HUMAN EXPLORATION OF THE SOLAR SYSTEM BY 2100

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It has been suggested that the U.S., in concert with private entities and international partners, set itself on a course to accomplish human exploration of the solar system by the end of this century. This is a strikingly bold vision intended to revitalize the aspirations of HSF in service to the security, economic, and scientific interests of the nation. Solar system distance and time scales impose severe requirements on crewed space transportation systems, however, and fully realizing all objectives in support of this goal will require a multi-decade commitment employing radically advanced technologies – most prominently, space habitats capable of sustaining and protecting life in harsh radiation environments under zero gravity conditions and in-space propulsion technologies capable of rapid deep space transits with earth return, the subject of this paper. While near term mission destinations such as the moon and Mars can be accomplished with chemical propulsion and/or high power SEP, fundamental capability constraints render these traditional systems ineffective for solar system wide exploration. 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, very long term HSF objectives for solar system wide exploration are examined in relation to the advanced propulsion technology solution landscape including foundational science, technical/engineering challenges, and developmental prospects.

INTRODUCTION

Exploration of the solar system to date has relied exclusively on robotic systems following a logical sequence of mission modes with increasing degree of difficulty. Initial flyby reconnaissance is followed by rendezvous encounters involving orbiters, probes, and landers, which sets the stage for intensive in situ study with roving laboratories and sample return. What is widely desired but yet to occur is the final step of in situ human exploration. Presently, all major planets have been the subject of flyby reconnaissance missions and orbiters have been successfully delivered to Mercury, Venus, Mars, Jupiter, and Saturn as well as our moon and a handful of minor bodies and comets (i.e., Eros, Vesta, Ceres, and Churyumov-Gerasimenko). Probes, impactors, and landers have reached the surface of Mercury, Venus, Mars, Jupiter, the Titan moon of Saturn, the asteroids Eros and Itokawa, and the comets Tempel and Churyumov-Gerasimenko. Over the next two decades, intensive in situ exploration will likely remain focused on Mars and the moon with human landings and colonization as an ultimate objective. It is envisioned that human in situ exploration would

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continue expanding in range leading to capstone human mission to the outer reaches of the solar system by the turn of the century.

The distance scales associated with the wide range of destinations, as illustrated in the solar system cartograph of Figure 1, are staggeringly large. 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. For most robotic missions, extended mission operations are an inconvenient but acceptable cost trade, for crewed missions however, unconstrained flight times are unacceptable due to the deleterious effects of space radiation and lack of gravity on human health. Such considerations impose hard limits on mission duration and the inferred requirements for rapid deep space transit exceed the performance capability of available propulsion technologies.

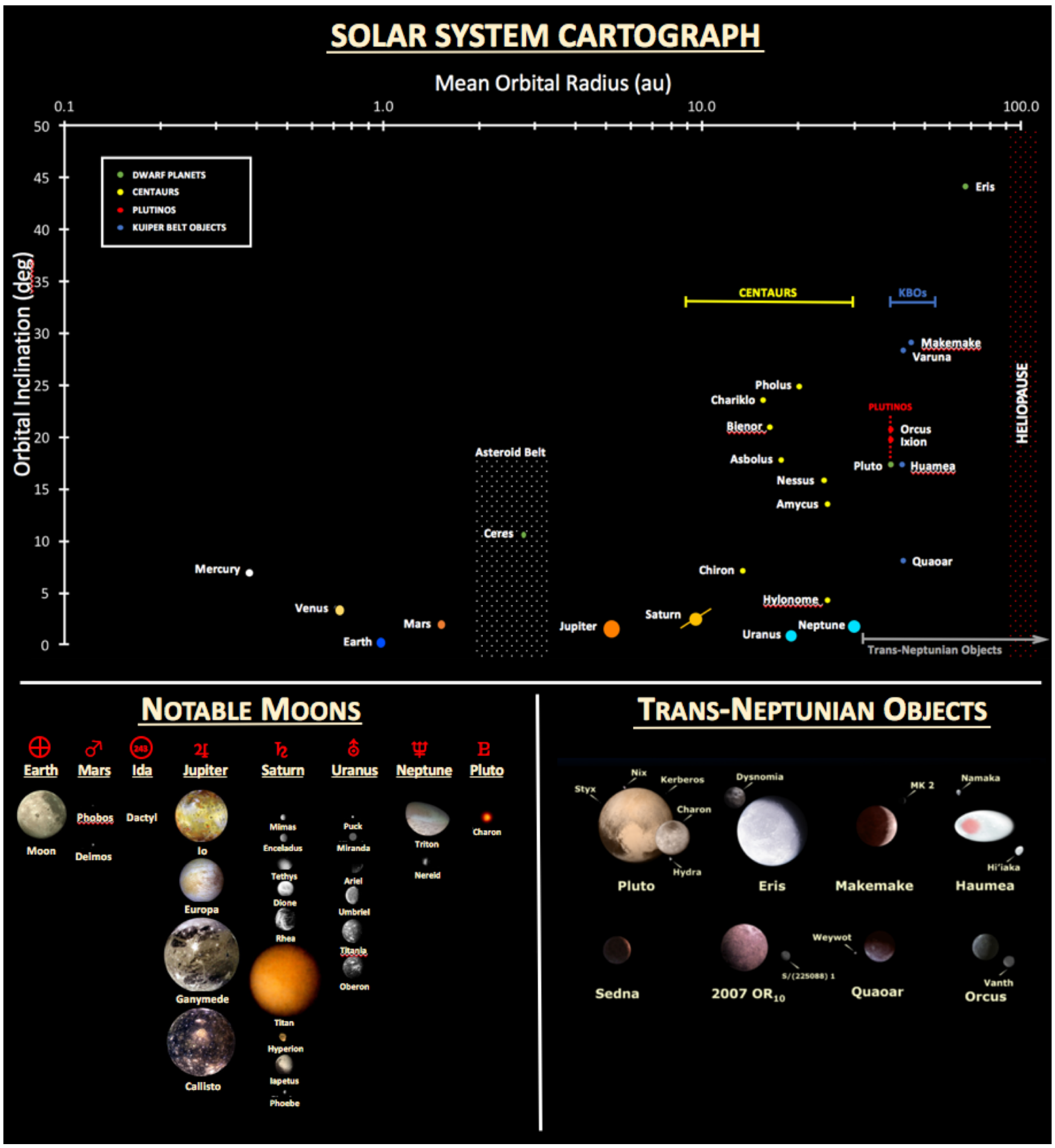


Figure 1. Cartograph of the heliosphere and interstellar medium.

From a destination perspective, current propulsion capability is sufficient for human exploration of the inner solar system, albeit there are unique environmental challenges associated with Mercury and Venus. Crewed missions beyond Mars, however, require new types of highly energetic propulsion that can rapidly convey spacecraft across vast interplanetary distances with modest usage of propellant. Over the years, a plethora of advanced energetic propulsion technologies have been suggested, studied, and investigated. Unfortunately, cost-trades with respect to near-term inner solar system mission utilization were never favorable and sustained research and technology investments never materialized. As a result, advanced in-space propulsion development has been rudimentary at best, with the exception of solid core nuclear thermal propulsion, which has progressed episodically under various program initiatives.

The focus here is on identifying long term propulsion technology needs for enabling human in situ exploration of the entire solar system by the end of the century. This is explored within the context of outer planet mission scenarios including the giant planetary systems Jupiter and Saturn and the icy giant systems Uranus and Neptune. Operational mission durations are constrained based on an examination of long duration space environment impacts on human health, and representative missions are analyzed to extract baseline quantifiable propulsion capability metrics. Long term Human Space Flight (HSF) objectives for solar system wide exploration are thereby examined in relation to the advanced propulsion technology landscape including foundational science, technical/engineering challenges, and developmental prospects.

DEEP SPACE TRANSPORT CHALLENGES & CAPABILITIES

The two fundamental sources of space radiation are Solar Energetic Particles (SEPs) emitted by periodic solar surface eruptions and near continuous Galactic Cosmic Rays (GCRs) originating from outside the heliosphere. SEPs occur as unpredictable proton showers that, if sufficiently intense, can be lethal. Fortunately, typical proton energies are low enough to permit effective shielding solutions. High energy heavy ion GCRs, on the other hand, are a more serious concern as shielding capable of assuring safety over long durations requires an effective depth nearly equivalent to the Earth's atmosphere. The implied mass requirements for absolute GCR shielding are therefore impractical and it becomes necessary to trade exposure limits with mission duration.

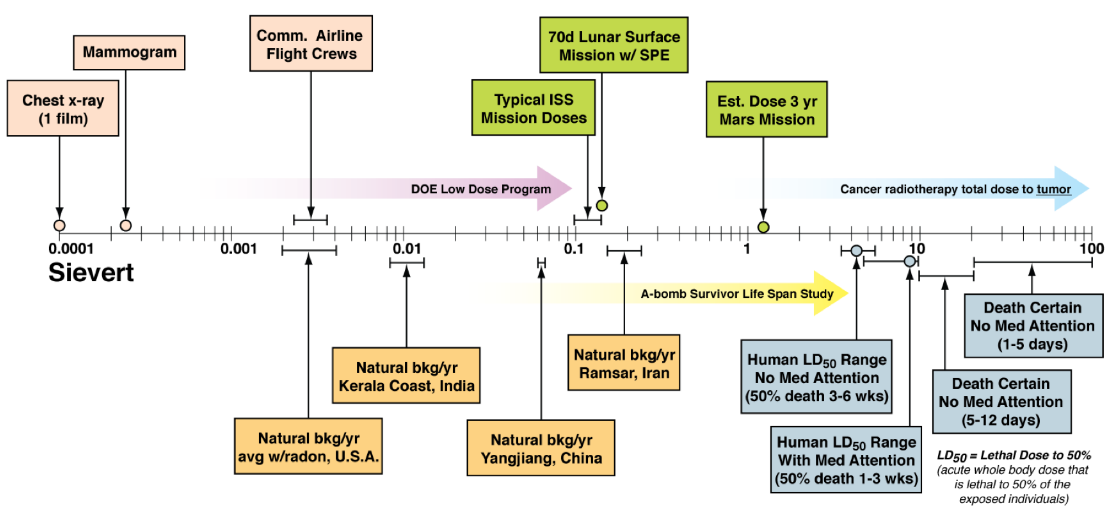
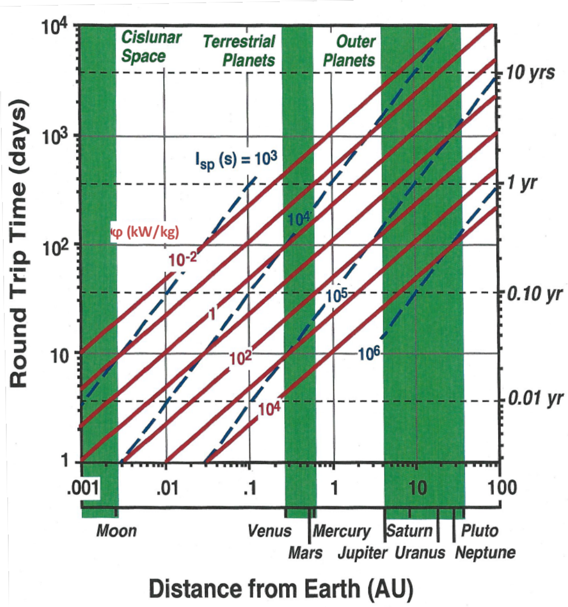


Figure 2. Spectrum of radiation dosage effects.

The biological effects of ionizing radiation are typically expressed in terms of derived Sievert units, which is equivalent to 100 REM. Figure 2 depicts the spectrum of radiation dosage effects in terms of Sieverts. Currently, middle aged astronauts are limited to 40 REM per year with a lifetime limit of 150 REM, which gradually extends to as much as 400 REM lifetime depending on age over 30. Older astronauts are allowed higher dosage as their normal life expectancy outpaces their risk for developing cancer. In consideration of GCR fluxes, not to mention the effects of prolonged zero gravity, piloted outer planet missions should be no more than 5 years in duration.

This top level constraint for roundtrip missions to the outer planets imposes very stringent performance requirements on the in-space transportation system. So stringent, in fact, that no conventional propulsion technology exhibits the requisite capabilities. Quite plainly, state-of-art space transportation for deep space penetration are fundamentally constrained by the specific energy, as reflected in Isp performance, and specific power (α) characteristics of traditional systems. The magnitude of difficulty is illustrated in Figure 3, which depicts the sensitivity of roundtrip time to propulsion system performance capability for a wide range of solar system destinations.



Mission	Isp (sec)	α (kg/kW)	φ (kW/kg)
Current Capability	≤ 10,000	≥ 50.0	≤ 0.02
Mars 1-year Roundtrip	≈ 3,000	10.0	0.1
Mars 150-day Roundtrip	≈ 10,000	1.0	1.0
Jupiter 5-year Roundtrip	≈ 9,000	20.0	0.05
Saturn 5-year Roundtrip	≈ 15,000	10.0	0.1
Uranus 5-year Roundtrip	≈ 20,000	1.0	1.0
Neptune 5-year Roundtrip	≈ 100,000	0.5	2.0

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

OUTER SOLAR SYSTEM MISSION CASE STUDIES

As a basis for understanding the scope of requirements associated with human in situ exploration of the outer solar system, we examine a set of mission case studies to the giant planetary systems Jupiter and Saturn and the icy giant systems Uranus and Neptune. Roundtrip in-space flight time is constrained to be no more than 4 years in all cases. Here, propulsion system performance is treated in a parametric fashion using fundamental capability metrics to capture technology independent transportation requirements. The resulting metrics can then be used as a basis for assessing and comparing a wide range of advanced propulsion technologies with respect to mission applicability.

Imposed mission parameters include the roundtrip flight duration, flyout time, and the flyout payload mass fraction, which includes the habitat, structures, propulsion system, and flyback propellant for Earth return. In each case, the flyout payload mass fraction was set at 20% assuming Earth escape speed as a starting condition (i.e., $C_3 = 0\ \mathrm{km}^2/\mathrm{s}^2$, which is the energy per mass of the spacecraft in excess of that required to reach escape speed). Imposed propulsion system parameters include total power and thrust efficiency. Other parameters are allowed to vary freely.

Flyout trajectory polar plots and velocity versus time profiles for all four mission cases are shown in Fig. 4. The spacecraft trajectory is depicted by the blue lines where the dotted midsections represent the coast phase. Note that the trajectories approach straight line transits with increasing heliocentric distance. This is a direct consequence of specifying a fixed flyout time, which drives the mission to minimize flight time at the expense of increased transfer energy requirements.

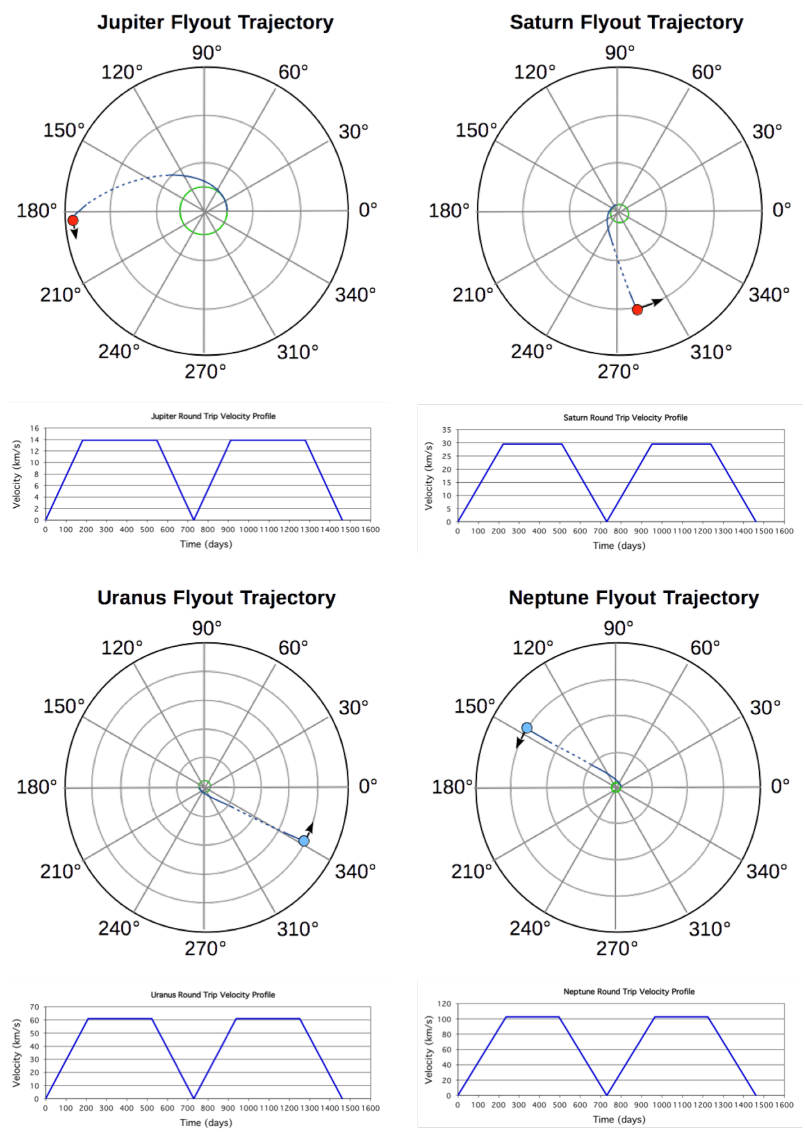


Figure 4. Outer planet flyout trajectories and mission velocity profiles.

Table 1. Mission case analysis summary for in situ human exploration of outer solar system.

Mission Data	Jupiter	Saturn	Uranus	Neptune
Heliocentric Distance (AU)	5.20	9.50	19.2	30.1
Round Trip Flight Duration (yrs)	4.0	4.0	4.0	4.0
Flyout Time (yrs)	2.0	2.0	2.0	2.0
Flyout Thrust Time (yrs)	1.0	1.2	1.1	1.3
Flyout Payload MF* (%)	20	20	20	20
Propulsion System Power (MW)	100	100	200	200
Thrust Efficiency (%)	80	80	80	80
C_3 (km^2/s^2)	0	0	0	0
Mission ΔV (km/s)	27.9	59.2	122.1	205.1
Mission Specific Energy (GJ/kg)	0.365	1.45	8.54	18.3
Thrust (N)	8734	4382	3619	2468
Isp (ksec)	1.87	3.72	9.02	13.22
Launch Mass (Mkg)	19.3	5.9	1.9	1.0
Launch Propellant MF (%)	93	93	93	93
Earth Return Payload MF (%)	2	2	2	2
$\alpha_{propulsion}$ (kg/kW)	3.47	1.05	0.163	0.090
$\phi_{propulsion}$ (kW/kg)	0.288	0.952	6.13	11.1

* Includes habitat, structures, propulsion system, and flyback propellant

Table 1 provides a detailed summary of the analysis results for all four outer solar system mission cases. The top half of the table defines the mission input data and the bottom half represents mission analysis results. Note that the Jupiter and Saturn missions assumed 100 MW of propulsion system power whereas Uranus and Neptune presumed 200 MW. In both cases, overall thrust efficiency was taken to be 80%. Isp and specific energy steadily increase with mission ΔV while thrust falls off due to the fixed power limit. Isp is near optimal but exact optimization was sacrificed to ensure an Earth return payload mass fraction of 2%. The total launch mass at Earth orbit departure is seen to decrease with increasing heliocentric distance and mission ΔV while launch propellant mass fraction was 93% in all cases. The key performance metrics of interest from a technological perspective are the propulsion system specific energy (GJ/kg), specific mass (kg/kW), and specific power (kW/kg). It is particularly noteworthy that the threshold values for accomplishing this ambitious mission set are far beyond what can be achieved using traditional chemical or solar electric propulsion technologies.

The energy content of chemical fuels, for instance, has reached a 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 along with the drastic fall off in solar energy availability with increasing heliocentric distance render it inapplicable for short duration outer solar system missions. 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.

A broad survey of the propulsion technology landscape, as shown in Figure 5, 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. Careful perusal of this performance map clearly indicates that in situ human exploration beyond Mars and into the outer solar system will require propulsion technologies relying on highly energetic nuclear processes.

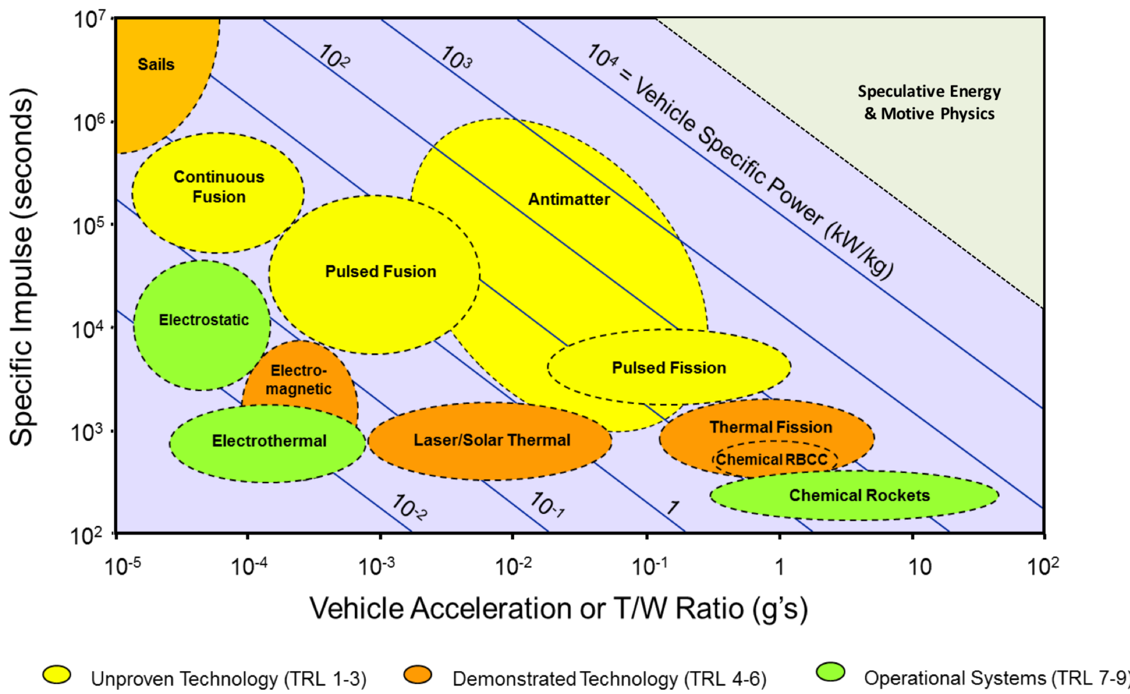


Figure 5. Survey of the propulsion technology landscape in terms of energetic capability.

ADVANCED PROPULSION TECHNOLOGY DEVELOPMENT STRATEGY

Given both near-term and far-term needs within the context of achieving human exploration of the solar system by 2100, a two prong research and development strategy is recommended. The first prong would be directed at maturing and fielding propulsion technologies to support lunar and Mars expeditions over the next 2 or 3 decades. The second prong, proceeding along a parallel research pathway over the same time frame, would aim to achieve proof-of-principle demonstration of advanced high capability propulsion technologies having the requisite specific energy and specific mass characteristics for supporting short duration outer solar system roundtrip missions. As the first prong technologies are developed and matured, investment in second prong technologies should be ramped up with the aim of fielding advanced systems by the middle of the century, which would set the stage for solar system wide exploration over a 50-year time span.

The broad scope of coverage should therefore 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 of level of activity aimed at leveraging new scientific discoveries and fundamental physics breakthroughs with revolutionary relevance to space transportation. A diversified propulsion capability vision is depicted in Figure 6.

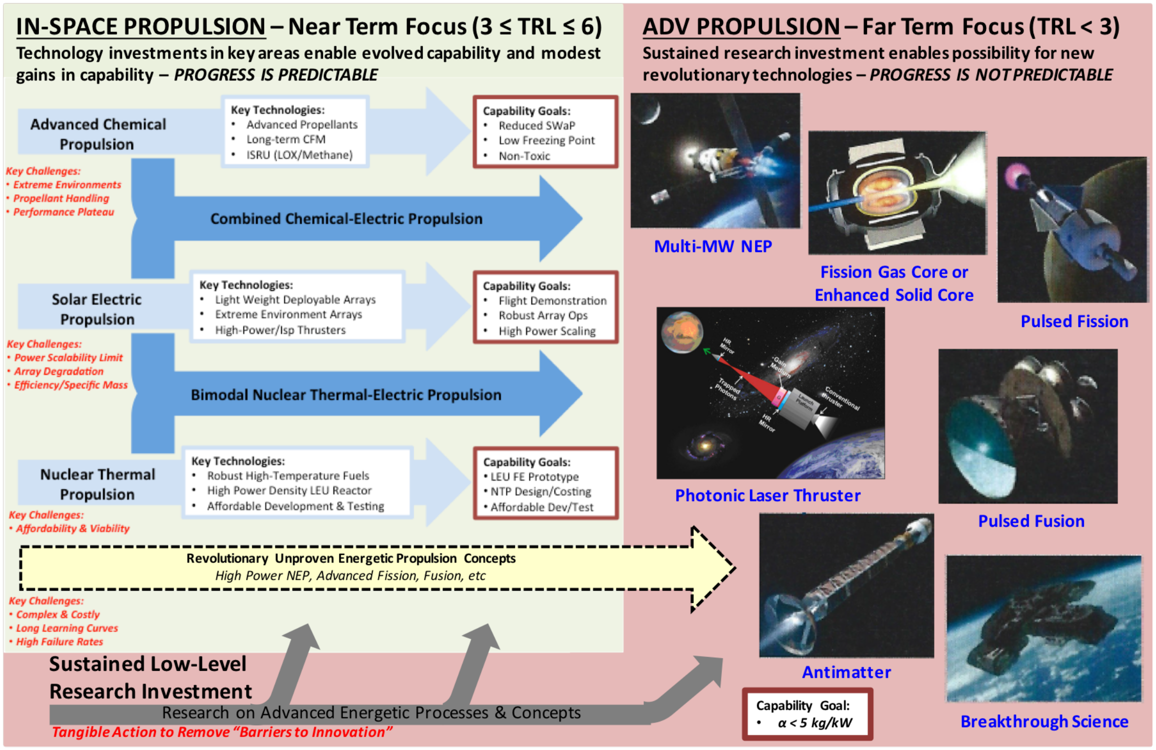


Figure 6. Diversified propulsion capability vision.

CONCLUSION

Human in situ exploration of the entire solar system is operationally constrained by mission duration due to space environment impacts on human health. The key technological limits are set by propulsion system specific mass and specific impulse. Examination of roundtrip outer planet mission case studies reveals a minimum specific impulse in excess of 10,000 secs with a propulsion system specific mass of no more than 0.1 kg/kW, which can only be achieved via advanced propulsion technologies relying on highly energetic nuclear processes. Enabling human exploration of solar system by the end of the century will therefore require a sustained and diversified research and development investment strategy aimed at revolutionary breakthrough propulsion capability. Human missions to the extreme reaches of the solar system represent an immense undertaking of enormous economic proportions and can only be accomplished through a dedicated multi-decade commitment involving public-private partnerships and international cooperation.