1.0 INTRODUCTION

1.1	**TITLE OF THE CANDIDATE TECHNOLOGY:**	Pulsed Plasma Thruster (PPT)
1.2	**ADT LEAD:**	Charles Zakrzwski, GSFC
1.3	**SPONSORING IPDT:**	MAMS IPDT
1.4	**CATEGORY OF PROPOSED USE:**	Category 3 (ACS)
1.5	**SUPPLYING ORGANIZATION:**	NASA LeRC/Primex Aerospace Co. (PAC)
1.6	**PRIMARY TECHNOLOGY CANDIDATE CONTACT:**	Tod Peterson, NASA LeRC (216) 433-5350 (216) 433-2995 (FAX) Todd.Peterson@lerc.nasa.gov W. Andrew Hoskins, PAC (206) 885-5000 (206) 882-5758 (FAX) wah@rocket.com Charles M. Zakrzwski, S/C Propulsion Group, NASA GSFC (301) 286-3392 (301) 286-1702 (FAX) charles.zakrzwski@gsfc.nasa.gov
1.7	**USEFUL SECONDARY CONTACTS:**	Frank Curran, Chief, On-Board Propulsion Branch, NASA LeRC (216) 977-7424 (216) 433-8311 (FAX) frank.curran@lerc.nasa.gov Dennis Asato, S/C Propulsion Group, NASA GSFC (301) 286-6433 (301) 286-1702 (FAX) dennis.asato@gsfc.nasa.gov

2.0 BACKGROUND

2.1 *Characterize the candidate technology:*

The Pulsed Plasma Thruster (PPT) is a small, self-contained electromagnetic propulsion system for spacecraft. The PPT uses solid Teflon propellant and is capable of delivering high specific impulse (900-1200 s), very low impulse bits (10-1000 μN-s) at low average power(<1 to 100 W). These characteristics make the PPT an excellent candidate as an attitude control device for providing precise stabilization and pointing accuracy previously obtainable only with reaction wheels. In future small/micro spacecraft missions, replacement of reaction wheels and associated momentum unloading components (e.g., magnetic torquers; gas/chemical reaction control components) with

PPT offers substantial reduction in mass, power and volume allocated to attitude control functions.

The PPT consists of a coiled spring to feed the Teflon propellant, an "igniter plug" to initiate a small trigger discharge, an energy storage capacitor and electrodes. Plasma is created by the ablation of the Teflon propellant from discharge of the storage capacitor across the electrodes. The plasma is accelerated by Lorenz force in the induced magnetic field to generate thrust. Multiple PPT units can be assembled into a module and be driven by a common capacitor to reduce mass and volume.

The PPT development program is funded by Code SM and directed by the NASA Lewis Research Center (LeRC). The Primex Aerospace Co. (PAC) is the supplier of the PPT.

2.2 *How will the utilization of this technology enhance science in the 21st century?*

Instruments such as the large scale interferometers planned for the Origins Program will require precision pointing and control of the spacecraft. Science requiring positioning of a "constellation" of small spacecraft will require precise velocity control of spacecraft. The very low impulse bit capability (10-1000 μN-s) of the PPT could provide the pointing and velocity control accuracy required for these missions. The use of solid propellant also eliminates the concern of liquid propellant slosh affecting pointing accuracy of the instruments.

With the new generation of small spacecraft, the PPT offers a low mass, power and volume alternative to the combination of reaction wheels, momentum unloading components, and conventional delta-V propulsion systems. The high specific impulse (900-1200s) of the PPT could provide additional benefits of increasing the science payload, increasing mission lifetime, or reducing launch mass for these small spacecraft.

2.3 *Why is this considered a revolutionary technology development?*

The PPT has unique characteristics not currently offered by any other propulsion system: 1) high specific impulse (900-1200 s) electric propulsion system capable of operating at low average power levels (<1 to 100 W); 2) minimum impulse bit capability lower than any chemical or gas propulsion systems; 3) solid state propellant reduces ground handling and safety costs, and eliminates slosh concerns for instruments requiring high pointing accuracy; 4) simplicity, self-contained module reduces S/C integration cost.

2.4 *Why is a space flight necessary to validate this technology?*

Space flight is necessary for the PPT to: 1) demonstrate fine attitude control & precision positioning capability; 2) confirm ground plume assessment test data; and 3) verify ground performance test measurements. Long term on-orbit data also provides credence for the reliability and performance of the PPT as an attitude control device for potential users. The I&T phase of the flight program will also provide an opportunity to assess the cost reduction potential due to the design simplicity of the self-contained PPT.

The PPT has been tested in orbit to perform velocity changes (LES 6 at 2.5 W, LES 8 & 9 at 25 W, and NOVA 1-3 at 35 W) The Air Force will fly advanced PPT modules for delta-V the MightSat II flight series starting in January 2000. The PPT has not been used for primary attitude control.

3.0 <u>PROPOSED INTEGRATION & VALIDATION APPROACH</u>

3.1 ***Describe your proposed approach to incorporating this candidate technology into the NMP/EO-1 flight and justify your categorization*:**

The proposed approach is to add a PPT module to provide backup attitude control for the pitch axis reaction wheel. On-orbit tests of the PPT capability to control pointing/attitude will be performed. The EO-1 PPT module would consist of a pair thrust producing electrode/fuel bar assemblies packaged in a single unit with a common capacitor. The PPT would be mounted to an external structure with unobstructed views for the thruster plumes. An electrical harness would provide access to S/C 28 V power, attitude control electronics, and the command/data handling subsystem.

The integration approach is to minimize unique S/C interface requirements to accommodate the PPT. Should unacceptable technical, schedule or cost risks with the PPT be identified, this approach will allow removal of the PPT module with minimal impact to the EO-1 Program. Since backup control of the pitch axis is not a primary function to ensure success of the mission, the proposed implementation of PPT module on EO-1 should be classified as Category 3.

3.2 ***Describe the approach in the budget which did not include the supplemental technology budget*:**

The current approach for attitude control of the EO-1 S/C is the use of a reaction wheel for each of the three S/C axes.

3.3 ***Describe how your proposed approach affects the original, baseline approach pursued by the Flight Team:***

The proposed approach is a Category 3 technology to provide backup attitude control function for the pitch axis reaction wheel. It does not affect the current approach of 3-axis attitude control via three reaction wheels.

3.4 ***Describe the interface with the spacecraft or the Advanced Land Imager (ALI):***

One PPT module with two thrust producing electrode/fuel bar assemblies will be mounted to the spacecraft with thrust vectors parallel to the spacecraft Z-axis. The PPT will produce positive or negative pitch torques by selectively discharging through one of the two electrode pairs. The PPT experiment will consist of disabling the use of the pitch axis momentum wheel and torque bar to control pitch disturbances and enabling the PPT to control in pitch. The spacecraft will provide power, commands, mounting surface and fasteners, control software, harnessing, and interface electronics for the PPT. The PPT will provide telemetry to the spacecraft, a mounting interface to the spacecraft, and will incorporate a thermal control design to maintain its temperature. Three command lines and seven telemetry lines will be required.

The PPT unit has no interface with the ALI.

3.5 ***Describe the impacts on the spacecraft or the ALI*:**

There is no impact to the ALI. Specific impacts to the spacecraft resources are provided under Item 3.8.

3.6 ***Describe your proposed approach to the integration and test of the candidate technology:***

The proposed integration & test approach for the PPT module is to subject the flight unit to functional and "Protoflight" level environmental tests at the component supplier facility (PAC) and the LeRC space simulation chambers (See Response to 3.8 and 7.0).

The PPT module will be integrated to the S/C at the Swales & Associates Inc. (SAI) facility. PAC, LeRC & GSFC will provide technical support, as required, to support the I&T tasks. The PPT module integrity will be verified during functional and environmental tests at the S/C level.

3.7 ***Describe your proposed approach to operations in general and to validation in particular for the candidate technology:***

The PPT will be controlled autonomously by the ACS in the same manner as a reaction wheel. Only the torque transformation matrix and possible the control constants will differ between the pitch reaction wheel and the PPT control logic. Ground commands will be required for the initial calibration of the PPT and for transitions between pitch axis PPT and momentum wheel control.

The primary validation objective is to show that the PPT can reliably control the pitch axis while the spacecraft is in normal science mode and meet the EO-1 mission objectives. The validation will: 1) demonstrate the control capability of the PPT, including pointing accuracy, response characteristics, and stability; 2) confirm benign plume/spacecraft interaction and EMI effects and 3) verify PPT performance. Validation of the PPT operation will be from analysis of on-orbit data of the PPT telemetry, the S/C subsystem telemetry (ACS, C&DH, power), and the telemetry from the ALI, LEISA, and Lightweight Flexible Solar Array experiments.

3.8 ***Describe the specific impacts on spacecraft resources*****:**

<u>Mass:</u> Increase by less than 6.0 kg (Does not include fasteners, internal harness, or ACE electronics)

<u>Power:</u> Orbital average power: Operation mode: < 10 W,

<u>Survival mode</u>: < 5 W.

<u>Volume</u>: main housing: (40-25)x25x20 cm, electrode assemblies 28.7x8.5x6 cm; unobstructed external view at nozzle exits required.

<u>Thermal</u>: PPT will incorporate thermostatically controlled heaters to maintain survival temperature.

<u>Propellant</u>: Impact Included in "Mass"

<u>C&DH</u>: Allocate 3 Command and 7 Telemetry Channels

<u>Comm</u>: No Impact

<u>ACS/pointing</u>: Will meet pitch axis control/pointing requirement

<u>Flight S/W</u>: Minor modifications to existing software. Requires transformation tables and gain constants to be modified. Accommodations required for PPT commands and telemetry.

<u>Environmental</u>: Plume contamination impact is TBD. NASA LeRC test of near-field (<0.4 m), including backflow region, shows negligible/low contamination. Facility to test

far-field (0.4-10 m), including different material & surface configurations, is being prepared at LeRC. Worchester Polytechnic Institute (WPI) has been given the task to develop the analytical plume code (DSMC/PIC) for the PPT. Additional tests at LeRC will be defined with SAI & GSFC to simulate EO-1 mounting configuration.

3.9 *Describe how we would contractually acquire the candidate technology*:

GSFC & LeRC will work with SAI to define a contract modification to the existing LeRC/PAC contract to acquire the flight PPT module for EO-1. A future contract modification with PAC will include the PAC resources to support I&T and on-orbit operation of the PPT.

NASA LeRC has proposed the following: 1. All non-recurring costs (approx. $50K for mods to MightSatII design) to be covered by the existing NASA LeRC PPT program; 2. NASA LeRC via the NASA "On-Board Propulsion" program would provide funds to cover the cost of the EO-1 PPT flight module (approx $300 K); 3. NASA LeRC will absorb the additional cost for tailoring the existing PPT contamination test program for the EO-1 configuration and 4. NASA GSFC will provide additional funds for a PAC contract modification to support spacecraft I&T and on-orbit operations through NASA LeRC.

3.10 *Describe any facilities issues or special GSE or FSE*:

Test facilities for the PPT are available at LeRC and PAC. There are no facility issues or special GSE/FSE required to be provided by the

EO-1 Project. Ground test equipment to support testing of the PPT module will be provided by PAC or NASA LeRC

4.0 <u>AVAILABILITY</u>

4.1 *Identify the earliest date when an ETU or comparable demonstration hardware (and/or software) would be deliverable to the project:*

The current spacecraft integration approach does not require the use of a PPT ETU.

4.2 *Identify the earliest date when flight hardware (and/or software) would be deliverable to the project:*

The earliest delivery date of the flight PPT to EO-1 is January 1998 (earliest need date is February 1998).

5.0 <u>RISK</u>

5.1 *Characterize the technical risk associated with this candidate technology. Identify specific risk mitigation approaches to the technical risk that you would recommend.*

Technical risks of using the PPT module as a functional backup to the ACS pitch wheel are judged to pose low threats to the EO-1 mission. Supporting evidence and actions taken to mitigate these risks include: 1) ground test data and on-orbit experimental data demonstrate performance and reliability of the PPT; 2) plume contamination tests for near field (< 0.4 m) indicate low/negligible contamination deposition; 3) qualification radiated and conducted EMI tests will be completed by June 1997; 4) NASA LeRC will perform more comprehensive plume tests to investigate far-field regions, effect of deposition on different material, and the EO-1 thruster mounting configuration; and 5)

PPT qualification tests for the Air Force's MightySatII missions will demonstrate more demanding requirements than for EO-1 (to be completed October 1998).

The technical risk of the PPT failing to meet the pitch pointing requirements is low. First order attitude control simulations performed for the EO-1 s/c baseline from the November 1996 Design Convergence Review indicated acceptable PPT performance for the proposed PPT control method. At this time, the changes that have occurred in spacecraft configuration are judged to be non-detrimental to the PPT attitude control performance. The first order attitude control simulations will be repeated for the current spacecraft configuration in the April 1997 time period.

Should technical or schedule problems of the PPT become insurmountable, the PPT module can be easily removed.

5.2 *Similarly, characterize the schedule risk associated with this candidate technology. Identify specific risk mitigation approaches to the schedule risk that you would recommend. Identify any schedule "trigger points" that represent decisions to shift to alternative development paths.*

The PPT schedule to deliver flight hardware by January 1998 provides at least a one month margin (need date of PPT flight hardware is February 1998). The schedule to address technical issue will resolve the most critical issues by spacecraft CDR which is scheduled for June 1997. The radiated EMI compatibility issue between the spacecraft and the PPT will be addressed before the spacecraft CDR by the completion of bread board demonstration testing. The control capability of the PPT will also be addressed before the CDR by the completion of high fidelity ACS simulations.

To minimize the risk to the PPT development schedule the internal PPT electronics and main capacitor were chosen to be identical to the MightySatII PPT. The choice of a common design, while not optimal for EO-1 with respect to mass and volume, reduces the schedule risk by eliminating the need for parallel development and test programs at NASA LeRC and PAC.

The critical schedule "trigger point" will be the EO-1 CDR.

5.3 *Lastly, characterize the budgetary risk associated with this candidate technology. Identify specific risk mitigation approaches to the budgetary risk that you would recommend. Identify the total budgetary reserve you would recommend to make the aggregate risk of incorporating this candidate technology acceptable.*

The two key budget risks are: 1. escalation in cost to develop PPT interface card in the ACE and/or to modify flight software to enable PPT to control pitch axis; and 2. escalation of non-recurring cost due to unexpected results in qualification program.

To minimize the budget risk for the development of the PPT flight unit NASA LeRC has committed to increase its contribution to cover the entire estimated cost of the flight hardware if necessary. The choice of a PPT design which is common to the MightySatII program reduces developmental risk. The larger MightSatII capacitor also increases design options and decreases the risk of requiring modification to the ACE electronic interface concept.

6.0 BUDGET

Determine the net cost to incorporate and validate the candidate technology by using a spreadsheet comparison between the budget distribution for the current approach and the candidate technology. Identify any cost-sharing with the supplier. Identify funding

for fiscal years 1996 through 1999 and subdivide the entries into Development, Integration & Test, and Operations which includes the validation of the candidate technology. Be sure to include and highlight the cost of the risk mitigation approaches you recommended under Risk.

COST DISTRIBUTION OF PULSED PLASMA THRUSTER (PPT) FOR EO-1

Activity	Source	Prior	Fy'97	FY'98	FY'99	Fy'00	Total
Development:	Tech Budget		70 K	65 K	20 K		155 K
	RTOP (LeRC from Code SM)	750 K	900 K	300 K			1950 K
Dev. Subtotals		750 K	970 K	365K	20K		
Spacecraft I&T	S/C Budget		170K	108 K			278 K
Validations;	Tech Budget				20 K	10 K	30 K
	RTOP						
Val Subtotals					***20 K***	***10 K***	
Annual Subtotals:		***750 K***	***1140 K***	***473 K***	***40 K***	***10 K***	

7.0 RECOMMENDED DISPOSITION

Justify the incorporation of this candidate technology on the NMP/EO-1 flight. Weigh the benefits described in the Introduction against the accommodation impacts associated with budget, schedule, and overall risk. Is the NMP/EO-1 flight a suitable, cost-effective testbed for this candidate technology? How well does this candidate technology contribute to the most robust technology mission that we can afford?

The EO-1 provides an excellent opportunity to demonstrate the capability of the PPT to perform precision pointing and control of a spacecraft. The PPT has unique characteristics which can enable low cost science missions involving small spacecraft: a high specific impulse provides mass reduction; a low minimum impulse enables precision pointing; low power and reduced volume yield a smaller spacecraft; the self-contained and solid inert propellant results in lower I&T and safety costs and long storage life; and lastly, the simplicity of design results in inherent high reliability.

The ground tests and on-orbit experiments (LES 6 at 2.5 W, LES 8 & 9 at 25 W, and NOVA 1-3 at 35 W) with the PPT indicate that this technology has low technical risks. To confirm that the PPT EMI/contamination will not pose a threat to the EO-1 mission, additional tests are planned at NASA LeRC and PAC and will be available for the EO-1 CDR. The Air Force's MightySatII PPT qualification program, which is scheduled to be run concurrently with the EO-1 PPT test program, will demonstrate capability of the PPT to meet a more stringent set of requirements than expected for the EO-1 mission.

Should any technical, schedule or cost issue pose an unacceptable risk to the EO-1, the PPTs can easily be removed. The existing Code SM program directed through NASA LeRC will provide substantial funding to help reduce cost impact to the EO-1 Program.

The velocity control capability of the PPT has been demonstrated in orbit. Demonstrating the capability of the PPT as an ACS device on EO-1 will provide an added impetus for the use of this technology in future missions. Steps have been taken to reduce the technical, schedule and cost risks of the PPT to the EO-1 Program. The PPT is recommended as a Category 3 technology to provide backup attitude control to the EO-1 pitch axis reaction wheel.

Should any of the on-going contamination tests, ACS systems analysis or assessment of S/W modifications reveal unacceptable technical, schedule or cost risks to the EO-1 mission, the PPT could be readily removed. The contamination test data and results from the ACS analyses will be presented at the EO-1 CDR.