Electric Propulsion Requirements and Mission Analysis Under NASA's In-Space Propulsion Technology Project

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I. Abstract

The In-Space Propulsion Technology Project (ISPT) is currently NASA's sole investment in electric propulsion technologies. This project is managed at NASA Glenn Research Center (GRC) for the NASA Headquarters Science Mission Directorate (SMD). The objective of the electric propulsion project area is to develop near-term and mid-term electric propulsion technologies to enhance or enable future NASA science missions while minimizing risk and cost to the end user. Systems analysis activities sponsored by ISPT seek to identify future mission applications in order to quantify mission requirements, as well as develop analytical capability in order to facilitate greater understanding and application of electric propulsion and other propulsion technologies in the ISPT portfolio. These analyses guide technology investments by informing decisions and defining metrics for technology development to meet identified mission requirements.

This paper discusses the missions currently being studied for electric propulsion by the ISPT project, and presents the results of recent electric propulsion (EP) mission trades. Recent ISPT systems analysis activities include: an initiative to standardize life qualification methods for various electric propulsion systems in order to retire perceived risk to proposed EP missions; mission analysis to identify EP requirements from Discovery, New Frontiers, and Flagship classes of missions; and an evaluation of system requirements for radioisotope-powered electric propulsion. Progress and early results of these activities is discussed where available.

II. Introduction & Background

In February, 2007, the management of NASA's In-Space Propulsion Technology Project was transferred from NASA Marshall Space Flight Center to NASA Glenn Research Center. At that time a new systems analysis plan was formulated to address the current needs for the project. This paper outlines the systems analysis plan as it applies to electric propulsion, and provides early results of mission analyses to define current requirements for new electric propulsion technologies.

Systems analysis is the intermediary between mission applications and technology development. Systems analysis provides an understanding of the requirements for a technology so that development activities can be focused on meeting them. Conversely, systems analysis provides an understanding of a technology's capabilities and potential benefits, as well as limitations, to missions considering application.

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Systems analysis activities sponsored by ISPT seek to support the propulsion technologies in the ISPT portfolio by:

- Identifying future mission applications
- Quantifying mission benefits
- Guiding technology investments and informing project decisions
- Defining metrics for technology development to meet future mission requirements
- Providing tools and capabilities to support analysis, acceptance, and application

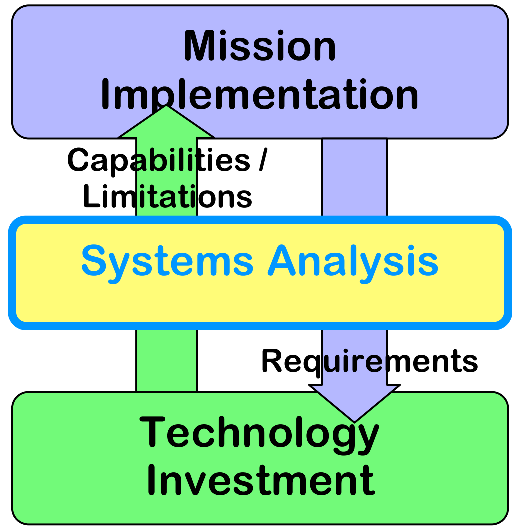

Figure 1: Systems Analysis in a Technology Project

III. Current Analyses in Electric Propulsion

The In-Space Propulsion Technology Project is approaching a crossroads where a decision is needed for the direction of continued investment in electric propulsion technology. At a time when NASA technology investments are being curtailed under tight budgets in favor of missions and flight system development, it is crucial that the next investments in electric propulsion address near and mid-term mission needs within the Science Mission Directorate (SMD) roadmap. Additionally, the ISPT project is seeking to facilitate increased application of propulsion technologies nearing maturity in its current portfolio by providing tools, information, and capabilities to teams proposing missions that can benefit from these advanced propulsion capabilities. Though developed prior to the ISPT project, the NASA Solar elctric propulsion Technology Application Readiness (NSTAR) thruster is one such EP technology which the project supports for further application. However, the prime ISPT technology development nearing flight maturity is the NASA Evolutionary Xenon ion Thruster (NEXT), developed to achieve higher specific impulse, propellant throughput, and efficiency than NSTAR at higher thruster power for larger missions. The system analysis plan seeks to guide the project decisions for further investment in electric propulsion by defining the requirements for EP within the SMD mission roadmaps, and emerging mission concepts that might be proposed. Finally, the plan includes improvements to analytical tools and capabilities needed to support EP technology development, mission analysis, and mission operations.

A. Standards for Electric Propulsion Lifetime Qualification

Lifetime qualification for electric propulsion systems for NASA science missions is a challenge for the technology, proposal, and user community. There is substantial cost and time associated with long duration life testing to prove that a thruster can perform a proposed mission. The nature of NASA missions requires significant throttle-ability, and actual mission throttle profiles are unknown prior to mission selection. Undoubtedly, the successful use of electric propulsion will require significant test and analyses. However, the time and cost for thruster life testing can be minimized if strong correlation can be developed between analytical models and physical life tests so that thruster life can be accurately predicted computationally. For this approach to be successful, it is important to establish and validate standards for life testing and modeling that are widely accepted by the electric propulsion and proposal review communities. The ISPT project is currently sponsoring a task to clearly define the lifetime qualification requirements suitable for NASA science missions and develop validated analytical models to accurately predict thruster life.

The approach of the lifetime qualification standards task is to define a standard method for lifetime qualification, accepted by the technology and user community, using specific ground test criteria coupled with numerical erosion and life model predictions which have been validated against experimental data; determine how to incorporate mission throttle profiles into thruster life modeling; and provide thruster life qualification tools openly available to the EP technology community that are acceptable to mission proposal teams and evaluations.

B. Electric Propulsion Requirements in the Current NASA Science Roadmap

The NASA science roadmap includes several missions with electric propulsion applicability. In order to justify the use of electric propulsion, often the mission must not only be enhanced, but enabled. The missions considered when establishing the electric propulsion system requirements fall primarily into three major SMD flight programs: Discovery, New Frontiers, and Flagship missions. Additional mission opportunities, e.g. Mars Scout, typically have requirements similar to Discovery Class missions.

1. Discovery

Discovery missions are Principle Investigator (PI) led missions that are openly competed through announcement of opportunities. Currently, Discovery missions must have a total cost of less than $425 million and the development time from mission start to launch can be no more than 36 months. The program has a goal of launching a mission every 12 to 24 months.

Limited mission project budgets and development schedules provide the primary need for technology development under ISPT. EP systems cannot be developed within the cost constraints of Discovery class mission. Further, the technology would be considered high risk if not TRL 6 prior to Preliminary Design Review (PDR). For electric propulsion applications; the life test alone could consume the full 36 months development schedule. To overcome the challenges to implementing new EP technologies for Discovery missions, a general set of missions that may be proposed is often used to compare electric propulsion system performance and determine propulsion system requirements prior to the release of each AO and mission selection.

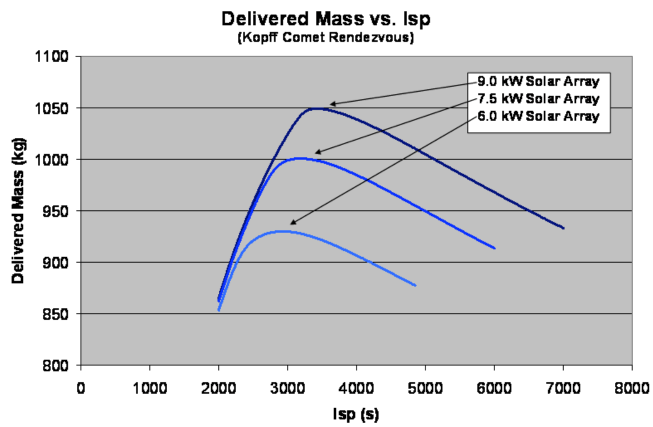

Figure 2. Optimized specific impulse for an example comet Kopff rendezvous mission.

The In-Space Propulsion Technology Project Office is investing in the High Voltage Hall Accelerator (HiVHAC) thruster specifically to address the cost challenges of Discovery class missions. The HiVHAC Hall task is expected to deliver a higher performance engine for these smaller missions with a significantly reduced cost over the state-of-the-art (SOA) NSTAR thruster.

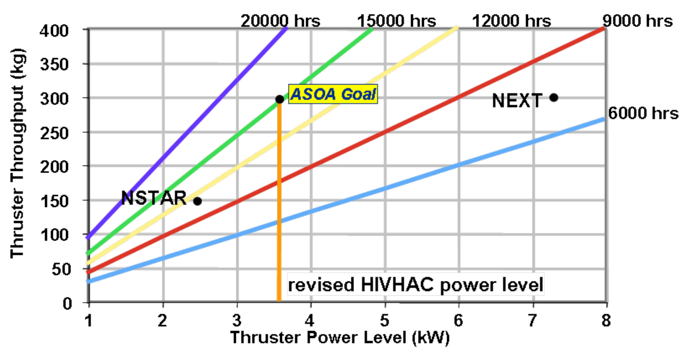

Figure 3. Throughput goal for the HiVHAC thruster.

Under a cycle two In-Space Propulsion NASA Research Announcement (NRA), the NASA Glenn Research Center was selected to lead the development of a 6-8 kW Hall thruster with moderate I_{sp} for Flagship class missions. After the focus of ISP shifted from large missions to smaller Discovery and New Frontiers missions, the HiVHAC program was re-vectored to develop a smaller HiVHAC thruster with a P_{max} of approximately 3 kW specifically to increase low power performance and reduce cost for Discovery class electric propulsion missions. The HiVHAC thruster has a large throttle range as well as a large specific impulse range.

Extensive systems analyses were conducted to determine the performance metrics of the current HiVHAC development. Analyses included specific impulse optimization for enveloping discovery class missions, lifetime requirement predictions, and power and throttle-ability sensitivity to performance and cost. There is a strong interdependency between the various propulsion system metrics. For example, higher specific impulse can increase erosion rates, high power operation can reduce throughput challenges, lower operating power limit can decrease required spacecraft power, etc.

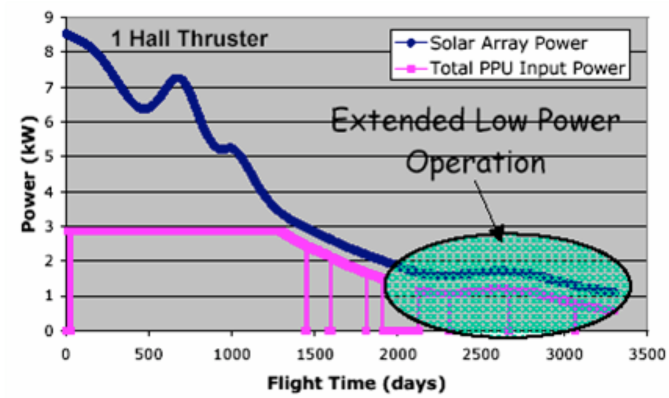

Figure 4. Observed power trends of Discovery class missions. [1]

The HiVHAC development effort continues towards the goal of a low cost 3.6 kW thruster with a lifetime goal of greater than 30,000 hours. The HiVHAC thruster is undergoing substantial wear testing throughout FY07 to validate the life extension techniques.

Finally, while the majority of systems analyses for Discovery class missions highlighted the benefits of the low-power Hall thruster; design changes to the lower end of the NEXT ion propulsion system throttle table have been implemented to improve NEXT performance for the lower cost capped missions. ISPT has also been investigating a standard architecture approach for electric propulsion systems to help reduce Non-Recurring Engineering (NRE) costs associated with EP missions.

2. New Frontiers

New Frontiers missions are also PI led missions selected through Announcements of Opportunity (AOs), but with a higher cost cap and the ability to use radioisotope power systems. The New Frontiers AOs also request specific targets including the South Pole Aitken Basin Sample Return, Venus In-situ Explorer, Jupiter Polar Orbiter with Probes, and a Comet Surface Sample Return (CSSR). The CSSR has been chosen as the electric propulsion reference mission for New Frontiers, though all missions have been evaluated.[2] Electric propulsion is enhancing for CSSR and Comet Nucleus Sample Return missions, and can be enabling to several targets of interest. Multiple studies[3,4] have illustrated the benefit of higher thrust throttle curves for completing these missions. Also, because of the increased budget, available power is usual higher for New Frontiers class missions than for Discovery Class missions. The increased power leads to the need for either high power or multiple simultaneously operating thrusters. Last, there have been studies[5] investigating the possibility to transform what would be a Flagship class mission into the New Frontiers class by using electric propulsion to significantly reduce the cost.

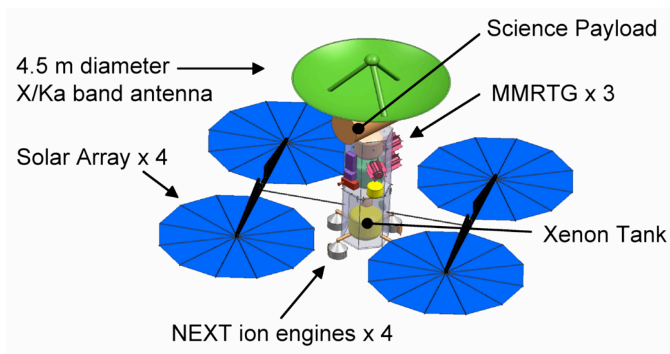

Figure 5. Notional electric propulsion Titan spacecraft.

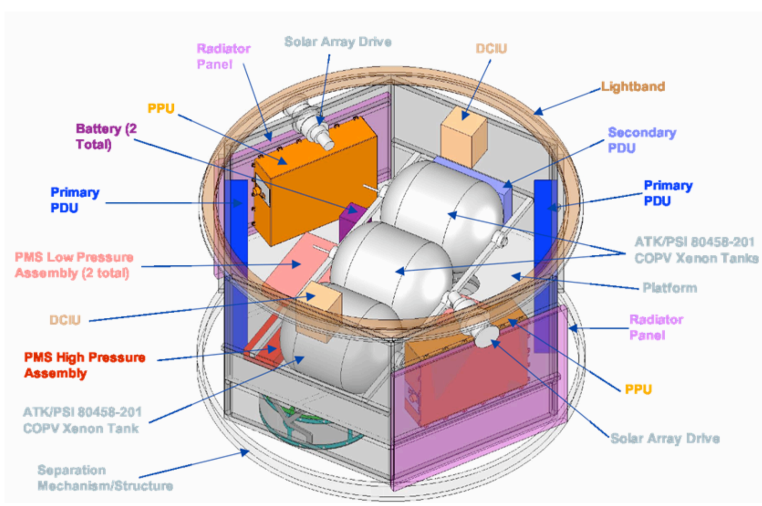

Figure 6. NEXT 1+1 SEP Module for Saturn Explorer.

3. Flagship Missions

Flagship missions are specified by the Science Mission Directorate to targets of high interest to the scientific community. The primary investment of In-Space Propulsion Technology is the NASA Evolutionary Xenon Thruster as a flagship class electric propulsion thruster. Though the NSTAR thruster was successfully demonstrated on DS1 and is scheduled for launch in September 2007 on the Dawn Discovery Class mission, it is inadequate for flagship missions. NEXT was designed as a higher power thruster with a significant increase in throughput capability and specific impulse exceeding 4,000s. Performance requirements were originally established for NEXT using Titan and Neptune reference missions, but the system as been evaluated for numerous missions including the recent Enceladus Flagship mission study.[6] NEXT has repeatedly been shown to significantly increase performance and/or reduce mission trip times to flagship mission targets.

Overall, systems analysis plays a major role in the determination of performance requirements for the ISP electric propulsion investments. Considerable progress to date has been made in developing systems for all of NASA SMD's mission categories. Figure 7 illustrates the key results of the analyses; that ISP technologies will be performance and cost enabling for a wide range of NASA mission applications.

	Discovery (<10 kW)			New Frontiers (< 20kW)			Flagship	
	Dawn	Near Earth Asteroid Sample	Comet Rendezvous	Titan Lander	CSSR	JPOP	Titan	Neptune
Single NSTAR	X	X						
Multi-NSTAR		X	X	?				
HiVHAC	XX	XX	XX	?	XX			
NEXT	X	X	X	X	X		X	X

X= Applicable
XX= Possibly Cost Enabling
?= Not Evaluated
Not Applicable

NSTAR: NASA Solar Electric Propulsion Technology Application Readiness
NEXT: NASA's Evolutionary Xenon Thruster
HIVHAC: High Voltage Hall Accelerator

Figure 7. Electric propulsion system mission applicability.

C. Electric Propulsion for Radioisotope Power Sources

Radioisotope powered electric propulsion (REP) is a capability whose component technologies are nearing maturity. Past analyses of REP have defined the practical requirement for the specific power of the system as greater than 8 W_e/kg. The NASA Advanced Stirling Radioisotope Generator (ASRG) is projected to have performance near 8W_e/kg at 140-160 W_e, and may be flight ready as early as 2011. The ISPT systems analysis plan includes a task to assess the requirements for the electric propulsion sub-system to pair with the ASRG, as it would be applied to potential missions of interest to NASA. These requirements will be used to define the EP technology investments to enable an REP system.

The EP sub-system for REP will have to be low mass, have long life, and be low cost if it would be practical for cost-constrained missions such as Discovery or New-Frontiers. The requirements for an REP thruster will be similar to those for the JIMO thruster for a nuclear reactor power source, albeit at a power scale 2-3 orders of magnitude lower at 200-2000W_e. The ISPT project is investigating how past technology investments in the JIMO thruster could be leveraged to support the development of an REP thruster.

D. Application of Commercially Available Thrusters

When NASA developed and demonstrated the Solar-electric propulsion Technology Application Readiness (NSTAR) thruster, the domestic use of multi-kilowatt gridded ion and Hall Effect thrusters on commercial satellites was non-existent. Of the thrusters that existed at the time, the lifetimes and total impulse capabilities were insufficient to meet NASA's science mission needs. Thus, NASA had no choice but to develop a thruster to meet it's mission requirements. Since then, NASA has continued to invest in very high performance thrusters, but the limited flight rate leads to the fact that these thrusters are expensive to fly, especially for the first user who must flight qualify them. There is simply not a high enough flight rate to gain any economy in production or operations.

With the increasing number of commercial electric propulsion systems available there is an increasing interest in investigating the use of purely commercial off-the-shelf (COTS) electric propulsion systems for NASA science missions. Commercially available thrusters have been shown to have adequate life and performance for some Discovery class missions.[7,8,9] The use of COTS thruster should provide significant cost savings for electric propulsion systems. However, commercial systems have limitations; for example, throttle-ability. They are also designed for the near-Earth environment and may not be capable of operation in the environmental conditions of deep space, or around other bodies. Despite the potential limitations, the ISPT project has initiated a study to evaluate performance capability, cost advantages, lifetime limitations, engineering or design change requirements, delta qualification requirements, and cost and schedule estimates to bring COTS systems to Technology Readiness Level (TRL 6) for NASA science missions.

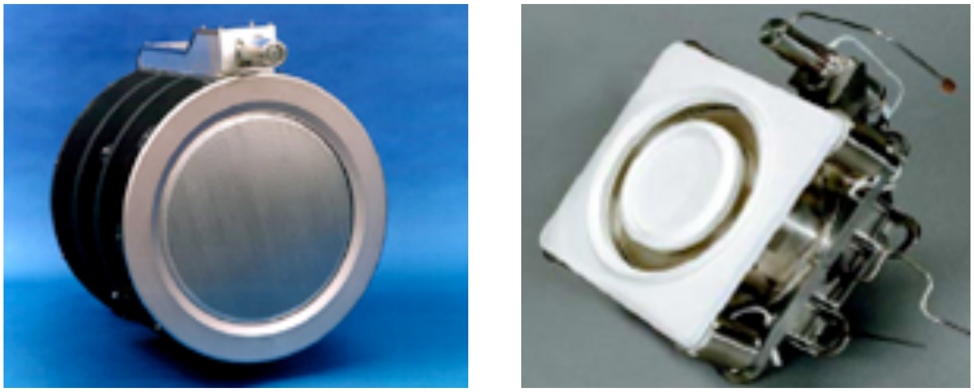

Figure 8. XIPS (left) and BPT-4000 (right) thrusters.

E. Low Thrust Analytical Tool Development

The ability to calculate the performance benefit of a new technology is critical to it's understanding, acceptance, and application. This is especially true of electric propulsion, where the performance and operation of the technology is not intuitive or widely understood. The ability to calculate the performance of complex electric propulsion missions is also intrinsic to the determination of propulsion system requirements. To that end, the in-space propulsion technology office has invested in the development and verification of a suite of low-thrust trajectory tools that can calculate and analyze low thrust trajectories to various degrees of fidelity.

The ISP low-thrust trajectory tools suite includes Copernicus, MALTO, Mystic. OTIS, and SNAP:

Copernicus is suitable for both low and high fidelity analysis as a generalized spacecraft trajectory design and optimization program.

MALTO (Mission Analysis Low Thrust Optimization) is a program used to perform medium fidelity low-thrust trajectory analysis and mission design. MALTO can also perform trade space investigation of up to 3 dimensions. Other uses for this tool include providing initial guesses for Mystic, Copernicus & OTIS when it's necessary. MALTO has some capability to perform high thrust analysis as well.

Mystic is a high fidelity tool capable of N-body analysis and is the primary tool used for trajectory design and analysis of the Dawn mission.

OTIS (Optimal Trajectories by Implicit Simulation) is a power and flexible tool for analyzing a wide range of trajectory types, including atmospheric vehicles, launch vehicles, and low and high thrust spacecraft in planetary or interplanetary space.

SNAP (Simulated N-Body Analysis Program and Optimization System) is a low and high fidelity mission and trajectory design tool that can propagate spacecraft position to a high degree of precision.

ChebyTOP (Chebyshev polynomial Trajectory Optimization Program) is an easy to use, low-fidelity low-thrust interplanetary trajectory tool for "first-look" type analyses. This tool uses a Chebyshev polynomial approximation method to generate trajectories. Due to the nature of low-fidelity tools, this is a limited application tool. This tool is an ideal starting place for 1st-year graduate students (or equiv.) pursuing research in the area of low-thrust trajectory analysis. ChebyTOP was not developed as part of the ISPT low thrust trajectory tools suite.

These tools are provided to the analysis, technology, and proposal communities on the In-Space Propulsion Technology website.[10] More information on these tools can be found there. ChebyTOP, Copernicus and SNAP are publicly available. MALTO, Mystic, and OTIS have limited distribution.

The ISPT systems analysis plan for electric propulsion includes the maintenance and continued improvement of these and other tools that support the analysis and application of propulsion technologies in the ISPT portfolio. Current efforts focus on closing gaps in analytical capability and developing tools that enable new type of analyses for missions on the SMD roadmap. Such missions may include the use of multiple propulsion technologies in combination. New analytical capabilities will be required to find the "sweet spot" for the balance of propulsion between high thrust, low thrust, and aeroassist capabilities on a single mission.

IV. Summary

The NASA In-Space Propulsion Technology Project in the Science Mission Directorate has a plan to guide the future investments in electric propulsion technologies, and advance the application of EP technologies nearing maturity. The systems analysis plan seeks to provide an understanding of the requirements for a EP technology in the SMD roadmap of missions so that development can be focused and relevant to the NASA customer. Additionally, the systems analysis plan seeks to provide an understanding of electric propulsion capabilities and potential benefits, as well as limitations, to missions considering the application of EP. The plan is being implemented in 2007, and includes activities over several years.

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[1] Oh, D. Y., "Evaluation of Solar Electric Propulsion Technologies for Discovery Class Missions," AIAA-2005-4270, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, AZ, July 2005.

[2] Oh, D., Benson, S., Witzberger, K., and Cupples, M., "Deep Space Mission Applications for NEXT: NASA's Evolutionary Xenon Thruster," 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 11-14, 2004.

[3] Dankanich, J. W., and Polsgrove, T., "Mission Benefits of Gridded Ion and Hall Thruster Hybrid Propulsion Systems," AIAA-2006-5162, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, CA, July 9-12, 2006.

[4] Witzberger, K. E., "Solar Electric Propulsion for Primitive Body Science Missions," JANNAF Conference, December 2005. [I am not sure if you want to refer to JANNAF papers at an international conference, since most folks can't get them.]

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[10] http://www.inspacepropulsion.com/LTTT/