ARGOSY: ARchitecture for Going to the Outer solar SYstem

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All solar system objects are, in principle, targets for human in situ exploration. ARGOSY (ARchitecture for Going to the Outer solar SYstem) addresses anew the problem of human exploration to the outer planets. The ARGOSY architecture approach is scalable in size and power so that increasingly distant destinations—the systems of Jupiter, Saturn, Uranus, and Neptune—can be reached with the same crew size and time requirements. To enable such missions, achievable technologies with appropriate margins must be used to construct a viable technical approach at the systems level. ARGOSY thus takes the step past Mars in addressing the most difficult part of the Vision for Space Exploration: To extend human presence across the solar system.

INTRODUCTION

The Vision for Space Exploration

> "*The reasonable man adapts himself to the world: the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man.*"[1]
>
> G. B. Shaw

On 14 January 2004, President Bush proposed a new four-point Vision for Space Exploration for NASA.[2]

1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond
2. Extend human presence across the solar system, starting with a return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
3. Develop the innovative technologies, knowledge, and infrastructures to explore and support decisions about destinations for human exploration
4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests

The focus to date has been on a "return to the Moon," with a cursory examination of how these same concepts can apply to human missions to Mars. Fulfillment of goal 2, specifically to "extend human presence across the solar system," has not been addressed significantly to date. However, the system-wide use of humans for science and exploration, resource assay, and eventually the consolidation of the solar system is an extremely ambitious and challenging goal, which has had little attention in the past. Its achievement will require standardized and modular-propulsion-capable vessels to reach the outer solar system in a timely fashion.

If this logical extension of point 2 is to be considered seriously, and if all stakeholders, both those of the new vision and those of previous plans, are to unite to further solar system exploration, then a comprehensive plan—or at least a framework for one—is needed.

All solar system objects that have been or can be reached by robotic spacecraft are, in principle, targets for human *in situ* exploration. The Moon and Mars have been the primary targets owing to relative accessibility and relatively benign environments. The inner planets, Venus and Mercury, pose special thermal issues even for robotic probes. Although Venus is about as easy to reach as Mars, any landing and return is problematic because of the planet's atmospheric properties.

Mars remains the immediate challenge for both robotic and human crews. Human missions to Mars of all types have been studied in some detail.[3] Such missions do not necessarily require a paradigm shift to be technically feasible, but they may to be "affordable," depending on the national perception of affordability for such a mission.

The Far Frontiers

The outer planets and their systems of rings and moons are a different matter. Perhaps counterintuitively, diminished distance to the Sun results in similar thermal requirements for any mission to Jupiter or beyond. For such missions the principal thermal input will come from the vehicle (notably the reject heat from the power generation system) itself.

Radiation exposure to the crew is primarily driven by relatively constant high-energy galactic cosmic rays, especially the heavy nuclei ("high-Z") component. At average energies of ≈1 GeV, shielding sufficient to make a significant decrement is on the order of that provided by Earth's atmosphere and typically prohibitive for a spacecraft because of the associated mass.[4] The problem can be dealt with by limiting exposure time to no more than a "few" years. The other principal component is that due to solar energetic particles. With appropriate warning, also required for extended lunar stays or crewed Mars missions, a small "storm cellar" (to limit the mass) can be used to protect against these lower-energy particles. Significant radiation backgrounds exist in the Jovian system, likely ruling out direct human visits to the moons Europa or Io (or closer, smaller satellites such as Amalthea). The radiation environment of Callisto is relatively benign, and some locations on Ganymede may be comparatively safe given its intrinsic magnetic field. From Voyager observations, the radiation environments of the other outer planets are well known and do not drive other significant radiation requirements.

Hence, a first-order analysis of radiation requirements makes time the primary limiting factor, with provision for solar energetic particles as needed, similar to current Design Reference Missions to Mars for human crews. We translate this time limitation into a requirement of no more than 4 years spent in transit. With a targeted crew size of six, the mission time can be used to derive the mass of expendables required: oxygen, water, and food. We rely on these supplies being carried from the outset and do not require significantly more recycling than is currently used, for example, on the International Space Station (ISS) for these inherently exploratory missions.

Science Rationale

In addition to the "need to explore," such human missions can, and will, fulfill several scientific roles. In our quest to search for life and/or possible habitats for life in the solar system as well as the details of our own origins,[5] the need for the collection and detailed study of samples is becoming clearer. In addition to the search for "obvious" macroscopic signs of past and/or present life, microscopic searches, including chemical, elemental, and isotopic assays, are needed. Such assays are also required for establishing the formation chronology of the solar system, including, but not limited to, periods of cataclysmic bombardment and how these have processed materials and surface features. In addition to Io's active vulcanism, the outer solar system is filled with numerous examples, including the cracks on Europa and the active water geyser on Enceladus; terrain differences between satellites and systems; Pluto's atmospheric blowoff; the wind streaks, plumes, and terrains of Neptune's moon Triton; and notably, evidence for Earth-like geologic processes recently discovered by the Huygens lander on Saturn's moon Titan.

As with current issues surrounding the Moon and Mars, samples need to be returned, but they also must be carefully chosen from an appropriate variety of well-characterized contexts. Hand selection, as was done with the Apollo returns, is preferred, with robotic or robotic-aided collection and return preferable to *in situ* study.

The Spirit and Opportunity rovers on Mars, while having vastly increased our knowledge of that planet, have also indicated the limitations of telepresence driven by one-way light time (OWLT). Significant teleoperations in sample and context examination and sample selection require limited OWLTs. Autonomous sample returns of even small quantities of surface material (≈1 kg) have remained difficult for the Moon and elusive for Mars. The situation is increasingly more problematic for the outer solar system.

By deploying human-crewed craft to these systems, a telepresence with restricted OWLT can be established in the system, making significant human *in situ* exploration and sample collection achievable. Human missions would not only allow Apollo-style exploration, context documentation, resource assessment, and sample returns, but could also team with robotic missions for similar tasks enabled by telepresence at interesting but inhospitable locations, e.g., Europa, Io, or perhaps the atmospheres of the planets themselves. The requirements to accomplish such diverse goals in a single, all-inclusive mission include a human crew, significant payload infrastructure and capacity for telepresence operations, and a way home to Earth, all in a timely manner.

Previous Concepts

Very few studies have been made of significant exploratory missions, especially involving humans, beyond Mars. Recently, the Jupiter Icy Moons Orbiter (JIMO) was proposed by NASA as a one-way nuclear electric propulsion (NEP) mission to the Jovian system with the goal of orbiting, in turn, the Galilean satellites Callisto, Ganymede, and Europa. The mission has subsequently been delayed indefinitely, reportedly because of a combination of NASA's long time requirement for autonomous reactor operation and high cost.

Orion

The Orion nuclear-pulse project (late 1950s–early 1960s) envisioned development of crewed interplanetary spacecraft.[6] With the motto "Saturn by 1970," the project envisioned the use of fission explosives against a "pusher plate" connecting to the main craft via a set of shock absorbers. The "advanced interplanetary ship" had an empty mass of 10,000 tons to propel a 1,300-ton ship to Enceladus and back in 3 years. The same ship could take 5,300 tons to Mars and back (in this context, 1 ton is presumably equal to 2,000 lb).

"Space Odyssey"

The ship in Kubrick's movie "2001: A Space Odyssey" was powered by a gas-core nuclear rocket with an initial mass in low-Earth orbit (IMLEO) of ≈725 metric tons (MT).[7] Gas-core nuclear rockets are discussed in the literature,[8,9] but are no more advanced from concept to implementation than other exotic propulsion means. A fusion-powered, piloted craft for missions to both the Jupiter and Saturn systems has also been discussed in the literature[10]: using a conceptual system with 11 MT of deuterium and ^{3}He for propellant, the IMLEO was estimated to be 1690 MT and involved seven heavy lift launch vehicle (HLLV) launches (251-MT capability each). A crew of 6 to 12 was assumed, with a 172-MT payload capability. With an output jet power of 4.8 GW (total fusion power = 7.9 GW), rendezvous trip times to the Jupiter and Saturn systems have been estimated as 118 and 212 days, respectively (note that a simple linear extrapolation gives a travel time to 30 astronomical units [AU], Neptune's distance from the Sun, of ≈1.8 years, although this mission was not included in the referenced study). (One AU = 1.495979×10^8 km; 1 light year [LY] = 63,240 AU, and Alpha Centauri, the closest star system, is 4.3 LY or 272,000 AU away. The termination shock of the solar wind is now known to be ≈95 AU from the Sun. The Kuiper Belt extends to ≈55 AU, just outside of Pluto's aphelion.)

HOPE

During the more recent time period of the Prometheus studies, a human mission to Callisto was studied under the Revolutionary Aerospace Systems Concept program called the Human Outer Planet Exploration (HOPE) concept.[11] That mission was defined for the year 2045 (or later) to survey the surface of Callisto and teleoperate a (robotic) Europa submarine for 30 days. The mission would also require leaving from Earth–Moon libration point 1 (EML1); a crew of six to the Jovian system, with a minimum of three crew to the surface of Callisto for at least 30 days; a maximum total time from EML1 of 5 years; and requirements based on radiation and low-gravity exposures. Some infrastructure would need to be delivered to the surface of Callisto as well. The concept included a robotic precursor mission, and various piloted vehicle concepts were considered, including binuclear thermal rocket propulsion, a variable specific impulse magnetoplasma rocket (VASIMR), magnetoplasmadynamic (MPD) propulsion, and magnetized target fusion propulsion. Radiation requirements would be established along with technology assumptions for surface operations.

A mission design to Callisto using the VASIMR approach and a 30-MW-powered spacecraft was studied by Park et al.[12] HOPE would use a precursor cargo transport followed by the crewed ship once various autonomous functions were established and confirmed. The IMLEO masses for the cargo and piloted ships would be 506 and 431 MT, respectively. For a round-trip time of 4.8 years, the VASIMR system would need 234 MT of propellant.

McGuire et al.[13] also studied the use of an NEP-MPD combination for the HOPE mission.

ARGOSY: BRIDGING THE GAP

Argosy, n *[Italian, a vessel of Ragusa], a large merchant ship, a fleet of such ships.*[14]

ARGOSY—ARchitecture for Going to the Outer solar SYstem—addresses anew the problem of supporting human exploration to Jupiter and destinations beyond in our solar system. While the previous concepts discussed all offer insights into the difficulties of such a task, they leave a significant gap. The Orion system, a promising concept, has associated extreme development, testability, infrastructure, and security issues. The Space Odyssey approach of either gas-core nuclear fission or deuterium-^{3}He fusion varieties has the obvious failing that neither has been demonstrated. For the fusion concept, the accumulation of 11 MT of ^{3}He is a questionable accomplishment in its own right.

The HOPE study has provided valuable information on radiation exposure requirements, suggesting that a 2-year, one-way trip for any contemplated human journey in the solar system is reasonable. The study of expendables and potential needs for exploring Callisto and projecting a telepresence into the Jovian system provides a valuable framework for the other outer planet satellite systems as well.

In ARGOSY, we first adopt many of the same requirements assumed in the HOPE study, in particular, a crew of six and one-way journeys lasting no more than 2 years. Unlike HOPE, we derive the architecture from two assumptions: (1) that the infrastructure assumes departure from an optimal location in space (see, e.g., Ref. 15) that can include the Sun–Earth L2 point as well as the EML1 point[16,17] and LEO, and (2) that the requirements for crew transport to and from the transport vehicle "parked" in one of these locations can be accomplished using the Block III Crew Exploration Vehicle (CEV) and its associated infrastructure.

The ARGOSY architecture is scalable in size and power so that increasingly distant destinations, i.e., the systems of the outer planets Jupiter, Saturn, Uranus, and Neptune, can be reached with the same crew size and time requirements. Regarding schedule, we posit that the first automated Jovian system return will be complete by 2045, with follow-on expeditions accomplished within the following 55 years—before the end of the 21st century. This is an optimistic schedule in that it provides a "what-if" scenario that is technology limited and not funding limited. Initial tests would use automated sample returns ("ARGOSY-R") that would enable an assessment of resources and conditions in the target system. Such activities would be coordinated with (notional) activities focused on the inner solar system, i.e., the Moon and Mars. This approach leads to the option of establishing permanent human bases in the outer solar system during the 22nd century (Table 1, cf. Table 6 of Refs. 18 and 19).

Unlike the HOPE study, and the "obvious" approach, we adopt proven and semi-proven technologies and let the IMLEO "float" to meet the transport requirements. In particular, we adopt high-powered NEP driven by a gas-cooled thermal spectrum reactor (e.g., Ref. 20). Such reactors are a proven high-efficiency technology but are not optimized for power density or minimum mass. Such systems as can be implemented have low specific powers and are inherently safe, with significant amounts of development time already invested in the technologies. Like Navy nuclear reactors, simpler and safer systems are also reliable and more likely to be available for actual implementation. As we will see, power density remains a significant technological issue, however.

Table 1. ARGOSY milestone goals.

Year	Goal
2030	Permanently staffed lunar base Human mission to Mars
2035	Robotic sample-return missions begin to the outer solar system (ARGOSY-R)
2045	Sample return from Jupiter system
2050	Human mission to Callisto (ARGOSY I)
2055	Sample return from Saturn system
2065	Sample return from Uranus system
2070	Sample return from Neptune system
2075	Human mission to Enceladus (ARGOSY II)
2080	Permanently staffed Mars base
2085	Humans to Miranda (Uranus system) (ARGOSY III)
2090	Humans to Triton (Neptune system) (ARGOSY IV)
2095	Sample return from Pluto/Charon system
2110	Human mission reaches Pluto before its aphelion (ARGOSY V)
2110+	Permanent human bases in outer solar system (post-ARGOSY)
22nd century	System-wide commerce

Given the ubiquity of water ice in the outer solar system (for potential *in situ* resource utilization [ISRU]) and the need for large power engines, some combination of liquid hydrogen and/or liquid water used in conjunction with MPD propulsion or pulsed inductive thrusters (PIT)[21] would be the possible approaches for the propulsion system and propellant. This implementation, in turn, requires a new class of extremely heavy lift launch vehicles (EHLLVs). We approach this from the perspective of some of the initial Nova launch vehicle concepts (Fig. 1) of the early 1960s.[22] Characteristics being sought at that time included a capability of 1 million lb to LEO (≈450 MT). We look at how far launch technology can potentially be pushed, and in particular consider possible EHLLVs with a capability of 1000 MT to Earth orbit.

It is worth recalling that Von Braun's original concept for Mars exploration[23] consisted of a large expedition of

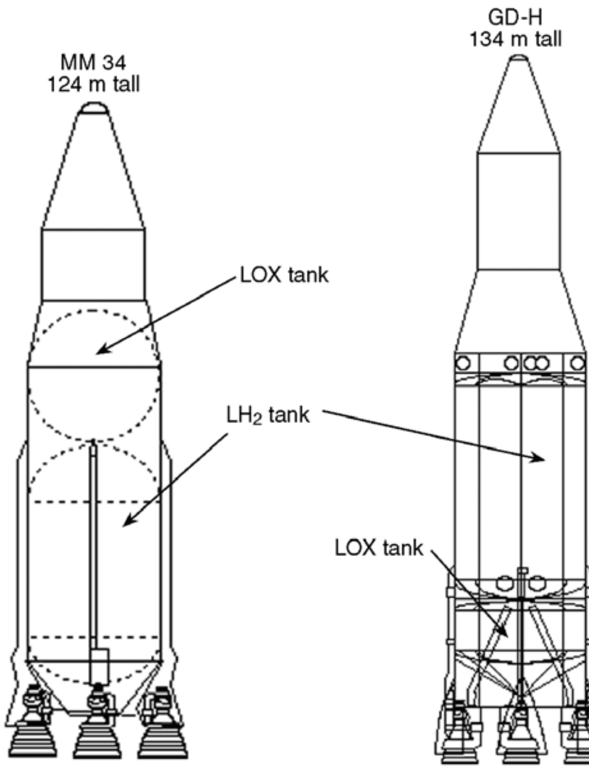

Figure 1. Two scalable Nova concepts from the 1960s using 1.5-stage LOX/LH_2 systems. Details about these and other designs are discussed later in this article. (Reproduced, with permission: © Mark Wade; http://www.astronautix.com/.)

10 ships (7 crewed and 3 supply) requiring an IMLEO of 37,200 MT, of which 35,555 MT were (chemical) propellant. This fleet was supposedly inspired by U.S. Operation Highjump in the Antarctic[3,24] and based on the need for absolute self-sufficiency if the crew was to complete the mission and successfully return to Earth. As a comparison, the total amount of mass of all systems launched by all nations from Sputnik I through 2004 is about 25,000 MT; 205 human flights contribute just under 11,000 MT to this number.[25–27] Nonetheless, implementation of human missions to the outer solar system will be significant undertakings.

ARGOSY thus takes the first step past Mars in addressing the implementation of the most difficult part of the Vision for Space Exploration: how to "extend human presence across the solar system" by considering new implementations of near-existing technologies.

TARGETS IN THE SOLAR SYSTEM

The distribution of gravity fields of outer solar system solid bodies is divided primarily into two broad classes: lunar-like (escape speeds of ≈2–3 km/s; see Table 2 [group 3 objects], cf. Table 5 of Ref. 18 and Table 2 of Ref. 28), and Phobos-like (<100 m/s escape speeds; Table 3). Some objects are in an "intermediate" class with escape speeds between 100 m/s and 2 km/s (group 4 in Table 2 as well as some of the objects in Table 3).

Table 2. Escape velocities for some objects.

Group	Object	Escape speed (km/s)
1	Earth	11.18
	Venus	10.36
2	Mars	5.02
	Mercury	4.25
3	Moon	2.38
	Io	2.56
	Europa	2.02
	Ganymede	2.74
	Callisto	2.44
	Titan	2.64
4	Rhea	0.64
	Titania	0.77
	Triton	1.45
	Pluto	≈1.20

Small objects that are easy to land on (escape speed of <100 m/s, color-coded green in Table 3) are preferred for any type of large transport. For studying one of the gas giant planets, natural satellites with prograde orbits are preferred (retrograde, color-coded yellow in Table 3). The object violating both of these preferences is Triton, the large and retrograde moon of Neptune. One trade that is required is the assessment of how deeply an ARGOSY-class vehicle would actually descend into the gravity field of the large planets vs. remaining at a more loosely bound orbit and carrying a CEV for orbits of the larger moons as well as landings.

Landing Sites

In the Jovian system, the closest small prograde object not inside the radiation belts is Leda. In the Saturn system, Hyperion, Mimas, and the inner satellites are available for low-gravity landings and ascents (escape speeds ≈100 m/s or less), while Titan is in the larger class of objects, such as Ganymede and Callisto, that will require high-thrust CEV systems for landing, similar to those being defined for the new round of crewed human landings on the Moon.

Direct landings on all Uranian satellites can be accomplished using a system with a capability in the 500–800 m/s escape speed range. Pluto's large moon Charon, as well as Iapetus and Rhea at Saturn, fall into this class as well, while Triton and Pluto require capabilities in escape speed regimes of 1000–1500 m/s.

Table 3. Small bodies with low escape speeds in the planetary systems within the solar system.[29]

System/radius (km)	Object	Retrograde in system?	Object radius (km)	Distance to primary (primary radii)	Surface escape speed (m/s)
Mars 3,397.2	Deimos		7.5 × 6.1 × 5.5	6.90 R_M	5.7
	Phobos		13.5 × 10.8 × 9.4	2.76	10.3
Jupiter 71,400	Sinope	Yes	18	332 R_J	24
	Pasiphae	Yes	25	329	31.9
	Carme	Yes	20	316	25.3
	Ananke	Yes	15	297	18.4
	Elara		38	164	52.2
	Himalia		93	161	117
	Leda		8	155	9.7
In Jovian radiation belt	Thebe		55 × 45	3.11	43.4
	Amalthea		135 × 84 × 75	2.54	84.2
	Adrastea		12.5 × 10.0 × 7.5	1.81	14.3
	Metis		20	1.79	25.3
Saturn 59,650	Phoebe	Yes	110	217.00 R_S	69.7
	Iapetus		730	60.00	586
	Hyperion		205 × 130 × 110	25.00	107
	Rhea		765	8.84	659
	Dione		560	6.33	223
	Tethys		530	4.94	436
	Enceladus		250	3.99	212
	Mimas		196	3.11	161
	Janus		98 × 96 ×75	2.54	52.3
	Epimetheus		72 × 54 × 49	2.54	32.2
	Pandora		57.0 × 42.5 × 32.5	2.38	22.7
	Prometheus		72.5 × 43.5 × 32.5	2.34	22.3
Uranus 25,900	Sycorax		95.0	471.00 R_U	Unknown
	Caliban		49.0	277.00	Unknown
	Oberon		761.4	22.49	729
	Titania		788.9	16.83	768
	Umbriel		584.7	10.27	538
	Ariel		578.9	7.38	541
	Miranda		235.8	5.01	189
	Puck		77.0	3.32	Unknown
Neptune 24,750	Nereid		170.0	222.80 R_N	Unknown
	Triton	Yes	1350	14.34	1450
	Proteus		200	4.75	Unknown
	Larissa		104 × 89	2.97	Unknown
	Galatea		79	2.51	Unknown
	Despina		74	2.12	Unknown
Pluto 1,137	-		1137	-	1222
	Charon		586	17.27 R_P	610

Retrograde system motion
Radiation belt location
Escape speed >1000 m/s
Escape speed 500–1000 m/s
Escape speed <100 m/s

NOTE: Items marked “Unknown” in the escape speed column are small bodies but with unmeasured masses; the escape speeds will be small but cannot be calculated with existing data.

Resource Possibilities

With respect to ISRU, water ice is readily available in all of these systems, as well as methane ice at the Uranus and Neptune systems. Argon ice may also be available at some level on some of these worlds as an electric propulsion system propellant or a minor (but significant) atmospheric constituent (if the temperature is not sufficiently low). Separation from impurities may or may not be an issue in "mining" these ices for propellant (LOX + LH_2 or LOX + CH_4 or Ar) or for water and oxygen to support a human presence in these distant systems.

The Role for an Automated CEV

While crewed missions will require significant technological advancements, one-way missions with a fully automated vehicle would not be as pressing (the analog here is the cargo precursor vehicle proposed as part of the HOPE architecture). An automated, basic CEV could be delivered to these diverse targets by an advanced NEP carrier vehicle, and then would be able to land on any of these targets for *in situ* analysis and/or sample collection (ARGOSY-R, cf. Table 1). Sample collection and return to the NEP vehicle would have far less of a gravity field to deal with than sample return on Mars. In addition, with an automated system, samples could be returned at a much more leisurely pace than would be required for a crewed vehicle. Viewed from a systems perspective, this would provide precrew tests of the required hardware. Given the timescales involved and the cost for even an uncrewed mission, the question will come down to whether a first (or only?) mission to these distant targets should be done with a crew from the start. Experience with Mars exploration will form an important input to the answer.

ARCHITECTURE PERSPECTIVE

Although crewed missions beyond the main asteroid belt may remain problematic (if even desirable) throughout this century, major scientific questions remain that can be answered only by going there, a situation that has not changed during the last 30 years.[5,30] Enigmatic Europa may contain even more clues than Mars about the evolution of life in the universe, yet actually remotely probing beneath that moon's icy crust will likely be as difficult as landing a field geologist on the Martian surface. But the entire solar system must be considered as part of the ultimate Vision if it is to take fire, go forward, and be sustainable.

A new perspective is needed, along with a new architecture, to implement that perspective. We envision a program that will last for decades and will, at some point, require costly pieces of equipment. An analogy of permanent science stations in Antarctica comes to mind. For the solar system to become our extended home, the effort involved must become "obvious" to the public and politicians alike as a long-term goal in the national interest. Only then can progress be maintained toward the consolidation of the solar system during the next century. A possible time schedule for some milestones has already been given in Table 1.

Top-level elements and requirements include capable HLLVs, such as the Cargo Launch Vehicle (CaLV, now known as the Ares V), or larger EHLLVs to push past Apollo tasks on the Moon and prepare the way for Mars, roles for L2 as a way-station and observatory for other star systems, and roles for automated CEVs wed to Prometheus-like vehicles (ARGOSY-R) for outer solar system exploration and sample returns. The current goal is to answer fundamental questions about our origins and the origins of life in this system,[5] but there will always be a need for a clear, yet evolving concept of where we can ultimately go if we choose to do so.[2]

THE ARGOSY CONCEPT

We assume the use of the Exploration System Architecture Study (ESAS)[31] in defining capabilities for human crew transport in cis-lunar space. And to minimize the in-space assembly of a complex power system, we assume that an EHLLV dubbed "Supernova" is available for launches.

Mission Requirements

To develop a set of top-level requirements, we assume a 2-year, one-way trip, i.e., 4 years in transit total, for crewed reference missions carrying six astronauts. At least one (and up to four) automated sample return missions (that can have a longer trip time) designated ARGOSY-R would come first. Propulsion requirements for human missions increase as the distance increases at a fixed maximum trip time. To implement this evolution, the total IMLEO will be allowed to grow as needed, relying on the typically decreasing specific mass of the power system with increasing overall system mass to provide the increased performance.

Spacecraft Systems

The key issue is the reactor and power conversion system. While typical low-thrust NEP systems have relied on fast reactors to minimize mass, such systems have relatively low conversion efficiencies and thus require large radiator masses at high power levels, even at high rejection temperatures. We assume that the most important issues are safety and reliability. This implies the use of heavy, but well-understood, thermal reactors. As an example, the General Atomics Gas Turbine-Modular Helium Reactor (GT-MHR), a 600-MW thermal system providing 286 MW of electricity at ≈48% conversion efficiency, gives a check on the size of such modular systems.[20] Such large efficiencies can significantly decrease requirements for secondary radiators. Without containment or shield masses, one estimate of specific mass of this system is ≈11 kg/kWe (kWe = kilowatts electric). Use of a thermal spectrum reactor can result in higher conversion efficiencies than for fast reactors such as those considered for the JIMO mission. Specific masses of power systems below ≈30 kg/kWe[32–34] are sufficiently small to be interesting for human-piloted interplanetary travel.

We consider high-power MPD, PIT, and VASIMR systems as essential electric engine trades. Scaling up conceptual systems to ≈10 MWe (megawatts electric) or higher, such as those discussed in Ref. 20, are appropriate.

In-Space Exploration Vehicle

The size of the solar system is measured in 10s of AU, with the distance to Neptune being ≈30 AU. At a speed of 1 AU/year equaling 4.74 km/s, the size of the solar system and the maximum allowable expedition time set the propulsion system requirements for the NEP In-Space Exploration Vehicle (ISEV). Taking the interplanetary "flyout" speed as equal to the planetary heliocentric distance divided by 2 years, the average required transit speeds are

Jupiter, 2.6 AU/year = 12.3 km/s
Saturn, 4.7 AU/year = 22.5 km/s
Uranus, 9.6 AU/year = 45.5 km/s
Neptune, 15.1 AU/year = 71.3 km/s

For an impulsive system, the total delta-V is ≈4 times the average transit speeds (accelerate to the transit speed, decelerate from the transit speed at the target, and repeat the pattern to return to Earth), so obviously neither chemical propulsion nor nuclear thermal propulsion is adequate, fusion and "advanced" propulsion are not credible for crewed missions (or even robotic ones), and very high specific impulse I_{sp} (≈5,000–30,000 s) is required. To meet these requirements, propulsion implementation cannot necessarily rely on ISRU for return, but it could help, so a prudent first cut is to use H_2O for the propellant of choice, although there are others which may be system specific.[35]

As noted above, one must maximize the electrical conversion efficiency and reactor reliability, and this can be accomplished by using a high-temperature gas-cooled reactor with a Brayton cycle thermal-neutron reactor. This, of course, then yields a very large and very massive in-space, low-thrust propulsion system. To investigate what may be possible, we consider scaling down the General Atomics example by a factor of 20. This yields a reactor thermal output of 30 MW thermal or ≈10 MWe at 30% efficiency with a mass of ≈150 MT.

Consumables for the crew include food, water, and oxygen.[4,36] At ≈4.5 kg/person/day with 70% of the oxygen and water recycled, the requirement could be reduced to 2.9 kg/person/day. For six people and 4.5 years, this amounts to 28.6 MT of supplies. To estimate, about the best we can do is to assume

- Optimal mass ratio of 4.90 (initial propellant fraction of 0.796) with ΔV = 1.59 $v_{exhaust}$ (Ref. 37)
- Total dry mass of 816 MT (+18.4% contingency = 1000 MT)
- Initial wet mass = 4.90 × 1000 = 4900 MT
- Total propellant load = 3900 MT
- 6% tankage factor or 294 MT for tanks
- 29 MT of consumables
- 150 MT for power system
- 7% of 4900 = 343-MT structure, engines, and crew quarters, where the structure includes radiators and shields

Performance

The required speeds are sufficiently high that some rough estimates of performance can be made assuming straight-line motion in gravity-free space. The mass ratio R is related to the required delta-V and propulsion system performance

$$R \equiv m_{\text{initial}} / m_{\text{final}} = e^{\Delta V / g I_{sp}} . \tag{1}$$

In gravity-free space, this equation can be integrated to yield the distance traveled x over a time τ assuming a constant mass flow rate and specific impulse, i.e., constant thrust as

$$x = g I_{sp} \tau \left[1 - \frac{\ln R}{R - 1} \right]. \tag{2}$$

For the optimal value of ln R = 1.59, the quantity in brackets is 0.59; in other words, using Eq. 1,

$$\begin{aligned} x &= \frac{v_{\text{final}} \tau}{\ln R} \left[1 - \frac{\ln R}{R - 1} \right] \\ &= v_{\text{final}} \tau \left[\frac{1}{\ln R} - \frac{1}{R - 1} \right], \end{aligned} \tag{3}$$

or , at the optimum,

$$x_{\text{optimum}} = g I_{sp} \tau (\ln R_{\text{optimum}} - 1) , \tag{4}$$

where

$$R_{\text{optimum}} = e^{1.59} = 4.90 \text{ is the root of}$$
$$R_{\text{optimum}}^{-1} = 1 - \frac{1}{2}\ln R_{\text{optimum}} \,. \quad (5)$$

Mission Scenarios

To minimize the amount of propellant carried, one could construct the following trial mission scenario:

1. Launch and fuel the system in LEO.
2. Refuel the spent upper stage with LOX and LH_2 (would also need to be carried to LEO) to boost the fully loaded 4900-MT ISEV to Earth-escape velocity.
3. Use the optimized NEP system to accelerate the ISEV during cruise.
4. Use atmospheric braking at the target planet (will not work for Pluto!) to capture into orbit in the planetary system.
5. Refuel the system at one of the target system moons (assuming the precursor robotic probe and sample return have shown this to be feasible).
6. Accelerate back to the inner solar system.
7. Use the Earth's atmosphere to capture and brake into orbit.

This scenario provides the most optimistic picture in placing the minimum requirements on the propulsion system.

To go to Neptune, we would have to traverse 30 AU in 2 years with the NEP system and then decelerate using the atmosphere of that planet as a brake. From Eqs. 4 and 5, the hyperbolic excess speed at approach of the planet would be ≈120 km/s, and the required specific impulse ≈7700 s. At a deceleration of 9 g's, the system would take some 23 min to slow down and would travel about 1.6 Neptune diameters. While the planet's atmosphere can be used to brake into a closer orbit in the system, this scheme will not work to actually slow down from the required interplanetary speed.

Suppose we use the NEP system both to accelerate and to decelerate. The mass ratio available for reaching the half-way point of 15 AU in 1 year is now $4.90^{1/2}$ = 2.21. From Eq. 2, the exhaust speed needed is 207 km/s and the corresponding specific impulse is increased to 21,100 s. The midpoint speed is 164 km/s (with no refueling at Neptune and use of the system for all prime propulsion, the available mass ratio to the halfway point drops to $4.90^{1/4}$ = 1.49, the required exhaust speed increases to 383 km/s, and the required specific impulse increases to ≈39,100 s).

Power Requirements

For the required power we have (assuming 100% efficiency)

$$P = \frac{1}{2}\dot{m}v_{\text{exhaust}}^2 = \frac{1}{2}\frac{m_{\text{propellant}}}{\tau}\frac{x^2}{\tau^2}\left[1 - \frac{\ln R}{R-1}\right]^{-2} . \quad (6)$$

For an optimized system accelerating to arrive at 30 AU in 2 years (and then somehow brake!), we have 3900 MT of water and 2 years or a mass-flow rate of 61.8 g/s. The exhaust velocity is 75.8 km/s and the required power level is 178 MWe, so with current technology we are already low by a factor of ≈6 in required power.

Cutting back to *in situ* refueling at the destination with a mass ratio of 2.21 and an exhaust speed of 207 km/s with a mass-flow rate (which remains constant) of 61.8 g/s, the required power has increased to 1325 MWe, ≈45 times what is available. By keeping the mass ratio fixed for the entire mission, the power requirements race upward.

For scalable power systems with a fixed specific power α (power per unit mass), the optimum is characterized by[32,33]

$$v_{\text{exhaust}}^2 \approx \alpha\tau \,. \quad (7)$$

At a 207-km/s exhaust speed and 1 year of acceleration, the optimum power system produces ≈1359 We/kg (0.736 kg/kWe); at 75 km/s and 2 years, the optimum is ≈180 We/kg (5.54 kg/kWe). For these optimal scaling values and required power levels, the power system masses are ≈975 and 986 MT, respectively, and about a factor of 6.5 larger than what we budgeted for the power system.

If we consider the *in situ* refueling scenario and increase the total flyout time from 2 to 3 years, the power requirement decreases by a factor of ≈3.4; an increase to 7 years of flyout time decreases the power requirement by a factor of ≈43 for the case of *in situ* refueling to ≈31 MWe. For the aerocapture case, increasing the flyout time to 4 years decreases the power by a factor of 8 to 22.2 MWe. With 4 years to reach 30 AU with an optimal mass ratio of 4.90, the final speed drops to 60.25 km/s and the required system exhaust speed drops to 37.9 km/s (specific impulse of 3860 s). At 9 g's the craft can brake in 11.4 min, during which it moves 41,100 km or ≈0.26 times its circumference.

We conclude that any crewed round-trip mission to the Neptune system will require *in situ* refueling for the return trip to Earth. At a round-trip time of 8 years plus time in the system, such a mission can be accomplished if aerobraking deep in the atmosphere is possible. If aerobraking is not an option, the flyout time increases to ≈14 years plus time in the system. Even if volunteers were found for such a mission, round-trip survival would be questionable as a result of exposure to galactic cosmic rays. Larger vessels with higher specific energy power systems would be required in this case. All else being equal, a human mission to the Uranus system has ≈10% the power requirement of a Neptune mission because of its closer proximity (Eq. 6). Not surprisingly, the limiting factor for ARGOSY is the specific mass of the power system.

Launch System

"Once you get to earth orbit, you're halfway to anywhere in the solar system."[38]

R. A. Heinlein

With these considerations as a guide, we assume one launch of 1000 MT to LEO for an empty ISEV and four launches of 975 MT of H_2O to LEO to load propellant tanks (975 MT of water occupies a volume of 975 m^3 or a spherical volume 12.3 m in diameter; 3900 MT would occupy a spherical volume 19.5 m in diameter). Hence we require five launches of a 1000-MT-class vehicle. This exceeds the capability of anything ever designed.

There are two nuclear approaches: Orion and gas-core nuclear. However, both would require significant test facilities, contain unknown fatal flaws in approach (both are at very low technology readiness levels), and produce significant atmospheric release and ground contamination with highly radioactive material.

These are the considerations that then drive the need for in-space assembly or EHLLV: the "Heavy" Nova or "Supernova." (Apparently Von Braun coined the term "Supernova" when he was Director of the Marshall Space Flight Center. It is not indicated what the capability would be, but the implication is that it would be greater than the Nova and/or Saturn C-8; Ref. 39.)

Although the Nova vehicles were explored in concept from 1959 to 1964[40–42] and sporadically thereafter[22] with the requirement of 1 million lb to LEO (≈450 MT), they were abandoned with the choice of the lunar orbit rendezvous approach for Apollo.[39]

Developing such vehicles will be costly. The trade is one Supernova (≈2.5 × Nova) vs. ≈10 CaLV/Ares V. A related question is: What is the largest chemical launch vehicle that is **technically** possible (cost is a whole other issue!). Scaling is a (nontrivial) matter of manufacturing,[43] likely at the launch site,[42] and a new, sufficiently large engine.[41]

The current ESAS architecture projects the design and use of a CaLV with a ≈125-MT capability to LEO. While a ≈290 MWe power supply with a mass ≈3000 MT is likely beyond what will be required for an ARGOSY vessel[20] (as well as being problematic to launch), ≈1000 MT may not be. (We define a "Hypernova" as a member of a class of ultra-heavy lift launch vehicles [UHLLVs] with a capability of 10,000 MT to LEO. A 3000-MT power system would require either a launcher in this class or an enormous amount of pre-emplaced infrastructure in LEO.)

For such a mass, a single or a few launches with some in orbit assembly may be preferable to 10s of launches and significant in-space assembly of potentially hazardous materials. Therefore, we have examined scalings of some of the Nova designs from the 1960s (Fig. 1). In those studies, the trades were the number versus size of the engines as well as reusability in terms of what would be extremely high hardware costs. Assuming a conservative growth ratio[22] of 20, the launch vehicle fully loaded with propellant would weigh ≈20,000 MT or about as much as a Trident missile submarine.

We examined past Nova designs for testability and technical maturity, choosing to avoid "advanced" plug nozzle approaches that have a full-scale test stand issue. We also rejected "advanced" single-stage-to-orbit approaches and looked only at concepts with near 10^6 lb payload capabilities (at least as advertised).

We then selected the remaining designs and scaled to a 1000-MT level. These included the General Dynamics (GD)-E, GD-F, GD-H, GD-J, Martin Marietta (MM) 34, and Saturn V-D configurations. The lowest initial mass-to-payload (1000-MT) ratios are found for GD-H and MM 34: ≈20.7. Both are 1.5-stage LOX/LH_2 designs, with no solids, and both use five advanced—and large—engines. Both have initial thrust-to-weight ratios ≈1.25. So the overall vehicle class has an initial loaded mass on the launch pad of 45.5 million lb (20,600 MT) and an initial thrust of 57.5 million lbf (≈253,000 kN).

With a required liftoff thrust of ≈56 million lbf, a configuration of eight engines at ≈7 million lbf each would suffice, or, adding margin, five engines at 12 million lbf each. As the cost of the engines will be significant, the 1.5-stage approach used in the MM 34 and GD-H Nova concepts (Fig. 1) is a likely option. Also, minimizing new engine development suggests that these would need to be LOX/LH_2 engines about 4.7 (eight engines) to 8.0 (five engines) times the capability of the M-1 engine under development for Nova in the early 1960s (Fig. 2).

Scaling the dimensions of the MM 34 by $(1.88)^{(1/3)} = 1.23$ gives a vehicle some 153 m tall × 41 m in diameter; scaling the somewhat more slender GD-H concept (slightly lower payload than the MM 34) gives 174 m tall × 35 m in diameter. For comparison, the Washington monument is just over 169 m tall and 24 m across a diagonal at the base and has a mass of 82,000 MT (hence about the same size but 4 times the mass).[44]

Borrowing from oil-tanker terminology, the next size "class" past the EHLLV would be an UHLLV with a capability of 10,000 MT to LEO. Assuming that we stick to a LOX/LH_2 1.5-stage vehicle, the dimensions would scale as $10^{1/3}$, while the masses (and stresses!) would scale by a factor of 10.

Such a vehicle would have an initial mass of ≈210,000 MT (about 2/3 the mass of the Empire State Building),

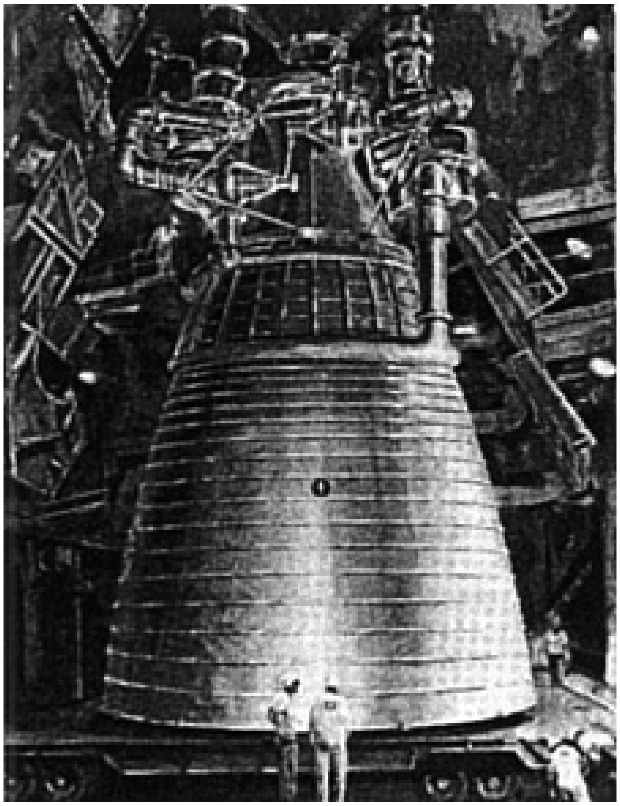

Figure 2. The 1.5-Mlbf thrust LOX/LH_2 M-1 engine. (Reproduced, with permission: © Mark Wade; http://www.astronautix.com/.)

require a thrust of ≈500 million lbf (≈2500 MN), and have a height of ≈330 m with a base diameter of ≈88 m. The structure comparison here is the Eiffel Tower with a height of 324 m, base size of 125 × 125 m, and structural mass of a wispy 10,000 MT,[45] the Hypernova payload mass to LEO. Size comparisons are shown in Fig. 3.

An alternative would be a two-stage vehicle similar to the Saturn V configuration used to launch Skylab. However, the initial Supernova weight would require at least 18 F-1A engines as well as five 6.8-m solid strap-ons to deliver the initial required thrust to lift from the launch pad or a new RP-1/LOX engine.

Launch sites for the original Nova were studied, and land purchased north of the current launch complex 39 was considered for siting. This area would be the likely site for such a complex to be constructed for the same reasons that the original studies all concluded that the optimum launch complex site would still be in the Cape Canaveral region (Fig. 4).

A revolution in our thinking is required if we are to open up the solar system to human exploration.

CONCLUSION AND PERSPECTIVE

Robotic missions are the pathfinders for solar system exploration, and this will not change!

Human presence across the solar system is possible, but infrastructure and implementation will be very expensive. This will be a decades-long effort that will require corresponding international cooperation. It can be done, e.g., ISS and Cassini/Huygens, but will not necessarily be easy as a technical or political accomplishment.

One very important note: if we keep waiting for propulsion "breakthroughs" that will increase speed and lower cost, we will always be waiting.

There are two paradigms to consider:

1. "Age of Exploration": spice trade driven by profits and national competition—"no holds barred" + colonial exploitation
2. "Antarctica": international distrust coupled with international cooperation, a permanent international presence, and scientific cooperation[49]

Where we are in space at the beginning of the 22nd century is entirely up to us and depends on what we do now.

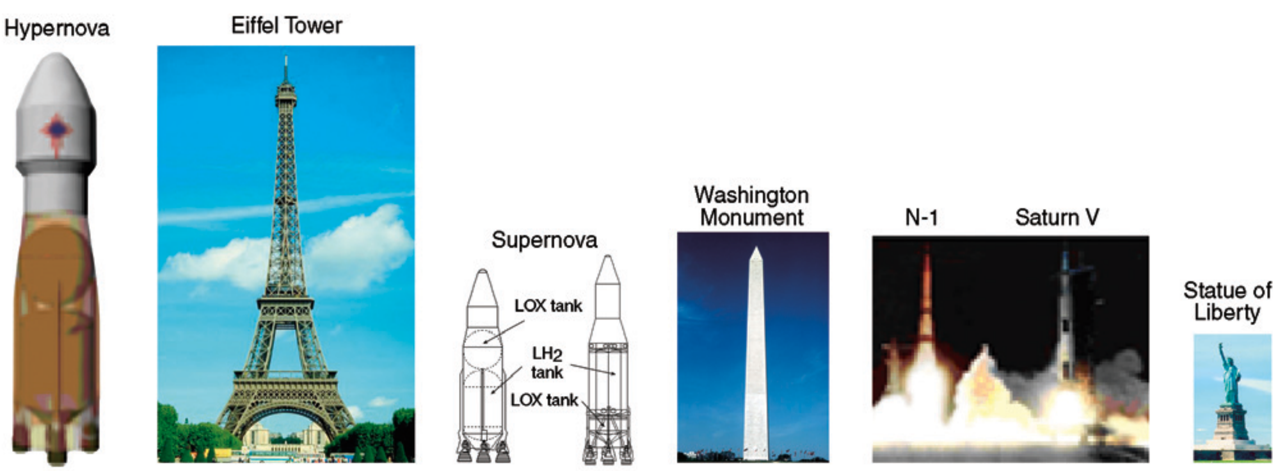

Figure 3. Comparisons (approximately to scale) of various existing and conceptual launch vehicles.[45–48] As an additional comparison, the Saturn V is 0.3 m shorter than the elevation from the ground to the top of St. Paul's Cathedral in London.

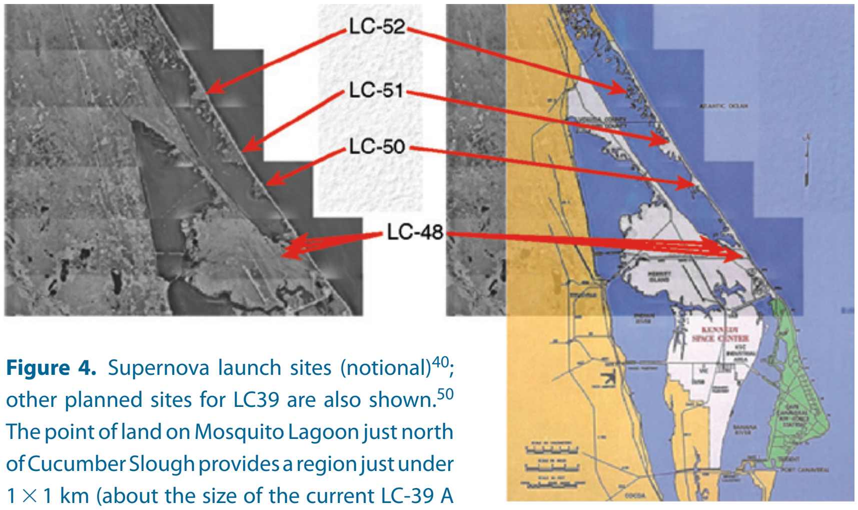

Figure 4. Supernova launch sites (notional)[40]; other planned sites for LC39 are also shown.[50] The point of land on Mosquito Lagoon just north of Cucumber Slough provides a region just under 1×1 km (about the size of the current LC-39 A and B). This appears to be consistent with what has been described as the southernmost of three Nova launch sites. While there is no indication in any online documents where the other two launch sites would be, the next northerly one could well be located opposite the Haulover Canal. The next most northerly region could well be somewhere northeast of Bird Island and Vann Island. If other facilities were to be as far north as possible, that would put them just east of Plantation Island to still be within Kennedy Space Center property.

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