details on performance, development, mission implementation, key spacecraft integration considerations, project participants and approach, contact information, system specifications, and a list of references. The In-Space Propulsion Technology (ISPT) project team at NASA Glenn Research Center (GRC) leads the technology development of the AMBR engine. Their NASA partners were Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL). Aerojet leads the industrial partners selected competitively for the technology development via the NASA Research Announcement (NRA) process.

1. INTRODUCTION

1.1 Background

While the need generally exists for higher performance propulsion systems, the component technologies have to mature for any new, successful engine development to take place. In September 2006, a NASA/industry joint effort was initiated to boost the (specific impulse, I_{sp}) performance of Aerojet's HiPAT[TM] engine. The motivation was to attain a more efficient, storable bi-propellant engine that will benefit future NASA's planetary science missions. By increasing the specific impulse and thrust, the more efficient engines can enable near-term missions, enhance their science capability and returns, reduce mission cost, and cut transit time. The developmental effort is called AMBR, which stands for the "Advanced Material Bi-propellant Rocket" where the "advanced material" refers to the iridium (Ir)-coated rhenium (Re) combustion chamber fabricated using the EL-Form[TM] process.

The AMBR engine development aims for two major objectives:
1. higher specific impulse engine performance
2. lower fabrication cost for the iridium/rhenium combustion chamber

To initiate the effort, NASA Marshall Space Flight Center (NASA-MSFC) and NASA Jet Propulsion Laboratory (NASA-JPL) conducted mission-level and system-level studies to translate the target engine performance into spacecraft performance. Four conceptual missions were selected and used for the analyses based on the current scientific interest, launch vehicle capability, and trends in spacecraft size:

- GTO to GEO, 4800 kg, ΔV for GEO insertion only ~1830 m/s
- Enceladus Orbiter (Titan aerocapture) 6620 kg, ΔV ~2400 m/s.
- Europa Orbiter, 2170 kg, total ΔV ~2600 m/s
- Mars Orbiter, 2250 kg, total ΔV ~1860 m/s

Applying the improved AMBR engine specific impulse of 335 seconds (approximately seven seconds higher than the state-of-the-art), the study shows a 23 percent payload gain for the Mars Orbiter mission. Similar payload gains are also evident for the other missions. Additional AMBR engine improvements include the 200 lbf thrust level as compared to the 100 lbf baseline engine HiPAT[TM]. And its fabrication cost is lower than the same baseline by 30 percent (achieved through the higher production yield rate and lower rhenium materials cost associated with the combustion chamber).

The final hotfire performance verification for the AMBR flight-like, developmental prototype engine is scheduled for 2008. It will be followed by environmental (shock and vibration), and life testing. The development plan completes by the beginning of 2009 with the AMBR engine prototype demonstrated in a relevant-ground environment.

The NASA In-Space Propulsion Technology Project Office contracted the AMBR engine development through a NASA Research Announcement (NRA) Cycle 3a contract (contract number NNM06AA93C) with the Aerojet Company at Redmond, WA. Other contributors to the effort are:
- Jet Propulsion Laboratory performed the mission and benefits analysis and will perform the prototype shock test.
- NASA Marshall Space Flight Center performed the major portion of the contract management, the AMBR propulsion system analysis, and the high temperature refractory metal material analysis and testing.
- NASA Glenn Research Center manages the AMBR development since late 2006.
- Plasma Process, Inc., Huntsville, AL (PPI) performed the Ir/Re chamber fabrication.

The NASA Science Mission Directorate (SMD) funds the In-Space Propulsion Technology (ISPT) Project Office located in the NASA John H. Glenn Research Center in Cleveland, Ohio.

1.2 System Summary

The AMBR engine is a high performance bipropellant engine using the iridium/rhenium chamber technology to obtain 335 seconds specific impulse (I_{sp}) with nitrogen tetroxide (NTO) and hydrazine (N2H4) propellants. AMBR engine promises to benefit significantly interplanetary missions by enabling reduced launch weight and/or increased payload and reducing propulsion system cost. Figures 1 and 2 are a line drawing containing physical dimensions and a color graphic of the AMBR thruster.
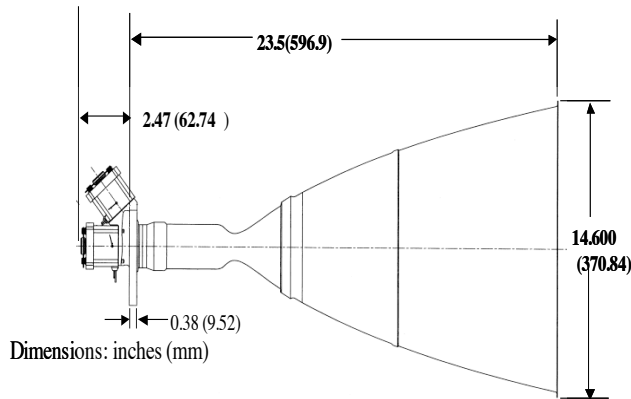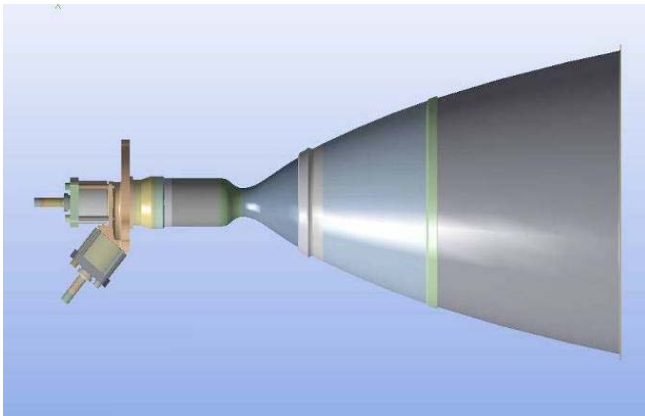

Figure 1. AMBR Thruster Physical Dimensions

Figure 2. A Color Rendition of the AMBR Thruster

AMBR engine development aims for the following specifications:
- 335 seconds steady-state I_{sp} with NTO/N2H4 (by test)
- 3-10 years mission life (by analysis & similarity)
- one hour operating (firing) time (by test)

Table 1 shows AMBR design characteristics side-by-side with the Aerojet's HiPAT™ Dual Mode engine, which is the baseline for AMBR development.

Table 1: AMBR Characteristics Compared with the Baseline HiPAT™ Thruster

Design Characteristics	AMBR	HiPAT™ DM
• Trust (lbf)	200	100
• Specific Impulse (sec)	335	328
• Inlet Pressure (psia)	400	250
• 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	

AMBR is capable of operating at a temperature of 2470°K.[4] The iridium/rhenium combustion chamber enables radiation cooling which sustains efficiency. It is fabricated using the advanced and cost reducing electroform process called EL-Form™. This process was selected after evaluating a group of candidates--Chemical Vapor Deposition (CVD), electroforming (El-Form), Low Pressure Plasma Spray (LPPS) and Vacuum Plasma Spray (VPS).

Of the processes listed above, the well understood CVD is the incumbent process used to fabricate the R-4D-15 HiPAT™ thrust chambers. The only other process that has been used to fabricate an Ir/Re chamber for a bipropellant engine was El-Form™. It was used successfully in year 2004 to fabricate and test the Aerojet's development engine R-42DM. Finally, neither LPPS nor VPS were ever used; therefore, they were dropped from consideration due to the lack of technical maturity.

The Figures of Merit used for the decision matrix were:
- Cost – Nonrecurring
- Cost – Recurring
- Schedule – Nonrecurring
- Schedule – Recurring
- Producibility
- Performance – Mechanical Properties
- Performance – Thermal
- Performance - Oxidation Resistance
- Performance - Mass
- Heritage/Risk – Design
- Heritage/Risk - Manufacturing

Weighting factors were assigned to the Figures of Merit based on the primary performance goals of the program.

For AMBR, the PPI El-Form™ process was finally down-selected due primarily to the lower development unit costs and production cost estimates. The El-Form™ process

carries more process risk than CVD since its development is less mature than CVD. However, the added risk is deemed worth the potential rewards in reduced costs.

Figure 3 below is a top-level schematic for a representative dual mode AMBR propulsion system. The system is "dual mode" because the same spacecraft fuel system supplies both the main engine and the Attitude Controlling System (ACS) thrusters (specific impulse of 210 seconds). Because of the similarity, the name ACS is interchangeable with Reaction Control System (RCS). This AMBR system and its components are designed and sized to enable assessments for potential mission benefit brought by the system. [4]
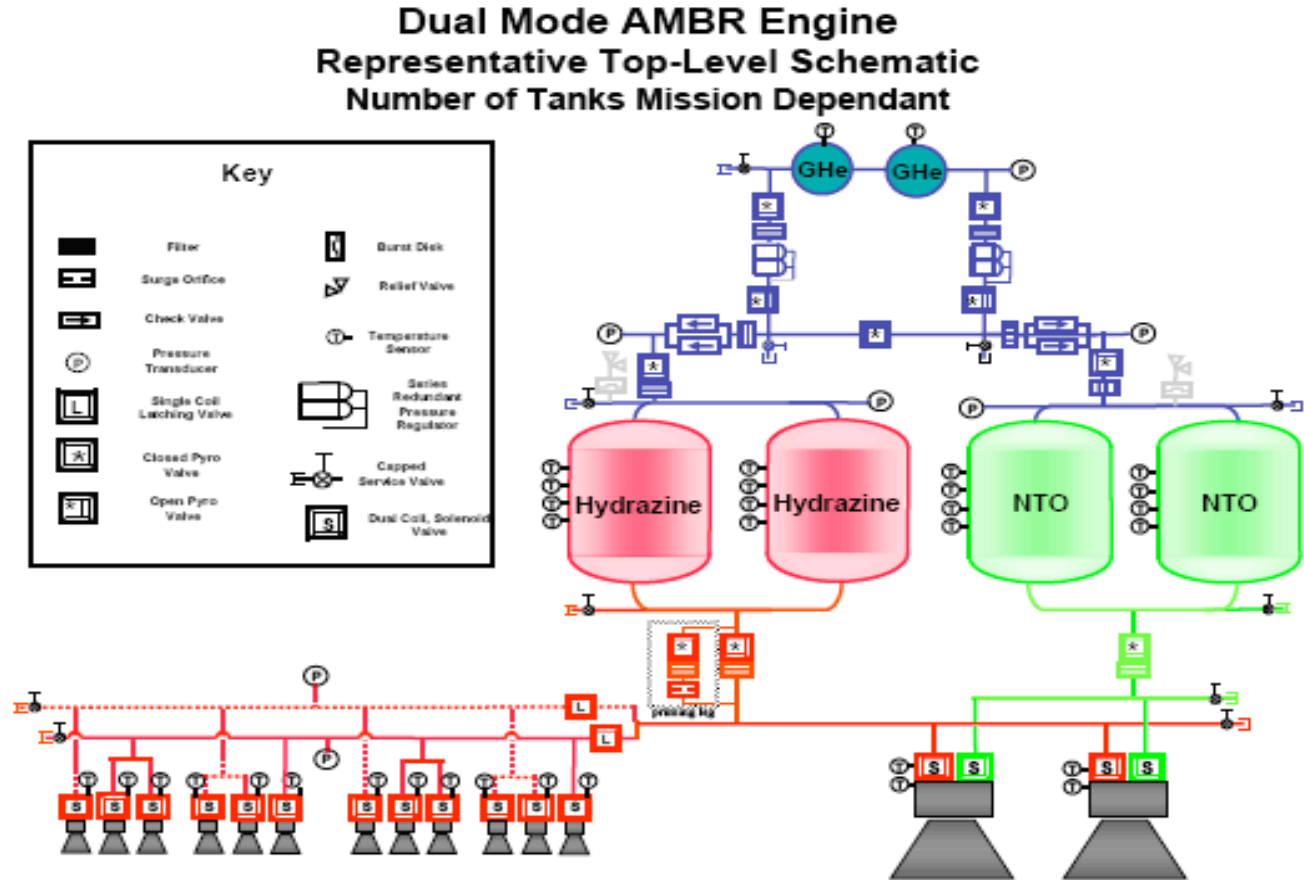

Figure 3. Example of AMBR Propulsion System

This representative AMBR propulsion system is single-fault-tolerant based on flight proven HiPAT^{TM} design and can use a significant amount of the HiPAT^{TM} heritage hardware. Most of the system hardware is at Technology Readiness Level (TRL) of 9 (flight proven through successful mission operations). The component masses (e.g., valves, regulators, filters, etc.) are based on those onboard flight proven spacecraft like the Mercury Messenger and Space Shuttle. A ten percent design contingency is used for the hardware.

1.3 Subsystem Summaries
For the representative AMBR system shown above, the pressure vessel characteristics are:

- Factors of Safety:
  - o Propellant Tanks – 1.5
  - o Pressurant Tanks – 1.5
- Materials:

- o Propellant Tanks – Ti (6Al-4V)
- o Pressurant Tanks – COPV
- Operating Pressures
  - o Propellant Tanks – 2.6 MPa (400 psia)
  - o Pressurant Tanks – 31 MPa (4,500 psia) down to 5.5 MPa (800 psia)
- Anti-slosh/propellant management device ~10 percent Propellant-tank shell mass
- Propellant tank ullage 5 percent (regulated)
- Propellant residual 1percent
- Helium pressurant sized for isothermal blowdown

As seen in Table 1, AMBR's propellant inlet pressure is required to be 400 psia. Hence the tank pressure is set at 400 psia and the tank is designed with a safety factor of 1.5. Tank material is fixed as titanium (6Al-4V), ullage volume at five percent and a surface tension propellant management

device (PMD) is assumed to add ten percent to tank weight with one percent of the initial propellant load unusable.

Table 2 shows a component list for the representative AMBR engine system. It contains mass estimates for a Europa orbiter mission.

Table 2: Representative Component List for an AMBR Engine System (Europa Orbiter Mission)

Quantity	**Europa Lander** Propulsion System Components	Unit Mass (kg)	Unit Mass (lbm)	Total Mass (kg)	Total Mass (lbm)	Comments:
2	Pressurant Tank (COPV)	10.5	23.1	21.0	46.2	Calculated Hardware
3	Fill and Drain Valve, High Press He	0.1	0.2	0.3	0.7	Messenger Hardware
6	Filter, He	0.11	0.2	0.7	1.5	Messenger Hardware
7	Pyro Valve, Pressurant	0.2	0.4	1.4	3.1	Messenger Hardware
2	Pressure Regulator	2.31	5.1	4.6	10.2	STS OMS
1	High Pressure Transducer	0.23	0.5	0.2	0.5	Messenger Hardware
4	Check Valves	1.36	3.0	5.4	12.0	STS OMS
4	Transducer, Low pressure	0.23	0.5	0.9	2.0	Messenger Hardware
0	Burst Disk	0.1	0.2	0.0	0.0	STS OMS
0	Relief Valve	2.31	5.1	0.0	0.0	STS OMS
4	Ground Checkout Hand Valve	0.07	0.2	0.3	0.6	Messenger Hardware
2	Propellant Tanks, Fuel (w/ PMD)	18.1	39.8	36.2	79.6	Calculated Hardware
1	Propellant Tanks, Oxidizer (w/ PMD)	25	55.0	25.0	55.0	Calculated Hardware
3	Pyro Valve, Propellant	0.2	0.4	0.6	1.3	Messenger Hardware
2	ISO Valve, Propellant, RCS	0.65	1.4	1.3	2.9	Messenger Hardware
6	Fill and Drain Valve, Propellant	0.15	0.3	0.9	2.0	Messenger Hardware
3	Filter, Propellant	0.29	0.6	0.9	1.9	Messenger Hardware
6	Transducer, Low pressure	0.23	0.5	1.4	3.0	Messenger Hardware
12	RCS Thruster (22 N, 5 lbf thrust)	0.65	1.4	7.8	17.2	Aerojet MR-106E 22N
2	AMBR Thruster (91 N, 200 lbf thrust)	5.5	12.0	10.9	24.0	
	Miscellaneous Hardware	10%		12.0	26.4	
	Design Contingency	10%		13.2	29.0	
	Total Dry Weight			145.0	318.9	
	Propellant: Usable			1111.7	2445.8	
	Residuals			11.1	24.5	
	Pressurant: Helium			1.7	3.8	
	TOTAL PROPULSION SYSTEM			**1269.6**	**2793.0**	

The assumption is made that the spacecraft propellant requirements will determine the tank size. This assumption may not be practical as it is often preferable to select an existing flight proven tank, even though the size may not be optimal, to avoid the developmental cost for a new tank.

Pressurant tanks are the next largest mass element of a propulsion system. Propellants are pressure fed from the tanks to the engine, so a composite-overwrapped helium pressure vessel was selected with size calculated assuming adiabatic blowdown of gas initially at 4500 psia down to a minimum regulator inlet limit of 800 psia.

For MSFC's system model, component masses are based on the mass of existing hardware that is flight proven in the space environment (TRL 9) in spacecraft like the Mercury Messenger or Space Shuttle. Additionally, ten percent

design contingency is applied to ensure that system mass is not under-estimated.

2. PERFORMANCE SUMMARY

2.1 Performance Characteristics
The AMBR engine performance characteristics are thrust level of 200 lbf, I_{sp} of 335 seconds, one hour operating (firing) time, and 3-10 yrs mission life. No combustion instability was observed in the hotfire testing using a substitute copper combustion chamber. More performance hotfire testing is planned for 2008 using the AMBR prototype Ir/Re chamber.

NASA MSFC and NASA JPL conducted mission level and system level studies to extrapolate improved engine performance into spacecraft requirements and performance. JPL chose four reference missions for this analysis based on

scientific interest, current launch vehicle capability, and trends in spacecraft size (at the time when the analysis was performed 2006-2007). Table 3 shows a summary of the results of the analyses. The Delft University of Technology provided the propulsion requirements for a GEO-sat, extrapolated for 15-year service life. [1]

Table 3: Summary of the Reference Missions

Mission	ACS ΔV	Axial ΔV, m/s	Launch Mass, kg	Deployed/ shed mass, kg
GTO-to-GEO	1,170 m/s	1,830	4,800	0
Europa Orbiter	23.4 kg	2,215	2,170	0
Mars Orbiter	20.0 kg	2,064	2,250	0
Titan-Enceladus Orbiter	50.0 kg	2,368	6,633	1,298, 59.2, & 345

The performance analysis assumes a dual-mode propulsion system. In a dual mode system, Attitude Control System (ACS) thrusters share the hydrazine monopropellant with the main engine which also uses the hydrazine from the same supply system as fuel for combustion with an oxidizer.

Appendix A describes the method used to derive the mission information.

Table 4 shows a summary of the propellant mass estimates calculated for reference missions at various main engine I_{sp} values. The baseline I_{sp} is 320 seconds for the GEO missions and 325 seconds for the planetary missions. AMBR thruster has an I_{sp} of 335 seconds. The analysis assumes an ACS I_{sp} of 230 seconds for monopropellant hydrazine.

Table 4: Propellant Estimates for the Four (4) Reference Missions

Mission	Total Propellant Load (kg) by Main Engine I_{sp}				
	320 sec	325 sec	330 sec	332.5 sec	335 sec
GTO-to-GEO	3,204	3,189	3,176	3,170	3,163
Europa Orbiter	N/A	1,131	1,120	1,116	1,109
Mars Orbiter	N/A	1,320	1,307	1,300	1,293
Titan-Enceladus Orbiter	N/A	2,969	2,942	2,928	2,914

These reference missions show the mass performance and benefits of the AMBR engine.

2.2 Benefits Over SOA

The baseline engine for AMBR's development is HiPAT^{TM}. The latter is currently the highest performing biprop engine in the 100-lbf thrust range with a specific impulse I_{sp} of 328 seconds. In contrast, the improved AMBR engine yields 200-lbf thrust, and its specific impulse is 335 seconds. Because of the increased specific impulse, the most significant benefit of AMBR is the mass benefit.

AMBR's increased thrust at 200 lbf enables better Thrust Vector Control (TVC). For example, a single engine is preferred for spacecraft with 200 lbf thrust operating for 5400 seconds to transit and insert into the orbit of either Jupiter or Saturn. Compared to multiple engines supplying the same thrust, a single engine simplifies the gimbals and thrust vector control.
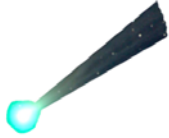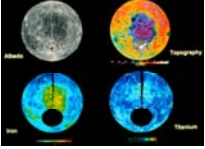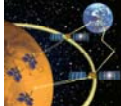
Higher thrust level also provides options for descent and ascent in terms of the capability to carry a heavier load or a spacecraft design using fewer engines.

AMBR's utilization as a dual-mode engine, allows integration with the spacecraft RCS and ACS, using the same propellant, and simplifying the propulsion system design and operation.

2.3 Summary: Potential Application to Candidate New Frontiers Missions

The In-Space Propulsion Technology Project Office performed a high level assessment of the AMBR technology's applicability towards the various candidate missions. The New Frontiers Program issued the results in the Community Announcement, May 12, 2008. Results of this assessment are in Table 5. The assessment in Table 5 is only preliminary and AMBR must be assessed specifically for each mission scenario.
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Table 5: AMBR's Applicability to Candidate NF Missions

	AMBR Benefits
Comet Surface Sample Return (CSSR)	Small body rendezvous and sample return missions have significant ΔV requirements. If a chemically feasible target is chosen, the improved Isp would have clear benefits with little added risk. AMBR improves: Propellant mass fraction Spacecraft margin/risk *High degree of applicability for a chemical CSSR*
Venus In-Situ Explorer (VISE)	A Venus In-Situ Explorer will benefit from direct entry, and therefore, not require any significant deep space maneuvers. An orbiter mission would benefit from AMBR's improved performance. *Limited VISE applicability*
Atkins, Basin Sample Return (ABSR)	Dependant on mission architecture and lander and ascent stage mass, AMBR may have appropriate thrust and throttle-ability. A bipropellant engine may add unnecessary complexity to ABSR. *Limited ABSR applicability*
Asteroid SR	Asteroid SR chemical mission are extremely target dependent. Some asteroids are easier to reach than the moon, while many are chemically infeasible. For targets applicable to chemical bi-propellant engines, AMBR would be appropriate. *High degree of applicability for a subset of ASR*
Ganymede or Io Observer	Orbiter missions to Ganymede and Io are propulsive challenges that could benefit from engine performance. Any chemical solution would clearly benefit from a bi-propellant AMBR class engine. Limited published analyses on Ganymede and Io Mission architectures. Analysis needed. *Applicable for Observers*
Trojan/Centaur	Trojan and Centaur chemical flyby missions obtain their necessary velocities by the launch vehicle and do not require significant deep space maneuvers. *AMBR is not applicable for these flyby missions.*
Network Science	If mass and controlled descent requirements are appropriate, AMBR may have limited applicability. Limited published analyses on network architecture. *Not applicable*

3. Development Summary (under ISPT)

3.1 Status
Initiated in year 2006, the AMBR effort has so far completed:

1. Baseline effort: by hot-firing a developmental HiPAT^{TM} engine, the thermal, propellant flow and pressure dynamic information were successfully collected for use in the AMBR thruster design.

2. Injector risk mitigation: the injector design was verified capable of achieving the developmental goal of 335 seconds I_{sp}. This was accomplished using a copper chamber for very short duration hotfire runs.

The plan is to complete the fabrication and perform the AMBR performance envelope hot fire testing, followed by the vibration, shock, and hot-fire life testing in year 2008.

3.2 Key Activities (Summary)
Beginning in the latter part of year 2006, AMBR thruster development progresses via a number of stages:

- Stage 1: Baseline Hotfire Test: hotfire developmental HiPAT^{TM} engine to collect thermal and dynamic information for use in designing the prototype. Engineers have successfully completed this step.
- Stage 2: Injector Design Verification/Risk Mitigation: verify injector design using a copper chamber; found design highly successful for meeting program goal. Engineers have successfully completed this step.
- Stage 3: Fabricate and test the AMBR prototype thruster: components needing fabrication include the complete injector assembly, combustion chamber, nozzle, and nozzle extension. This step is ongoing as of July 2008 and the AMBR performance envelope hotfire testing is planned for 2008.
- Stage 4: Perform life hotfire and environmental testing (shock and vibration).

4. NEW FRONTIERS MISSION IMPLEMENTATION

4.1 Subsystem Selection
Information needed for selecting subsystems is given throughout this document. Section 1.2 System Summary describes the AMBR system details which are the basis for subsystem selection.

The higher propellant inlet pressure of the AMBR propulsion system may require special consideration (400 psia versus the HiPAT^{TM}'s 300 psia). The inlet pressure impacts the design when reviewing the existing flight hardware (tanks, valves, etc.) for an appropriate match.

4.2 Planned ISPT Tasks
Taken from Section 3.3 Key Activities, the remainder tasks of the AMBR development include:
- Fabricate and test the AMBR prototype thruster. Components to be fabricated include: the complete injector assembly, combustion chamber, nozzle, and nozzle extension. The AMBR performance envelope hotfire testing is planned for year 2008.
- Perform life hotfire and environmental testing (shock and vibration)

4.3 Timetable for Completing TRL 6
Upon completing all planned tasks and successfully passing the engine performance verification and environmental tests, AMBR engine system will demonstrate its intended application in a relevant environment on the ground. The plan (shown in the schedule in Figure 4) is having AMBR engine ready for flight development in 2008.
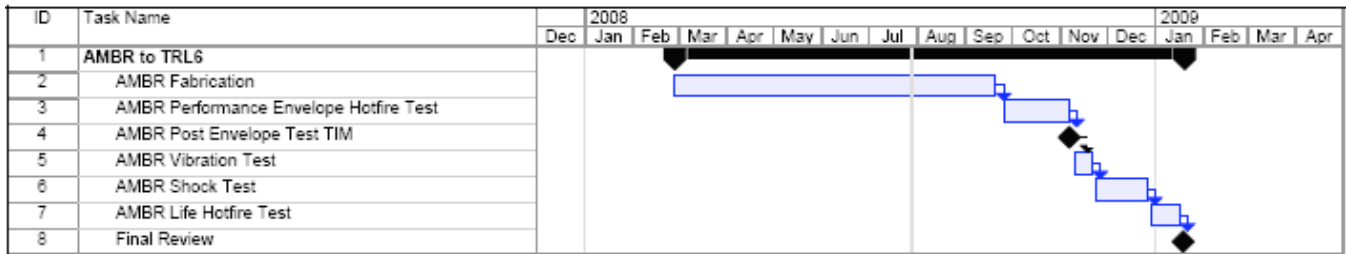

ID	Task Name	2008												2009			
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1	AMBR to TRL6																	
2	AMBR Fabrication																	
3	AMBR Performance Envelope Hotfire Test																	
4	AMBR Post Envelope Test TIM																	
5	AMBR Vibration Test																	
6	AMBR Shock Test																	
7	AMBR Life Hotfire Test																	
8	Final Review																	

Figure 4. Schedule for the Remaining AMBR Developmental Activities

4.4 Mission Success
The AMBR propulsion system development summarized here was done with rigor and depth of considerations required for a high performance bi-propellant system suitable for NASA planetary missions. The development is accomplished via a multi-year, multi-partner (NASA Centers, JPL, Aerojet Corporation, etc,).

The AMBR technology is an improvement upon the existing HiPAT^{TM} engine, a member of the Aerojet Corporation's R-4D Family of thrusters. The R-4D family of thrusters has the following heritage: >1000 engines delivered, >650 flown, 100 percent success rate. [2]

5. CONTACT INFORMATION

Please direct all inquiries and requests related to the AMBR engine to the following individual:

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REFERENCES

[1] Scott Miller, Scott Henderson, Aerojet General Corporation, et al., "Performance Optimization of Storable Bipropellant Engines to Fully Exploit Advanced Material Technologies," 2006 NASA Science and Technology Conference, July 2007

[2] Aerojet Space Propulsion, Redmond, WA, "Performance Optimization of Storable Bipropellant Engines to Fully Exploit Advanced Material Technologies—NASA Cycle 3A NRA Program Kickoff Meeting," 2006-H-3411, September 28, 2006

[3] Aerojet Space Propulsion, Redmond, WA, project review packages including the Based Period Test Readiness Review (TRR), post hotfire Technical Interchange Meeting (TIM), Option I Manufacturing Readiness Review (MRR), copper chamber TRR and post hotfire TIM, 2006-2008

[4] Ron Portz, et al, "Advanced Chemical Propulsion System Study," AIAA 2007-5433, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2007

[5] Chris England, NASA JPL, a number of NASA/JPL internal briefing charts and spreadsheet report, 2007

[6] Jack Chapman, NASA MSFC, "Hot Rocket Propulsion System Sizing Performance Comparison," a NASA internal report, 2007

[7] D. Krismer, A. Dorantes, S. Miller, C. Stechman, F. Lu, "Qualification Testing of a High Performance Bipropellant Rocket Engine Using MON-3 and Hydrazine," AIAA Paper 2003-4775, July 2003

[8] Robert Hickman and Sandra Elam, NASA MSFC, Scott O'Dell and Anatoliy Shchetkovskiy, Plasma Process, Inc., "High Temperature Materials for Chemical Propulsion Applications," 54th JANNAF Propulsion Meeting, Denver Colorado, May 14-14, 2007

APPENDICES

A. METHOD FOR DERIVING THE REFERENCE MISSION INFORMATION:

For each mission, the mass of the spacecraft at launch is estimated based on the expected launch vehicle capability and the terminal velocity which the launch vehicle is obligated to impart. The spacecraft trajectory is planned, in some cases taking advantage of planetary momentum exchange to modify the spacecraft velocity. Main engine burns are an essential part of trajectory planning to keep the spacecraft on course. In one case, the scientific requirements of the mission require deployment of spacecraft elements such as a heat shield or independent landing craft, requiring accounting for the mass decrements. Demands placed on the attitude control system are modeled based on historical data, acceptable limits of spacecraft pointing and statistical distributions of spacecraft attitude perturbations due to internal and external influences. The calculated propellant load is increased by one percent to account for the inability of propellant tanks to completely discharge their contents. Finally, because of the uncertainties inherent in engineering, a five percent margin is added to the propellant load.

Once the accounting is in place for mass and velocity changes, assumptions are made regarding the efficiency of the propulsion system elements. These assumptions are based on a database of past engine performance or in this case on the goals for improved main engine performance. The propellant mass required to execute the velocity changes required by trajectory planning and ACS analysis are determined by means of the rocket equation or similar calculation.