

STRATEGIC TECHNOLOGIES FOR DEEP SPACE TRANSPORT

Ronald J. Litchford*

Deep space transportation capability for science and exploration is fundamentally limited by available propulsion technologies. Traditional chemical systems are performance plateaued and require enormous Initial Mass in Low Earth Orbit (IMLEO) whereas solar electric propulsion systems are power limited and unable to execute rapid transits. Nuclear based propulsion and alternative energetic methods, on the other hand, represent potential avenues, perhaps the only viable avenues, to high specific power space transport evincing reduced trip time, reduced IMLEO, and expanded deep space reach. Here, key deep space transport mission capability objectives are reviewed in relation to STMD technology portfolio needs, and the advanced propulsion technology solution landscape is examined including open questions, technical challenges, and developmental prospects. Options for potential future investment across the full compliment of STMD programs are presented based on an informed awareness of complimentary activities in industry, academia, OGAs, and NASA mission directorates.

INTRODUCTION

Growing interest in deep space science and exploration has given rise to a plethora of highly ambitious mission concepts that stretch the limits of established technological capability, including human missions to Mars and asteroids; outer planet rendezvous, penetrators, and landers; and interstellar probes. Particularly troublesome is the lack of highly energetic propulsion systems that can rapidly convey spacecraft across vast interplanetary distances with modest usage of propellant. The distance scales can be staggeringly large, as exemplified in the deep space cartograph shown in Figure 1. Missions to the outer planets, for instance, are measured in multiple 10's of AU with the edge of the heliosphere extending well beyond 100 AU. The immense difficulty and expense of deep-space-class missions can be appreciated from a perusal of Figure 2, which summarizes the major heritage missions of note. Only a small number of deep space missions have been successfully mounted and executed, and of these, only a select few operational spacecraft have broached the outer realms of the heliosphere. Most notable are the iconic Voyager-1 and Voyager-2 spacecraft launched in 1977 and the New Horizons spacecraft launched in 2006. Voyager-1, humankind's first interstellar probe, is the farthest out after 38+ years of travel, whereas New Horizons recently accomplished a close flyby of Pluto in July of 2015 and is on course to encounter Kuiper Belt Object (KBO) 2014 MU69 in 2019. The reach of human spaceflight has been more constrained, primarily due to extensive mission mass requirements and associated launch costs, but also due to the severe detrimental effects of long duration space radiation exposure on human health. Because the added dead mass for adequate crew shielding is prohibitively

* Principal Technologist, Space Technology Mission Directorate, NASA HQ, 300 E St. SW, Washington DC 20546.

DEEP SPACE TRANSPORT CHALLENGES & CAPABILITIES

Put simply, state-of-art space transportation capabilities for deep space penetration are fundamentally constrained by available propulsion technology. That is, the specific energy (Isp) and specific power (α) characteristics of traditional space propulsion systems are simply too low to effect dramatic improvements in mission capability, as may be inferred from Figure 3 depicting the sensitivity of round trip time to propulsion system performance capability for a range of solar system destinations. A broad survey of the propulsion technology landscape, as shown in Figure 4, clearly indicates that the range of available demonstrated propulsion system solutions is inadequate to the task whereas those that offer true potential are technologically immature and in many cases yet unproven.

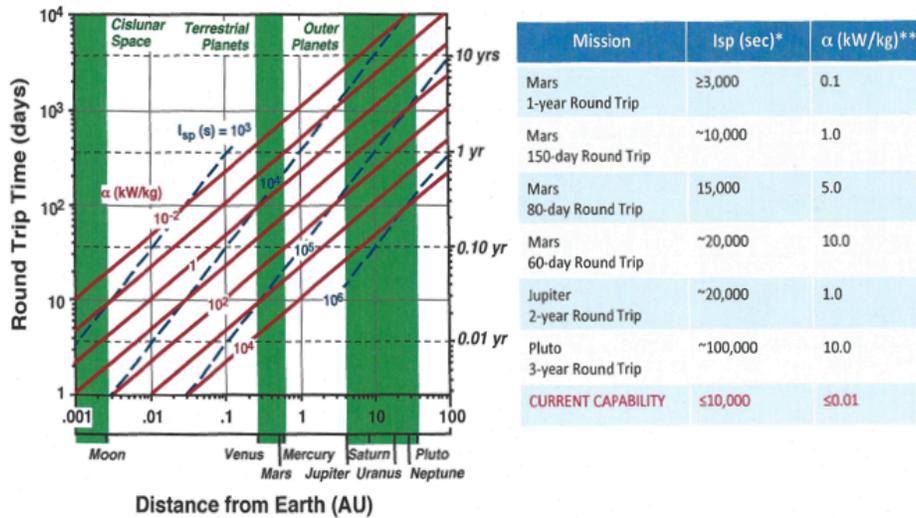


Figure 3. Sensitivity of round trip times to propulsion system performance capability.

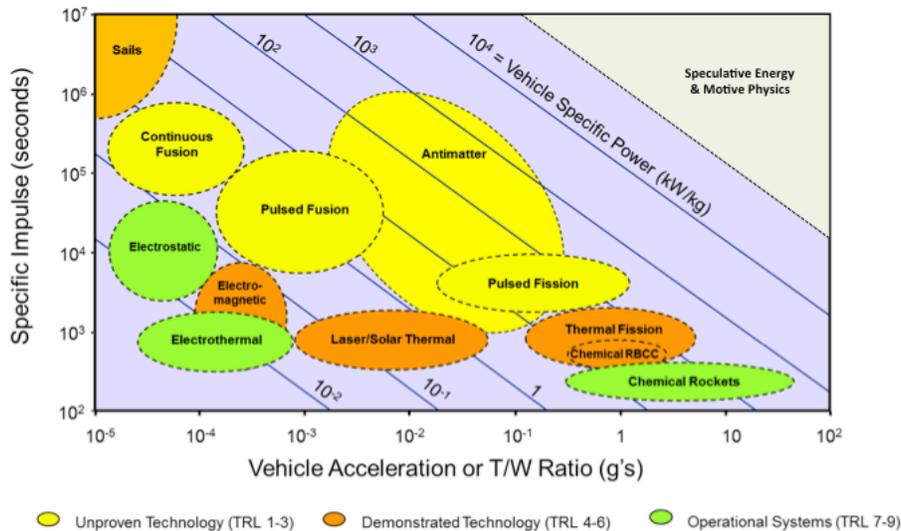


Figure 4. Survey of advanced energetic propulsion landscape.

DEEP SPACE TRANSPORT CHALLENGES & CAPABILITIES

The energy content of chemical fuels, for instance, has reached its natural plateau beyond which only marginal improvements can be expected, and this fundamental limitation places severe constraints on the amount of payload that can be delivered for a given vehicle size. Moreover, the low thrust-to-weight ratio and high specific mass characteristics associated with available low-power electric propulsion invariably yields excessively long interplanetary trip times. There is, therefore, a broad technical gap between the presently available level of space propulsion system performance and the level that will ultimately be required to fulfill future deep space mission needs.

To address this shortcoming, there is a need for basic & applied research focused on advanced energetic processes and concepts to enable the emergence of high specific energy/power propulsion and power systems. The broad scope of coverage should include advanced chemical propulsion emphasizing high energy density propellants and advanced engine cycles; advanced high-power electric/plasma thrusters and associated high-temperature technologies, electromagnetics, and flight-weight magnetic systems; utilization of nuclear based energy sources emphasizing high-temperature fission thermal propulsion methods, low-specific-mass fission space power plants, and fusion propulsion; and advanced energetic processes emphasizing off-board resources, beamed power, and ultra energy storage. As a hedge, the proposed program of research should also contain a modest level of activity aimed at leveraging new scientific discoveries and fundamental physics breakthroughs with revolutionary relevance to space transportation.

ADVANCED PROPULSION TECHNOLOGY DEVELOPMENT STRATEGY

For optimal outcome, it is recommended that the future development of advanced propulsion capability proceed along parallel technology development pathways, one near-term path for proven but immature technologies (TRL \geq 3) based on proven processes and a second far-term path for unproven but high capability concepts (TRL $<$ 3) that could completely revolutionize mission possibilities.

The near-term pathway would ideally have a four-prong emphasis: (1) advanced chemical propulsion, (2) electric/plasma propulsion, (3) nuclear thermal propulsion, and (4) hybrid nuclear thermal/electric propulsion. The fundamental concepts and outcome objectives are summarized in Figure 5. The key technology focal points are as follows:

- Advanced Chemical Propulsion
 - Long-term cryogenic propellant storage and handling
 - In Situ Resource Utilization (ISRU)
- Robust High Power/Isp Thrusters
 - Advanced Hall/Ion thrusters
 - MPD thrusters
 - Plasma & Pulse Inductive thrusters
- Nuclear Thermal Propulsion
 - High-performance high-temperature reactor fuels
 - Affordable & regulatory compliant nuclear engine system testing
- Dual Mode Reactor Propulsion & Power Systems

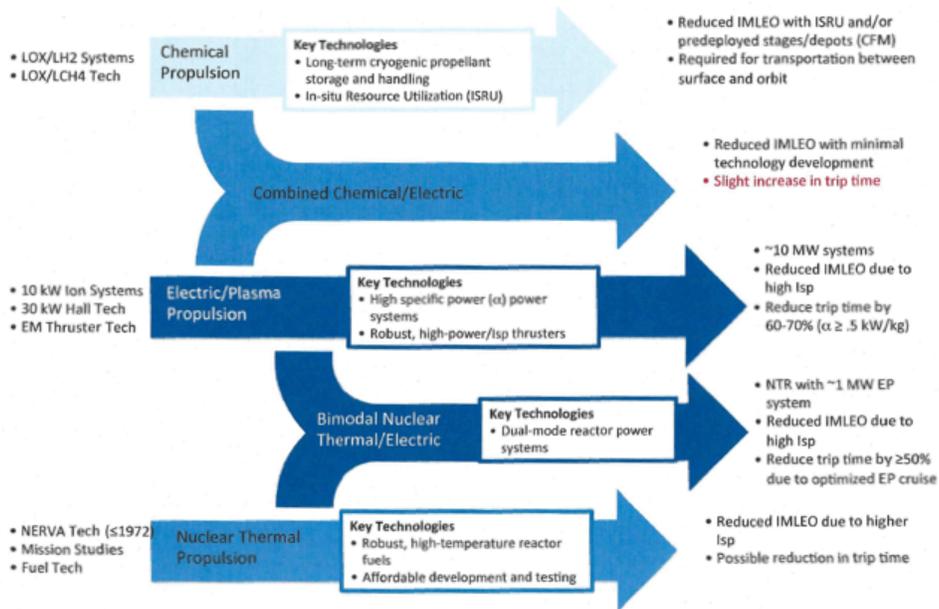


Figure 5. Near-term advanced propulsion strategy overview.

The far-term pathway would ideally concentrate on sustained R&D for advanced energetic concepts and processes that could create the basis for revolutionary propulsion systems capability. These fundamental technologies are largely unproven and uncharacterized and inherently high-risk investments. Moreover, they require a sustained focus on proof-of-principle demonstrations that can be complex, costly, require long learning curves, and inherently prone to high failure rates. Consequently, there has been a strong aversion to these types of far-term investments. Nevertheless, these far reaching technology pathways represent our best hope for overcoming fundamental limits and are deserving of modest continuing investigations where progress cannot be predicted. The fundamental components of a combined near/far-term technology development strategy are summarized in Figure 6. The key technology focal points are as follows:

- Advanced Low-Specific-Mass Nuclear Electric Propulsion
 - Advanced nuclear brayton/rankine powerplants
 - Advanced power conversion subsystems
 - Advanced high-temperature radiator and heat rejection subsystems
- Advanced Fission Thermal Propulsion
 - Enhanced solid core & gas core configurations
 - Fission fragment configurations
 - Nuclear pulse fission configurations
- Fusion Propulsion
 - Fission-driven-fusion configurations
 - Pure continuous & pulsed fusion

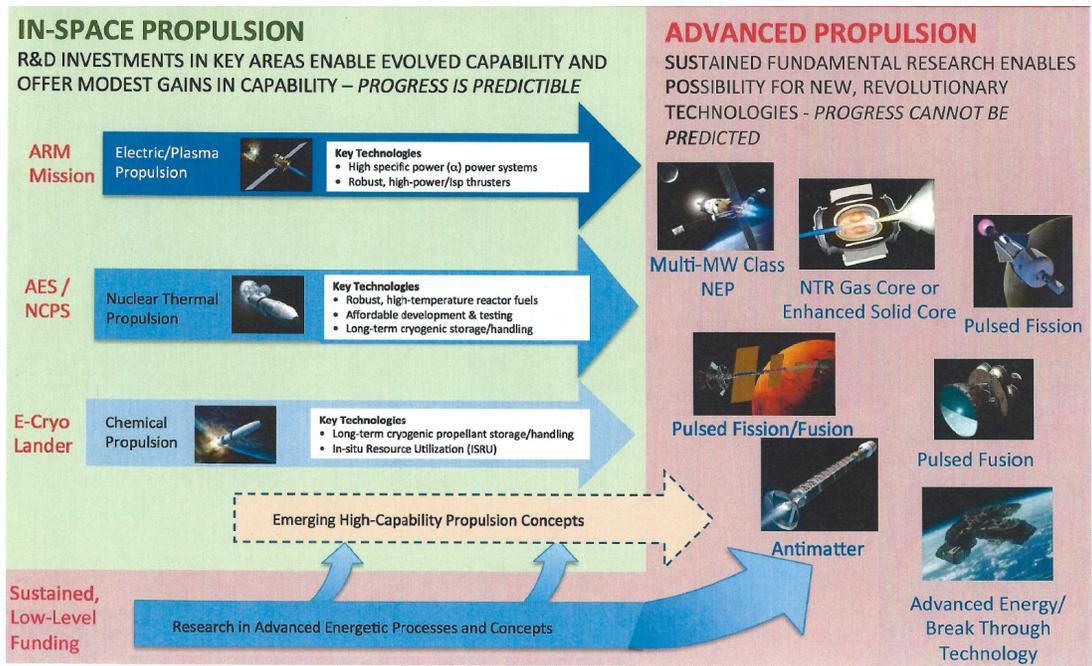


Figure 6. Combined near/far-term propulsion technology development strategy.

NASA’s Space Technology Mission Directorate (STMD) is charged with developing critical space technologies in support of the agency’s future science and exploration mission goals. These investments span the technology maturation spectrum from emerging concept to flight demonstration (TRL 1-8), and are implemented via a consistent structure of interconnected programs as illustrated in the diagram of Figure 7. This figure depicts the TRL investment range focus for each major program resulting in a double hourglass transition and infusion model. Agile spiral development practices are adopted with consistent inter-program handoffs, as shown in Figure 8.

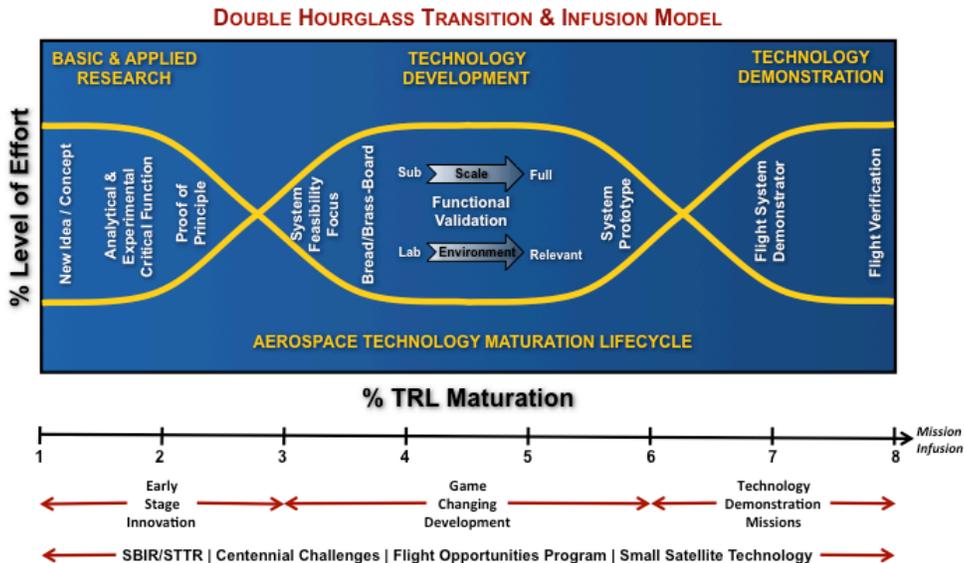


Figure 7. NASA STMD strategic cross-program technology development structure.

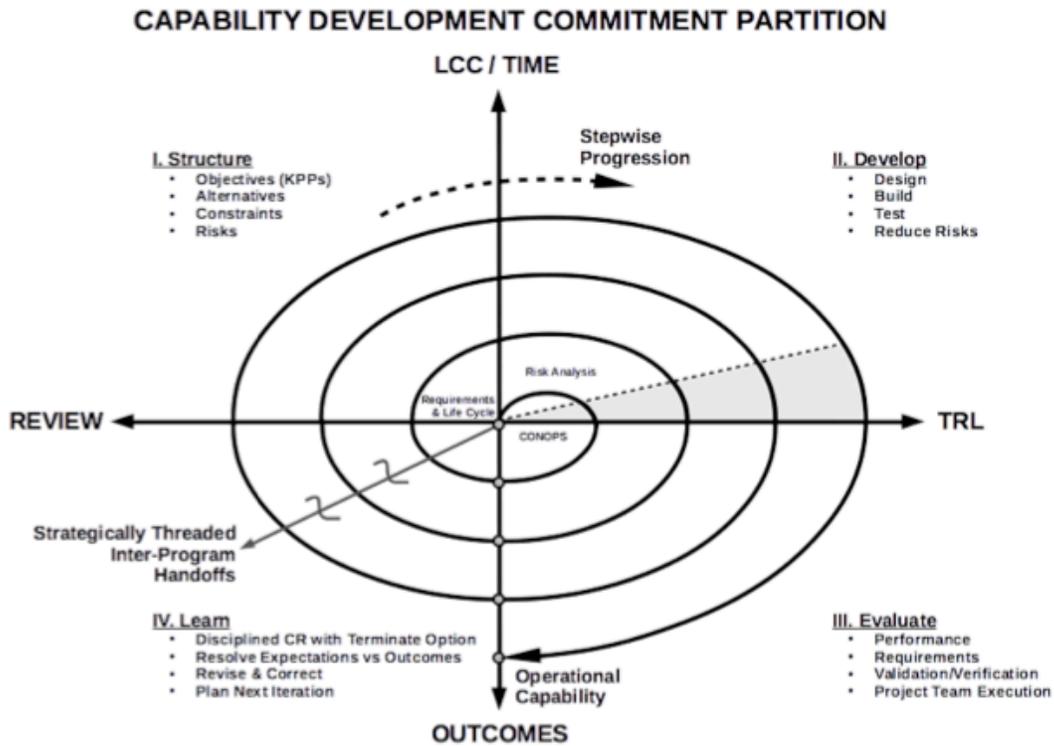


Figure 8. Agile spiral technology development practices.

CONCLUSION

The development of strategic technology maturation and investment plans by STMD follows a formal process rooted in capability development recommendations formulated and structured by the directorate's Principal Technologists. These capability recommendations are thoroughly vetted by STMD senior management and program executives and ultimately approved and published as guidance to the space technology community. The baseline scope for these capability development plans is a 5 year technology development outlook with a 5-25 year mission outlook. Current future capability recommendations under consideration include a strategy for developing affordable nuclear propulsion and advanced energetics for rapid deep space transport. Approval and release of a formal investment plan is anticipated to occur during the spring of 2016.

ACKNOWLEDGMENTS

The ideas and concepts presented in this paper are largely the outcome of many years of spirited advocacy, passionate discussion, occasional disagreement, but always collegial and professional respect between a number of key contributors including George Schmidt, Harold Gerrish, Michael Lapointe, James Gilland, Ioannis Mikellides, and John Cole. As in all genuine collaborations, the original source of particular ideas is often lost as they become inextricably threaded into a common shared perspective. To these colleagues, I express my sincere thanks and deep appreciation for their invaluable contributions.