Breakthrough Propulsion Study

Assessing Interstellar Flight Challenges and Prospects

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First Year Report

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ABSTRACT

Progress toward developing an evaluation process for interstellar propulsion and power options is described. The goal is to contrast the challenges, mission choices, and emerging prospects for propulsion and power, to identify which prospects might be more advantageous and under what circumstances, and to identify which technology details might have greater impacts. Unlike prior studies, the infrastructure expenses and prospects for breakthrough advances are included. This first year's focus is on determining the key questions to enable the analysis. Accordingly, a work breakdown structure to organize the information and associated list of variables is offered. A flow diagram of the basic analysis is presented, as well as more detailed methods to convert the performance measures of disparate propulsion methods into common measures of energy, mass, time, and power. Other methods for equitable comparisons include evaluating the prospects under the same assumptions of payload, mission trajectory, and available energy. Missions are divided into three eras of readiness (precursors, era of infrastructure, and era of breakthroughs) as a first step before proceeding to include comparisons of technology advancement rates. Final evaluation "figures of merit" are offered. Preliminary lists of mission architectures and propulsion prospects are provided.

ACKNOWLEDGMENTS

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ACRONYMS

ACS	Attitude Control System	NIAC	NASA Innovative Advanced Concepts
AI	Artificial Intelligence	PMAD	Power Management and Distribution
BPP	Breakthrough Propulsion Physics	RF	Radio Frequency (Electromagnetic Waves)
C&DH	Control and Data Handling	RP-OM	Received Power – Onboard Reaction Mass
CY	Calendar Year	RP-XM	Received Power – External Reaction Mass
ESO	European Southern Observatory	RTG	Radioisotope Thermal Generator
FTL	Faster Than Light	SMTD	Space Mission Technology Directorate
GNC	Guidance Navigation and Control	SRL	Scientific Readiness Levels
IP-OM	Internal Power – Onboard Reaction Mass	TRL	Technology Readiness Levels
IP-XM	Internal Power – External Reaction Mass	TVIW	Tennessee Valley Interstellar Workshop
JBIS	Journal of the British Interplanetary Society	WBS	Work Breakdown Structure

1. EXECUTIVE SUMMARY

Dozens of interstellar mission concepts have been published that are based on known physics—and dozens more will be published in the future. All of the concepts require the maturation of one or more technologies or the building of infrastructure—or both. The US is not ready to launch a genuine interstellar mission, but is ready to start making investments to get ready to launch a mission within a few decades. The investment of limited resources will be required to get from where we are today to a future of interstellar travel. Careful selection of where to invest the resources is essential.

Choosing which concepts to fund requires the comparison of very different approaches. A challenge is to compare technologies as disparate as a fusion rocket and a ground-based laser pushing on a sail. In addition, not all of the proposed approaches to interstellar travel rely entirely on known physics. Champions of various technologies have a tendency to focus only on what is good about a given concept, sans implications for a complete system design. Therefore, an additional motivation for our metrics is to help identify "if it is real, would it also be useful?"

Many of the concepts of interest could revolutionize travel within the solar system, in addition to getting us closer to interstellar travel. Thus, investing in mission concepts that can both be employed usefully in near-term missions and be on the roadmap to future interstellar missions is of high interest.

This report derives figures of merit based on the physics of propulsion technologies and other mission factors. The metrics will allow policymakers to make decisions about which technologies would be more valuable, and to identify the subset of technologies that would do double-duty by enabling both longer-term interstellar missions and ambitious nearer-term missions.

At its foundation, these metrics rely on three core parameters: 1) how much energy will be expended, 2) how long does it take to perform a mission, and 3) distance traveled. It's like comparing modes of transportation: an airplane is faster than a car, but travel by car uses less energy and is therefore cheaper. Mission funding can compare the energy it will take versus a scientific objective (such as destination of interest) versus how long it will take to get the data.

1.1. At-a-glance highlights in this report

- Flowchart to guide a user in applying the assessment of a technology: Section 6.2, page 30.
- Sample data plots using the methodology with hypothetical technologies: Section 9, pages 60-61.

1.2. Content by Section

Section 2	reviews the background and objectives of this study.
Section 3	provides a technical background about interstellar travel.
Section 4	identifies problems of interest that will be needed to make interstellar travel attainable, such as propulsion, power, and data transmission.
Section 5	is a wide-ranging list of technological approaches identified from the literature for how to solve the problems—to be evaluated in Stage II.
Section 6	organizes the metrics into a work breakdown structure, and provides a flowchart to guide a user in applying the assessment of a technology.
Section 7	summarizes key mission choices and variables that must be defined in order to assess a mission approach—such as where is the mission going, how long will it take to get there, how much data will be returned, and type of mission: fly-by or orbiting.
Section 8	lays out the comparison metrics for how dissimilar mission concepts can be quantitatively compared in an equitable manner. The process defines four different propulsion types according to their source of power and reaction mass (internal or external). Each type requires different analyses, where their unique performance measures are converted into the more general measure of energy.

Section 9 shows examples of data charts based on the methods of Section 8. At this stage the comparisons are only with hypothetical propulsion technologies to test the methods and plotting options. These will be further refined in Stage II.

Section 10 discusses Stage II of this project.

Section 11 provides a list of references.

2. INTRODUCTION

Interstellar destinations are about three orders of magnitude farther away than can be reached using current technology. Many advanced propulsion concepts have been conceived, but their performance predictions are not yet certain enough to be ranked reliably using traditional trade studies. Further, the mission architectures in which these concepts were proposed used different assumptions that make equitable comparisons impossible.

There have been several overviews of the challenges and prospects of interstellar flight, most notably starting with the 1976 interstellar exploration program proposed to congress [1], the 1989 *Starflight Handbook* [2], the 1992 *Prospects for Interstellar Travel* [3], 2001 "Interstellar Flight Primer" [4], and the 2004 *Centauri Dreams* [5]. Among the large number of technical papers, several volumes of the *Journal of the British Interplanetary Society* were devoted to interstellar flight [6-8]. There has not, however, been an impartial, overall evaluation of the prospects and related next research steps.

There is a need for a new assessment method that can compare the uncertain, long-term prospects of emerging technology for interstellar flight. The assessment method must be able to equitably compare concepts that use entirely different propulsion methods (sails, rockets, and others). The comparisons should show which concepts might be the most advantageous and under what conditions, plus identify the most impactive supporting technologies. Further, given the long timescales of interstellar flight, the assessments should have provisions for considering advances that might reach fruition over decades of further advancement. And finally the assessments should suggest a prudent portfolio of next-step research.

2.1. Provocations

The impetus for this study dates back to a 2006 workshop held at Princeton University. As with prior interstellar sessions, various propulsion and mission concepts were presented as if to advocate their selection [9]. In the subsequent discussions, it was agreed that it was not possible to pick a winner. Each concept used different assumptions, plus the performance predictions are unproven. Rather than attempt far-future decisions, the discussion turned to identifying the most critical make-break questions for each approach, and of those, which can be affordably researched next. Pursuit of these questions shaped the goals and strategies of the nonprofit Tau Zero Foundation that was incorporated that same year [10].

Interest in interstellar flight is increasing. The continuing discovery of exoplanets, the announcements of privately funded mission plans, and the inkling that faster-than-light flight is now at least theoretically possible, provokes more interest. The following paragraphs describe some of the more significant provocations, in chronological order.

Theories for faster-than-light (FTL) flight are now part of the scientific literature. The first traversable wormhole article was published in 1988 [11], the first warp drive paper in 1994 [12], and the first scholarly book compiling these challenges along with other breakthrough propulsion pursuits was published in 2009 [13]. Even the hint that FTL might someday be possible, makes interstellar flight more attractive.

In 2014, the first potentially habitable Earth-size exoplanet (Kepler-186f, ≈ 500 ly) was confirmed by the Keck and Gemini Observatories. Now it is certain that potentially habitable planets exist, perhaps even Earth-like planets [14].

In April 2016, an ambitious plan for an interstellar mission was announced, with an offering of $100 Million for its initial research from Russian billionaire, Yuri Milner. The project, called "Breakthrough StarShot," is based on using a powerful laser array to push a small light-sail up to 20% lightspeed to reach Alpha Centauri within a 22 year flight time [15]. This project continues to receive significant media attention, further amplifying public interest in interstellar flight.

And in August of 2016, a potentially habitable exoplanet, Proxima b, was discovered orbiting our *nearest* neighboring star, Proxima Centauri, at only 4.2 ly distant [16]. Though subsequent analysis casts doubt that the planet could support human life, due to the intense radiation from its sun, the fact that our nearest neighboring star hosts an exoplanet that is roughly similar to Earth's size and temperature spurs further interest in the search for habitable worlds.

Congressional interest followed. An 18 May 2017 report for the fiscal 2017 Appropriations Committee included the following instructions: "The Committee encourages NASA to study and develop propulsion concepts that could enable an interstellar scientific probe with the capability of achieving a cruise velocity of 0.1c. These efforts shall be centered on enabling such a mission to Alpha Centauri, which can be launched by the one-hundredth anniversary, 2069, of the Apollo 11 moon landing." [17].

2.2. Objective and Approach

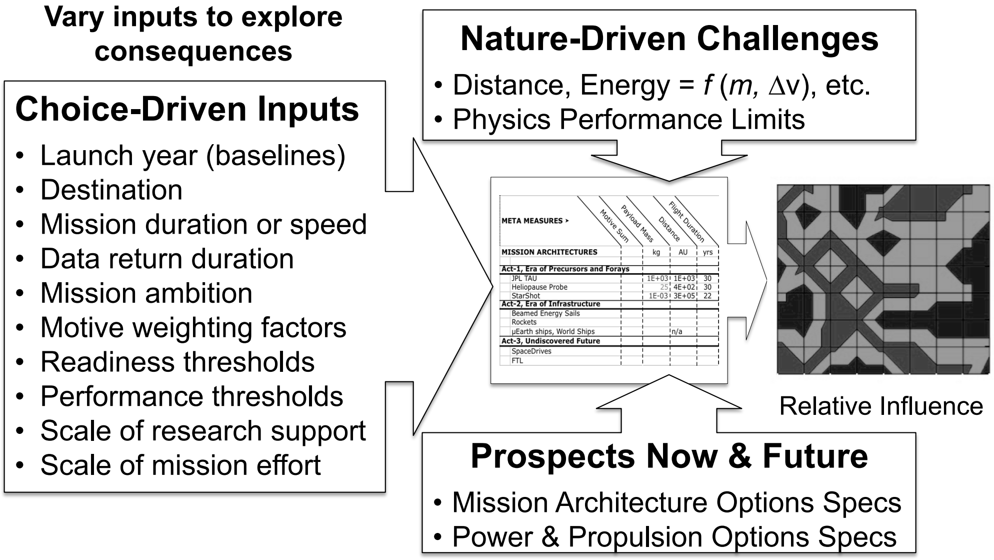
The objective of this study is to create a process for equitably comparing different mission architectures and possible propulsion and power technologies, in order to determine which research paths have the greatest leverage for improving NASA's ability to explore farther, faster, and with more flexibility. The specific goal of achieving 10% lightspeed was included by Congress, and it is likely that this goal will require the combination of a number of different technologies to succeed. The more exact questions that arise from further analysis are: which elements of that goal have more leverage toward success, and what knowledge gaps remain to solve each of those problems?

Toward that end, the process shall establish common performance measures for the disparate propulsion and power approaches, and accommodate the uncertainty in the performance predictions. The comparisons will include the scale of infrastructure needed to build and launch interstellar missions, include consideration of potentially disruptive advancements for spaceflight, and suggest how to plan a research program that systematically seeks the most desirable of such advancements.

In contrast to mission trade studies that seek the best technology to meet a set of well-defined requirements, this study will use *topological analyses*. Topological methods have been devised recently to compare general goals to broad technology areas to produce "topological maps" that identify research areas of potentially greater impact (instead of creating "road maps" to develop a specific technology) [18, 19]. These tools can determine the sensitivity of mission choices to performance requirements, as well as determining which technologies have greater impact on meeting those requirements (e.g. common elements of more than one subsystems). Figure 1 shows this analysis process in principle, and where the example maps are from Gilland [19].

In support of the general topological comparisons, more deterministic analyses are also developed. This includes the equations to convert the varied propulsion performance measures into common figures of merit.

Since the timescales for interstellar flight are comparable to historic examples of the emergence of breakthrough technologies, it is desired to include promising long-range research whose prospects are still speculative and whose mission impacts cannot yet be quantified. Presently, the practice is to wait until new prospects emerge on their own in a form ready to be evaluated per the familiar mission trade studies. However, this "wait and see" posture lets potentially revolutionary advances languish with little progress.



META MEASURES >	Motive Sum	Payload Mass	Distance	Flight Duration
MISSION ARCHITECTURES		kg	AU	yrs
Act-1, Era of Precursors and Forays				
JPL TAU		1E+03	1E+03	30
Heliopause Probe		25	4E+02	30
StarShot		1E-03	3E+05	22
Act-2, Era of Infrastructure				
Beamed Energy Sails				
Rockets				
μEarth ships, World Ships			n/a	
Act-3, Undiscovered Future				
SpaceDrives				
FTL				

Fig. 1a. Inputs to Determining Topological Maps

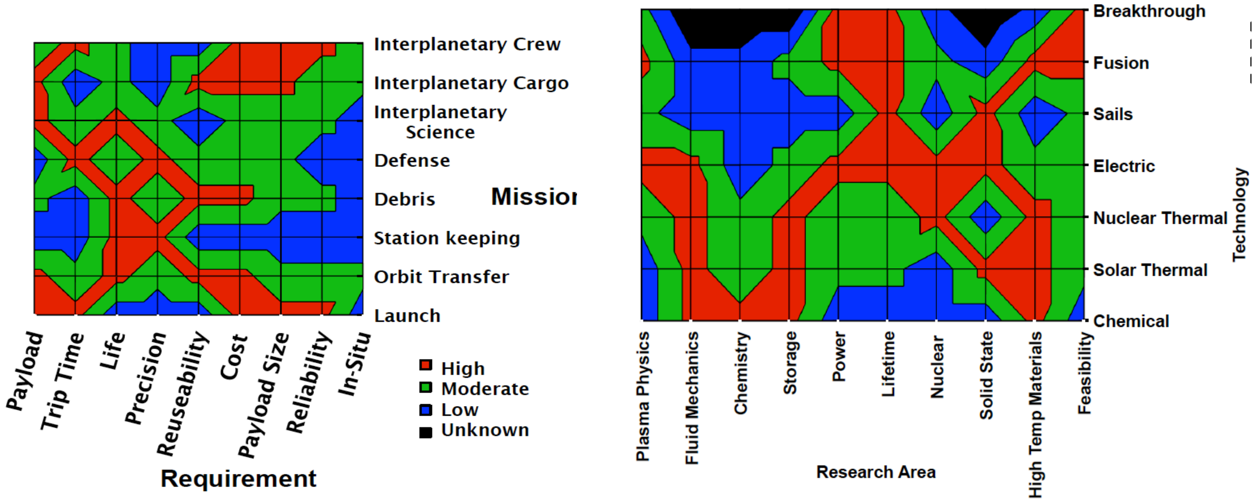


Fig. 1b. Example Map, Missions & Requirements **Fig. 1c. Example Map, Technologies & Research**

Fig. 1. Topological Assessment Process in Principle

To search for such latent prospects, this study will include the topic of breakthrough propulsion physics. The term "breakthrough propulsion physics (BPP)" comes from the NASA project by that name which examined non-rocket spacedrives, gravity control, and faster-than-light travel [20]. In contrast to technological advancements rooted in known physics, BPP pursues entirely new technologies from further advances in physics. The grounding reference for this portion of the study is the book, *Frontiers of Propulsion Science* [13].

The first step of the scientific method is to define the problem. Similarly, this study will begin with an assessment of the challenges and prospects in a manner suitable to the unique situation of interstellar flight. Sponsored by a multiyear NASA grant NXX17AE81G, this "Breakthrough Propulsion Study" is divided into three stages, 1) defining the problem, 2) collecting information, and then 3) analytical testing.

The scope of this report covers the first stage of this study: defining the problem of tracking, assessing, and planning the most effective research paths to reach the stars.

2.2.1. Stage I – Defining the Problem as a Work Breakdown Structure (WBS)

The challenges of interstellar flight and the technological prospects for answering those challenges are examined to determine how to proceed later with a fully-rigorous and impartial assessment. Or, in other words, this stage aims to ask the right questions.

2.2.1.1. Challenges – Top Down Mission Awareness

The prior goals from interstellar studies will be refined to encompass a more complete set of factors – in short to understand the whole problem before suggesting solutions. Recent investigations of interstellar prospects found: 1) mission motivations are often implicit and limited in scope, 2) vehicle concepts often neglect the interplay with the infrastructure needed to build, power, and launch the vehicle, and 3) the major impediments to interstellar flight are less about technological prowess than about limitations of energy, where it appears that roughly two centuries remain before sufficient energy is likely to be available to launch an interstellar mission, regardless of the choice of flight method [21]. Note, however, that the uncertainty bands of those estimates are substantial.

2.2.1.2. Prospects—Bottom Up Technological and Scientific Principles

A wide span of interstellar flight prospects, from the basic solar sail all the way to the speculative FTL flight will be included to 1) provide a cursory understanding of their projected performance, and 2) devise methods to convert their disparate performance measures into common terms. Though the options use a widely varying range of parameters to describe their performance, energy is chosen as the central measure for this commonality. In essence, energy is the fundamental currency of all motion.

With the participation of Tau Zero Personnel, the "Tennessee Valley Interstellar Workshop (TVIW)" was convened in October of 2017 to gain an up-to-date summary of the projections and status of interstellar flight options and issues, discussed in Section 5.4.

In this report, the combination of challenges and prospects are used to create a new WBS to collect the complex information in an organized manner. A set of variables corresponding to that WBS are defined to guide the information collection process of Stage II. This will be expanded to identify which operating parameters of the different propulsion and power methods will need to be collected to continue the analysis.

While the focus of this first stage is the development of the overall structure for the data to be subsequently collected in later phases, some values have been specified as starting estimates, for which more accurate and defensible numbers are sought. If readers have more accurate numbers for any of these values, please contact the authors with that information along with a reference citation for those more accurate values. Further, note that most values herein are specified to only about two significant digits—consistent with the current fidelity of interstellar flight estimates.

2.2.2. Stage II – Comprehensive Update to Interstellar Challenges & Prospects WBS

In Stage II, a web-based system will be created to allow subject matter experts from around the globe and from the span of relevant disciplines, to populate the WBS with their most recent data. Early drafts of technology development roadmaps will begin, with the intent to impose consistent methods of estimating the development durations.

The initial equations and analysis process will be refined, including running test cases with illustrative missions, payloads, and propulsion types. From there, the topological analysis methods will be adapted to this problem.

2.2.3. Stage III – Remaining Analysis and Recommendations

Stage III is where the analyses will be iteratively run and refined to ensure that it is meeting the needs of NASA and the interstellar flight community. The analyses should show which concepts might be the most advantageous, plus identify the most impactive supporting technologies. This includes identifying which knowledge gaps have the highest potential for improving the technology, and then how to solicit research to fill those gaps. This includes prospects for disruptive advancements and ancillary influences. And finally, the assessments will suggest a prudent portfolio of next-step research.

Once completed, technology roadmaps can be devised that are rooted in common standards to allow fair comparison of one roadmap to the other.

2.3. Outside Scope of Study

There are two activities related to interstellar flight whose assessments and recommendations are beyond the scope of study, "interstellar precursor missions," and "world ships."

Interstellar precursor missions are those that can be launched from Earth using foreseeable spacecraft technology and without needing substantial new infrastructure [22-33]. By "foreseeable technology" it is meant those technologies that are mature enough for mission trade studies. This study instead focuses on longer-term and farther-reach technologies whose performance measures are less certain. These precursor missions will, however, be used in this study as performance baselines and scaling examples. Further progress on precursor trade studies are a valuable aid to these longer-range interstellar flight assessments. An example of a precursor mission that would help resolve questions for future interstellar mission planning is the concept of a "**Look-Back Mission**." A look-back mission would test a suite of exoplanet instruments by looking back toward Earth at various distances to determine the effect of viewing distance and time on target for collecting meaningful information.

Another group of mission and technology concepts which are beyond the scope of this study are "world ships" – concepts for multi-generation, self-sustaining colonies of humans living aboard spacecraft headed toward potentially habitable exoplanets [34]. Even though such goals address the important motive of the sustained survival of humanity, they are out of scope since their major research goals involve sustainable habitats and cultures instead of propulsion.

3. PRIMER ON THE DISTINCTIONS OF INTERSTELLAR FLIGHT

Interstellar flight is far more challenging than any prior space mission. The distances, timescales, and energy levels of interstellar flight are beyond precedent. In colloquial terms, interstellar distances are so vast that they make lightspeed seem slow. This section offers a preview of these differences to set the context for the assessments that follow.

3.1. Distance

Voyager has traveled farther than any other spacecraft to date, yet it has traveled less than one-thenth of one percent of the distance to Proxima Centauri (142 AU by 2018, 0.053% of 270,000 AU). It took Voyager over four decades to reach that distance and would take another 80-thousand years to span the distance equal to reaching the Centauri stars (velocity ~ 0.00006 c). The farthest conceivable missions based on contemporary technology could only reach less than a half-percent of the way to Proxima Centauri in 50 years (1000 AU, 0.37% of 270,000 AU) [32].

In addition to the challenge of raw distance, there is the challenge of how much distance there is between interesting destinations. The logarithmic scales used in figure 2, and similar charts from other studies, can be misleading when trying to grasp the true scale of interstellar destinations. When plotted on logarithmic scales, it appears that destinations of interest are spread evenly. When listed linearly however, the vast gaps between points of interest become more apparent. If a chart encompassing the distance to our nearest star spanned the full height of this report's margins (270,000 AU ≈ 23 cm, 9"), then the maximum distance achievable within a 50 year flight time using existing technology would only barely distinguishable from the chart's origin (1000 AU ≈ 1 mm ≈ 1/32").

Table 1 lists interstellar destinations by distance along with other factors that come into play in later parts of this report. Note in particular the column "ESI," which stands for "Earth Similarity Index," from the "Planetary Habitability Laboratory" at the University of Puerto Rico at Arecibo. An ESI of 1.00 would be fully Earth-like. The other key destinations are as follows. The edge of our solar system can be defined as beyond around 200 AU. The next destination of interest past that point is 550 AU, where the gravitational lensing effect of our sun can be used to magnify images of whatever is on the opposite side of the sun [36]. It has been proposed that this solar gravitational lens has the magnification to be able to image an exoplanet with enough resolution to distinguish land features [37].

Beyond that point, the next targetable object is almost 500 times farther away, specifically the Centauri star systems (270,000 AU, 4.2 ly). In the vast void between those points of interest there exist only sparse densities of comets and asteroids; the Hills cloud (2,000 AU), Oort cloud (10,000 AU), and the G-cloud (41,000 AU) [38]. These features are difficult to discern using Earth-based astronomy, but probes passing through them could make direct in-situ measurements of the fields and particles.

Once past the Centauri systems, there are already eight potentially habitable planets detected within 41 ly, half of which are within 22 ly. Based on the astronomical data available before 2010, Claudio Maccone created statistical estimates for how far away the nearest Earth-like planet might be, and how far away the closest extraterrestrial civilizations might be. The distance estimates to the closest Earth-like planet span roughly 50 ly to 100 ly. The distance estimates to the nearest possible civilization are beyond 2000 ly [39]. Though these are rough statistical estimates, they at least help convey the scale of the challenge.

Another aspect of distance is time—how far can be reached within human timescales and the ultimate longevity of spacecraft. A common mission duration cited for interstellar concepts is 50 years, perhaps based on a long career span where the people who launched the mission will still be able to witness its findings. There has not been a study to assess the limits of human patience for interstellar missions.

There has also not been a study to estimate the longest possible operating duration for a space probe, yet 200 years is a fair starting estimate. Thus, even at lightspeed, the farthest a probe could reach into our galaxy is 200 ly.

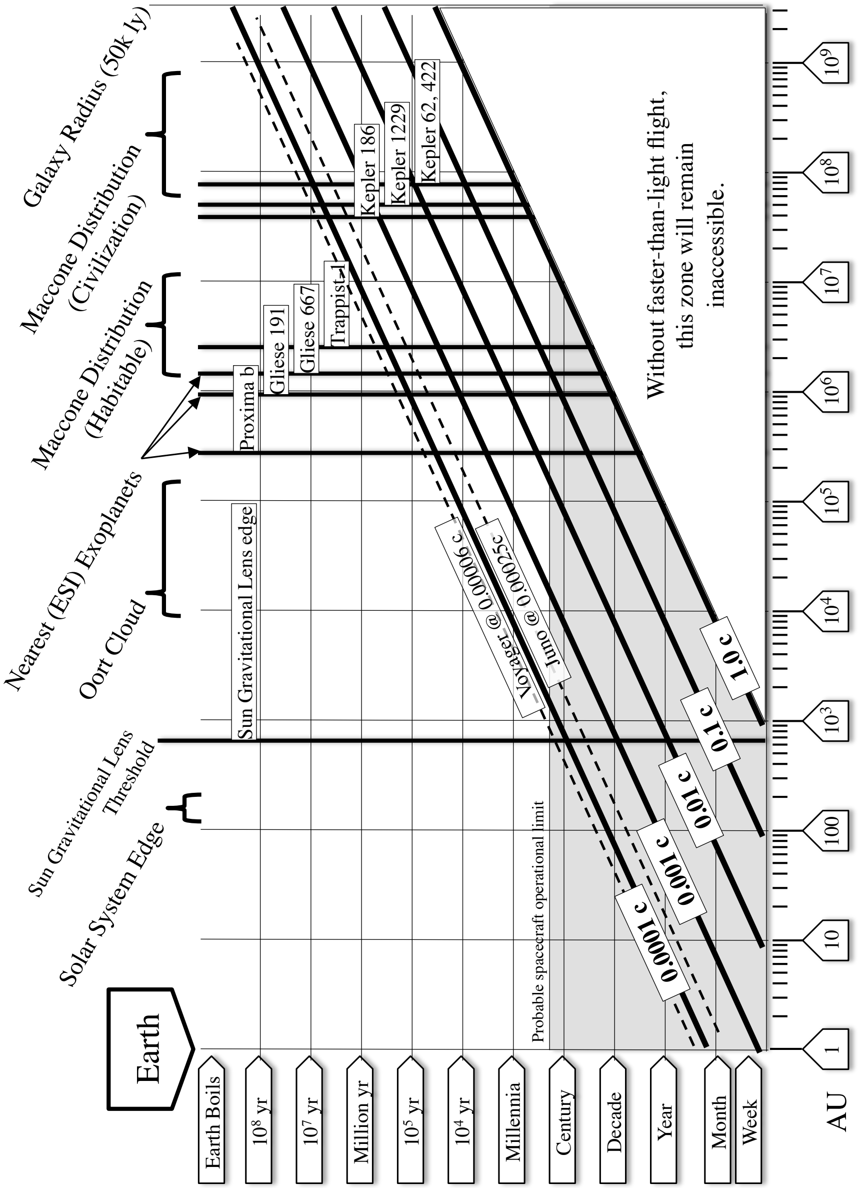


Fig. 2. Correlating Interstellar Distances with Human Timescales and Flight Speeds

Figure Caption: This figure shows the correlation between long timescales, interstellar distances, and average flight speed. Both the distance and timescales are logarithmic. The horizontal scale spans the radius of the Milky Way galaxy (50,000 ly), while the time scale extends all the way to the certain end of Earth's habitability (~1 billion years [35]). The assumed upper limit for the operational duration of a space probe (200 years) is shown. The diagonal lines represent different speeds, starting on the left with Voyager's 0.00006 c. The faster Juno spacecraft (0.00025 c) is also shown. The other diagonal lines are in terms of fractional lightspeed, shown in increasing factors of 10 all the way up to lightspeed. For each factor of 10 increase in speed, the required energy goes up by at least a factor of 100.

Table-1 Destinations of Interest, Including Potentially Habitable Exoplanets.

Destinations (*Dn*)	**Distance (Dd)**				**Interest Factors**			
	ly	**AU**	Extends		Level of Interest Score (Subjective). Values shown are starting points for discussion and resolution.			
	start	start	to	***ly***	**(*Di*)**	**Type**	**ESI***	**Description, Relevance**
μEarth Ships Placeholder					100%			Destination irrelevant "μEarth ship," "Colony Ship," "World Ship"
"Oumuamua" object	≈ 3 AU in 2017 +5AU/yr**				80%	?		Interstellar Asteroid: long aspect ratio object through solar system ≈5 AU/yr
Kuiper Belt	0.0005	30	55	0.001	5%	In Solar System		Origin of most short period comets. 100,000 icy objects > 100 km diam.
Eris	0.001	38	98	0.002	10%			Dwarf planet
Sedna	0.001	76	1,000	0.016	10%			Dwarf planet
Heliopause	0.002	120			5%	Interstellar Medium		Transition from our solar system toward the galactic background
Voyager Spacecraft	0.002	140			50%			Historical artifact, long duration exposure evidence
Interstellar "wind"	0.003	200			5%			Fully outside our solar system
Planet Nine (?)	0.004	280	1120		10%			Hypothesized, farthest planet of our solar system
Solar grav' lens start	0.009	550			80%	? Exo Image		Maccone 1998
Solar grav' lens nominal	0.010	650			80%			Turyshev 2017, TVIW
	0.016	**1,000**				Interstellar Medium		Milestone, 1000 AU (TAU)
Hills Cloud (Torus) (?)	0.032	2,000	20,000	0.316	5%			
VLIM	0.033	2,063		0.000	5%			Very Local Interstellar Medium [McNutt 2016]
LISM	0.047	3,000	20,000	0.316	5%			Local Interstellar Medium [McNutt 2016]
Oort Cloud **sphere** (?)	0.16	10,000	200,000	3.163	15%			Far enough to compare parallax to Hubble red-shift distance (basic physics)
G-Cloud ??	0.60	3.8E+04	0.7 ly		5%			Next transition into local interstellar medium ?
	1.0	**6.3E+04**						Milestone, 1 light-year
	1.6	**1.0E+05**						Milestone, 100,000 AU
Proxima Centauri	4.2	2.7E+05			90%	Nearest Exoplanets	.85 b	Closest hab-cat exoplanet. Red-Dwarf (M5.5V), 1 planet in HabZone (b)
Alpha Centauri A & B	**4.3**	**2.7E+05**			85%			A is like our Sun; B is spectral type K2, Maybe 2 planets around B
Barnard's Star	6.0	3.8E+05			70%			Project Daedalus target. Low-mass red dwarf No exoplanets confirmed.
	7.9	**5.0E+05**						Milestone, 500,000 AU
	10.0	**6.3E+05**						Milestone, 10 light-years
Epsilon Eridani	10.5	6.6E+05			80%			K2 star, similar planetary system to a young Sun. Unconfirmed exoplanet (b)
Procyon	11.5	7.2E+05			10%			Binary system with white dwarf star
Tau Ceti	12.0	7.6E+05			80%			Closest lone star similar to sun Unconfirmed 2 of 5 planets in HabZone (e, f)
GJ 273	12.4	7.8E+05			80%			M3.5 star. 1 of 2 planets in HabZone (b)
Gliese 191 (Kapteyn b)	13.0	8.2E+05			**85%**		.67 b	M1.0 star. 1 of 2 planets in HabZone (b)
Wolf 1061	13.8	8.7E+05			80%			M3.5 star. 1 of 3 planets in HabZone (c)
Gliese 687	14.7	9.3E+05			80%			M3V star. 1 of 1 planets in HabZone
Gliese 876	15.3	9.7E+05			80%			M4V star. 2 of 4 planets in HabZone (b,c)
	15.8	**1.0E+06**						Milestone, 1-Million AU
Observable Biomarker?	16.0	1.0E+06			N/A			Predicted 2030 astronomy biomarker detection range [51]
GJ 682	16.6	1.0E+06			80%			M3.5V star. 1 of 2 planets in HabZone (b)
HD 20794, 82 G Eridani	19.8	1.3E+06			80%			G8V star. 1 of 3 planets in HabZone (d)
Gliese 581	20.3	1.3E+06			80%			M2.5V star. 1 of 5 planets in HabZone (g)
Gliese 832	21.0	1.3E+06			80%			M1.5 star. 1 of 2 planets in HabZone (c)
Gliese 667	22.0	1.4E+06			**95%**		.84 Cc	M1.5 V (3-star system). 4 of 7 in HabZone (.84 Cc, .77Cf, .60 Ce) 3-ESI's
GJ 1132	39.3	2.5E+06			90%	Habitable?		M3.5 star. 1 of 1 planets in HabZone (b)
Trappist-I	39.5	2.5E+06			**95%**		.85 e	M8V star. 3 of 7 planets in HabZone ? (.85 e, .68 f, .58 g) MULTIPLE
LHS 1140	40.7	2.6E+06			**95%**		.68 b	M4.5 star. 1 of 1 planets in HabZone (b)
Nearest hab exoplanet?	70.0	4.4E+06						Highest probable distance of nearest habitable planet [Maccone 2010]
	100	**6.3E+06**						Milestone, 100 light-years
K2-72	227	1.4E+07						
Kepler 186	561	3.5E+07			95%		.61 f	First discovered potentially "Earth-like" exoplanet
Kepler 1229	770	4.9E+07			100%		.73 b	
	1000	**6.3E+07**				Inhabited?		Milestone, 1000 light-years
Kepler 442	1115	7.1E+07			100%		.84 b	
Kepler 62	1200	7.6E+07			100%		.67 f	
ET Civilization?	2000	1.3E+08			100%			Probable distance of nearest extraterrestrial civilization [Maccone 2010]
To Center of Galaxy	25000	2E+09						

* ESI = Earth Similarity Index: http://phl.upr.edu/projects/habitable-exoplanets-catalog/results

** In comparison, Voyager is ≈ 3.5 AU/yr, and Juno ≈ 15.5 AU/yr

Yellow refers to distance numeric milestones

3.2. Timescales

A mission takes longer than just the time to reach its destination. There is also the time-of-flight for the return signals to reach Earth, and the time it takes to finish transmitting the data. This last duration, transmit time, is not trivial. For example, at the extremely low power levels envisioned for the Breakthrough StarShot mission, it has been estimated that it will take 20 years to transmit the data [40]. Hence, the total mission duration for Breakthrough StarShot is roughly 46 years (22 yr trip, 4 yr signal delay, 20 yr transmit time).

For this study, "Total Mission Duration," Tm, is defined as the sum of the "trip time," Tt, to reach the destination, the "signal time," Ts, for the data to begin to reach Earth, and the "transmit time," Tx, to send the acquired data. Figure 3 shows a comparison between the projected timescales for precursor missions, the StarShot mission, and the mission suggested in the 2016 congressional language [17].

The timescales of some historic technological breakthroughs are shown for comparison on figure 3. For example it took only six decades from the discovery of natural radioactivity to having a nuclear power plant on the electrical grid (1890-1950). It took a little over two decades from the creation of the rocket equation to the first liquid rocket, and another four decades before humans walked on the moon (1903-1926-1969). Another fitting example is the 1-century between the steam power era, when Jules Verne wrote his fictional depiction of a Moon mission (1865) and the first actual lunar landing (1969). If scientists and engineers of the steam era were contemplating Moon missions, would they have debated which steam cycle to use, or perhaps even considered Verne's cannons? What was missing at that time was the undiscovered future of electrical power, liquid rockets, and nuclear power. What is next in our undiscovered future?

Since the timescale for revolutionary technological developments are comparable to interstellar mission durations, the potential impact of future advancements are considered as part of this study. While it is not possible to predict the future with certainty, the historic patterns of technological revolutions can be used as guides for this study [41].

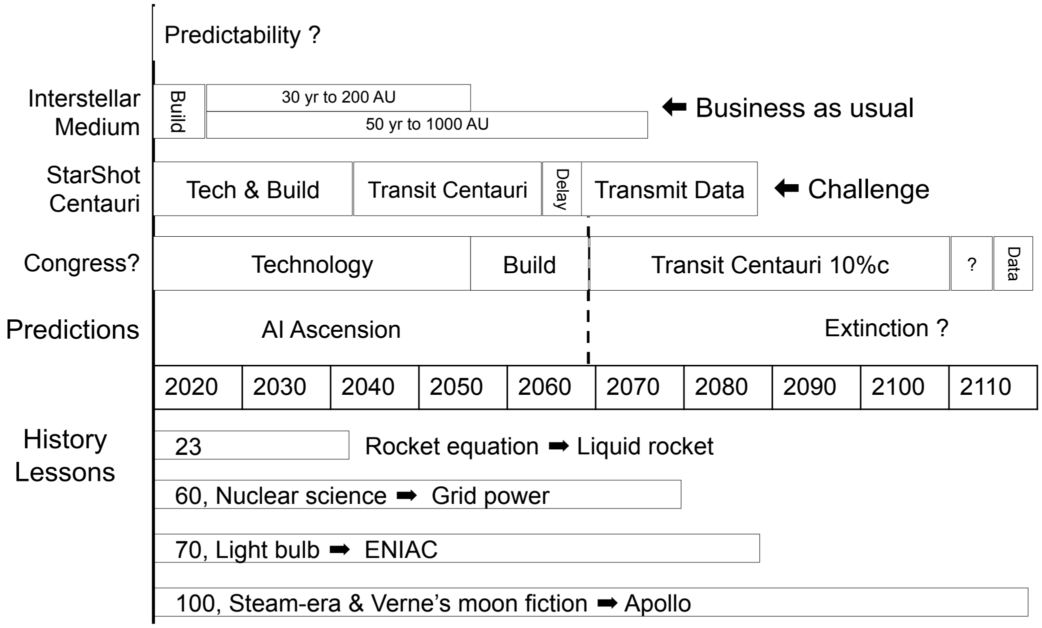


Fig. 3. Timescale of Interstellar Missions and Historic Technology Advances

There will also be unpredicted impacts from ancillary advances, such as from Artificial Intelligence (AI). Predictions of when AI will eclipse the capacity of the human mind (measured in "operations per second") span from 2030 to 2050 [42]. Speculating, will the AI advancements solve the challenge of fully-autonomous probe operation? Will AI processors become able to more quickly (and impartially) devise and test "grand unification" theories—perhaps resolving the unknowns of new propulsion physics? Either of these would be a significant, positive impact. If such desired functionality is pursued, it will at least offer a more optimistic path for when AI eclipses human abilities.

Another ancillary advancement that might impact the priorities behind interstellar flight is transhumanism, which means the continued merging of technology into the human body to enhance performance. Transhumanism has fewer scholarly articles from which to extract predictions and implications, yet it is already happening. Examples include dental fillings, eye glasses, hearing aids, pacemakers, replaced joints, cochlear implants, etc. Will this expand to making humans able to tolerate indefinite periods at low gravity, or able to enter synthetic hibernation to endure long space voyages? While only crude speculations at this time, the potential impact to watch for is a shift in priorities from probes to human journeys.

As much as continuing advances in science and technology will make it easier to launch an interstellar mission, these advances also create a quandary, the "**Incessant Obsolescence Postulate**"—no matter when an interstellar probe is launched, a subsequent probe will reach the destination sooner and with more modern equipment. This is only a postulate, not a theorem nor even a principle. It is presented here not as an immutable constraint, but as one of the assumed impediments for pursuing interstellar missions.

> As an aside, the term, Incessant Obsolescence Postulate, was first coined by the author around 1999 [5 p.157]. This same notion has been called "catch me if you can" [43], the "incentive trap," by Andrew Kennedy [44] and "Zeno's paradox in reverse," by David Brin (a term possibly originating during the 1994 workshop; "Interstellar Robotic Probes–Are we ready?" [43])

Although this Incessant Obsolescence Postulate might appear valid, it will eventually expire. Due to the combination of the nonlinear nature of both advancement trends and relativistic spaceflight, there will be a point where an optimum launch opportunity occurs [44,45]. Waiting longer does not get you to the destination sooner. Kennedy dubbed his optimization calculation the "wait equation" [44]. Approximately when missions begin to take less than a generation (20-30 years), there is no need to wait longer [45]. Conversely, when mission times are much longer, then investing in technology to improve mission time is a credible strategy.

In addition to the eventual expiration of incessant obsolescence, the most significant factor that renders it irrelevant is if the motive is something other than being first, such as technology development.

3.3. Energy

Trip time is a function of propulsion energy and payload mass. Higher speeds or greater spacecraft mass demand more energy. Following the kinetic energy equation ($KE = \frac{1}{2}mv^2$) as the lowest bound on required energy (where propellant mass and inefficiencies are ignored), doubling the spacecraft mass at least doubles the required propulsive energy. Doubling the velocity at least quadruples the required propulsive energy, since energy goes as the square of the velocity. Note, relativistic effects do not become significant (> 1.0%) until past 14% lightspeed.

One of the largest impediments to starflight is the gap between the energy required for propulsion and the energy available, regardless of the choice of propulsion. Calculations that compared the rate of humanity's growing energy prowess to the energy required for propulsion suggest that perhaps two centuries remain before sufficient energy is likely to be available [21]. This estimate took into consideration that only a portion of total world energy would be allocated for space missions. By comparing the Space Shuttle launch history to the US energy capacity over the same years, an estimate for that allocation is found to be one-millionth. Granted, such a rough estimate could be off by an order of magnitude or two, which should be taken in consideration. Figure 4 shows that comparison from the 2010 paper (with revisions & corrections).

For an example of the magnitude of propulsion energy, consider the 1-gram StarShot spacecraft traveling at 20% lightspeed. Just its kinetic energy is approximately 2 TJ. When calculating the propulsive energy in terms of the laser power and beam duration, (100 GW for minutes) the required energy spans 18 to 66 TJ, for just one probe. The full suite of 1,000 probes would be 1,000 times that span. For comparison, the energy for that suite of 1,000 probes is roughly the same as 1-4 years of the energy consumption of New York City (NYC @ 500 MW).

If instead of a 1 g spacecraft, the kinetic energy is calculated using the mass of a Voyager type spacecraft (≈ 1,000 kg) traveling at 10% lightspeed, then the kinetic energy becomes 4.5×10^5 TJ. For comparison, this is about one-thousandth of the total world energy consumption in 2016 (5.5×10^8 TJ [46, 47]).

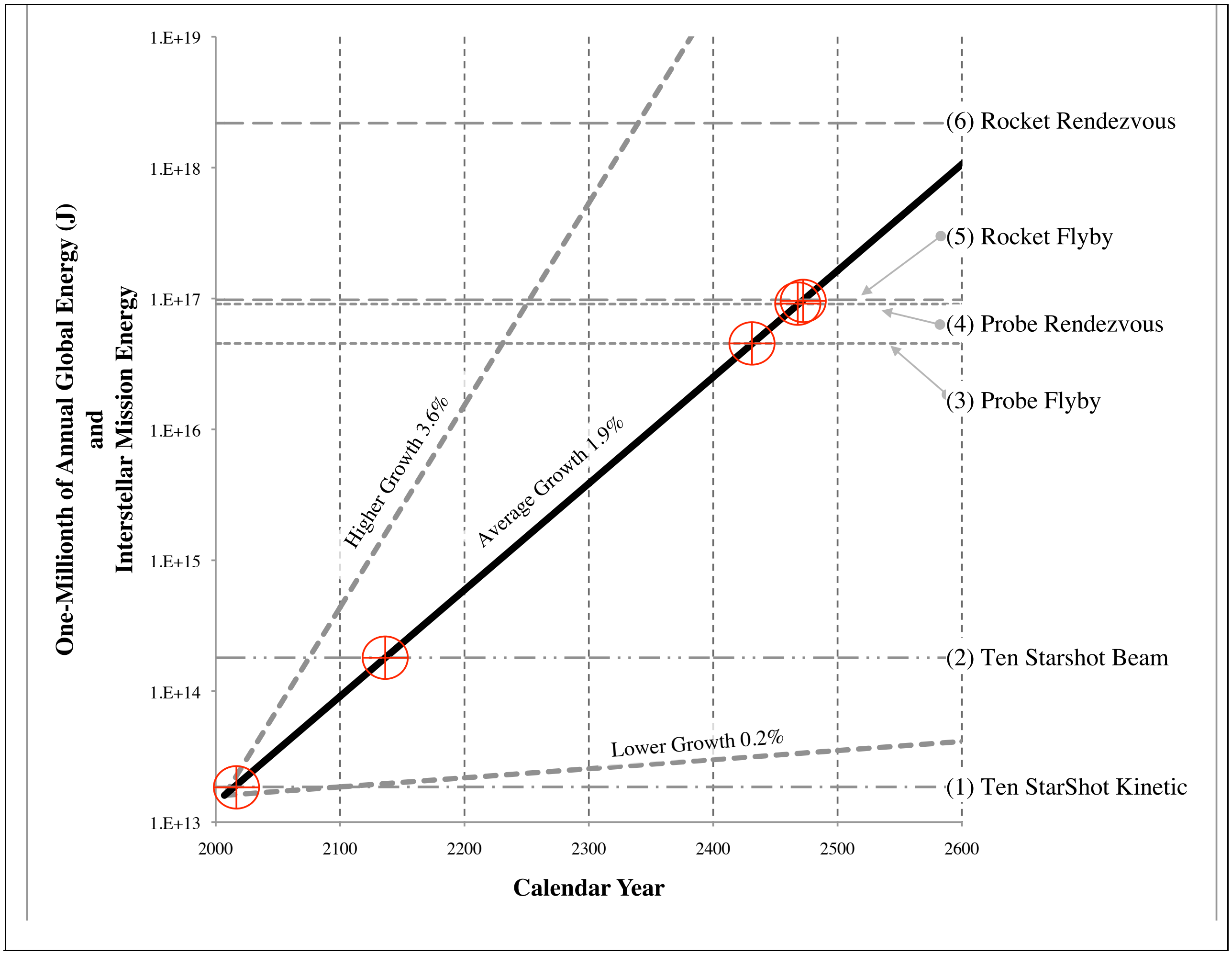


Fig. 4. Interstellar Mission Energy Versus Available Energy

Figure Caption: This chart compares the amount of energy likely to be made available for interstellar missions (one-millionth of total world energy) to the energy required for interstellar missions. The central diagonal line is the nominal energy growth from extrapolating data spanning 1980-2007. The upper and lower diagonal lines are ± one standard deviation of that data. The horizontal lines represent the energy requirements for the following missions:

1. Ten StarShot Probes (0.01 kg total) at 20% c – kinetic energy only (1.9×10^{13} J)
2. Ten StarShot Probes (0.01 kg total) at 20% c – energy beamed from lasers (1.8×10^{14} J)
3. Flyby Probe (100 kg) at 10% c – kinetic energy only (4.5×10^{16} J)
4. Rendezvous Probe (100 kg) 10% c – kinetic energy only (9.1×10^{16} J)
5. Flyby Rocket Probe (100 kg) at 10% c, with 10^6 sec Isp – rocket energy (eq. 1) (9.8×10^{16} J)
6. Rendezvous Rocket Probe (100 kg) at 10% c, with 10^6 sec Isp – rocket energy (eq. 1) (2.2×10^{18} J)

To estimate when the energy will be available for such missions, look at the calendar year beneath the intersection of that mission energy to predicted energy availability trend lines.

3.4. Infrastructure Dependence

Interstellar precursor missions that are based on existing technology do not need new infrastructure, but anything beyond that will. For example, even the 1 g StarShot probe will require the construction of a 100 GW laser array, estimated to span 1 km^2, and require one million 100 kW lasers.

While the StarShot infrastructure is considered to be built on Earth, other interstellar concepts envision using future in-space infrastructure. For example, the laser lightsail concepts of Robert Forward required a 26 TW laser, firing through a 1,000 km diameter Fresnel lens placed beyond Saturn (around 10 AU), aimed at a 1,000 km diameter sail with a mass of 800 MT [48]. The Project Daedalus study envisioned needing 50,000 MT of Helium 3 mined from the atmospheres of the gas giant planets [49]. This not only requires the infrastructure for mining those propellants, but also processing and transporting that propellant to the assembly area of the spacecraft.

Thus, it is an inescapable requirement that missions beyond the era of precursors will need substantial infrastructure. Section 8.3 describes how the infrastructure growth will be predicted and methods to compare the interstellar dependence of planned missions.

4. INTERSTELLAR TECHNOLOGY CHALLENGES (Top-Down)

Though the focus of this study is on propulsion technology, the payload challenges are also addressed because they significantly affect the propulsion requirements, and hence the ultimate success of an interstellar mission. The greater the payload mass, the more challenging the propulsion requirements, which ripples back through the rest of the systems needed to deliver that mass to the destinations.

The "top 10 challenges" of interstellar flight are listed below. These are not in priority order, since determining such priorities is what the study aims to determine later. Many of these are payload technologies:

- Communication*
- Navigation*
- Instrumentation to collect information at the destination that Earth-based astronomy cannot*
- High-density and long duration energy storage
- Long duration and autonomous spacecraft operation (plus survive cosmic radiation and dust impingement)
- Propulsion that can achieve 400 times greater ΔV than chemical rockets
- Energy production sufficient to enable that high-velocity propulsion
- High efficiency energy conversion
- Braking and maneuvering at destination
- Infrastructure creation in affordable increments

*For those marked with an asterisk, there is a possibility of shared technology elements. For example, could a telescope intended to study the destination also be used for optical communication? Could a dish used for navigation also be used for communication?

4.1. Payload Challenges

A typical starting point for planning a mission is determining the mass of the payload, since this significantly affects the propulsion and other system requirements. The payload mass is a combination of:

- Science instruments that acquire data at the destination
- Communication system to send that data back to Earth
- Power supply for that instrumentation, communication system, and rest of spacecraft system
- Attitude control system (ACS)
- Guidance navigation and control (GNC)
- Command and data handling (C&DH)
- Power management and distribution (PMAD)
- Excess heat radiators

The basic challenge is how to provide all those functions with the least amount of power, energy, and mass. While continued miniaturizations will improve the situation, some functions will have a finite lower limit (e.g. antenna size to match long wavelengths). Even with miniaturization, there will be some lower limit eventually reached (one molecule per pixel?).

Communication

The power and mass for the communication system are perhaps the most significant drivers for the payload, and the data rate is a significant driver of the communication system. The data rates are a function of the transmitter power and aperture. The power (and mass) requirement can be reduced by more efficient technology or by reducing the data transmission rate. Since reducing the data rate can add years to the total mission duration, this is a significant technical challenge (StarShot uses 20 years to transmit the data [40]).

Note: the concept of using a stream of smaller trailing spacecraft to relay signals at lower power is considered here as being part of the whole spacecraft system, instead of individual spacecraft. Part of the reason for this stance is that such a string of relay spacecraft would only be useful to the one mission ahead of it and inaccessible to any other missions sent in different directions.

To reduce the mass of the power supply, higher-density energy sources are required (J/kg, W/kg). This challenge should be pursued in concert with very long term energy storage. The power supply must still produce enough energy at the end of the mission for operating the science instruments and data transmission. As mentioned previously, interstellar missions will probably span a minimum of four decades when considering both the trip time and data transmission time. Batteries do not hold their charge for anywhere near that duration. Radioisotope thermal generators (RTGs), like those on Voyager, have demonstrated the ability to function for over four decades, but also have less power as time progresses due to their radioactive decay.

Navigation

Similarly to communication, any navigation equipment must also be as energy and mass efficient as possible. While one approach is to remove the navigation system altogether—for those approaches whose probes lack any propulsion to make course corrections—there will still be need for equipment to discern when the probe is nearing its destination and then aim the scientific instrumentation.

The navigation system will traverse roughly three orders of magnitude farther than all prior missions. To appreciate the scale of this challenge, consider aiming with an accuracy of 1 AU after traveling 270,000 times that distance. Emerging navigation techniques involve using x-ray pulsars [50].

Instrumentation

The challenge of the science instrumentation, in addition to the mass and power efficiencies already stated, is that they need to measure phenomena at the destination that will not be possible to measure by Earth-based astronomy, even after decades more of astronomy advancements. For example, from a lecture by M. Kasper of the European Southern Observatory (ESO), given at the Technical University of Dresden in the summer of 2017, it was predicted that by 2030, the ESO will be able to detect biomarkers as far out at 16 ly [51]. That calendar year is decades before StarShot reaches its destination and almost five decades sooner than StarShot will have finished transmitting its data.

The next challenge for the science instruments is that they need to be able to acquire their data at distances from the target that might be between 1 and 100 AU (depending on aiming, navigation and limited maneuvering propulsion) and at flyby speeds as high as 20% lightspeed.

Long Duration & Autonomous Operation

All those previously described functions must be able to be performed after decades of coasting at high velocity. This includes surviving the cosmic radiation and any high-velocity dust impacts.

The final challenge of the spacecraft is that it will be too far from Earth for routine back-forth communication. Even as close as 1000 AU, the round trip communication delay is about 12 days. Thus, the spacecraft operations will have to be entirely autonomous.

4.2. Propulsion & Power Challenges

Speed

To convey the challenge of reaching 10% lightspeed, consider the improvements between the 1977 Voyager and the 2011 Juno missions. In roughly three decades there was a four-fold increase in speed. At that rate, it would take another 130 years to reach 10% lightspeed. The gap between achieved speeds and the goal of 0.1c is a factor of 400 (Juno achieved 0.00025c). Hence, the technical challenge is to increase spacecraft ΔV by at least 400 times more than presently possible with chemical rockets.

Energy

The energy challenges of interstellar propulsion are two-fold. First there is the challenge of producing and controlling large amounts of energy, and second, to use that energy efficiently to minimize waste heat.

Under ideal circumstances and velocities below roughly 20% lightspeed, energy requirements scale linearly with spacecraft mass and are a squared function of spacecraft speed. Thus, for the Juno spacecraft, the additional energy needed to reach 10% lightspeed is at least 1600 times more than its Jupiter mission velocity. For rockets, the energy scales roughly as an exponential of speed, far in excess of a squared function (eq 1) [13, p 145].

$$E = \frac{1}{2} m \left(v_e \right)^2 \left(e^{\frac{\Delta v}{v_e}} - 1 \right) \qquad \text{Eq. 1}$$

Where

m = Mass of spacecraft without propellant (kg)

v_e = Exhaust velocity (m/s)

Δv = Change in velocity (m/s)

For laser sails, the low conversion efficiencies ramp up the energy requirements. Prior examples of interstellar propulsion energy spanned the low end of tera-joules to tens of thousands of tera-joules (Section 3.3).

Energy Efficiency

With those large amounts of energy, conversion efficiencies become a more critical issue. For example, even a 99% efficient energy conversion of 100 GW still produces 1 GW of waste energy that needs to be radiated. On Earth this is less of a challenge than in the vacuum of space. Radiating excess heat in space is more difficult and likely to become a significant portion of the whole system. In addition to improving efficiencies, the related technical challenge is to create more effective radiators, with lower specific mass (kg/W).

Braking at Destination

Another technical challenge is to find propulsion methods that can slow down at the destination. Virtually all prior interstellar mission concepts are envisioned as a flyby. The shorter the trip time, the shorter the time that the spacecraft will be in range of the target to acquire its mission data. For example at 20% lightspeed, a spacecraft would only be within ± 1 AU of the target for less than 90 minutes. Even relaxing that to only 1% lightspeed and a range of ± 2 AU, the spacecraft will only be in that range for 56 hours. (See table 8 in Section 7.2.1 for more examples.)

4.3. Incremental and Affordable Infrastructure Creation

Most interstellar mission concepts rely on substantial infrastructure in our solar system to build, power, and launch their vehicles. Further, many of those concepts also assume that this infrastructure is already there, ready to be used. Presently, there are no commonly accepted predictions of the rate of infrastructure growth to determine when the infrastructure will be ready to begin the construction of interstellar hardware. Estimating the growth of infrastructure is addressed in Section 8.3.2.

The infrastructure will be providing service to more than just the interstellar missions, so the system level consideration of that infrastructure is relevant. For example, could the same laser arrays envisioned for an interstellar mission be an integral part of the infrastructure—beaming power to remote segments of infrastructure? If so, then there is the need for system level trade studies at the infrastructure level.

What is seldom addressed, however, is how to begin the construction of that infrastructure. Many concepts for space solar power assume that one large investment will create a functional infrastructure as one project. Even though space solar power is usually conceived as sending the energy to Earth, it is analogous to the scale of energy needed for an in-space infrastructure. What is missing are concepts for building the in-space infrastructure in affordable increments. This challenge remains open.

5. PROPULSION & POWER PROSPECTS (Bottom-Up)

Dozens of concepts for interstellar flight have been conceived, and likely many more will follow. Within their system level mission concepts, there are key technologies that will have to be solved, and of those, many will need significant further research. The challenge that this project aims to solve, is how to determine which of those key technologies might have greater impact for overall success and under what circumstances. In some instances, a technology is unique to its mission utility (e.g., fusion pellet particle beams). In other cases, the technology is common across many applications (thermal radiators, high-density energy storage, lasers, etc.).

These options need to be cataloged in a way that makes it easy to compare and to focus on which performance parameters need attention. To start, historic baselines of space exploration are compiled to draw attention to the data volume and the data rates of prior missions—specifications that are significant drivers of the power and mass of the payload. To proceed after that, the basic hierarchical scope of information goes as follows:

- Mission-propulsion architecture concepts
- Power and propulsion prospects
- Key technologies within those systems
- Research to deliver the envisioned performance abilities

At this stage only the mission and propulsion lists have been drafted, with many of the specifications for each remaining to be filled in. The priority for the Stage II work is to populate those tables (spreadsheets) with more current estimates.

To review recent progress in the prospects and understanding of the challenges, a workshop was held in October of 2017 with the participation of the Tau Zero Foundation. A summary of that workshop is included.

5.1. Historical Spacecraft Baselines

Table 2 lists major historic exploration missions as a baseline comparison for data, payload, and spacecraft speed. This also serves as a starting point for the Stage II analysis of comparative rates of advancement. At this point, the table is only partially populated with data, but does show key relevant factors. The missions are listed in order by launch date, and the columns thereafter are listed roughly in order of the questions for designing a mission, per Section 7.

Table 2. Historic Exploration Mission Baselines

Mission	**Year**	**Data & Communication**			**Power**	**Mass**			**Duration**	**Max Speed**		**Build**
	Launch	Data Volume	Data Rate	Xmit duration (mo)	Spacecraft Power (W)	Power Supply (kg)	Payload Mass (kg)	Spacecraft empty mass (kg)	*Tm* (yrs)	$\frac{km}{s}$	(%c)	Mission Dev, *Tdev*, (yrs)
Luna 3	1959	1MB							<1			
Mariner 4	1964	1MB										
Mariner 9	1971	2GB	16 kbps	0.4					1			
Voyager 1	1977		160 bps		450 (1977) 178 (2025)		105	723	>40	17.3	0.006	
Galileo	1989		7.7 kpps		600			2380	14			
Ulysses	1990					56 (11kg Pu-238)				11.3	0.004	
Cassini-Huygens	1997	635GB			800			5600				12
Deep Space 1	1998				2,500			374				
Kepler	2006		4.3 Mbps Mbps									
Dawn	2007				10,000		30	1250				
New Horizons	2009	50GB 7GB (?)		15	200		30	585 478				6
Juno	2011									73.6	0.025	

5.2. Proposed Interstellar Mission-Propulsion Architectures

Table 3 shows concepts for interstellar mission architectures, listed in approximate order of ΔV, and then by the concept date. The table is only partially populated with data, but does show key factors to compare. In the propulsion columns, there will be pointers to the listing in table 4, "Interstellar Power & Propulsion Prospects." In preparation for missions that might use different propulsion at different phases of the mission (e.g. laser sails to start, plasma magnet to brake), placeholders for such possibilities are now included.

A more complete version of this table (as spreadsheet) will include other factors, such as the figures of merit outlined in Section 7.5, and further variables from table 6.

Table 3. Interstellar Mission-Propulsion Architecture Concepts

Mission - Propulsion Concept	Concept Year	Reference #	Interstellar Era	Arrival Trajectory	Distance		Claimed Cruise Speed	Trip Time	Data Transmission Duration	Data Volume	Data Rate	Payload Power	Payload Mass	Acceleration Propulsion	Course Correction propulsion	Braking Propulsion	Orbit Insertion	Spacecraft Empty Mass	Spacecraft Launch Mass	Mass of Base System	Total Energy for Propulsion	Maximum Propulsion Power
					AU	(ly)	c	yr	yr			W	kg	Propulsion (link to tbl 4)				kg	kg	kg	J	TW
Orion (interplanetary ref)	1950	Ulam	1		2																	
Vista (interplanetary ref) ICF	1987	Orth	1		2																	
The Interstellar Probe	1990	Holze	1		200																	
Innovative Interstellar Explorer	2003	McNu	1	Flyby	200																	
Interstellar Heliopause mission	2009	Wimr	1	Flyby	200																	
JPL Heliopause Interstellar Probe	2000		1	Flyby	400			30														
Solar Gravity Lens RTG-Ion probe	2012	Davis	1	Flyby	625			121					1E+03									
Solar Gravity Lens Focus (SGLF)	2017	[37]	1,2	Flyby	625																	
TAU (Thousand AU) Mission	1987	JPL	1	Flyby	1,000			30					1E+03									
AIMStar to 10 TAU	1999	Lewis	1,2	Flyby	10,000			50														
StarLight to Centauri	2016	Lubin	2	Flyby	270,000	(4.3)																
Forward's Classic Sail Missions (1)	1984	[48]	2	Flyby	270,000	(4.2)	0.1	40					1000							(1000 km lens)		7.2
Forward's Classic Sail Missions (2)	1984	[48]	2	Flyby	270,000	(4.2)	0.1	40					71000						7E+05			26
Breakthrough StarShot (Stream)	2016	[48]	1	Flyby	270,000	(4.2)	0.2	22	20				0.001									0.1
Enzmann Starship to Centauri	1964	Enzm	2	Slows	270,000			130														
BIS Daedalus to Barnard's Star	1978	[49]	2	Flyby	380,000	(6)	0.1	50														
Project Longshot to Orbit Centauri	1988		2	Orbit	270,000	(4.3)																
Forward's Classic Sail Missions (3)	1984	[48]	2	Return	660,000	(11)																
Starwisp	1985	Forwa	2	Flyby	770,000			21					0.02									0.01
μEarth ships, World Ships																						
Hollowed Asteroid	1950	Campbell																				
Earth orbiting colonies	1970	O'Neil																				
Valkyrie	2009																					
World Ship (biome study)	2015	Cobbs et al																				

Columns that are not yet shown include:

- Infrastructure elements required to build mission hardware (check list)
- Infrastructure energy for mission development, *Eti* (J)
- Infrastructure time to build mission hardware (same as Mission Development Duration, *Tdev* (yrs)

5.3. Propulsion & Power Concepts

Table 4 lists concepts for interstellar propulsion and power. The tactic taken here is to first sort the prospects as a one-part or two-part system (just the spacecraft, or the spacecraft plus some base support, like laser systems). Thereafter sorting is by thrusting method, and then by major power source. To reveal systems with multiple stages that are not captured by the concepts' more familiar name, columns will be included to encompass those elements.

The final version of this table (spreadsheet) will include:

- Sorting Category
- Concept Name, & Abbreviated Description
- Concept Date
- Reference Citation
- Interstellar Era (see Section 8.1 for definition)
    1. Era of Precursors
    2. Era of Infrastructure
    3. Era of Breakthroughs
- Propulsion Type Analysis, IP-OM, RP-OM, RP-XM, IP-XM, see Section 8.4

– – – These remaining columns will be added to the Stage II work – – –

- Base System, when applicable
    - Source of power (Earth based electrical grid, in-space solar, or nuclear)
    - Energy conversion method
    - Output power to spacecraft
    - Thermal radiators
- Intermediate Base System Components (lens, beamed particles)
- Spacecraft System
    - Power receiver (if applicable)
        - Conversion to thrust
        - Conversion to operating power
        - Thermal radiators
    - Onboard power source
        - Propellant self energy (chemical fission, fusion, antimatter)
        - Separate primary power generator (e.g., Beamed power receiver, RTG, Fission reactor)
        - Thermal radiators
    - Thruster type
        - Energy conversion
        - Key components (e.g., magnetic nozzles)
        - Thermal radiators
- Other system performance measures (see variables list, table 6)
- Technology Readiness Levels (TRL) of system elements performance as proposed (list of elements)
- Comparative TRL-6 performance levels of those same elements (if not at TRL-6)

Devising a means of sorting the information was a challenge. All of the following initial sorting methods were attempted with difficulties encountered with each. This final system (one- or two-part system, then thrusting method, then power) is still not free of confusions, but it was the least problematic of the following sorting methods:

- **Traditional Concept Discipline**: (where the breakouts starts at the level of sails {solar or beamed}, rockets {chemical, electric, nuclear} and propulsion physics {spacedrives, FTL}). Though familiar, it only draws attention to one key element, rather than reflecting on the broader functionality.
- **Primary Power Source**: This gets ambiguous when there are two power conversions (e.g., solar-to-laser, laser-to-sail).
- **Primary Power to Spacecraft**: This gets ambiguous for concepts whose key elements are a power source in one mode and a reaction mass in another concept (e.g., solar photons).
- **Thrusting Method First**: Ambiguities encountered with crossover of power source and reaction mass, especially between onboard and externally supplied systems.

- **Primary Reaction Mass**: Ambiguities encountered between energetic propellants and reaction masses that require a separate source of power to accelerate them.
- **Technical Maturity**: This is not a constant. This is a factor to track over time with each concept.
- **Performance Level**: There is no accepted ranking on performance level since those are mission specific as well as being a non-constant discriminator.

Table 4. Interstellar Power & Propulsion Prospects

Sorting	Concept Name (Description)	Date	Reference	Era	Type
I. INDEPENDENT SPACECRAFT					
I.I. Photon Momentum					
	Photon Rocket	1953	Sänger		IP-OM
	Dynamical Casimir Effect (vibrating mirror)	2009	Maclay & Forward	3	IP-OM
I.II. External Particle and Field Interactions					
	Electric Sail & Stellar Winds	2005	Pekka Janhunen	1	IP-XM
	Magnetic Sail & Stellar Winds	2000	Winglee	1	IP-XM
	Plasma Magnet & Stellar Winds	2013	Slough	1	IP-XM
	Alfven-wave plasma propulsion	1996	Moore, R.		IP-XM
	Plasma Wave	2013	Gilland		IP-XM
	Interstellar Ramjet	1960	Bussard		IP-XM
I.III. Propellant With Energy					
Fission	Nuclear Fission Pulse Propulsion	1950	Teller-Ulam		IP-OM
	Fission Fragment Rocket	1988	Chapline		IP-OM
	Pulsed Fission-Fusion (PuFF) Propulsion	2017	Adams, R.		
Fusion	Enzmann (3MT frozen deuterium ball to fusion rocket)	1964	Enzmann, 1973 Duncan		IP-OM
	BIS Daedalus (Pulsed fusion, inertial confinement fusion)	1978	Bond	2	IP-OM
	Vista Inertial Confinement Fusion	1987	Orth		IP-OM
	Project Longshot (Fission reactor pwr, fusion pulse propulsion)	1988		2	IP-OM
	Project Icarus (Pulsed fusion, inertial confinement fusion)	2011		2	IP-OM
	Continuous Electrode Inertial Electrostatic Confinement Fusions	2017	Sedwick		IP-OM
	Fusion Driven Rocket (Direct Conversion)	2017	Slough		IP-OM
	Gradient Field Imploding Linear Fusion Propulsion System	2017	LaPointe		IP-OM
	Multi-stage fusion rocket				IP-OM
Antimatter	ICAN-II, Positron catalyzed fission fusion	1998			IP-OM
	Antimatter-Catalyzed (pulse) Fusion (AIM star)				IP-OM
	Antimatter - Matter Annihilation Propulsion		Forward		IP-OM
I.IV. Power System to Expel Reaction Mass					
	Solar to Electric Ion Propulsion			1	RP-OM
	RTG, Ion	2011		1	IP-OM
	Nuclear Electric propulsion				IP-OM
	Nuclear Thermal Propulsion				IP-OM
	Gas Core Nuclear Reactors		Guven		IP-OM
	Tachyon Rocket	1996	Cramer	3	
I.V. Inertia & Inertial Frame (gravitation)					
	Negative Mass Propulsion	1957	Bondi-Forward	3	IP-OM
	Mach Effect Thruster	1994	Woodward	3	IP-XM
I.VI. Spacetime Warping					
	Alcubierre, Warp Drive (Expansion/Contraction)	1994	Alcubierre	3	IP-XM
	Warp Tunnel		Krasnikov	3	IP-XM
	Slipping		Natario	3	IP-XM
II. SPACECRAFT –PLUS– SUPPORTING BASE					
II.I. Photon Momentum					
	Forward's Beamed Energy Sails (incl)Starwisp	1984	Forward	2	RP-XM
	StarLight	2016	Lubin	2	RP-XM
	Breakthrough StarShot	2016		2	RP-XM
II.II. External Particle and Field Interactions					
	Particle-Beam Pushed Plasma Magnet		Greason	2	IP-XM
	Sailbeam, Beam of self-steering impact masses		Greason	2	RP-XM
II.III. Propellant With Energy					
	Fusion pellet runway (Bussard Buzz Bomb)	1997	Kare	2	RP-XM
	Antimatter ablated Light Sail	2005	Jackson		(mix)
II.IV. Power System to Expel Reaction Mass					
	Solar Thermal propulsion				RP-OM
	Laser powered ion propulsion		Brophy	2	RP-OM
II.V. Inertia & Inertial Frame (gravitation)					
II.VI. Spacetime Warping					
	Gravitational Dipole	1963	Robert Forward	3	SP-XM
	Traversable Wormholes	1988	Thorne, Visser	3	SP-XM

5.4. 2017 Workshop Review

With the participation and co-sponsorship of Tau Zero via this grant, a workshop was held from October 3rd-6th, 2017, in Huntsville, Alabama, called the "Tennessee Valley Interstellar Workshop (TVIW)." The event brought in over 140 attendees, who spent three days hearing the most current and cutting-edge presentations by leaders in space development and interstellar flight and exploration fields. Speakers were from the Breakthrough StarShot Initiative, General Dynamics, Johns Hopkins Applied Physics Lab, several NASA facilities, University of California, University of Washington, two United States Congressmen, and several representatives from the United States Air Force. Globally, speakers' origins spanned from Sweden, to Germany, Japan, Italy, and Russia.

This is a continual and evolving forum to enable working discussions on interstellar research and exploration to encourage continued advances, and the publication of those advances, spanning education, technical research, societal facets, literature and cultures, and to enhance public attitudes and dialogue about interstellar exploration.

Table 5 lists the presentations and their authors, grouped by topic. Instead of showing the titles, short descriptors of the talks are given. The individual reports have not yet been published. Some will be published in a future issue of the *Journal of the British Interplanetary Society*. However, all the presentations can be viewed on line at: *https://tviw.us/2017-presentation-video-archive/*

Table 5. 2017 Workshop Lectures & Authors

Mission Considerations and Overviews		
Summary of workshop	Paul Gilster	[52]
How to assess interstellar challenges and prospects	Marc Millis	[53]
Precursor mission studies with current technology	Pontus Brandt	[32]
Exoplanet mission concepts from NASA JPL	Stacy Weinstein-Weiss	[33]
Solar gravitational lens viewing of exoplanets - prospects	Slava Turyshev	[37]
Solar gravitational lens viewing of exoplanets - issues	Geoff Landis	[55]
Exoplanets	Angelle Tanner	[56]
Breakthrough StarShot		
Introduction & roadmap	Pete Klupar	[57]
System model	Kevin Parkin	[58]
Propulsion	Robert Fugate	[59]
Sail options and issues	Jim Benford	[60]
Data return	David Messerschmitt	[40]
Closest approach estimates based on initial aim parameters	Al Jackson	[61]
Dust impacts	Richard London	[62]
Propulsion – Sails		
Smaller scale laser sails, progress on lasers	Phillip Lubin	[63]
Braking with plasma magnetic sails	Jeff Greason	[64]
Sail deformations	Giancarlo Genta	[65]
Interstellar sails	Olga Starinova	[66]
Diffractive meta sails	Grover Swartzlander	
Propulsion – Nuclear		
Fission fragment rocket	Pauli Laine	[67]
Fusion, direct	Gary Pajer	[68]
Magnetic nozzles	Jason Cassibry	[69]
Antimatter storage	Marc Weber	[70]
Antimatter production	Gerald Jackson	[71]
Breakthrough Propulsion Physics		
Experimental fidelity	George Hathaway	[72]
Infrastructure		
Cislunar infrastructure	Jonathan Barr	[73]
In-space manufacturing	Tracy Prater	[74]
Societal Aspects		
Energy responsibility	Brent Ziarnick	[75]
Sustainable worldship - peace	Ore Koren	[76]
Sustainable worldship - ethics	James Schwartz	[77]

6. PROPOSED WORK BREAKDOWN STRUCTURE (WBS)

To collect the complex information in an orderly manner, the following "work breakdown structure (WBS)" is proposed, along with an associated table of variables (table 6). By definition, a WBS is breakdown of a project into smaller, more manageable components, typically organized in a hierarchical structure. Detailed discussion of what these WBS elements mean and how they are measured is presented in the next two sections. The letters shown in parentheses are abbreviations for that WBS level, while the letters within brackets are the variables associated with that level (variables listed in table 6). The intent is to identify the least number of questions necessary to assess the options. A preliminary concept for how these items will be processed is shown as a flow diagram (figure 5.).

6.1. WBS Hierarchical List

- Mission Choices, Top-Down
  - Destination (MD) [*Dn, Dd, Di*]
  - Mission Ambition (MA) [*Wa*]
    - Arrival Trajectory (MAT) [*ΔV, Do, Dr, Tot*]
    - Science Sought (MAS) [*Ir, Iv*]
  - Timing (MT) [*Ttp, Trl, Tdev (=Tscb+Tbd), Tm (=Tt+Ts+Tx)*]
  - Motive (MM) [*Wm*]
  - Baseline Mission and Payload Scenarios (MB)
    - Solar Gravitational Lens
    - Deep Interstellar Medium
    - Centauri Flyby
    - Centauri Slower Flyby
    - Centauri Orbiter
- Technical Challenges, Top-Down
  - Payload Challenges
  - Propulsion & Power Challenges
  - Incremental and Affordable Infrastructure Creation
- Propulsion and Power Prospects, Bottom-Up
  - List of Propulsion and Power Prospects
  - Distinct Eras – Distinct Analyses
    - Era of Precursors
    - Era of Infrastructure
    - Era of Breakthroughs
  - Propulsion and Power Types (for energy calculations) (PP)
    - Type IP-OM: Internal Power & Onboard Reaction Mass
    - Type RP-OM: Received Power & Onboard Reaction Mass
    - Type RP-XM: Received Power & External Reaction Mass
    - Type IP-XM: Internal Power & External Reaction Mass
  - Infrastructure Dependence (I)
    - Earth-Based Beaming Infrastructure
    - Infrastructure Energy Availability & Usage Expense [*Esi, Pia, Msc, Mb, Esc, Eb*]
    - Mission Development Duration [*Tdev*]
  - Comparative Rates of Advancement (R)
    - Baseline Performance Trends of Shared Technologies & Resources
    - Technology Maturation Step Durations
    - Power & Propulsion Experiences Modeled as S-Curves
- Flight Trajectory Analyses (FT)
- Figures of Merit (FOM)
  - Mission Composite Value (maximize) [*W*]
  - Total Mission Expense (minimize) [*Etm (=Eti+Etp)*]
  - Total Project Duration (minimize) [*Ttp*]
  - Mission Efficiency (maximize) [*We*]

6.2. Basic Analysis Flow Diagram

The flow diagram in figure 5 is for guiding both the relative and deterministic analyses. This version is expected to be refined during the Stage II work. For the relative analysis, this diagram represents a more detailed version of the topological analyses introduced with figure 1. It is expected that the analysis questions can flow more than one way. For example, one can either specify the total mission duration, data rate, and data volume to determine the required trip velocity, or specify the desired trip velocity and data rate to determine the total mission duration. The type of questions that the topological analysis aims to answer include:

- Which mission choices are the most difficult to achieve?
- Which mission architectures have the greatest ratio of "composite mission value" to "total mission expense"?
- Which mission architectures have the greatest ratio of "composite mission value" versus "total mission duration"?
- Which technology elements within the propulsion and power options are more impactive to the final figures of merit?

This flow diagram is also to guide the more deterministic calculations to answer questions such as:

- Assess trades of "travel time" versus "data transmission time" within bounded "total mission durations."
- Calculate how much energy it takes for the different propulsion and power options to reach 10%c.
- Compare the payload mass delivery capability of different propulsion and power concepts as a function of trip time and destination distance.

The key differences between this analysis and prior interstellar mission analyses include:

- Infrastructure dependence is included as part of the total mission cost and duration.
- Different technologies are compared using the same mission and payload specifications.
- The overall impact of different data transmission rates is part of the trade space.
- Provisions are included for comparing the impact of different technology maturation rates.

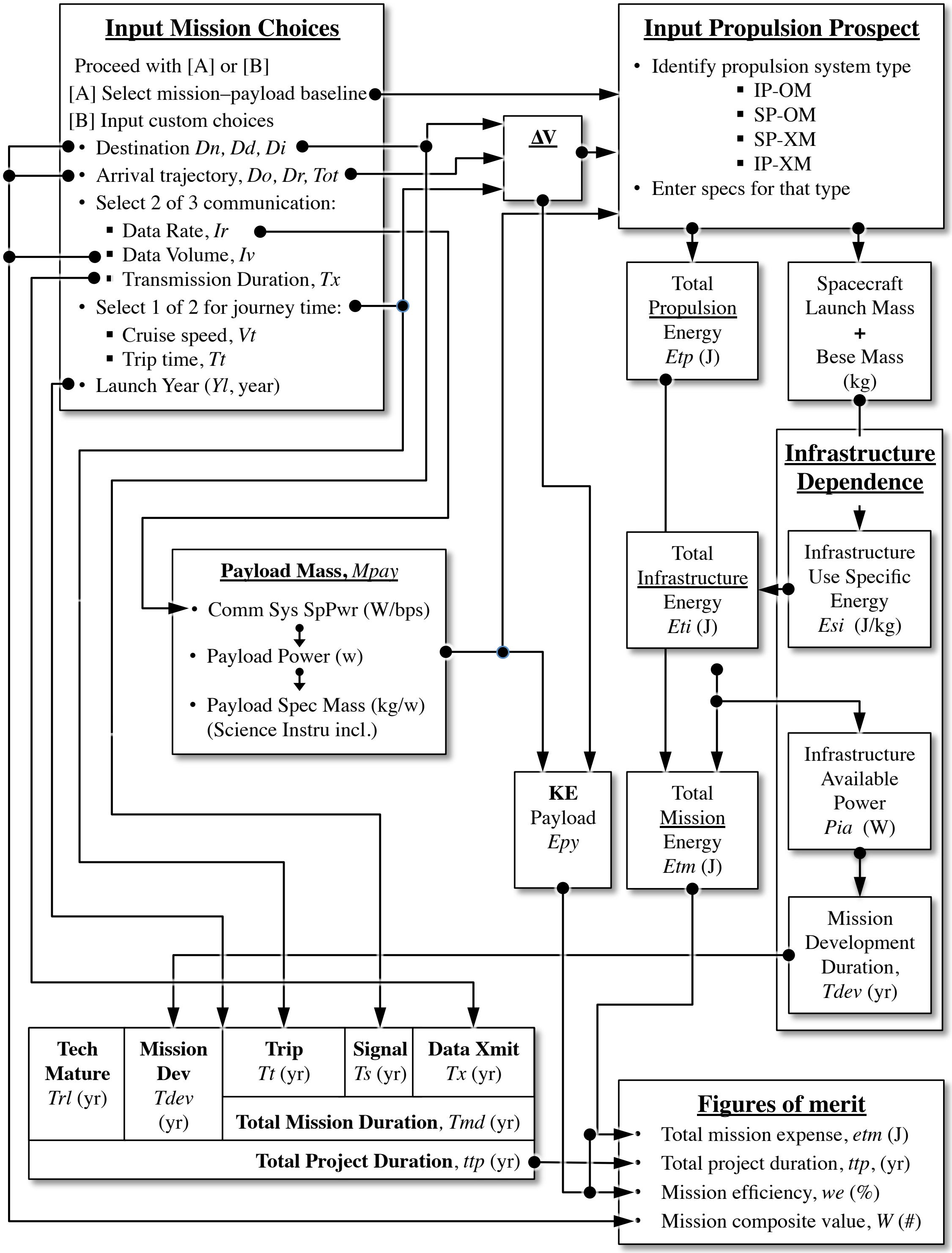


Fig. 5. Basic Analysis Flow Diagram

6.3. List of Variables

To guide the creation of the analysis algorithms, the following table of variables has been compiled. How these are measured and their functional dependence are described in the next two sections.

Table-6 List of Variables

WBS Relevance	Variable Name	Symbol	Base Units	Input or Output	Section	Comments
FT	Acceleration	*a*	m/s^2	I or O	8.4	
FT	Acceleration (average)	$\bar{a}$	m/s^2	I or O	8.4	
FT	Acceleration (time) Duration	*Ta*	s	I or O	8.4	IP-XM
FT	Acceleration Distance	*Da*	m	I or O	8.4	
MTY	Arrival Year	*Ya*	CY	I or O	7.3	Goal or calculated
MT	Base Hardware Build (develop) Duration	*Tbd*	yrs	O	8.3	Calculated from infrastructure J and W
I	Base Hardware Build Energy	*Eb*	J	O	8.3	Calculated from infrastructure J/kg
I	Base Hardware Mass	*Mb*	kg	O	8.3	Calculated from propulsion specs
PPB	Beam - Energy Cost of Beam	*Ebhw*	J or $	O	8.4	RP-OM, RP-XM
PPB	Beam Aperture Area	*Ab*	m^2	I	8.4	RP-OM, RP-XM
PPB	Beam Director Cost		$	I	8.4	RP-OM, RP-XM
PPB	Beam Director Cost per Aperture Area		$/m^2	I	8.4	RP-OM, RP-XM
PPB	Beam Director Cost Scaling		rad√$	I	8.4	RP-OM, RP-XM
PPB	Beam Divergence Angle	Θ	rad	I	8.4	RP-OM, RP-XM
PPB	Beam Generating Power	*Pgb*	W	I or O	8.4	RP-OM, RP-XM
PPB	Beam Power Generating Efficiency	η_B	%	I	8.4	RP-OM, RP-XM
PPB	Beam Range Limit	*Dbl*	m	I	8.4	RP-OM, RP-XM
PPB	Beam Range Limit Correction Factor		%	I	8.4	RP-OM, RP-XM
PPB	Beam Source Cost Scaling		$/W	I	8.4	RP-OM, RP-XM
PPB	Beam Transmitted Power	*Pbx*	W	I or O	8.4	RP-OM, RP-XM
MAS	Closest Approach	*Do*	AU	I	7.2	
FT	Coasting (time) Duration	*Tc*	s	I or O	8.4	
PPB	Cost of Beam Source		$	O	8.4	RP-OM, RP-XM
FT	Cruise Speed	*Vt*	m/s	I or O	8.4	Goal or calculated
MAS	Data (Information) Rate	*Ir*	bps	I or O	7.2	Corresponds to communication system
MAS	Data (Information) Volume	*Iv*	Mb	I or O	7.2	Corresponds to communication system
MT	Data Transmission (time) Duration	*Tx*	s	I or O	7.3	Corresponds to communication rate
PPX	Delta V of media by thrusting effect	ΔVt	m/s		8.4	IP-XM
MD	Destination Distance	*Dd*	AU	I	7.1	Pull from Table 1
MD	Destination Level of Interest	*Di*	#rank	I	7.1	Pull from Table 1
MD	Destination Name	*Dn*	text	I	7.1	Select from Table 1
PP	Effective Exhaust Velocity (jet velocity)	*Ve*	m/s	I	8.4	IP-OM, RP-OM
R	Energy Storage Energy Density *f*(y)		J/kg	I	8.5	Design standard trend to model
R	Energy Storage Power Density *f*(y)		W/kg	I	8.5	Design standard trend to model
MTY	First Data Arrival Year	*Yd*	CY	I or O	7.3	
I	Infrastructure Available Energy	*Eia*	J	I or O	8.3	Need to create per-decade estimates
I	Infrastructure Available Power	*Pia*	W/kg	I or O	8.3	Need to create per-decade estimates
I	Infrastructure Use Specific Energy	*Esi*	J/kg	I	8.3	Need to create per-decade estimates
MAS	Instrument Range	*Dr*	AU	I	7.2	
PP	Jet Power	*Pj*	W	I	8.4	IP-OM, RP-OM
FOM	Kinetic Energy of just Payload	*Epy*	J	O	7.5	Total ΔV x Payload Mass
MTY	Launch Year	*Yl*	CY	I or O	7.3	Goal or calculated
PPX	Mass Flow Rate of Media Thru Thruster	*dm/dt*	kg/s	I	8.4	IP-XM
MA	Mission Ambition	*Wa*	#	O	7.2	$a_V \bullet \Delta V \bullet a_D \bullet (Dr - Do) \bullet a_T Ttot \bullet a_I \bullet Iv$
MTY	Mission Commit Year	*Ym*	CY	I or O	7.3	Actual starting point, assumes TRL >6
FOM	Mission Composite Value	*W*	#	O	7.5	Weighted sum of Di, Wa, Wm
MT, I	Mission Development Duration	*Tdev*	yrs	O	7.3	Sum of Tbd and Tcsd
FOM	Mission Efficiency	*We*	%	O	7.5	Epy/Etm
MTY	Mission End Year	*Ye*	CY	I or O	7.3	When all data has reached Earth

Table-6 List of Variables – *continued*

WBS Relevance	Variable Name	Symbol	Base Units	Input or Output	Section	Comments
PPB	Particle Beam Mass Flow Rate	*dm/dt*	kg/s	I	8.4	RP-XM
PPB	Particle Beam Velocity	*Vb*	m/s	I	8.4	RP-XM
PPB	Particle Mass Expended	*Mp*	kg	I	8.4	RP-XM
MB, PP	Payload Mass	*Mpay*	kg	I	8.4	Baseline with respect to data rate
PPB	Pellet Specific Energy	*Esp*	J/kg	I	8.4	RP-XM
PPB	Pellet Velocity Incident to Spacecraft	*Vip*	m/s	I or O	8.4	IP-XM, RP-XM
PP	Propellant Mass Expended	*Mp*	kg	O	8.4	IP-OM, RP-OM
PP	Propellant Mass Flow Rate	*dm/dt*	kg/s	I	8.4	IP-OM, RP-OM
PP	Propellant Specific Energy	*Esp*	W/kg	I	8.4	IP-OM
R	Propellant Specific Tankage Fraction *f*(y)		Mt/Mp	I	8.5	Design std trend to model (STS ET =3.7)
PP	Propulsion Power Source Specific Power	$1/\alpha$	W/kg	I	8.4	IP-OM, RP-OM
PP	Propulsion System Specific Power	*Psp*	W/kg	I	8.4	
PP	Propulsive Power	*P*	W	I or O	8.4	
R	Radiator Specific Mass, *f*(K°) *f*(y)		kg/W	I	8.4	Design standard trend to model
PPB	Receiver Aperture Area	*Ab*	m^2	I	8.4	RP-OM, RP-XM
PPB	Receiver Areal Density		kg/m^2	I	8.4	RP-OM, RP-XM
PPB	Receiver Flux Limit		W/m^2	I	8.4	RP-OM, RP-XM
MTY	Research Commit Year	*Yrc*	CY	I or O	7.3	
MT	Signal Time	*Ts*	yrs	O	7.3	Function of Dd
MT	Spacecraft Build (develop) Duration	*Tscd*	yrs	O	8.3	Calculated from infrastructure J and W
I	Spacecraft Build Energy	*Esc*	J	O	8.3	Calculated from infrastructure J/kg
PP	Spacecraft Empty Mass (w/o Payload)	*Mse*	kg	O	8.4	Calculated from propulsion specs
PP	Spacecraft Launch Mass	*Msl*	kg	O	8.4	IP-OM version: Mse+Mpay+Mp
PP	Specific Impulse	*Isp*	s	I or O	8.4	
MM	Sum of Motives	*Wm*	#	O	7.4	(needs graduated scale)
R	Tech Maturation Increment Duration *f*(Li)	*ΔLi*	yr	O	8.5	Calculated (TBD)
R	Tech Maturation Increment Pattern *f*(Li)	*ΔLi*	yr	I	8.5	Historic relative duration between steps
R	Tech Maturation Level (TRL, SML)	*L*	#	I	8.5	Table **13**
MT, R	Technology Maturation Duration	*Trl*	yrs	O	7.3	Time between now and TRL 6
PP, FT	Thrust	*F*	N	I	8.4	
PP	Thrust Conversion Efficiency	η	%	I	8.4	
MA	Time on Target	*Tot*	sec	I or O	7.2	Time that spacecraft within instru' range
MA, PP, FT	**Total ΔV**	*ΔV*	m/s	I	**7.2**	The total velocity change for mission
FOM, I	Total Infrastructure Energy Expense	*Eti*	J	O	8.3	Eti = Es + Eb
MT	Total Mission Duration	*Tm*	yrs	I or O	7.3	Sum of Tt + Ts + Tx
FOM	Total Mission Expense (energy)	*Etm*	J	O	7.5	Sum of Etp + Eti
FOM, MT	Total Project Duration	*Ttp*	yrs	I or O	7.5	Time between Yrc and completion (Ym)
FOM	Total Propulsion Energy	*Etp*	J	O	8.4	Energy for all mission propulsion
MT	Trip Time	*Tt*	yrs	I or O	7.3	
FT	Velocity of Spacecraft	*Vs*	m/s	I or O	8.4	RP-XM
PPX, FT	Velocity of Spacecraft Through Media	*Vsm*	m/s	I or O	8.4	IP-XM

7. MEASURING MISSION CHOICES (Top-Down)

The starting point for a mission is deciding where to go, what to do once there, and how soon to get there. The WBS choices for these are named "Destination," "Mission Ambition," "Timing," and "Motive," all discussed below.

The options for answering these choices will require trade-offs and further refinements, based on what the technologies can ultimately deliver. The compilation of all these factors are ultimately ranked by "Figures of Merit," some of which are subjective. To enable equitable comparisons between options, this study explicitly defines those Figures of Merit.

7.1. Destination

The first question is, "Where to go?" Already there is trade between easier missions and more interesting destinations. Typically, the more interesting destinations are further away. The variables for this part of the analysis are:

Destination Name, *Dn*: The name of the chosen destination as selected from table 1, which then has corresponding other measures; distance and level of interest.

Destination Distance, *Dd*, (AU): The distance to the destination, measured in AU or ly. For most cases this is a simple number, but there are destinations that span large distances (such as the Oort cloud), plus the special case of the "Oumuamua" object, which is a fast moving extrasolar object (5 AU/yr) that is still relatively close (2018, 3 AU) [78].

Destination Interest, *Di*: This is a subjective value, where different people might have different notions of what is more or less interesting. For the sake of this study those subjective differences are cast into specific values, which can later be debated if found that the choices heavily sway technical priorities. Those provisional values are listed in the "Level of Interest" column of table 1.

7.2. Mission Ambition

Another question is, "What to do there?" This includes the trajectory at the destination, what data will be taken, how much data, and at what fidelity (e.g. image resolution).

7.2.1. Arrival Trajectory

Almost all interstellar mission concepts assume a flyby at whatever coast velocity the spacecraft has achieved, and where the closest approach is determined by how accurately the spacecraft was originally aimed. Anything else requires additional propulsion and the associated increases in mass and power (and subsequent increases in trip time or required energy). To more systematically include the trajectory options in the analyses, the following categories of arrival trajectories are listed in order of increasing ΔV in table 7:

Table 7. Arrival Trajectory Options that Affect Total ΔV

Arrival Trajectory Options	Initial Acceleration	Course Correction	Braking	Orbit Insertion
Flyby Fast (cruise velocity)	Maximum Possible	Maybe	0	0
Flyby Slower	Maximum Possible	Maybe	Some	0
Orbit Star	Maximum Possible	Yes	Significant	Yes
Orbit Exoplanet	Maximum Possible	Yes	Significant	Yes

The most straightforward way of quantifying the mission value of the trajectory options is in terms of total ΔV, closest approach, and time on target. Thus, the factors to measure include:

Total ΔV (m/s): Calculated as usual. In principle, the sum of the individual ΔV's in a row in table 7.

Closest Approach, *Do* (AU): Presumably measured in AU, this is defined by how close the probe passes the target star or exoplanet. Closest approach is affected by the initial aiming accuracy of the spacecraft, plus any maneuvering capability later. The maneuvering capacity is already measured as a part of the total Δv.

Instrument Range, *Dr* (AU): This value is a function of the technology used for the scientific instruments. In the absence of existing specifications, fixed test-case values will be assigned.

Time on Target, *Tot* (s): Presumably measured in hours or days, time on target is how long the probe is within the instrument range. For flyby missions, this is inversely proportional to the cruise velocity. For orbital missions it is equal to the remaining functional life of the spacecraft. Table 8 shows different times-on-target for six different instrument ranges and five different flyby speeds. For example at 20% lightspeed, a spacecraft would only be within ± 1 AU for less than 90 minutes. Even relaxing that to only 1% lightspeed and a range of ± 5 AU, the spacecraft will only be in that range for 139 hours.

As a representative example of reasonable minimum viewing durations, it is fitting to examine how much time it takes for an Earth-viewing satellite to integrate enough images to be able to subtract the cloud interfearance and reveal the ground features. Is this duration hours, days, or months?

Table 8. Time on Target Verses Flyby Speed

Flyby Speed	**Instrumentation Range ± AU** **0.5**	**1**	**5**	**10**	**50**	**100**
(c)		— hours —			— days —	
0.01	14	28	139	12	58	116
0.05	2.8	5.5	28	2.3	12	23
0.10	1.4	2.8	14	1.2	5.8	12
0.15	0.9	1.8	9.2	0.8	3.8	7.6
0.20	0.7	1.4	6.8	0.6	2.8	5.7

7.2.2. Science Sought

What scientific instruments should an interstellar probe carry to collect information that cannot be obtained from Earth-based astronomy alone (even after decades of further advances in astronomy)? Would the trajectory's closest approach and time on target be sufficient to collect this information and how much data is sufficient to reach meaningful conclusions?

> NOTE: Before proceeding to quantify the science ambitions, this topic presents an excellent example of the utility of precursor missions to this study. As stated before, precursor missions are not assessed as part of this study, but do provide suitable baseline examples. To help resolve the question of required instrumentation, range, and time on target, a fitting precursor mission would be a "**Look Back Mission.**" A suite of exoplanet instruments can be tested by looking back toward Earth at various distances (1-100 AU?) to determine the required closest approach and time on target for collecting meaningful information.

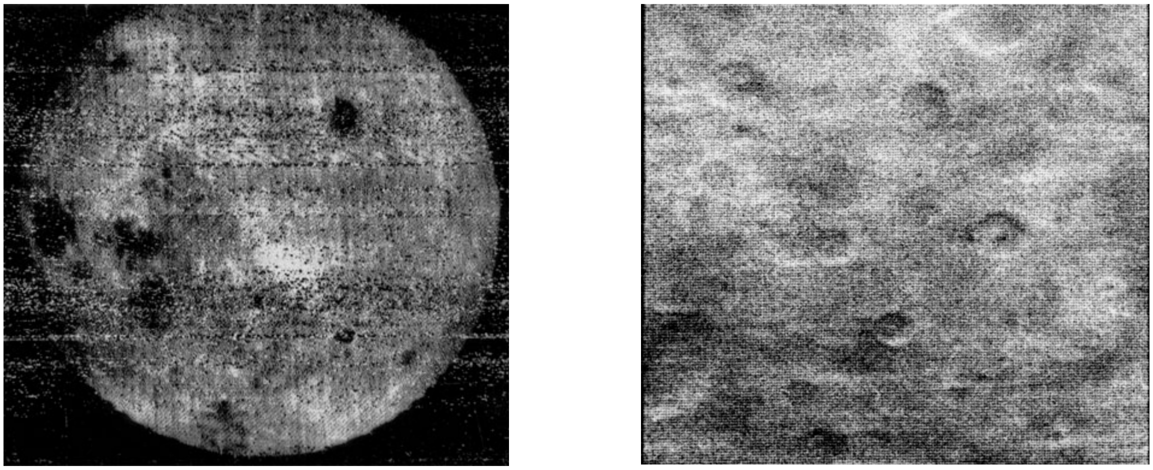
The basic trade here is between smaller, less capable payloads that can reach the destination sooner, versus larger, more capable payloads that will take longer to get there. As discussed previously, the total mission duration includes the time to transmit the data, which is a function of the amount of data taken and the data transmission rate.

Data Rate, *Ir* (bps): The trades here involve the choice between sending a small and fast payload with long data transmit time, or larger, slower payload with shorter transmit times.

For example, the StarShot mission allocates 20 years for transmitting the data back to Earth, where that very long duration enables the use of an incredibly low power and low mass communication system on the payload. Since this is a significant proportion of total mission duration, it is an important factor to specify. Data return time is a function of the data rate, measured in bits per second (bps), and the total amount of data, measured in bits (or bytes, 8 bits = 1 Byte).

Data Volume, *Iv* (bits or Bytes)**:** How much date is enough data? Like the question of what will be measured, there is no consensus on the total quantity of data. Since greater quantities of data can extend the total mission duration, the total quantity of data is considered in the trade space.

As examples of what might be considered sufficient data, consider some of the first historic missions that imaged the Moon and Mars, such as Luna 3 (first mission to image the Lunar far side) and Mariner 4 (first Mars flyby) both of which returned roughly 8 Megabits of data (1 MB). Here are examples of images from those first flyby missions.



(6a) 1959, Soviet Luna 3
Composite image of the backside of the Moon
Source:
https://nssdc.gsfc.nasa.gov/imgcat/hires/lu3_2.gif

(6b) 1964, NASA Mariner 4
Image of Mars
Source:
https://nssdc.gsfc.nasa.gov/imgcat/hires/m04_09d.gif

Fig. 6. "First Image" Examples from History
Estimated to be equivalent to 8 Megabits (1 MB) each

Extending the analogy to a possible orbiter mission, consider the Mariner 9 mission, the first Mars orbiter. That mission produced roughly 16 Gigabits (2 GB) of data. While these data quantities are small compared to recent planetary probes, such as Cassini-Huygens at over 600 GB, that was a Saturn probe at only about 10 AU from Earth. That's 27 thousand times closer to Earth with communication that much easier. For our first interstellar missions, what are the lower bounds of what would be acceptable images? For example, a single image of an exoplanet in 6 bit gray scale, with 30 pixels across the equator (which would represent a tremendous leap beyond anything currently possible with astronomy) is about 4200 bits (0.5 kB).

Data Fidelity, *If* (?)**:** Perhaps an additional factor could be how much is learned from a given volume of data, though how to quantify such a parameter is uncertain.

Mission Ambition," *Wa* (#): Finally, these factors combine to give a relative score for Mission Ambition. Since the individual terms use different units, normalizing and weighting coefficients, *a*, must be included for each term. A tentative equation for Mission Ambition is:

$$W_a = a_V \Delta V \, a_D \left(D_r - D_o \right) a_T T_{ot} \, a_I I_V \qquad \text{Eq. 2}$$

where higher interest is proportional to more time on target, higher data return, useful science at more distant instrument ranges, and more capable propulsion systems denoted by higher ΔV capabilities. Note that if the closest approach, *Do*, is greater than the instrument range, *Dr*, then the score for Mission Ambition goes negative. In other words, if the spacecraft cannot get close enough to the destination for the science instruments to do their job, then the mission is a failure. Additional variations of Mission Ambition can be considered in developing an optimized metric.

7.3. Timing

The next question is about the duration of the mission, or more broadly the entire project. Since this study includes the research that predates the mission, those stages are also measured. Many stages have trades. The stages are:

Total Project Duration, *Ttp* (yrs): This term means the entire span encompassing all the other stages, from the point the research begins until receiving all of the data back from the probe.

Technology Maturation Duration, *Trl* (yrs): This is the time between the start of the research and when that research has advanced to approximately TRL-6, or advanced enough to allow planning and developing a mission. The trade here is whether to select less capable but more near term technology that will be ready sooner, or more capable technology that might be available later. This is related to the Incessant Obsolescence Postulate, which is mostly affected by subjective mission motives.

In the case of the "Precursor Era" missions, sufficient technology maturation exists to initiate trade studies, albeit the best projected performance can only reach 1,000 AU in 50 years with a 38 kg payload [32]. In the case of both the "Infrastructure Era" and "Breakthrough Era," the Technology Maturation Durations have not yet been estimated.

Devising a means to estimate the durations of technology maturation and mission development are part of the goals of this Stage I study. These details are discussed in Section 8.5 "Estimating Comparative Rates of Advancement."

Mission Development Duration, *Tdev* (yrs): This is the time between the beginning of the mission trades studies and the launch of the mission. It will likely be different for each of the three interstellar eras and therefore estimated differently. The trade here is to use less complex systems that can be built faster, or more capable systems to launch later. Again, this is related to the Incessant Obsolescence Postulate, but this time the duration is also a function of how soon the infrastructure will be available.

For the precursor era missions, this duration will likely fall within the 6-12 year span of the development of the New Horizons missions and Cassini-Huygens, respectively.

In the case of mission architectures of the infrastructure era, this is dominated by the time for using the presumed preexisting infrastructure to build the spacecraft and any supporting new infrastructure (such as laser systems). Accordingly and per the methods in Section 8.3 "Measuring Infrastructure Dependence," these following two development times will be estimated:

> **Spacecraft Build Duration**, *Tscb* (yrs): This is the time it takes to build the spacecraft and fully load it with propellant using the infrastructure available at the time.
>
> **Base Hardware Build Duration**, *Tbd* (yrs): This is the time it takes to build any of the supporting propulsion infrastructure such as anything that needs to beam energy or reaction mass to the vehicle.

Total Mission Duration, *Tm* (yrs): The time between launch and receiving all of the data back from the probe. It is the sum of these sub-stages:

> **Trip Time**, *Tt* (yrs): The time between launch and arrival at the destination. This is a function of the payload mass, the energy available for propulsion, and the performance of the power and propulsion system.
>
> **Signal Time**, *Ts* (yrs): The lightspeed signal return time, a simple function of the destination distance and lightspeed.
>
> **Data Transmission Time**, *Tx* (yrs): The time it takes to transmit the full suite of the data back to Earth. This is a function of the communication system, its power, and apertures (both on the spacecraft and the receivers on Earth), where in principle smaller payloads with less power will have lower data rates and hence longer transmission times.

The demarcation points between these times are defined as:

Research Commitment Year, *Yrc* (calendar year, cy): This is the calendar year when the commitment is made to begin advancing the required technologies up through TRL-6, initiating the development of the spacecraft and base hardware. Technology maturation is initiated at the start of the Research Commitment Year and extends to the Mission Commitment Year.

Mission Commitment Year, *Ym* (cy): The calendar year when the commitment to developing the mission is made. The required technology must be mature enough for reliable trade studies at this point, specifically TRL ≥ 6. Currently only the Precursor Era missions satisfy that condition. Mission development begins at the start of the Mission Commitment Year and extends to the Launch Year.

Launch Year, *Yl* (cy): The launch date is often cited as a primary mission goal, but the decisions needed to meet that goal are made years earlier. The challenge in developing the analysis is that sometimes this will be an input value, and sometimes a calculated value, depending on what are set as the driving parameters. The launch year follows the start of the Research Commitment Year and encompasses the sum of Technology Maturation Duration and Mission Development Duration.

Arrival Year, *Ya* (cy): This is the year the spacecraft reaches the destination, or more specifically, when its scientific instruments are within functional range of the target—able to begin acquiring and transmitting data back to Earth.

First Data Arrival Year, *Yd* (cy): This is when the first data arrives at Earth, thus confirming that the spacecraft has arrived and is still functioning.

Mission End Year, *Ye* (cy): This is the point when all data from the probe has been received on Earth.

7.4. Motive

The final facet of starting a mission is the basic question, "Why?" Of all the facets of an interstellar mission, this facet is seldom examined. In the prior literature, the motives were often implicit, but with the implication that *first arrival* was the main purpose. Accordingly, there was often discussion about what is now called the Incessant Obsolescence Postulate, (that a newer probe will pass the older, so why launch yet?) and how that was an impediment to progress toward interstellar research. The postulate favors waiting until the technology has reached some peak performance before committing to a mission (such as possible mission durations of less than 30 years). However, this posture is only valid if the motivation is to reach the destination first.

There are many other motivations for an interstellar mission other than the bravado of being the first to the goal line. Another motivation is the survival of humanity, where the relevant technologies of sustainable habitats would have value on Earth long before any interstellar world ships would be possible. Another motivation is technology development, of launching missions for the goal of testing the technology and testing the environment through which future probes will follow. A closely related motive is commercial endeavors, where the technology developed under the theme of interstellar flight would have nearer-term commercial applications. Perhaps this is a significant motive for StarShot, where powerful lasers and further miniaturized spacecraft have marketable potential, even if the technology never reaches the levels for enabling an interstellar mission. And last, but certainly not least, are the motives of science and curiosity—finding out what is really out there.

Sum of Motives, *Wm* (#): This variable is introduced to bring this often implicit and overlooked motivation factor into the discussion. In principle, for any given interstellar mission, that mission would be considered more valuable, and hence fundable, if it satisfies multiple ambitions and multiple stakeholders: NASA, commercial space, science, national security, global security, and general public interest. To provoke discussion on those relative motives, table 9 lists a number of motives, the consequential emphasis of each, and a subjective provisional value score. These provisional scores are based on Maslow's hierarchy of human needs (survival, security, belonging, self-actualization). Sum of Motives is calculated simply as the sum of importance scores for each motivation that the mission addresses.

Table 9. Span of Motivations, Consequences, and Provisional Rankings

Motivation	**Consequential Technology Focus**	**Subjective (provisional) Importance Score**
Survival of humanity	• Sustainable habitats	100
Technology development	• Commercial utility (ROI) • Learn by doing • Maturing technology to readiness	80
Scientific curiosity	• Instrumentation • Pursuing propulsion and power research that are beyond marketable fruition	60
Bragging rights (being first)	• First to launch or arrive • First to exceed some milestone	1

7.5. Figures of Merit

What, ultimately, is most important to mission planners? Presumably, it's having an interesting enough mission that will appeal to a number of stakeholders and be accomplishable within a reasonable time and expense. To make these explicit and measurable so that mission and propulsion options can be compared, the following variables are introduced:

Mission Composite Value, *W* (#): The value of a mission is defined here as a function of the interest in the destination, the number of motives answered by the mission, and the fidelity of the data that the mission will collect. In principle, this is envisioned as a weighted sum of the "Destination Interest," *Di*, "Mission Ambition," *Wa*, and "Sum of Motivations," *Wm*. The higher the value, the better.

Total Mission Expense, *Etm*, (J): This is a measure of the resources required to build, launch, and operate the mission. Instead of using financial cost, whose estimations require subjective predictions, the measure will be in terms of the energy, a fundamental, calculable physics parameter shared by all methods. The energy to "build" the mission will be in terms of the required infrastructure, while the energy to launch the mission will be in terms of propulsion energy. Since the expense of operating the mission after launch is assumed to be much smaller than the other factors, it will not be quantified. Specifically, then, "Total Mission Expense," *Etm*, (J) is the sum of "Total Infrastructure Energy," *Eti*, (J) and "Total Propulsion Energy," *Etp*, (J). The lower the value, the better.

Total Project Duration, *Ttp*, (yr): As mentioned previously, this is a measure of how much time remains between now and the point where all the data has been transmitted back to Earth. The lower the value, the better.

Mission Efficiency, *We*, (%): The final figure of merit is the efficiency of the mission, which is defined here as the ratio of the kinetic energy imparted to just the payload, *Epy*, and the Total Mission Expense, *Etm*. The higher the value, the better

An alternative definition of Mission Efficiency could be in terms of the Data Volume, *Iv*, and perhaps Data Fidelity, *If*, delivered per Total Mission Expense, *Etm*. In that case, the prior definition of *Epy*/*Etm* could be called "Vehicle Efficiency."

It is anticipated that the Stage II and III analyses will reveal which of these factors are more or less impactive of the technology requirements. Thereafter, choosing the relative importance of the options can be informed choice.

8. METHODS FOR EQUITABLE COMPARISONS

Tied to the mission choices, it is necessary to measure the associated propulsion performance and the expense to deliver that level of performance. To make these calculations equitable across differing missions and differing propulsion methods, the basic strategies are: 1) start with comparing technologies that are at comparable readiness levels before advancing to compare across significantly different readiness levels 2) compare different propulsion and power concepts using common payload and mission scenarios, 3) devise a common means to measure the expense of building the mission hardware, 4) measure the performance of the disparate propulsion and power approaches using fundamentally common units, and finally 5) devising methods to compare technologies that are at different readiness levels and advancing at different rates.

8.1. Distinct Eras of Interstellar Flight

A starting point is to separate concepts that are at substantially different readiness levels. After reviewing the span of mission concepts and technology prospects, they can be divided into these distinct eras of interstellar flight:

1) Era of Precursors
2) Era of Infrastructure
3) Era of Breakthroughs

The major difference between the first two eras is the degree of infrastructure needed to support the mission. The distinction of the third era is that it requires further advances in physics (whose infrastructure needs are temporarily unknown). Comparisons *within* these eras are more easily achieved than comparisons across these eras.

8.1.1. Era of Precursors

This era refers to missions that can be launched from Earth with foreseeable technology and without needing substantial new infrastructure. By "foreseeable technology" it is meant those technologies that are already at, or above TRL-6. Examples in this era include:

- Voyager
- Heliopause Interstellar Probe concept of 1999 [22, 24, 25]
- Innovative Interstellar Explorer concept of 2006 [23]
- Interstellar Medium Mission concepts 2015... [29, 31]

For assessment purposes, the performance projections of those technologies are accurate enough to proceed to mission trade studies. Thus, they are not subject to the assessment methods of this report. These concepts are however used as baselines and scaling examples in this study.

8.1.2. Era of Infrastructure

The era of infrastructure refers to propulsion and power concepts that are rooted in the established laws of physics and are a matter of further engineering. This is where the bulk of interstellar propulsion concepts reside. The reason this is called the era of infrastructure is because even the smallest payload example from this group (1 g) requires substantial new infrastructure, specifically a 100 GW laser array spanning 1 square km. Examples of concepts in this era include:

- Project Daedalus, 1978 [49]
- Forward's Microwave Staged Lightsails, 1984 [48]
- Project Icarus (started 2009) [79]
- Breakthrough StarShot, 2016 [7, 40, 57-62]

The performance projections of these concepts are ambitious and still unproven, making the use of traditional trade studies unreliable. The other unknown for each concept is the remaining time required to mature its suite of technologies to mission readiness. And lastly, these concepts assume that the required infrastructure already exists—but there are no roadmaps yet to develop that infrastructure. The process for estimating the dependency of the mission architectures on infrastructure is explained in Section 8.3.

8.1.3. Era of Breakthroughs

The era of breakthroughs refers to concepts aimed at the highest impact, revolutionary performance gains that go beyond extrapolation of existing technology. This requires further advances in physics. A starting reference for the span of these concepts and the next-step research required to further assess them, is the book, *Frontiers of Propulsion Science* [13]. Examples of concepts in this era include:

- Negative mass propulsion, 1957 [80, 81]
- Propellantless thrust via inertial fluctuations (1994), now called "Mach Effect Thruster" [82-86]
- Spacedrives, in general [87]
- Dynamical Casimir Effect, 2004 [88]
- Traversable wormholes, 1988 [11, 13 ch.15]
- Warp drive, 1994 [12, 13 ch.15]
- Faster than light communication [13 ch.16, 89-91]

In addition to propulsion and power breakthroughs, breakthroughs in communication can also play a powerful role in enhancing the mission—especially considering the impact on total mission duration. If FTL communication was possible, then the mission duration would be shortened up to a year for each light-year distance. The possibilities of FTL communication are discussed in the literature, including some quantum and other communication systems [89-91].

For assessment purposes, some of the breakthrough concepts have matured to the point where their propulsive energy can be calculated. For others, hypothetical analogs will need to be specified. In the case of generic spacedrives, for example, the propulsive energy can be modeled with basic kinetic energy and an efficiency factor for energy conversion. Section 8.4.4 describes the initial attempts for making estimates of this group.

Regarding their infrastructure dependence, this cannot be accurately determined until after they have been sufficiently advanced to TRL 3.

8.2. Baseline Mission & Payload Scenarios

To compare different propulsion and power methods equitably, the same payload and mission scenarios are employed. To begin this process, five test-case mission and payload scenarios are envisioned. These scenarios do not need to accurately match an actual mission, but are close representations to allow comparisons of the different technologies.

One of the seldom specified details of proposed interstellar mission architectures is how much data will be returned and at what rate. Without specifying the amount of data to return, it is not possible, even in principle, to compare different mission architectures with different data rates. That is why the payload specifications are fixed with these mission scenarios. For the first four scenarios, the baseline payload is 100 kg, which is roughly based on a 200 W communication system intended to transmit 8 Megabits of data (1 MB) and assuming contemporary technology. Though this is a small amount of data, it is a minimum threshold comparable to the first historic flybys of the Moon and Mars (Luna 3 and Mariner 4, respectively) shown in figure 6 in Section 7.2.2.2. For the orbiting scenario, the payload and data quantity are increased. The payload for an orbiter is 1,000 kg, with a data about of 16 Gigabits (2 GB), analogous to the first Mars orbiter, Mariner 9.

1) Solar Gravitational Lens, > 660 AU (0.1 x 10^{15} m, 0.01 ly)
2) Deep Interstellar Medium, > 27,000 AU (4.1 x 10^{15} m, 0.43 ly)
3) Centauri Flyby, > 270,000 AU (41 x 10^{15} m, 4.3 ly)
4) Centauri Slower Flyby, > 270,000 AU (41 x 10^{15} m, 4.3 ly)
5) Centauri Orbiter, = 270,000 AU (41 x 10^{15} m, 4.3 ly)

Plots of the data for the first three of these missions are provided in Section 9, using different hypothetical technology examples spanning the propulsion types described in Section 8.4.

In the final analysis system, individual mission choices can be specified. These initial examples are to verify that the assessment methods function as intended.

8.2.1. Solar Gravitational Lens

This mission in analogous the "FOCAL" missions of Claudio Maccone [36], and the more recent "Solar Gravitational Lens" mission of Slava Turyshev [37]. It involves sending an imaging payload out past 550 AU where focal length of the gravitational lensing of our Sun begins to appear (and continues outward). Using the magnifying effect it has been estimated that an exoplanet on the opposite of the Sun could be imaged to 10 km scale resolution.

There is also the possibility that the lensing effect can serve as a communications relay experiment for long-range microwave communication or optical communications relay for a high-data rate interstellar missions, and hence change the power requirements for a specified data rate. The reason this scenario is used is because it represents an actual purposeful location that is close to the threshold of what could be reached with precursor era technology. In other words, it is probably the first step to future, full-fledged interstellar missions.

8.2.2. Deep Interstellar Medium

In the vast void between the gravitational lens location all the way to the Centauri stars, there exist only sparse densities of comets and asteroids; the Hills cloud (2,000 AU), Oort cloud (10,000 AU), and the G-cloud (41,000 AU) [38]. Or in other words, it is the next easiest destination short of the big jump to Centauri. These features are difficult to discern using Earth-based astronomy, yet probes could make direct in-situ measurements. Consider a cloud sampler (particle and fields data, dust counters, radiation detectors) and discover how those values differ in different regions. Again a 100 kg payload mass and 200 W for communication is baselined.

8.2.3. Centauri Flyby

For the first flyby missions of an exoplanet, the analogy used to determine a minimum threshold of data is the first flybys of the Moon and Mars, specifically Luna 3 and Mariner 4, respectively. (see figure 6 in Section 7.2.2). The total quantity of data for each of these was roughly 8 megabits (1 MB). While this lowest threshold might seem too low, consider that Luna 3 showed enough to determine that the far side of the Moon was different than the front, and Mariner 4 showed that Mars was not like Earth.

8.2.4. Centauri Slower Flyby

This scenario has the same payload and data requirements of the simple flyby, but this scenario is introduced to consider the added value and expense of slowing down for the flyby.

8.2.5. Centauri Orbiter

To broaden the trade space, the more challenging and rewarding trajectory of entering orbit is included. In principle, the Δv of this mission is roughly twice that of flyby missions. The premise is that the spacecraft would have a telescope that could find all the “planet-sized” bodies in the system while approaching the system, and then have the ability to maneuver into an orbit around a target of interest (ideally perhaps with a flyby or two along the way of other bodies). Thereafter the spacecraft can observe long enough to see seasons, weather, imaging of the planet, solar wind and stellar activity, and send back this kind of data. For this scenario, the baseline payload and data quantity are increased. The payload is now 1,000 kg, with a data about of 16 Gigabits (2 GB), analogous to the first Mars orbiter, Mariner 9.

Ideally, propulsion for such maneuvers should be free of any dependence on propellant or beamed energy. They could either use onboard power or energy harvested as the spacecraft approaches the star system. If there is an ample stellar wind from the target star, then sail concepts like magnetic, plasma magnet, and electric could be considered.

This is also the kind of maneuver where the spacedrives of breakthrough propulsion physics apply. Or to rephrase; the ability to decelerate upon reaching the mission target, or more generally to maneuver without dependence on propellant or energy beamed from Earth, is a *goal* for which breakthroughs are sought. If the Mach

Effect Thruster, now under test, is found to be both feasible and scalable, then one of its higher-performing successors might make these double-delta-v missions achievable.

8.3. Measuring Infrastructure Dependence

This study includes the use of infrastructure as part of the total mission. For two concepts whose performance is otherwise equal, the one requiring less infrastructure is preferred. Consider the classic interstellar concepts like Daedalus or Forward's microwave sails which assumed the preexistence of a substantial in-space infrastructure. Which of those divergent approaches would require less time and energy to build, assuming all other factors were equal? For example: will it be easier to mine He3 from the atmospheres of the gas giants to support fusion propulsion, create a dedicated antimatter factory to support antimatter rockets, or to build TW lasers and 1000 km diameter Fresnel lenses? And in the course of answering those questions, which requisite technologies might be revealed to be more crucial or broadly applicable?

Recall the distinction between the *era of precursors* and the *era of infrastructure*. In the strictest sense, the *era of precursors* use established ground-based infrastructure and propulsion methods that are mature enough to proceed to trade studies. Hence those dependencies are not measured here. For true interstellar missions, however—the ones reaching to the nearest starts—new infrastructure is required. Regarding the *era of breakthroughs*, those concepts will fall into either the precursor or infrastructure era, on a case-by-case basis, depending on the scale of mass and energy required. Those concepts might need to be advanced to TRL 3 before such a determination can be rendered.

There is a split in the *era of infrastructure* concepts; those concepts that involve power beaming from the surface of the Earth (like StarShot), and those concepts that assume the use of preexisting in-space infrastructure (like Daedalus and Starwisp). These require two different assessment methods.

The fundamental units for comparing infrastructure dependence are mass, energy, and time. In principle, larger and more massive spacecraft will require more time and energy to build. The same is true for the systems that beam energy to the spacecraft.

For the ground based infrastructure systems, only the energy to build the beam system is measured, not mass nor the time to build that beam. This is because Earth-based construction will likely be considerably faster than in-space construction. For the in-space systems, both energy and time are measured. For the in-space scenarios, two factors need to be assessed, 1) predicting what infrastructure will be available for use over the future years, and 2) then estimating how much of that infrastructure is used to support the development of the mission.

These analyses are more *relative* than *deterministic*. In other words, the assessment can distinguish which mission plans will require more or less infrastructure, but will not be able to accurately predict how much time and energy that process will require.

One further note: It is reasonable to consider that the same kind of laser array considered for propulsion might also be the primary source of power delivery for the entire infrastructure. The assessment methods to include that possibility have not yet been established.

8.3.1. Earth-Based Beaming Infrastructure

For those concepts which aim for true interstellar distances (≥ 270,000 AU) and that assume their beaming infrastructure resides on the surface of the Earth, it is already possible to compare those systems against each other in terms of financial cost, instead of the more general measure of *energy* used throughout this study. To compare these concepts in energy terms, a conversion factor of \$0.06/kW-hour, or 60 MJ/\$ will be used. The economic theory behind this conversion [92] would be a lengthy discussion. Put simply, because energy is such a fundamental input to almost everything else made and used in civilization, the “real” cost of energy (in terms of how many goods and services a ‘unit of energy’ buys) changes very slowly with time. Small errors in the figure chosen as a conversion factor is not very serious in terms of comparing propulsion systems, so long as it is used consistently. The estimates for capital cost of a given beam can then be converted to energy terms using that conversion factor. If inventions change the capital cost of a given type of beam (lower \$/Watt), then that is essentially equivalent to improving the “propulsion efficiency” of that type of beam, in that the lower \$/Watt of beam power shows up in the comparison charts as a lower “total energy” (because of the reduced capital cost of the installation, expressed in energy terms).

It is conceivable that some Earth-based infrastructure might also have in-space components (hybrid concepts such as ground based optical beams with space-based focusing optics, or space-based particle beams with their power fed from the ground, are possible). The cost to create these new elements can be estimated by the launch costs ($/kg, J/kg) required to get that hardware into its orbital position.

8.3.2. Estimating In-Space Infrastructure Availability and Growth

For the more general suite of interstellar concepts that presume the existence of in-space infrastructure, the two major questions are" "When will the needed infrastructure be ready to support the mission?" and "How much will it cost in energy and time to use that infrastructure to build and launch the mission hardware?"

Currently, there are no substantive predictions about in-space infrastructure capacity and growth. As a starting point, the author sought the opinions from a number of subject matter experts (discussions with Brandt, Lewis, and Lubin, and cited values from Hoffman, Klupar) and merged them together to produce table 10 (with subjective compromises for mismatched predictions). Note how many fields remain unspecified. The rest of this table will be populated with estimates in Stage II of this work.

To get a grounding reference to scale the situation, the growth of world energy production has been extrapolated to fill out the first row in table 10. The data behind those extrapolations span 1888 through 2017 [46-47]. In the second row those values are converted into equivalent power (J/yr into J/s=W). The third row contains estimates from subject matter experts.

Since these projections will be used for *relative* comparisons only, it is not necessary that these growth projections be accurate. They only need set an approximate scale and then have that scale used consistently throughout the rest of the analyses.

Table 10. In-Space Infrastructure Availability and Growth Estimates

	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
REFERENCE POINT: World Energy Production Extrapolation,	5.3×10^{20}	6.4×10^{20}	7.6×10^{20}	9.1×10^{20}	1.0×10^{21}	1.2×10^{21}	1.5×10^{21}	1.7×10^{21}	2.0×10^{21}	2.3×10^{21}
REF: World Equivalent Power Capacity, (W)	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}	5.3×10^{13}
Predicted Infrastructure Available Power, (W)		1×10^{8}	2×10^{9}	1×10^{10}					3×10^{13}	
Functionalities:										
Mining Capacity (kg/yr) Specific Energy (J/kg)		 10^{0} -	 10^{5} -							
Material Processing Capacity (kg/yr) Specific Energy (J/kg)										
Manufacturing & Construction Capacity (kg/yr) Specific Energy (J/kg)										
Connecting Transportation Capacity (kg/yr) Specific Energy (J/kg)										

The lower rows of table 10 refer to both the *capacities* (kg/yr) and *specific energies* (J/kg) of the various infrastructure functions:

- Mining raw materials (including propellants)
- Processing the raw materials into usable stock [100 MJ/kg aluminum?]
- Manufacturing components from stock
- Constructing objects from components and stock
- Transporting items within the infrastructure

Infrastructure Use Specific Energy, *Esi* (J/kg): For the analyses that follow, the *specific energies* for each of those functions will need to be estimated during stage-II. The sum of those specific energies will then represents the total Infrastructure Use Specific Energy, *Esi*, to be used when calculating the use of infrastructure. It is assumed that theses values might change over the decades of progress.

Infrastructure Available Power, *Pia* (W): The other key descriptor for the infrastructure will be Infrastructure Available Power, *Pia*, whose values will significantly change over the decades of progress, as provisionally indicated in the 3rd row of table 10. That factor will be used to determine how quickly the infrastructure energy can be expended, to estimate how long it takes to build things in space. Ideally, it would be more accurate to create a measure of infrastructure capacity, (kg/yr), from the estimates for the *capacity* for each of those functions. In the absence of that more detailed information, however, the more basic measure of Infrastructure Available Power, *Pia* (W), will have to be estimated as used for estimating how quickly things can be built with the infrastructure. Note that the only estimates obtained so far for capacity are for mining (kg/yr) for the 2030 and 2040 decades.

8.3.3. Estimating In-Space Infrastructure Usage

In principle, larger and more massive spacecraft will require more time and energy to build. The same is true for any beaming system for the mission. Thus, the first step of assessing infrastructure dependence requires knowing the total mass of the spacecraft and any supporting launch (beaming) hardware (whose calculations are described in Section 8.4):

- Spacecraft Launch Mass, *Msl,* (kg)
- Base Hardware Mass, *Mb,* (kg)

Spacecraft Hardware Build Energy, *Esc* (J): This is the measure of how much energy is required from the infrastructure to build the spacecraft. It is the product of the Spacecraft Launch Mass, *Msl,* (kg) and Infrastructure Use Specific Energy, *Esi*, (J/kg).

Base Hardware Build Energy, *Eb* (J): This is the measure of how much energy is required from the infrastructure to build the base hardware. It is the product of the Base Hardware Mass, *Mb,* (kg) and Infrastructure Use Specific Energy, *Esi*, (J/kg).

Total Infrastructure Energy Expense, *Eti*, (J): This is the sum of both the spacecraft and base hardware build energies, representing the total amount of energy needed to prepare the mission. The propulsive energy to perform the mission is discussed in Section 8.4.

The next question is: "how long will it take to build those objects?" The crude model used as a starting point is to divide the *Build Energies* by the Infrastructure's Available Power, *Pia*, (W), and convert the answer from seconds to years, whose sum is the variable named **Mission Development Duration**, *Tdev* (yrs).

Spacecraft Build (develop) Duration, *Tscd* (yr): This is the measure of how long it will take to build the spacecraft, calculated by dividing the Spacecraft Hardware Build Energy, *Esc*, by the Infrastructure's Available Power, *Pia*, (W), and convert the answer from seconds to years.

Base Hardware (develop) Duration, *Tbd* (yr): This is the measure of how long it will take to build the Base Hardware (like laser arrays), calculated by dividing the Base Hardware Build Energy, *Esc*, by the Infrastructure's Available Power, *Pia*, (W), and convert the answer from seconds to years.

8.4. Measuring Disparate Propulsion & Power

This is part of the more deterministic portion of the analyses. The objective is to quantify the performance of each propulsion and power concept with respect to payload mass and total mission ΔV. The challenge is that the propulsion concepts are significantly different, each with its own components and figures of merit. For example, rocket performance is described in terms of specific impulse and thrust. Laser-sail performance is described in terms of beam power, beam divergence, etc. To compare these disparate methods equitably, the strategy is to reduce each to the most fundamental physics measurements of energy, mass, time, and power. In essence, energy is the fundamental currency of all motion. Specifically, this requires converting their usual performance parameters into the following more basic measures that are used in other parts of the analysis:

- Total Propulsion Energy, *Etp* (J)
- Spacecraft Launch Mass, *Msl* (kg)
- Base Hardware Mass, *Mb* (kg) (For in-space infrastructure)
- Energy Cost of Beam, *Ebhw* ($, converted to J using a J/$ scaling factor, for Earth surface hardware)

From these measures, other figures of merit can be calculated. To accommodate the span of possibilities, four different analysis techniques have been developed to cover the range of the power and propulsion methods. The distinctions depend on if the concept's power is received from an external source (R) or internally (I), and if their reaction mass is onboard (O) or external (X). The variables associated with each of these distinct assessments are listed in table 6, "List of Variables," along with annotations of which variables apply to which group.

Table 11. Power & Propulsion Analysis Types

Propulsion Type	Examples	Power Source	Reaction Mass
IP-OM	Chemical Rocket Nuclear Rocket	Internal	Onboard
RP-OM	Solar Thermal Rocket Laser (or solar) Electric Propulsion	Received	Onboard
RP-XM	Laser (or solar) Sail Particle Beam	Received	External
IP-XM	Plasma Magnetic Sail SpaceDrive	Internal	External

At this stage, only some of the conversion methods have been outlined, with further refinements to occur in Stage II. Also, for this first introductory stage, the proposed equations are nonrelativistic. This is a reasonable initial assumption since relativistic changes do not become significant (> 1.0% change) until past 14% lightspeed. In Stage II the relativistic equations will be included.

It should be noted that this approach is not the only method for analyzing missions in more general terms. In particular there is the "method of equivalent lengths" for both "energy limited" (e.g., chemical, high-thrust systems) and "power limited" (e.g., low thrust ion propulsion) systems [93-97].

Another caveat is that this starting assessment assumes that the same propulsion method is used for the entire journey. Future refinements would include assessing the merit of different propulsion types at different stages of the mission. For example, consider the prospects of accelerating the craft first by laser, then later by rocket, and then braking perhaps with a magnetic sail. It has been postulated that rockets might make better second stages, while laser propulsion would make better first stages. This is because the laser performance decreases as the spacecraft increases speed, and the ΔV of a rocket is independent of its velocity at ignition. Further refinements are necessary to evaluate such trades.

8.4.1. Type IP-OM: Internal Power & Onboard Reaction Mass

This type refers to systems which carry their own energy supply and reaction mass, such as chemical rockets, nuclear thermal rockets, nuclear-electric rockets, and antimatter rockets. For this case, there is no beam system.

Energy in the Reaction Mass

The key performance characteristics of concepts in this category, where the propellant is also the energy source, can be distilled to these two parameters:

- Propellant Specific Energy, *Esp* (J/kg)
- Propulsion System Specific Power, *Psp* (W/kg)

A given propellant has its unique specific energy *Esp* (J/kg), and a given propulsion method has an overall thrust conversion efficiency η (the fraction of the energy in the propellant which appears in the exhaust stream power). Energy which is lost to space, turned in to waste heat for the cooling system, etc., does not appear propulsively and so only that portion of the energy which appears in the exhaust stream is suitable for computing exhaust velocity and subsequent parameters. The amount of waste heat has an important impact on the mass of the spacecraft system (radiators, for example), discussed later.

An overall propulsion system (defined here to include all the spacecraft masses except payload and propellant) has a unique Propulsion System Specific Power, *Psp* (W/kg), that can be expressed in terms of the jet power *Pj* (W), propellant mass flow rate, *dm/dt* (kg/s), thrust force, *F* (N), and effective exhaust velocity, *Ve* (m/s).

$$P_j = \frac{1}{2}\left(\frac{dm}{dt}\right)V_e{}^2 = \left(\frac{dm}{dt}\right)E_{sp}\eta \qquad \text{Eq. 3}$$

From this it follows that:

$$V_e = \sqrt{2E_{sp}\eta} \qquad \text{Eq. 4}$$

Where

$$F = \left(\frac{dm}{dt}\right)V_e \qquad \text{Eq. 5}$$

So either the effective exhaust velocity, *Ve* (m/s), or propellant specific energy, *Esp* (J/kg) can be used, as convenient.

The relation between the mass of the spacecraft, *Mse* (kg), and the Propulsion System Specific Power, *Psp* (W/kg) is:

$$P_{sp} = \frac{P_j}{M_{se}} \qquad \text{Eq. 6}$$

where the mass of the spacecraft (empty and without payload), *Mse* (kg) is defined to include:

- Propellant storage
- Engine
- Nozzle
- Radiators
- Remaining spacecraft structure and elements (typically insignificant to those other masses)

For equitable comparisons, any design parameters used to calculate the masses of those subsystems should be identified. When comparing competing concepts that use common systems (tankage, radiators, etc.) they should all use the same design parameters. For example, concepts that use the same propellant should use the same tankage fraction (kg-tank/kg-propellant), and concepts which use the same radiator technology should use the same radiator specific masses (W/kg). The exception to this is when the competing systems that are based on different *mission commitment years*, *Ym*, where those design specs might have improved for the later model. Tracking how the design parameters might improve over the years is covered in Section 8.5.3.

Therefore, from this relation it can be seen that the Propulsion System Specific Power controls acceleration:

$$a = \frac{F}{M_{se}} = \frac{2}{V_e}P_{sp} \qquad \text{Eq. 7}$$

The achievable change in velocity in free space, *ΔV*, comes from the familiar rocket equation (burnout form which assumes thrusting time is << trip time. Note: Chemical and nuclear rockets usually have very high thrust to weight {high *Psp*} and hence, the thrusting time is << trip time. This is not necessarily true for other systems.):

$$\Delta V = \ln\left(\frac{M_{se} + M_{pay} + M_p}{M_{se} + M_{pay}}\right) \qquad \text{Eq. 8}$$

And where:

M_{se} = Empty Mass of Spacecraft associate with Propulsion System Specific Power (kg)
M_{pay} = Mass of Payload (kg)
M_p = Mass of Propellant expended (kg)

From these, the Spacecraft Launch Mass, *Msl* (kg)—a value used in other portions of the analysis—is:

$$M_{sl} = M_{se} + M_{pay} + M_p \qquad \text{Eq. 9}$$

Acceleration can be integrated for changing mass ratio, and for relativistic cases, should be. An approximation used here is based on average acceleration. Average acceleration, $\bar{a}$, (if not artificially limited to reduce loads on the payload), is then simply thrust, F, divided by the spacecraft empty mass, payload mass, and half the mass of the propellant as shown:

$$\bar{a} = \frac{F}{M_{se} + M_{pay} + \frac{1}{2}M_p} \qquad \text{Eq. 10}$$

For a flyby mission, the relationship between the total mission *ΔV*; acceleration (ave), $\bar{a}$; acceleration time, *Ta*; acceleration distance, *Da*; coasting time, *Tc*; mission distance, *Dd*; and trip time, *Tt*; follow these relations:

$$\begin{aligned} T_a &= \frac{\Delta V}{\bar{a}} \\ D_a &= \frac{1}{2}\bar{a}{T_a}^2 \\ T_c &= \frac{D_d - D_a}{\Delta V} \\ T_t &= T_a + T_c \end{aligned} \qquad \text{Eq. 11}$$

Recall the other mission time parameter, Data Transmission Duration, *Tx*, discussed in Section 7.2.2, and 7.3.

For orbiter missions, one must also account for braking time and braking energy, both of which can be significant. For that reason, orbiter missions often use a different propulsion method for braking. The extension from the above equations for type IP-OM systems is straightforward—half the delta-V available to accelerate, and half to brake. If another type of system is used, compute the braking time as appropriate for that system, and add it to the mission time.

Energy Separate From the Reaction Mass

This sub-category of IP-OM types refers to systems like nuclear electric propulsion, where a separate power source (e.g., nuclear reactor) supplies energy to a rocket to expel an inert propellant (e.g., Xenon ion thruster). These are usually treated in terms of specific power (kW/kg) or alpha (kg/kW), and specific impulse (or effective exhaust velocity).

However, in these cases, “propellant specific energy” doesn’t fit. One cannot turn the energy into thrust without the reaction mass (propellant). A general assumption can be made that one runs out of propellant before running out of energy. Therefore, treating the propellant capacity as the limiting factor, there may indeed be a meaningful specific energy to define. Still, in any given case, the achievable acceleration and *ΔV* are usually clear from the particular apparatus in question.

8.4.2. Type RP-OM: Received Power & Onboard Reaction Mass

This type refers to systems which receive energy from external sources but carry their own reaction mass, such as solar-electric or solar-thermal rockets, or laser-illuminated electric or thermal rockets. The initial analysis provided here addresses the case of ground-based beam infrastructures which draw their power from the electrical grid. Their calculations for the *propulsion energy* also applies for the case of space-based infrastructure, but the additional cost to create that space-based hardware is explained in Section 8.3.3. Recall that the parameters that need to be calculated from the specifics of these types of propulsion include:

- Total Propulsion Energy, *Etp* (J)
- Spacecraft Launch Mass, *Msl* (kg)
- Energy Cost of Beam, *Ebhw* ($, converted to J using a J/$ scaling factor)
- Base Hardware Mass, *Mb* (kg) (For in-space infrastructure) [not yet addressed]

For The Spacecraft Portion

As these are still rockets, the equations of Section 8.4.1 still apply as far as computing trip time. However, now the jet velocity, *Ve*, is no longer determined by the energy intrinsic to the propellant as in type IP-OM, it is instead an adjustable parameter (within the limits defined by a given thruster technology; some thrusters have a narrow range of exhaust velocities, some a wide range). A given mission design therefore needs to specify the specific energy imparted to the reaction mass (alternatively, the exhaust velocity and thrust efficiency, which is equivalent, eq 5). In general, these systems are usually employed with total velocity change (ΔV) which is comparable to or less than the exhaust velocity because the mass of power receptions and thrusters are often high enough to be incompatible with high mass ratios. Efforts to circumvent those limitations are ongoing.

The Propulsion System Specific Power *Psp* of these systems is usually dominated by the power supply, and affiliated systems, sometimes mistakenly neglected in naïve analyses, such as power conversion machinery and radiators for waste heat.

Furthermore, acceleration has to be analyzed in two phases: 1) when the beam or solar radiation fully illuminates the receiver at the limit of the power capacity of the spacecraft—in which case, it is the spacecraft which determines the attainable acceleration, and 2) when the spacecraft is too far to intercept full power of the beam, in which case the beam's divergence causes available power to drop off with distance. A similar case exists for solar-electric propulsion, when the falloff of sunlight ($1/r^2$) drops below the limit of the power capacity of the spacecraft.

For the Beam Portion

The process specified here is for ground-based beam systems, where the beam's figures of merit are usually discussed as $/watt of beam power, and $/square meter of transmitter aperture. Thus the first generally relevant figure of merit for beams is:

$$\text{Beam Source Cost Scaling} = \frac{\text{Cost of Beam Source } (\$)}{\text{Power of Beam Source } (W)} \qquad \text{Eq. 12}$$

Where "Beam Source" is the energy supplied to the beam, in terms of the beam's output power.

Since beams are, very roughly, characterized by a certain cost per unit area of aperture, and twice the aperture radius gives half the divergence angle, but four times the area, that implies a beam with half the divergence angle has the "aperture contribution" to beam cost roughly four times higher.

Note that it is really the divergence angle of the beam that controls what the beam can do—different beams have different divergence properties that scale differently with aperture. Therefore, to define a figure of merit which is suitable for comparing *both* optical and particle beams, we want a figure of merit that is based on divergence angle. For *optical* beams, divergence angle is proportional to wavelength, and inversely proportional to the radius of the aperture. The beam director cost factor for an *optical* beam would be: Beam Director Cost ÷ Aperture Area, ($\$/m^2$).

But that doesn't work for other types of beams, including synthetic sparse apertures and particle beams, especially beams that include a degree of self-focusing. Instead, the second generally relevant figure of merit for beams is defined here as:

$$\text{Beam Director Cost Scaling} = \text{Divergence Angle (radians)} \times \sqrt{\text{Beam Director Cost } (\$)} \qquad \text{Eq. 13}$$

Where "Beam Director" is the aperture-scaled hardware for focusing the beam. The utility of that rather odd factor is clearer when put in terms of cost:

$$\text{Cost (\$)} = \left(\frac{\text{Beam Director Cost Scaling}\left(\text{radians}\big/\sqrt{\$}\right)}{\text{Divergence Angle}\left(\text{radians}\right)} \right)^2 \qquad \text{Eq. 14}$$

It is obvious that a smaller divergence angle (tighter beam), gives a higher cost. So the divergence angle has to be in the denominator. Because of the scaling being such that, very approximately, half the divergence angle tends to be four times (or more) the cost, not twice. Given those two factors for a given beam technology, other beams of higher or lower power, or smaller or larger divergence angle, can be roughly estimated.

8.4.3. Type RP-XM: Received Power & External Reaction Mass

This type refers to systems in which both the reaction mass and energy are supplied from external sources, such as solar sails, solar-wind magnetic sails, laser-pushed lightsails, and particle beam pushed magnetic sails. It also covers “pellet runway” concepts in which pellets, prepositioned ahead of the spacecraft, contain an energy source that the spacecraft uses to accelerate those pellets as a reaction mass (such as fusion-fuel pellets, e.g., Jordan Kare's "Bussard Buzz Bomb," an idea not published in journal form, but discussed in [98 p.112]).

While the details of each such system are quite different, and it takes some careful consideration of each system to fit it in to the overall comparison framework, they can be compared to each other, and to other systems, with the following approach.

As discussed in “Type RP-OM,” a given power transmitted by the beam, *Pgb* (W), and a given divergence angle, Θ (radians), is characterized by a beam source cost scaling factor (\$/W) and a beam director cost scaling factor (radians/√\$). A given beam also has a given speed of the energy transmission, *Vb* (m/s), which is the speed of light for photons and less for particle beams. For particle systems, the speed of the beam can be varied during the mission which is a powerful tool for optimizing total energy used.

The beam in turn pushes on something, called here the “receiver”—which has a characteristic ‘Areal Density’ (that is, mass, per unit area of the receiver, kg/m^2), and a ‘Flux Limit’ (the maximum power per unit area of the receiver, usually set by thermal limits of the materials, W/m^2). When the receiver is saturated, operating at its power limit, we can define the now-familiar Propulsion System Specific Power *Psp* for this situation:

$$P_{sp} = \frac{\text{Receiver Flux Limit}\left(\text{W/m}^2\right)}{\text{Receiver Areal Density}\left(\text{kg/m}^2\right)} \qquad \text{Eq. 15}$$

As in more conventional forms of propulsion, the specific power in turn controls acceleration, while the beam is saturated. In the general case, however, there are usually two distinct phases of flight, 1) limited by the receiver, in which the receiver is saturated and taking all the power it can handle, and 2) limited by the transmitter, in which the receiver area (and mass) is determined not by power limitations, but by the divergence of the transmitting beam. For any given concept, it is usually clear how to handle these to develop overall trip times. However, the optimization of trip time for a given set of technology assumptions is not always straightforward. In order to be able to handle the variables, a concept should list both the areal density (kg/m^2) and the flux limit (W/m^2) of the receiver, because some calculations need the parameters broken out.

Acceleration (Thrust/Mass) is then integrated over time to get velocity change. While in a realistic situation, the thrust tapers off as the beam diverges and less and less power is intercepted by the receiver, the equations have the same form as if the beam simply had a finite range. For example, Lubin has determined that for photon sails, the maximum velocity change is 1.4x the velocity obtained if the beam were cut off when the sail no longer intercepts the full beam (Beam Range Limit, *Dbl*) [99]. Therefore, while there is a correction factor (of order less than two), the velocity gain becomes:

$$\Delta V = \text{Beam Range Limit Correction Factor} \times \sqrt{2\left(\frac{F}{M_{sl}}\right)D_{bl}} \qquad \text{Eq. 16}$$

Where:

Msl = Spacecraft Launch Mass (= Payload + Spacecraft Empty Mass,) (kg)
Dbl = Distance of Beam Range Limit (m)

The Beam Range Limit, *Dbl*, is determined by the divergence angle of the beam and the aperture of the receiver.

For Photon Beams:

For non-relativistic spacecraft speeds, the thrust for a photon beam is simply the power transmitted by the beam, *Pbx* (W), divided by lightspeed:

$$F = \frac{P_{bx}}{c} \qquad \text{Eq. 17}$$

For relativistic spacecraft speeds, one must reduce the value of beam power due to Doppler shift of the incoming beam.

The power to generate that photon beam, *Pgb* (W), is simply:

$$P_{gb} = \frac{P_{bx}}{\eta_B} \qquad \text{Eq. 18}$$

Where:

Pgb = Power to generate the beam
Pbx = Power transmitted by the beam
η_B = Power efficiency of generating the beam

For Particle Beams:

The nonrelativistic thrust for a particle beam is:

$$F = \left(\frac{dm}{dt}\right)\left(V_b - V_s\right) \qquad \text{Eq. 19}$$

Where:

dm/dt = Participle Beam Mass Flow Rate (kg/s)
Vb = Particle Beam Velocity (m/s)
Vs = Velocity of Spacecraft (m/s)

The power to generate that particle beam, *Pgb* (W), is:

$$P_{gb} = \frac{\frac{1}{2}\left(\frac{dm}{dt}\right){V_b}^2}{\eta_B} \qquad \text{Eq. 20}$$

Where:

Pgb = Power to generate the beam (W)
dm/dt = Participle Beam Mass Flow Rate (kg/s)
Vb = Particle Beam Velocity (m/s)
η_B = Power efficiency of generating the beam (%)

The energy cost for the beam is then the sum of the energy actually used in generating the beam times the acceleration duration (beam on) (*Pgb* x *Ta*) and the “energy cost equivalent” of the beam and the beam director (discussed in Sections 8.3.1 and 8.4.2).

For a given mission concept, all these factors can be adjusted to optimize trip time and power for a given destination, so a single number does not really express the capabilities and one must explore how the system scales to destinations of different distances at different power levels, generating a set of contours. This is the plan for presenting the (deterministic) data for the concepts so they can be meaningfully compared (see Section 9 for sample plots).

The same physics discussed above applies to "sailbeam" concepts in which, rather than launching particles or photons to the spacecraft, we use a photon or particle beam to push some kind of "nano-craft" or "chipsat" or "smart pellet" which have some ability to correct their own trajectory and thus home-in on a traveling craft [100]. This approach allows the resulting "smart pellets" to be used as propulsive mass by a suitable receiver on an accelerating spacecraft. This effectively creates a divergence-free beam, allowing for much longer acceleration times and hence lower power levels, balanced against the potentially higher cost (converted to energy equivalent) of the pellets and the added mass of a shock-absorbing system on the spacecraft (since each 'pellet' imparts an impulse to the spacecraft that is large compared to a photon or elementary particle).

The last class of concept of type RP-XM is the "pellet runway" [98 p.112]. The physics of this approach is somewhat different—in a pellet runway, rather than shooting "smart pellets" at the spacecraft, the pellets are launched *before* the spacecraft, and the spacecraft "runs over" the pellets as it accelerates. While this is purely type RP-XM by the nomenclature, the analysis is a hybrid approach—the launching of the pellets (and the energy equivalent of that), is computed using the equations of this section. However, the pellets, containing both the energy and the reaction mass, require some modification of the 'propeller equations' discussed under type IP-XM in the following section. For the majority of the trajectory in which the speed at which the spacecraft encounters the pellets, *Vip* (m/s) is large compared to the increase in velocity provided by the 'jet', the thrust is controlled by the specific energy of the pellets, *Esp*, and their thrust conversion efficiency η (as with type IP-OM), and one can approximate the thrust as:

$$F \approx \left(\frac{dm}{dt}\right)\left(\sqrt{2E_{sp}\eta + V_{ip}^{\ 2}} - V_{ip}\right) \qquad \text{Eq. 21}$$

Where:

dm/dt = Participle Beam Mass Flow Rate into the spacecraft (kg/s)

Esp = Pellet Specific Energy, where the pellets are both a reaction mass and carry energy (J/kg)

η = Thrust conversion efficiency (%)

From this one can see that the mass flow required for a given thrust rises with the speed that the spacecraft encounters the pellets, until the power limit of the machinery that converts the pellets to thrust (a reaction chamber and nozzle) is reached. The beam cost in this approach is potentially much lower, because the pellet speeds can be much lower. However, the mission time is increased, because to the flight time must be added the time to pre-position the pellets; that factor limits the potential energy savings.

8.4.4. Type IP-XM: Internal Power & External Reaction Mass

This type refers to systems which receive reaction mass from external sources but carry their own energy. This is analogous to aircraft engines, where air is the reaction mass, and the energy source is the fuel. In terms of interstellar flight, this includes, for example, Bussard ramjets that gather protons and accelerate them with the help of onboard energy [101], and spacedrives that convert some form of stored energy into propulsive motion (kinetic energy) using as-yet-unconfirmed physics [82-87].

This category also includes "drag devices" such as magnetic sails (magsails) or plasma magnet sails. These devices are possible solutions to the challenge of braking at the destination. Without braking, the flyby time is very short. See table 8 in Section 7.2.1 for examples. After a flight time of decades, a flyby time of just hours seems disproportionate and would limit the fidelity of observations.

Therefore, the problem is not only one of how to get up to speed, but how to get rid of the speed. Drag devices—devices that serve the same purpose in interstellar flight as do aerobrakes and parachutes in planetary exploration—in principle dissipate the kinetic energy of the spacecraft against something else (usually, the ionized gases in the interstellar medium).

Finally, there is a class of potential "plasma wave" drive concepts in which traveling waves are launched in to the interstellar medium at a velocity far below the speed of light, and the resulting reaction force propels the spacecraft [102]. These are usually low specific power (low thrust) drives but they use the surrounding medium as reaction mass. Such an ability is similar to the goal of a spacedrive, but using existing physics.

Depending on the nature of the reaction mass, the analysis methods vary. For things like plasma, interstellar protons, or stellar wind, analogies to aircraft propellers can be used. For new breakthrough propulsion physics (devices that can be viewed as using inertial frames or the properties of spacetime as an effective reaction mass), then other techniques are suitable.

Plasma Reaction Mass:

For concepts that interact with plasmas or interstellar protons, the fundamentals of conservation of energy and momentum result in the 'propeller equations' familiar for propeller and air-breathing jet operation within an atmosphere can be used:

$$P = \frac{1}{2}\left(\frac{dm}{dt}\right)\left[\left(V_{sm} + \Delta V_t\right)^2 - \left(V_{sm}\right)^2\right] \qquad \text{Eq. 22}$$

Where:

dm/dt = Mass Flow Rate of media through thruster (kg/s)
Vsm = Velocity of spacecraft through media (m/s)
ΔVt = Delta V of media by thrusting effect (m/s)

And where:

$$F = \left(\frac{dm}{dt}\right)\Delta V_t \qquad \text{Eq. 23}$$

In the case of interacting with the interstellar medium, during the dominant part of the trajectory, the speed of the spacecraft through the media, Vsm, is much higher than the delta V that the thrusting effect can impart to a portion of that media, ΔVt ($Vsm >> \Delta Vt$). In that case, the power equation can be approximated by the much simpler form which illuminates the fundamental truth of all such propulsion—that the faster the spacecraft, the higher the power requirements:

$$P \approx F \times V_{sm} \qquad \text{Eq. 24}$$

For acceleration using plasma reaction, Propulsion System Specific Power (*Psp*) of these propulsion systems is still very important; usually this is dominated by the power supply carried with the spacecraft. Because Type IP-XM systems are not limited by their stored reaction mass, the energy content of the power supply is what ultimately controls the ΔV available.

$$\Delta V = \frac{F}{M_{sl}} T_a \qquad \text{Eq. 25}$$

Where:

ΔV = Change in velocity imparted to the spacecraft, (m/s)
Msl = Spacecraft Launch Mass (= Payload + Spacecraft Empty Mass), (kg)
Ta = Acceleration Duration (s)

This applies both to thrust and drag devices—however, while available power supplies tend to have low *Psp* and hence low accelerations, some drag devices offer high decelerations because they are dissipating power in to the interstellar plasma rather than consuming it. Drag devices may be power-limited (in which case they can be modeled as thrust devices), or they may have a constant "ballistic coefficient" like a parachute, in which case their drag varies with the square of the velocity through the medium, *Vsm.*

In the case where *Vsm* is high, one also must check whether thrust, *F*, needs to be replaced by a "net thrust" or thrust minus drag. It may seem counterintuitive that one would be concerned with "drag" in the thin interstellar medium, but devices to collect reaction mass, almost by definition, have some way of interacting with the interstellar medium and so do offer drag. Neglecting this led to some early over-estimates of performance of some types of Bussard ramjets, for example. While the means of estimating drag is rather specific to the particular device in question, it is usually sufficient for comparison purposes to check if it is significant at the speeds in question (it often is not), and to account for it only in cases where this is not so.

Spacetime & Inertial Frames as Effective Reaction Mass:

Concepts like negative mass propulsion, the Mach Effect Thruster, and the warp drive all face the challenge of an ambiguous reaction mass. Regardless of those specifics, the techniques to estimate their performance can be crudely estimated in terms of converting stored energy into kinetic energy of the spacecraft, with some conversion efficiency, η, and a Propulsion System Specific Power, Psp, (W/kg). Absent of better values, comparable efficiencies and specific powers from other concepts can be considered as a starting point.

For the special case of the warp drive, energy conversion equations exist [13 p.491, 103], but there are no equations yet that remotely resemble Propulsion System Specific Power.

8.5. Estimating Comparative Rates of Advancement

The timescales for interstellar missions are comparable to prior technological revolutions (figure 3). Thus it is entirely possible that a revolutionary technology will emerge and surpass the performance of a more evolutionary technology already in development. But how does one predict if, and when, that might happen and what to do about it?

Recall that the objective of this study is not just to reveal which propulsion concepts might be the most advantageous (and under which circumstances), but also to identify the most impactive supporting technologies to guide the selection of a prudent portfolio of next-step research. This requires developing methods to estimate, not only the impact of a particular technology, but also estimate when that technology might be ready for mission commitment.

While it is not possible to predict the future, technology developments do follow patterns that can be used as a guide. First, there are the "Technology Readiness Levels (TRL)," that are both a way to assess the readiness of a given technology as well as identifying what further steps are needed to advance that technology to mission readiness. Second, there is the "S-curve" pattern to technological improvements and revolutions that suggest how to model that process [41]. Another source under consideration is the "Technology Forecasting and Readiness Assessment" methods of Darryl Web, et al [104].

There are at least two distinctly different rates of advancements to model: 1) where the performance values of mission-ready (TRL ≥ 6) technology improve over the years, and 2) where potential increases in performance levels advance up the TRL scales, from concept to mission readiness. That first type, advancing performance over time, pertains mostly to baseline technologies shared by the different propulsion of power concepts (such as payload miniaturization). That second type, the maturation of new performance abilities, pertains more to the propulsion and power concepts being assessed.

All of these assessments will be *relative* rather than *absolute*. In other words, the assessment will judge if one technology might reach fruition before another, but will not be able to accurately predict the actual time when either will reach fruition. The key here, is that all the competing methods are compared to the same standards.

Caveat: At this time, none of these predictive tools have been completed and tested. This is an area where much will be learned in the attempt, but predicting the future, even in relative terms, carries with it a great deal of uncertainty. Absent of any alternatives, however, these methods are at least a starting point.

8.5.1. Baseline Performance Trends

To equitably compare different propulsion and power concepts, it is necessary that the parameters that they share in common be set to the same, baseline values. As previously discussed, identical payload and ΔV requirements are imposed when comparing different propulsion concepts. In addition, this is extended here to include common subsystem technologies that are the same across different propulsion methods, such as thermal radiators, tankage fraction (for the same propellant-based systems), and energy density for systems using the same energy storage technology.

These baseline values, however, will change over the years. To compare the overall performance of missions begun in different years, the rates and limits of these trends will have to be modeled. For consistency with the definition of "Mission Commitment Year, Ym," described in Section 7.3, the values estimated for each year shall be those that have reached TRL ≥ 6. Table 16 shows an example of how this tracking might begin. Note that the last column is labeled "physics limit." Trends can hit a limit. Miniaturization will reach a point where the number of molecules per function cannot be further reduced. An example of a real propulsion limit is the maximum theoretical *Isp* of hydrogen-oxygen rockets, which is 528.5 sec Isp, (based on 100% conversion of stored energy into kinetic energy and a propellant specific energy of 13.43 MJ/kg).

It is expected that these trends can be modeled by exponential equations or nested S-curves (Section 8.5.3). To guide those equations, data on the performance level changes over the years and any limits (to set asymptotes) is required.

Table 12. Tracking Advancement Trends of Common Technologies

Trends to Model Performance levels of TRL-6 technology	2020	2030	2040	...	Physics Limit
Available Mission Energy (J/y) (see table 10.)	5E+14 ?	6E+14 ?	8E+14 ?		none?
Payload Mass (by Miniaturization) (kg/function)	30 kg ?		1 g ?		?
Shared Design Standards					
Power Source Power Density (W/kg)	0.5 kw/kg ?				
Energy Storage Density (J/kg)					c^2
Tankage Fraction (for a given propellant)	3.7% (STS ET)				
Radiator specific mass (kg/W)					
Etc.					

Related to these are the advancement rates for infrastructure readiness. This was already discussed in Sections 7.3 and 8.3. and repeated here for contextual reference.

8.5.2. Technology Maturation Rates

New power and propulsion concepts that show promise for increased performance (such as higher *Isp*, higher thrust, or lower beam divergence) will have to advance up the "Technology Readiness Levels (TRL)" to the point of being ready for mission consideration (TRL ≥6). But how long will it take for the technology to advance through the technology readiness levels?

The Technology Readiness Levels are both a way to assess the readiness of a given technology as well as identifying what further steps are needed to advance that technology to mission readiness. A possible tactic is to use the TRLs as a proportional scale of advancement time, where the time to advance from TRL-n to TRL-n+1 and the time to advance from TRL-n+1 to TRL-n+2 follow similar ratios. Granted, there are significant variations that render this tactic inexact, but if used just for relative, rather than absolute, comparisons, then it is a fair starting point. A provisional proportionality of TRL advancement durations is presented in table 13.

Note that table 13 also lists "SRLs," "Scientific Readiness Levels," for the scientific advancement that precede new technology. The levels shown are adaptations from the "Applied Science Readiness Levels" outlined for the NASA Breakthrough Propulsion Physics project [13 p. 683].

For example, what if a concept is now at TRL-3, and we want to estimate how long before it reaches TRL-6. If the history of that concept shows that it took two years to go from TRL-1 to TRL-3, (for which the provisional duration increments are 1+2=3), then its TRL rate multiplier is 66%, (2 yrs actual)/(3 units). By multiplying that rate to the remaining seven duration increments gives an estimate that it will take four to five more years to reach TRL-6. To determine a representative set of these relative TRL durations, the histories of several comparable technologies will need to be examined, and then their results merged into a baseline set of TRL durations. The factors that need to be specified include the challenges of the technology itself and the history of resources devoted to the advancements. Again, these predicative models are only meant to be relative, not absolute. The key is that the difference concepts are compared with identical models.

From experience, the advocates for a particular technology tend to overestimate the readiness of their concept. To get more accurate readings on a technology's actual readiness level, the US Air Force developed a "Technology Readiness Level (TRL) Calculator" that is accessible online [105].

Table 13. Technology Maturation Levels and Relative Durations Between Them

Level Duration Unit	Description of Level	Comments
TRL 7-9	From system prototype to flight proven	Considered here to be part of the Mission Development Duration
(indeterminate)		"Valley of Death"
TRL-6	System/Subsystem model or prototype demonstrated in a relevant environment	Ready for mission trades studies and mission commitment
4		
TRL-5	Component and/or breadboard validated in relevant environment	
2		
TRL-4	Component and/or breadboard validated in laboratory	
1		
TRL-3	Analytical and experimental critical function proof of concept	
2		
TRL-2	Technology concept and/or application formulated	
1		
TRL-1	Basic principles observed and reported	
4		
SRL-7	Experimental test devised for a new power or propulsion mechanism	If found viable, ascends to TRL-1
4		
SRL-6	Hypothesis devised for a new power or propulsion mechanism	
4		
SRL-5	Problem statement devised to seek a new power or propulsion mechanism based on established effects	
1		
SRL-4	New effect observed and reported that is relevant to power or propulsion goals	
3		
SRL-3	Experimental test devised for an effect relevant to power or propulsion	
1		
SRL-2	Hypothesis devised for an effect relevant to power or propulsion	
3		
SRL-1	Problem statement devised for an effect relevant to power or propulsion	

To create these estimates, it would be helpful to examine the histories of key parameters like those listed in table 12. In addition to plotting performance steps over time, it would be helpful to know the resources expended to attain each improvement.

There are more influences on advancement rate than just the ratio of TRL steps. If a concept does not have enough history (or inconsistent history or resources and commitment), then the following additional factors require consideration:

- Level of available resources—where greater resources lead to faster progress
- Operating power of concept—where lower power devices are easier (faster) to advance
- Complexity of concept—where simpler devices are easier (faster) to advance
- Relation to S-curve—where the rate of progress is fastest when midway between the performance level of the first embodiment to the level of its upper physics limit

That last item, the "S-curve," is the subject of the next subsection.

8.5.3. Modeling Technology Advancement Rates in General

Technological advancements follow recurring patterns. One of those patterns is the "S-curve" of technology advancement as described by Foster [41].

The S-curve evolution, shown in figure 7, is typical of any successful technology. The pattern begins where the initial efforts produce little improvement until a breakthrough is reached. The breakthrough, at the lower knee of the curve, is where the technology has finally demonstrated its fidelity. After this point significant progress is made with ever-improved versions of the same concept. Eventually, however, the physical limits of the technology are reached and continued efforts result in little additional advancement. This upper plateau is "the point of diminishing returns." To go beyond these limits a new alternative technology, with its own S-curve, must be created. Examples include how jet aircraft surpasses the speed limits of propeller aircraft, or how steam ships surpassed the performance of sailing ships. Note, the horizontal axis is not time as expected, but rather the resources ($ and time) devoted to the research.

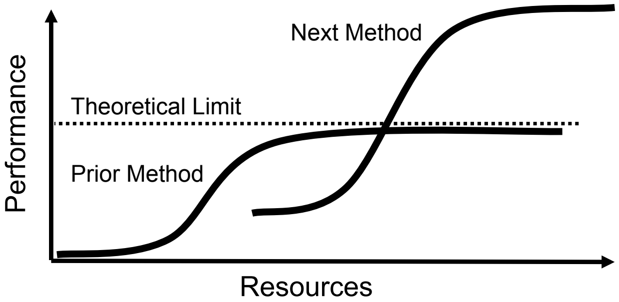


Figure 7. S-Curve Pattern of Technology Advancement

There are multiple lessons that that go along with this recurring pattern:

- The appearance of long-term exponential growth in performance is actually a series of S-curves
- Advancement rates vary depending on how mature the concept
- Indicators exist for when it is appropriate to seek new S-curves ("breakthroughs")
- This pattern is mathematically describable by a "Logistic Function"

Exponential Growth: Sometimes it appears that performance gains follow an exponential growth, such as "Moore's law." Moore's law is the observation (and subsequent extrapolation) that the number of transistors in an integrated circuit double about every two years. While this trend might hold for a while, eventually a limit is reached. For example in the extreme, is it safe to assume that transistors can never get smaller than a single subatomic particle? Further, it has also been shown that these apparently exponential growths in performance are actually a sequence of overlaid technology "S-curve" advancements [106].

Changing Advancement Rates: Note from figure 7 that the rate of performance gains, verses resources applied, is the greatest when a given technology is at the midpoint of its development. As expected, early progress is slow. What is often overlooked with well established technologies (ones near the top of their S-curve) is that additional performance gains get increasingly more costly to obtain and reach a point where no further performance gains are possible. An example of this is the history of LH2 rocket engines, where its theoretical limit is 528.5 sec *Isp*, (based on 100% conversion of stored energy into kinetic energy and a propellant specific energy of 13.43 MJ/kg) and the Space Shuttle Main Engines achieved 452 sec *Isp*, after considerable investment.

Thus, when considering the rates of future advancement of a technology if using the TRL step analogy, then that rate will become slower for technological concepts that are approaching their upper theoretical operating limits.

Indicators for Emerging Breakthroughs: History has repeatedly shown that the conditions are ripe for breakthrough technologies to emerge when the following two conditions have been met: 1) The prior technology is reaching the point of diminishing returns, and 2) Clues have emerged for how to seek those breakthroughs (that it's not just science fiction any more). By "clues" it is meant that there are actionable and relevant research steps that can now be taken.

An arguable case in point is the emergence of the "Mach Effect Thruster" and other claims of propellantless propulsion. In this case the prior technology, rocketry, is at, or nearing, its point of diminishing returns. The degree of progress that can be gained for a given level of investment is far less now than in the early years of rocketry. The second criteria is the emergence of clues for alternatives. In this case, the correlation between the desired breakthrough of a propellantless thruster and specific unexplored topics of physics were identified and published spanning the mid-1990s through 2010 [13]. One of the relevant open questions in physics regards the origins and structure of inertial frames—clues for where to look [107].

Research on the open question about inertial frames led to the Mach Effect Thruster, now under test [85]. Consistent with historic patterns, the (unconfirmed) initial performance is not practical (~ 3 μN @ 30 W input), but this is only the first iteration. If the physics principles behind this device are found viable, then those new principles can be applied in other contexts leading to other advancements. And consistent with historical patterns if that verification is achieved, expect to hear common, but naive phrases like: "Yes, it might work, but it is not all that useful," and, "We don't need it for the mission."

Mathematical Models: Mathematically, the "S-curve" is a "Logistic Function" following the form of Eq. 25. It should be noted that the x-axis is not *time*, but rather the *level of resources* devoted to the project.

$$y = L\left(\frac{1}{1+e^{-k(x-x_0)}}\right) \qquad \text{Eq. 26}$$

Where:

L = Upper asymptote, analogous to the physics limit of the concept

k = Maximum rate of progress at the mid point of the concept's development

y = A measure of performance of the concept (*Isp,* thrust, w/kg, etc.) where the y=0 point is approximately the first demonstrated functionality of the device

x-x_0 = Level of resources expended

In principle, the correlation of further advancements versus investment can be modeled by knowing the performance of the earliest embodiment of the method, along with the investment expended to reach that point, plus it's theoretical limit, and at least one other performance versus resources point.

For each key technology, it would be helpful to know the following:

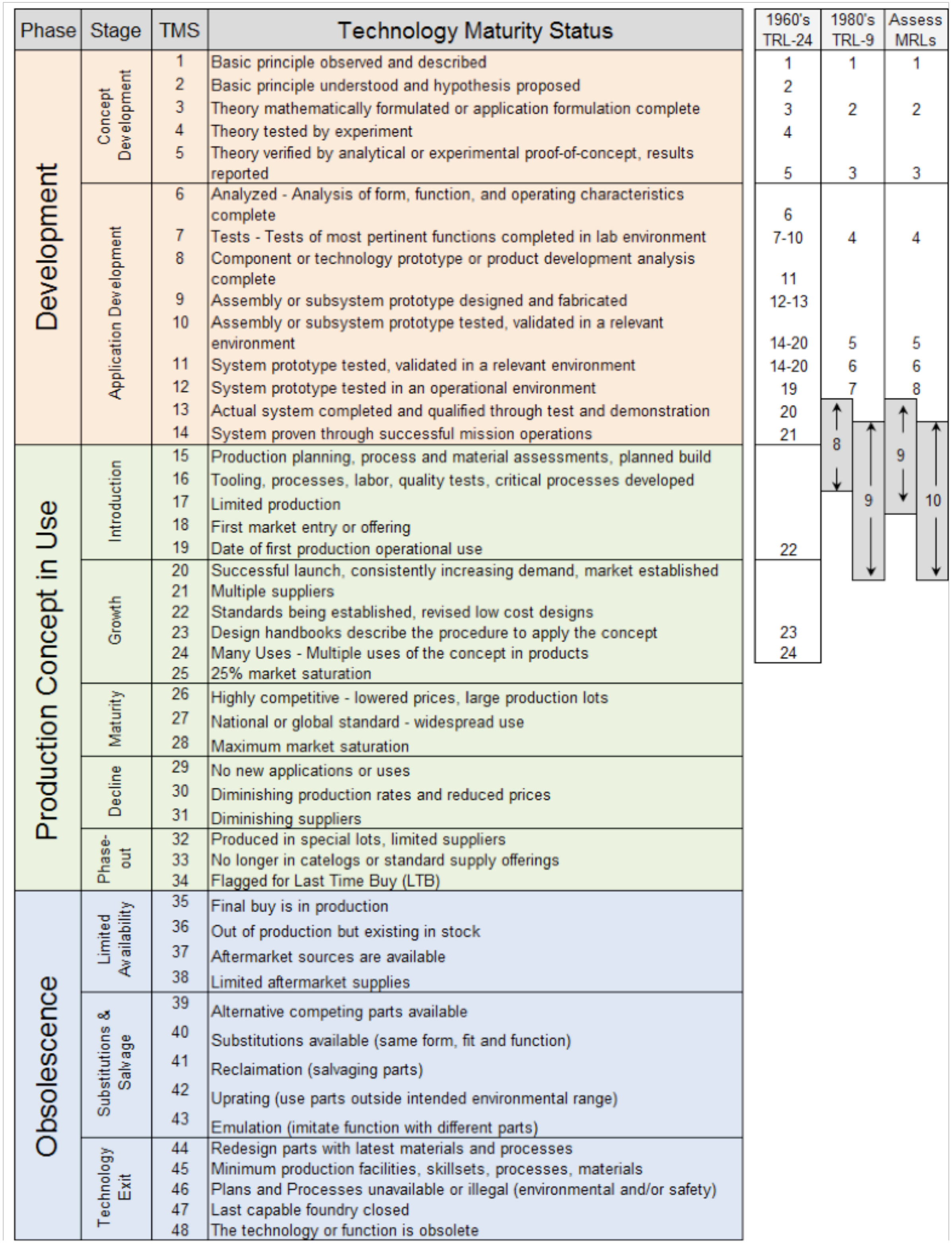
- Current performance value for TRL-9 technology, and the year that TRL threshold was reached
- Next generation (TRL-6) performance value, and the year when that TRL threshold was reached
- Predicted, new performance level currently in research, and its current TRL level.
- Theoretical ultimate performance level

8.5.4. Other Methods Under Consideration

After this study was well into it's third quarter, another set of technology advancement predictions, by Darryl Webb, were encountered. These will be examined in the next stage. Webb's method dissects the stages into other terms where advancement rates were inferred. An example of the comparison of Web's "Technology Maturity Status (TMS)" to the TRLs, and "Manufacturing Readiness Level (MRL)" is shown in table 14 (Reprinted with permission). This also shows how the TRL definitions have evolved over time.

Table 14, Alternative Progress Measures, Linking Performance, Schedule, and Cost

[Table 1 from Webb, AIAA 2014-4483, with permission]



Phase	Stage	TMS	Technology Maturity Status	1960's TRL-24	1980's TRL-9	Assess MRLs
Development	Concept Development	1	Basic principle observed and described	1	1	1
		2	Basic principle understood and hypothesis proposed	2		
		3	Theory mathematically formulated or application formulation complete	3	2	2
		4	Theory tested by experiment	4		
		5	Theory verified by analytical or experimental proof-of-concept, results reported	5	3	3
	Application Development	6	Analyzed - Analysis of form, function, and operating characteristics complete	6		
		7	Tests - Tests of most pertinent functions completed in lab environment	7-10	4	4
		8	Component or technology prototype or product development analysis complete	11		
		9	Assembly or subsystem prototype designed and fabricated	12-13		
		10	Assembly or subsystem prototype tested, validated in a relevant environment	14-20	5	5
		11	System prototype tested, validated in a relevant environment	14-20	6	6
		12	System prototype tested in an operational environment	19	7	8
		13	Actual system completed and qualified through test and demonstration	20	↑ 8 ↓	↑ 9 ↓
		14	System proven through successful mission operations	21	↑ 9 ↓	↑ 10 ↓
Production Concept in Use	Introduction	15	Production planning, process and material assessments, planned build			
		16	Tooling, processes, labor, quality tests, critical processes developed			
		17	Limited production			
		18	First market entry or offering			
		19	Date of first production operational use	22		
	Growth	20	Successful launch, consistently increasing demand, market established			
		21	Multiple suppliers			
		22	Standards being established, revised low cost designs			
		23	Design handbooks describe the procedure to apply the concept	23		
		24	Many Uses - Multiple uses of the concept in products	24		
		25	25% market saturation			
	Maturity	26	Highly competitive - lowered prices, large production lots			
		27	National or global standard - widespread use			
		28	Maximum market saturation			
	Decline	29	No new applications or uses			
		30	Diminishing production rates and reduced prices			
		31	Diminishing suppliers			
	Phase-out	32	Produced in special lots, limited suppliers			
		33	No longer in catalogs or standard supply offerings			
		34	Flagged for Last Time Buy (LTB)			
Obsolescence	Limited Availability	35	Final buy is in production			
		36	Out of production but existing in stock			
		37	Aftermarket sources are available			
		38	Limited aftermarket supplies			
	Substitutions & Salvage	39	Alternative competing parts available			
		40	Substitutions available (same form, fit and function)			
		41	Reclaimation (salvaging parts)			
		42	Uprating (use parts outside intended environmental range)			
		43	Emulation (imitate function with different parts)			
	Technology Exit	44	Redesign parts with latest materials and processes			
		45	Minimum production facilities, skillsets, processes, materials			
		46	Plans and Processes unavailable or illegal (environmental and/or safety)			
		47	Last capable foundry closed			
		48	The technology or function is obsolete			

9. SAMPLE DATA PLOTS

Using the propulsion comparison methods outlined in Section 8.4, trial data plots are offered next. The intent is both to test the analysis methods and show how to present their findings in a comprehendible manner. The charts are merely for illustrative purposes, with notional missions and representative technologies to give some sense of the trends and what the data will look like when the charts are based on more complete data in Stage II.

To make the complicated trade space of interstellar flight more comprehensible, it is important to make the interpretation of the data "as simple as possible, but no simpler." To that end, the basic figures of merit are plotted; *distance*, *time*, and *energy*. Though these can be shown as 3D plots with lines representing the performance levels of different technologies, the charts offered here are slices through that 3D trade space, at three different distances:

1) Solar Gravitational Lens Mission, > 660 AU (0.1 x 10^{15} m, 0.01 ly)
2) Deep Interstellar Medium, > 27,000 AU (4.1 x 10^{15} m, 0.43 ly)
3) Centauri Flyby, > 270,000 AU (41 x 10^{15} m, 4.3 ly)

Note that these distances match the first three baseline mission & payload scenarios described in Section 8.2. Only the flyby missions are plotted at this time because there is not yet enough data for the slow-down or orbiter missions to create useful illustrations.

The axes of these 2D slices are fundamentally *energy* and *time* for various mission *distances*, showing five data points that represent the performance of five hypothetical propulsion concepts. Those five hypothetical concepts include a chemical rocket, a basic nuclear rocket, a higher thrust fusion rocket, a laser sail, and a sailbeam. These provisional charts deliberately do not identify which data point is associated with each method, since the values for those methods are arbitrary test cases at this time.

Two sets of plots for each of these three different distances are offered, one that is more in terms of comparing *technologies*, and the other more in terms of comparing *mission* performance with those technologies.

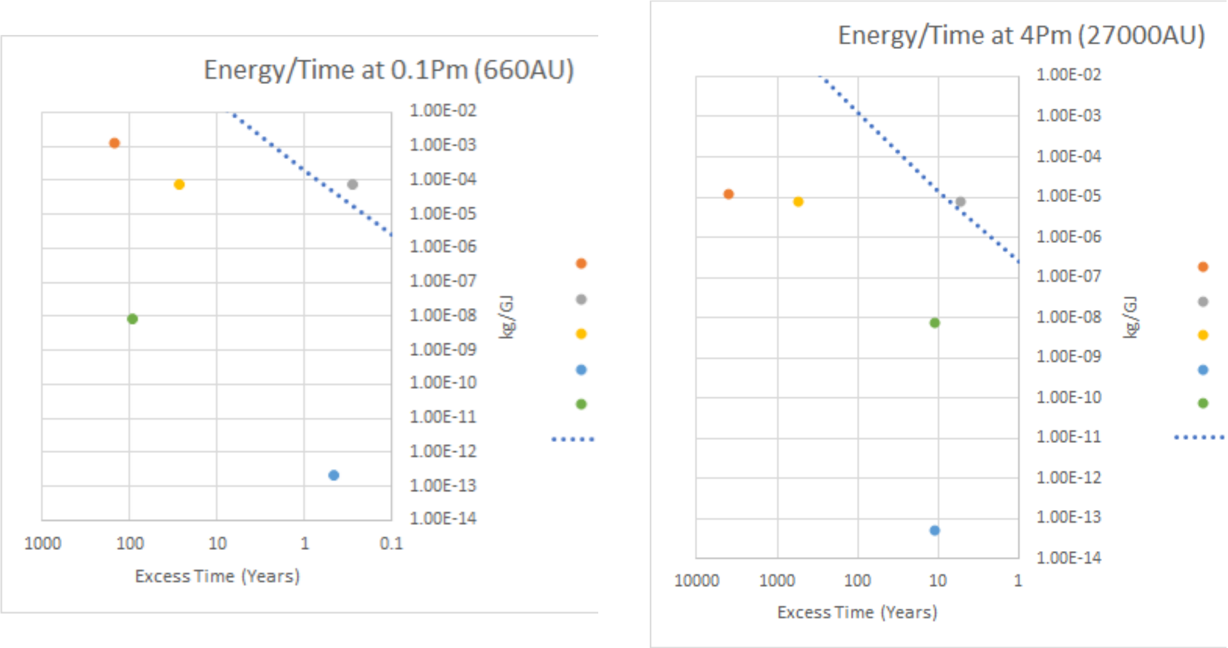
9.1. Technology Comparisons

The "Technology Comparisons" essentially show how quickly a payload mass can be delivered to a certain distance per an energy cost. More specifically, the trip time and its associated payload delivery capacity is shown for the five hypothetical propulsion concepts.

For the time axis, it was found that a more effective use of chart space is to plot that axis in terms of "Excess trip time" instead of "trip time." "Excess trip time" is defined as the trip time minus the lightspeed flight time (where lightspeed flight time is distance ÷ lightspeed). For the long trip times of interstellar flight this technique is simply a way to make better use of the logarithmic chart space, in effect spreading out the points that would otherwise tend to cluster.

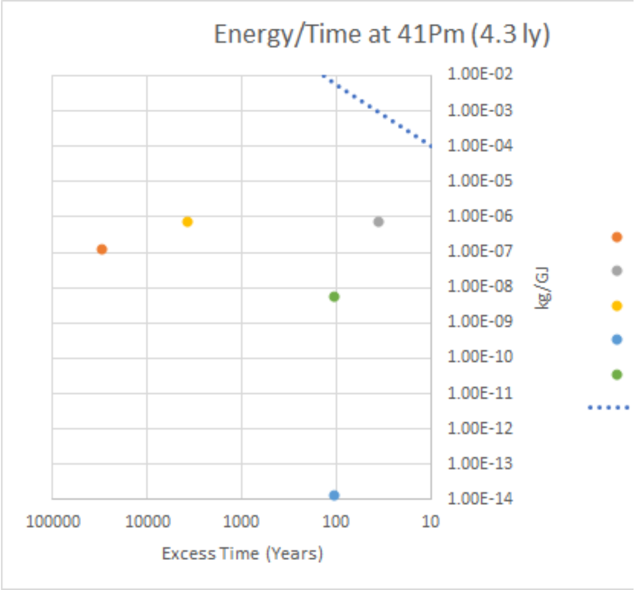
To convey the payload delivery capacity, it is helpful to speak in terms of the "**specific equivalent energy.**" The specific equivalent energy is really a figure of merit for cost, in which elements such as capital cost of ground infrastructure are converted into energy terms (using the conversion factor of 60 MegaJoule/dollar for bulk electricity, see Section 8.3.1). The plots show the reciprocal of that figure (kg/J), so that superior technologies are at the top of the chart. In other words, the more mass delivered per Joule, the better.

The technology charts also include a "**conventional limit**" line. This essentially represents a 100% conversion of supplied energy into the kinetic energy of the spacecraft. Note, since this includes an energy cost factor ("wall plug" price of power, 60 MJ/dollar) this is not a hard physics limit, but a limit that might be able to be surpassed depending on the cost of energy. For example, technologies which harvest energy from ambient sources, or which employ forms of energy which are significantly cheaper than the "wall plug" price, can in principle supersede that limit. The line illustrates the ideal performance zone on the chart, the upper right corner. The more desirable approaches are fast (right side of the chart) and deliver more payload per energy (top of the chart). In other words, shorter trips using less energy.



(8a) 660 AU (SGL)

(8b) 27,000 AU



(8c) 270,000 AU (Centauri)

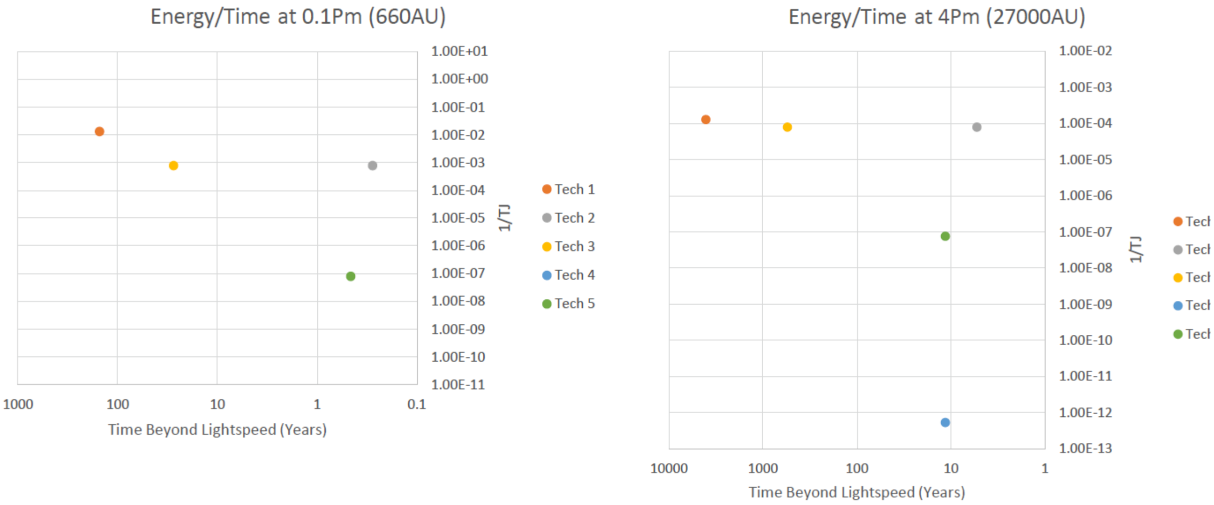
Figure 8 Technology Comparison Plots (time, kg/J)

9.2. Mission Comparisons

The "Mission Comparisons" essentially plot mission duration verses energy. More specifically, the combined time for the trip and signal return are compared to the propulsive energy expended, for each of the five hypothetical propulsion concepts.

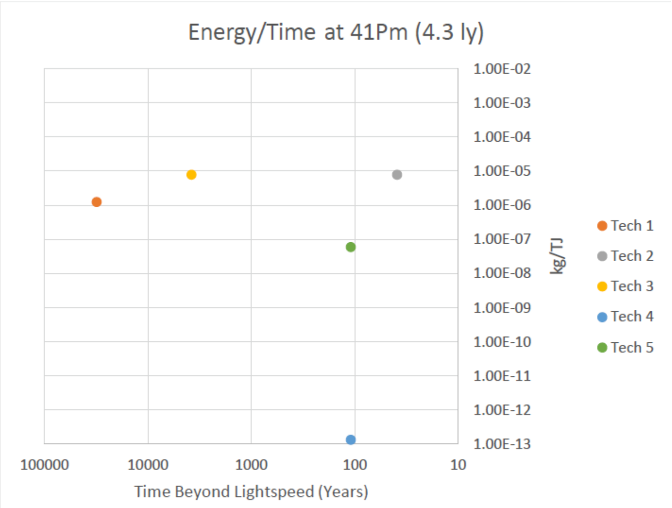
On the mission charts, the time axis is a different "Excess Time," one that now accounts for the time for the data signal to reach Earth. Specifically, the excess time on the mission charts is defined as the trip time minus twice the distance ÷ lightspeed. Again, this helps spread out the data of the different propulsion performances so they can be more easily distinguished.

In the case of the mission charts, the z axis is also slightly different. Instead of plotting kg/J, the axis is just in terms of energy. To retain the same sense of "good" missions being at the top right side of the chart, the z-axis is the reciprocal of total energy (1/J) instead of energy.



(9a) 660 AU (SGL)

(9b) 27,000 AU



(9c) 270,000 AU (Centauri)

Figure 9 Mission Comparison Plots (time, kg/J)

10. STAGE II PLANS

The Stage II work will focus on the collection and display of the information needed to conduct these analyses and then to begin the analyses. Much of this information will be openly accessible via an online repository. Access to the analysis tools themselves, where the user can vary the parameters to assess the consequences, might be more limited. The information portals (or front ends), fall into these categories:

- Portal where subject matter experts check, and add to, the online repository of information
- Analysis portal, where select operators can vary the mission choices and technology prospects to assess the results.
- Distilled summaries of mission, prospects, and findings; suitable for general audiences

10.1. Collection and Display of Information from Subject Matter Experts

In Stage II, a web-based system will be created to allow subject matter experts from around the globe, and from the span of relevant disciplines, to enter the information needed to have their concepts assessed in the context of interstellar flight. This will involve iterations to ensure that the questions being asked match what information is determinable. The starting points are the tables throughout this report. The overall intent is to collect enough information to assess the span of prospects under equitable conditions, so that ultimately the most impactful technologies can be identified along with research plans to advance those technologies. To get through that process, the information lists will be at four levels of scope:

- Mission-propulsion architecture concepts (and mission choices), e.g. table 3
- Power and propulsion prospects, e.g. table 4
- Key technologies within those systems
- Research needs to deliver the envisioned performance abilities

Mission-Propulsion Architecture Concepts List: Compiling a list of mission-propulsion architectures, like that of table 3 in Section 5.2, will be done in two contexts. First, the proponents of a given propulsion and power concept have the opportunity to document their concept in a mission context of their choosing—typically where their technology has an advantage. Second, to insure that the information needed for equitable comparisons is collected, the questions for the mission architecture will require explicit specification of core details such as the assumed data rates, data volume, payload power, etc, as outlined in Section 7 and the variables in table 6.

More General Mission Choices: Recall that the premise of this analysis allows the mission choices to be varied to assess their impact, so the ultimate mission candidates might be quite different than those originally proposed. In addition to those missions already listed in table 3, this assessment process will examine the propulsion concepts in different mission contexts, and for equitable comparisons, will use identical mission and payload baselines, such as those outlined in Section 8.2, and spanning the specific questions of Section 7.

Power and Propulsion Prospect List: The prospects list, similar to table 4 of Section 5.3, is where the power and propulsion concepts are described as a system—specifying all components of the system that are necessary for its success. The information provided here will feed into the analysis methods specified in Section 8.3 and 8.4, and thus must provide all the required information.

To insure that the information needed for equitable comparisons is collected, the questions for the prospects list will require explicit specification of core details such as the subject columns outlined in Section 5.3. This includes the level of details where design parameters used for the subsystems are revealed (such as tankage fraction, conversion efficiency for power sources, specific masses, etc.). In addition, the TRL levels associated with the projected performance values must be listed. This includes the variables outlined in table 6.

Key Technologies List: Within all power and propulsion system prospects, there are key technology elements. Some of these will be unique to a particular system, but many will be common across many systems. For example, different laser-sail concepts might use the same laser and power conversion technology, or different fusion rockets might require similar magnetic nozzle technology. Another common element is the thermal radiators needed to dissipate unusable energy.

To insure that the information needed for equitable comparisons is collected, the claimed performance levels, associated TRL levels, and the critical make-break issues for each technology will need to be specified. This also feeds into the next list—the research tasks required to answer those issues and deliver those performance projections.

One of the key technology areas for which more substantive estimations are sought are for trends of available energy and infrastructure (table 10), and trends of common design parameters (table 16).

Required Research: The advocates for power and propulsion concepts will also be asked to specify the next-step research required to advance their concept. It is anticipated that these research tasks will focus on only the key points of interest from the advocated concept, instead of covering all the key issues needing to be resolved. Any possible differences between what the technologist proposes to work on, and what might actually need to be worked on, is what this study hopes to reveal.

10.2. Analysis Portal

In addition to the span analyses to be conducted offline, it is desired to create a limited-access site with a partial analysis tool, where key options are available as 'sliders' and the outputs are in easily understandable graphics. Key challenges here are on creating an effective user interface and comprehensible graphs of the results. By attempting this key-factors front end, it may help improve the design of the deeper level of details for selecting analysis inputs and selecting how to convey the results.

The analysis *inputs* will include key mission choices (Section 7.) in a way that follows the "Basic Analysis Flow Diagram" of figure 5. As a starting point to envision the *outputs* of the analyses, consider both the sample "Topological Maps" from figure 1 and the data plots from Section 9.

10.3. General Audience Website

In addition to the portals whose information is at the practitioner level, it is desired to distill the information down for the general public. For this, the concept of "Trading Cards" is envisioned, where mission-vehicle concepts are presented in the same one-chart format, showing an iconic graphic and numeric key figures of merit. Similarly, this concept would be used to convey the major power and propulsion concepts separate from a the mission context.

10.4. Concluding Remarks

Any challenges to the assumptions and initial estimates in the report are welcome. While the focus of the first stage work was the development of the overall structure for the data to be subsequently collected in later phases, some values have been specified as starting estimates, for which more accurate and defensible numbers are sought. The online repository is the envisioned mechanism to keep these values up to date. Prior to that system being available, readers who have more accurate numbers for any of these values, please contact the authors with that information along with a reference citation for those more accurate values. Further note that most values herein are specified to only about two significant digits—consistent with the current fidelity of interstellar flight estimates.

11. REFERENCES

To not obscure the body of the text with large "[Author yyyy]" citations, and to offer the alphabetical-by-author bibliography style, the following compromise is used: The citations in the text follow the more discrete number sequence, and then those numbers are shown below in the [Author yyyy] citation style, followed by a bibliography. The utility of the biography style is that it makes is easy for readers to check if certain references have been cited.

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