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Space Architecture for Industrial-Scale Space Solar Power

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Of the potential strategic goals human space flight might adopt in the 21st century, the one least examined is industrial development of geosynchronous orbit to produce electrical power for Earth. Integrated system requirements for large-scale operations that could provide a significant fraction of terrestrial grid power are comparatively unstudied; among the unstudied system requirements are those for Space Architecture. The spacefaring population likely required to support even aggressively robotic space solar power industrialization scenarios—up to hundreds of professional space workers—is distinct from other population types: space tourists in low Earth orbit; small, deep-space exploration crews; or lunar settlers. What space solar power workers would need in the way of Space Architecture is therefore distinct, and additive to the types of systems needed for other spacefaring objectives like 2030s tourism and early lunar operations. The paper explores and bounds the nature of Space Architecture system requirements to support full-scale implementation of a space-based power industry. Habitable-system requirements are derived for geosynchronous industrial operations (e.g., transportation, mobility, construction, maintenance) and living (e.g., habitation, assembly, recreation, tourism), based on physical, psychological, and sociological drivers. The paper assesses applicability to these requirements of demonstrated system capabilities, yielding a technology-development agenda that could support the habitation needs.

Acronyms

ALSPE	=	anomalously large solar proton event	*LEO*	=	low Earth orbit
APAS	=	Russian/European berthing adapter	*LOC*	=	loss of crew
CBM	=	common berthing mechanism	*LOX/LH$_2$*	=	liquid oxygen and liquid hydrogen
EVA	=	extra-vehicular activity	*MMSEV*	=	Multi Mission Space Exploration Vehicle
EVR	=	extra-vehicular robotics	*NRC*	=	National Research Council
GEO	=	geosynchronous orbit	*ORU*	=	orbit-replaceable unit
GNC	=	guidance, navigation & control	*RV*	=	recreational vehicle
HSF	=	human space flight	*SLS*	=	space launch system
ISS	=	International Space Station	*SPS*	=	space solar power
IVA	=	intra-vehicular activity	*SRB*	=	solid rocket booster

I. Introduction

THIS paper focuses on Space Architecture for industrial-scale implementation of SPS (space solar power) platforms. Per the Millennium Charter,[1] Space Architecture denotes "the theory and practice of designing and building inhabited environments in outer space." This meaning is distinct from other conventional but vague uses of the term "architecture" in the aerospace profession.

The core topic of the present treatment is the nature of the "architecture program" (i.e., the design requirements) to support very large-scale implementation of SPS—large enough to comprise a meaningful fraction of terrestrial base-band electrical power. Various estimates in the literature provide a sense of the potential scale. In the extreme,[2] total provision of terrestrial electrical power to (1) attain and sustain a western standard of living for the world population, assuming aggressive conservation, (2) desalinate ocean water for potable needs of that population, and (3) produce hydrogen for mobile power, would require building and operating a ring of complexes in GEO (geosynchronous orbit) comparable to five times the total right-of-way of the U.S. National Highway System (i.e., about 13 times its total paved area).[3] For derivation of Space Architecture requirements, detailed validation of such

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estimates is incidental—undershooting the scenario described by three orders of magnitude still leads directly to types and magnitudes of Space Architecture unlike anything previously framed.[4]

II. Scope of the Requirement

Enabling commercial industrialization of GEO for terrestrial electrical power would require a clear break from the traditional focus of six decades of government investment in HSF (human space flight) as led by NASA: planetary exploration.[5] Such a change could occur in one of two ways: by shifting the government HSF goal *away* from human planetary exploration; or by *adding* the SPS focus to it. Neither path is straightforward or avoids programmatic disruption. The former path could be essentially budget-neutral, but would require a seismic repurposing of national HSF programs. NASA's is first among these due to its funding primacy. Adopting an SPS focus would re-charter NASA's multi-decade HSF investment (of order $\$10^{11}$ spread over a few decades) to first demonstrate end-to-end SPS, and then to demonstrate the technologies needed to scale up to operational SPS (e.g., modular solid-state power conversion and transmission; low-polluting, cost-efficient, heavy-lift launch; routine HSF access to GEO and sustained operations there; and large, mass-produced, land-use-compatible ground rectennas).

The alternative, additive path could allow NASA to continue pursuing eventual human Mars exploration, but would require a separate government initiative, perhaps channeled through a different agency, focused on SPS demonstration and scale-up. The present analysis assumes this path for multiple reasons: (1) cultural barriers to repurposing NASA HSF might be insurmountable; (2) U.S. industrialization of GEO for SPS would require collaboration among many domestic agencies in any event, including DOE, DOI (BLM), DoD, DoC, EPA, and DoS, so there are options for its leadership other than NASA; and (3) full-scale implementation of operational SPS would require significant private capital anyway, because operational infrastructure would be constructed and run under a public-private-partnership model as with other utilities. For habitable space systems, the key implication of the additive path is that SPS Space Architecture would exist in a broader Space Architecture context, and thus be able to leverage systems already developed and deployed for other purposes: commercial space passenger travel and government human space exploration.

Table 1, taken from Ref. 2, summarizes the classes and scale of Space Architecture systems reasonable for the decade of the 2030s, presuming the additive scenario: (1) continued, commercially driven growth of the space passenger travel market into LEO; (2) continuance of U.S. investment in HSF at the level of $\$10^{10}$/yr and augmented by international government co-investments aligned with it; (3) a new, likely international, government investment initiative aimed at SPS demonstration and scale-up; finally followed by (4) infusion of capital investment in SPS industrialization by both government and corporate sources. The subsequent requirements derivation analysis explores the system types summarized in the table.

III. Operations-Based Needs for Industrial-Scale SPS

The underlying driver for the subject Space-Architecture program is the SPS implementation scenario itself. Defensible assumptions for a reference scenario can be based on three drivers: contemporary technologies for large space systems including SPS; ISS-based experience with in-space operations; and overall system economy.

SPS system architectures have evolved considerably since Peter Glaser's patent in 1973.[6] Originally SPS system architectures, whether based on solar photovoltaic or solar dynamic conversion, and on microwave or laser transmission, were envisioned as very large space platforms comprising large-scale, discrete subsystems. The first wave of mega-concepts was judged circa 1980 by the NRC (National Research Council) to be impractical. Continued studies and small-scale technology demonstrations led to a second wave of analysis by NASA in the 1990s; at that time the NRC validated conceptual technical feasibility, but found economic viability still lacking given contemporary energy costs. Since the second wave, however, interest has slowly and unevenly grown in Japan, Europe, India, the U.S. (including DoD), and China.

Several technology advancements have now led to a "Type III" SPS architecture far superior to prior concepts in elegance, simplicity, modularity, and scalability. Ref. 6 provides a full description. This architecture eliminates the need for a discrete power management and distribution subsystem, and complex high-power rotating joints, through a solid-state sandwich configuration that combines photovoltaic conversion (in the zenith-facing layers) directly with wireless power transmission (in the nadir-facing layers) and thermal rejection functions. The SPS core is made up of large numbers of identical sandwich modules that can be launched stacked, and each of which operates via retrodirective phased-array beam steering to stay locked on a designated ground receiving rectenna. Sunlight is directed onto the zenith face of the core array by large numbers of tracking mirrors in a gossamer superstructure. Apart from mass, reliability, and launch-packaging advantages, the Type-III architecture dramatically reduces the complexity of on-orbit assembly required, and this improvement directly governs the nature of associated Space Architecture to implement the concept.

Table 1. Taxonomy and capacity of Space Architecture types that could support industrial-scale SPS, space passenger travel, and lunar surface operations in or after the 2030s. (From Ref. 2.)

Activity	Location	Function	Capacity × Frequency	Duration	Habitation System Class
Tourism and Lunar	Earth – LEO	Access/ return	10^3 passengers/yr	Hours	**Commuter-jet-size cabin** in reusable launch/entry vehicle
	LEO	Habitation	10^2 tourists	Days	**Dual-occupancy staterooms** **Outfitted hotel** including assembly spaces (lobby, bar, diner, restaurant, theater, ballroom, spa/gym, infirmary)
			10^2 staff	Months	**Dormitory** + hotel facilities
	Cis-lunar	Orbit transfer	10^1 tourists + 10^0 crew × 10^1 trips/yr	Days	**Dual-occupancy staterooms in small deep-space cruise ship** for excursion tours
			10^0 crew x 10^0 trips/yr	Days-weeks	Deep-space **living/work trailer**, infirmary, intermittent use
	Lunar surface or trans-lunar	Exploration operations	10^0 crew x 10^0 trips total	Weeks-years	Developmental **campsites** (applications laboratory, habitable rovers, airlock/suit, food growth, surgery-capable infirmary), intermittent use
For Space Solar Power (additive)	Earth – GEO	Access/ return	10^2 workers/yr	Hours	**Commuter-jet-size cabin** in reusable launch-GEO-entry vehicle
	GEO	Orbit transfer	10^1 workers	Continuous use	Reusable **commuter bus** between worksites and habitat
		Habitation	10^1 tourists	Days	**Cabins**, dual/quad occupancy **Long-life hostel** facility (mess, observation, infirmary)
			10^1 tourism staff	Months	Long-life **apartments** Hostel facilities + gym
			10^2 workers + 10^1 – 10^2 operations staff	Months	**Dormitory Assembly/recreation spaces** (bar, mess, theater, gym, surgery-capable infirmary)
		EVA/EVR operations	10^2 workers	Continuous	**Routine, quick-egress EVA** (e.g., suitport, man-in-can)

Five key assumptions drive the present treatment's subsequent derivation of SPS-industrialization Space Architecture requirements:

1) SPS flight system architecture based on Type-III SPS concept (hyper-modular, solid-state, integrated sandwich configuration of bus elements for conversion and phased-array microwave transmission; with steerable, thin-film solar reflectors; nadir-facing and located in GEO)
2) Assembly operations based on robotically actuated gross berthing of modular units designed for auto-alignment, auto-interconnection, and coordinated operation
3) Operational maintenance activities (monitoring, fault-detection and recovery, inspection, diagnosis, and change-out repair) also based on autonomy and robotics
4) Hierarchical sparing architecture for SPS modules and the robots that service them (hot spares that provide online supercapacity; cold spares that can be brought online; proximate stores of spare SPS modules, assemblies, subsystems, and components; ground-based spares inventory launched over time to replenish proximate stores)
5) In situ human mediation in assembly and maintenance activities, principally aimed at supervisory control, oversight with capacity for intervention, troubleshooting, jury-rigging, preparation of proximate spares for

installation, decommissioning and refurbishment of removed units, and servicing and repair of the robots that do most of the work.

This reference operations scenario drives a habitable-system Architecture that provides the three transportation and operations-related functions in the SPS portion (lower half) of Table 1: EVA/EVR (extra-vehicular activity/extra-vehicular robotics); orbit transfer; and access/return.

A. EVA/EVR Operations

A spectrum of four system approaches could enable direct human action at a GEO work site:

1) Suited/gloved astronaut, positioned by either fixed foot-restraint, robotically-positioned foot restraint, or propulsive maneuvering unit
2) Personal "man-in-can" capsule, with external gloves and/or EVR manipulators, positioned via grapples and/or propulsion
3) Small cab (for two, or a few, crew) with external gloves and/or EVR manipulators, positioned via grapples and/or propulsion, with suitports for contingency EVA
4) Teleoperation of mobile EVR manipulators from inside a proximate or remote habitat, with suitports or airlocks for contingency EVA.

Derived requirements—Approach 1 has been used extensively in ISS operations, while Approaches 2, 3, and 4 have been used in the analogue environment of undersea industrialization (e.g., drilling and salvage operations). Contemporary NASA concepts for small-rover lunar and asteroid surface operations favor Approach 3. The most reasonable approaches to posit for SPS operations might be 1 (because of existing, extensive operations experience), 3 (because industrial use in GEO could leverage NASA investment in and experience with systems for lunar and/or asteroidal environments), and 4 (because the predominant activity mode for SPS assembly and maintenance, per the reference scenario, is robotic with supervised autonomy).

B. Orbit Transfer

Most of Earth's power-consuming population is in the northern hemisphere. Large southern populations can be easily irradiated with near-overhead geometry (using Sydney, Cape Town, and Buenos Aires as proxies, all of which are on the Tropic of Capricorn, 23.5° south latitude). SPS is challenged to supply Earth's northernmost cities directly (the slant angle results in a GEO satellite being only about 30° above the horizon), but there are multiple technical solutions to compensate, including ground transmission lines from more southerly rectennas, and Lissajous SPS orbits that oscillate out of the equatorial plane. The present discussion is based on the simplified assumption of equatorial SPS stations in GEO itself, with overhead longitude.

Industrial-scale SPS complexes would be distributed around GEO, albeit unevenly, with at least five longitudinal clusters: over the Americas, Europe/Africa, Middle East/Russia, India/Pakistan, and Asia (Fig. 1). A single Americas cluster would cover the greatest range: almost 90° of longitude from Vancouver to Brazil. At GEO orbital altitude this arc equals 66,000 km of range along the orbit track. The 60,000 km end-to-end chord separation poses a 0.4 sec maximum round-trip teleoperation signal latency within the cluster.

For human access during assembly and on a continuing basis thereafter we can define four distinct system-habitation Architecture options, ordered here by increasing impact on the reliability architecture of the SPS systems themselves:

1) **Dispersed resident workforce**, with hundreds of small crews each devoted to a respective, locally-accessible region of SPS complexes, and able to reach any of them within a day's work shift using proximity-operations propulsion and systems.
2) **Crew town** centralized in each cluster, with crews commuting routinely as needed to reach work sites within the cluster. Per Figure 1 this would lead to at least five such towns. Commute times of just hours are technically feasible (for example, geosynchronous transfer orbits from Earth-launch up to GEO have an impulsive coast time of about five hours), but would require full-stage burns and trips through the van Allen radiation belts. The high propellant cost, along with retanking, depot, and stage-refurbishment operations, might nonetheless turn out to be acceptable as part of an integrated SPS architecture because of the huge Earth-to-GEO lift capacity needed anyway to emplace SPS hardware.
3) **Itinerant crew complex** (a mobile town), that slowly repositions along its cluster over months-long periods to enable construction and scheduled maintenance at the SPS complexes closest to the town at a given time. Longitude drifting is used today to reposition communication satellites efficiently; for example, from February to August 2000 Marisat was moved at about ⅔ °/day from 72.5°E to 33.9°W. The move took 5.3 months, but only enough propellant to raise the orbit 50 km above GEO; at the higher altitude, orbital speed decreased so the satellite drifted westward. In this scenario SPS complexes would need

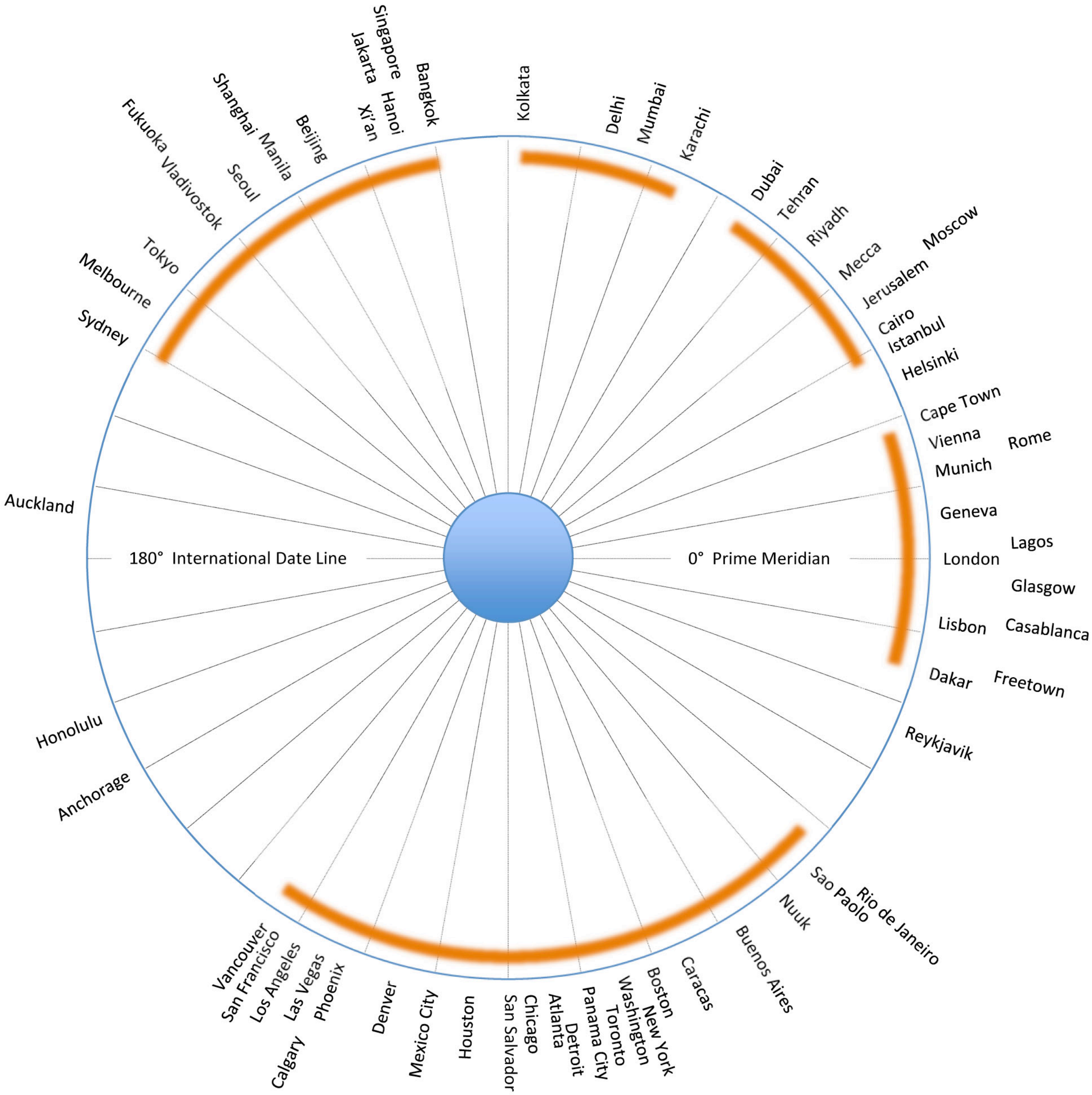

Figure 1. Major global cities are proxies for terrestrial power consumers. City longitudes are shown mapped up to GEO, viewed from above north pole; central blue disc represents Earth to scale; orange arcs indicate reasonable extent of SPS clusters along the GEO orbit.

sufficient redundancy to operate at full capacity despite individual modules or even significant fractions of complexes going down for months at a time. In the extreme, a single large crew town could service the entire GEO ring.

4) **No long-term GEO habitation**, with assembly and servicing accomplished almost fully robotically, and with only short supervisory visits up from LEO by small crews, only as needed (when automated or teleoperated robotics cannot perform the required tasks).

The differences among these options are profound both for SPS implementation and for Space Architecture.

There would be a high economic incentive to avoid the costs of either one-time or extensive, ongoing human presence; or of extensive, routine travel within and around the GEO ring. Thus we can expect significant non-recurring investment in robotic capabilities, autonomous operations, and reliability management, and significant redundancy in built systems, all "baked into" the SPS system architecture to avoid HSF-related costs as much as possible. Yet Option 4 relies on a scale and scope of automation and robotics that is too far beyond present capability to be a sound analytical basis today for an energy scenario on which human civilization could come to depend.

Option 1, while less extreme, is reminiscent of von Braun's dated, labor-intensive vision of a manned telecommunications-relay space station; this option does not leverage approaches for modular design, system redundancy, and robotic telepresence that can already be confidently designed into a reference SPS architecture. This option would also be unlikely to obviate the need for an adjunct "town" Architecture anyway; a large, distributed working population without any means to gather for social intercourse would be unprecedented. For example, even in rural settings on Earth, farms obtain social benefits from villages, and farmers go to town occasionally.

Derived requirements—Of the remaining options, Option 2 embeds the highest transportation cost and risk. Option 3 offers the most elegant marriage between an SPS architecture based on advanced robotics, sustained autonomy, and robust operational redundancy, and the need for a workable support-crew habitation Architecture. It also naturally supports a sustained, practical assembly and commissioning sequence in which SPS capacity at given orbital longitudes can be incremented gradually over time. Crew presence during assembly thus transitions seamlessly into crew presence for operations support.

Itinerant crew towns established in super-GEO would slowly drift westward relative to the SPS arcs, without further need for major propulsive maneuvers. The drift rate, strictly a function of altitude above GEO, would be determined by the average linger-time requirement for operations at a given longitude, which in turn is a function of the actual reliability and redundancy architecture of the SPS platforms as well as the longitudinal density of SPS platforms. Stationkeeping of a massive town could be done by high-capacity electric propulsion, since avoidance of major propulsive maneuvers is important for economy and practicality and the entire SPS architecture benefits from a power-rich environment. For example, compare ISS as a template for a proto-town. As fully assembled it masses about 450 metric tons, and could support ~20 crew (if it were not also a sophisticated laboratory). In June 2011 the ESA ATV *Johannes Kepler* used about 1.5 metric tons of propellant to boost ISS just 35 km in altitude. This benchmark demonstrates that an SPS support-town complex should be orbit-shifted as little as possible, and take advantage of the I_{sp} of electric propulsion to do it.

Thus the reference orbital-transfer architecture requirement for the present analysis collapses to one primary and one secondary function. The primary function is to shuttle work crews back and forth between a town complex and a set of SPS platforms within 10^2–10^3 km range, and support them while at a work site. The proximity-operations maneuver regime means transfer durations on the order of a few to several hours; typical operations at a work site would range between hours and days. So the habitation requirement is analogous to a terrestrial RV (recreational vehicle) but with the capacity of a tour bus: up to ~20 people with duration up to a few days. A work shift, including transfers out and back, would last for a portion of a week, directly establishing a near-weekly work-break rhythm. For reference, assume a 6-day cycle (4-on/2-off), which integrates well with the habitation scenario described in the next section.

During the work cycle, activity would proceed around the clock, so the "bus" habitation Architecture would need to support multiple shifts, with simultaneous work, rest, and sleep periods for shift crews. IVA operations provisions would include EVR workstations, meeting/planning space, IVA workshop, airlock/suitlocks, berths with IVA crew transfer for free-flyer operations-cabs, and bus flight stations. Habitation provisions would include spaces for rest/sleep with multi-day stowage, recreation lounge, galley, hygiene, contingency medical, consumables stowage, and a configuration for solar-flare storm shelter.

The secondary function is to transfer crew from one town to another reasonably quickly. There is no clear operations requirement for this function—perhaps the quick transfer of a specialist or tiger team to handle an emergent issue, or relocation of assembly crews during uneven buildup of the SPS ring—but it seems reasonable if there are multiple GEO towns that people should be able to get from one to another occasionally without returning to LEO enroute. To first order this function can be met with the same type of bus just described, augmented by a high-thrust propulsion module.

Scaling this orbit-transfer architecture could be accomplished by increasing the number of transfer buses and propulsion modules.

C. Access/Return

Economy would exert pressure for GEO-crew duty tours to be as long as possible within manageable constraints of psychological and physiological health. The predominant physiological limiters would be radiation exposure, microgravity exposure, and emergent medical conditions.

Psychologically, GEO would be a remote-duty assignment. The Earth subtends about 20° of the sky, presenting about the aspect of a soccer ball held at arm's length. Feelings of isolation and immediate hazard would be mitigated within the context of various-size work crews and the sociology of a work town, but social interaction would still be limited to fellow-workers. The rest of human society would be packaged into voices in headphones and images in screens, and crew would be separated from family while on orbit.

Being in the outer edge of the outer (electron) van Allen belt, GEO poses a more challenging radiation environment than LEO. It is clear that without breakthroughs in biochemical countermeasures, cabin shielding and limits on the duration and number of duty tours would be the only means available to curtail annual and lifetime integrated exposure.

The same applies to microgravity deconditioning, indicating (for a first analysis) individual tours of duty comparable to current ISS experience. ISS tours of duty in LEO are typically six months, 25% less than the overwinter duration at South Pole Station in Antarctica. So the reference access/return architecture should accommodate exchanging the total GEO population over a six-month period. Assuming a GEO population n, and launch/entry system with capacity 20 passengers per flight, yields a flight rate of $2n/20 = n/10$ flights per year. Depending on the assembly rate and continuous support scenario, n could reach several hundred (including both the industrial workers and the on-orbit support they would require). If $n = 1200$, consistent with the subsequent discussion, biweekly flights and a small fleet of access/return transports would be required.

Derived requirements—Derived Space-Architecture requirements include: a reusable, high-acceleration, atmospheric-flight cabin capable of sustaining ~20 people for up to half a day; and 60 flights every six months (one every three days) to exchange the population in the course of six months, assuming three 400-person GEO towns (one for the Americas, one for Europe/Africa and the Middle East/Russia, and one for India/Pakistan and Asia). A turnover of 1/6 of a town's population every month, for a town size of less than 400 people, would establish a sociological dynamic that shares some elements with both a mid-size hotel (small community, rapid turnover, strangers) and a rural village (small community, stable, well-known). Each individual would undergo a duty-tour relationship lifecycle: six months in the environment, but shorter timescales for meeting new people, establishing relationships, and saying goodbye because of the staggered rotation schedule.

Space-Architecture implications of this access/return scenario—including a habitation Architecture to host transients on a staggered schedule and facilitate a short-turn relationship lifecycle—are explored below, in the section on living-based needs.

D. Depot

The reference scenario introduces a fourth Space-Architecture function not listed in Table 1. The scenario posits twelve 23-person work teams (20 workers + 3 flight crew) for each mobile town (Fig. 2). At any given time two sets of four teams are away from the mobile town, on staggered four-day work excursions. As the mobile town drifts by SPS stations in succession, the work teams visit them to perform oversight of assembly and commissioning (during buildup), inspection, and equipment change-out of both the maintenance robots and SPS subsystems. The buses carry a cargo of ORUs (orbit-replaceable units) for this purpose.

The third set of four teams stays at the mobile town for two days before departing again. During that time they work "day shifts" at the depot and have evenings for social recreation. The flight crews process their buses (flight subsystem maintenance including recharging consumables and propellant); the work crews do salvage and refurbishment of SPS ORUs. If depot work continued the shift schedule of each work team, 46 people at a time would be working while the other 46 were off duty.

This scenario appears to be the most economical because it makes maximum use of physical facilities; work equipment, work spaces, and social spaces would be in use at all times. However it minimizes social interaction beyond the population of the work teams sharing the same shift schedule, so it is the least satisfactory from a sociological standpoint. Full implications of such a sociology-vs.-facilities tradeoff for a deep-space industrial scenario are a subject for future analysis.

Derived requirements—The depot function would require (1) berths for 12 work buses (for the contingency when the entire population is at the mobile town, e.g., for a predicted solar flare); (2) EVA/EVR provisions for bus servicing; (3) SPS ORU warehouse; (4) shirtsleeve workshop with cargo airlock for component-level teardown, refurbishment, and rebuild of ORUs.

Detailed requirements, e.g., dimensions and capacities of the depot facilities, depend on fully integrated concept engineering of the SPS systems, robotics, and transportation architecture and is not treated further here.

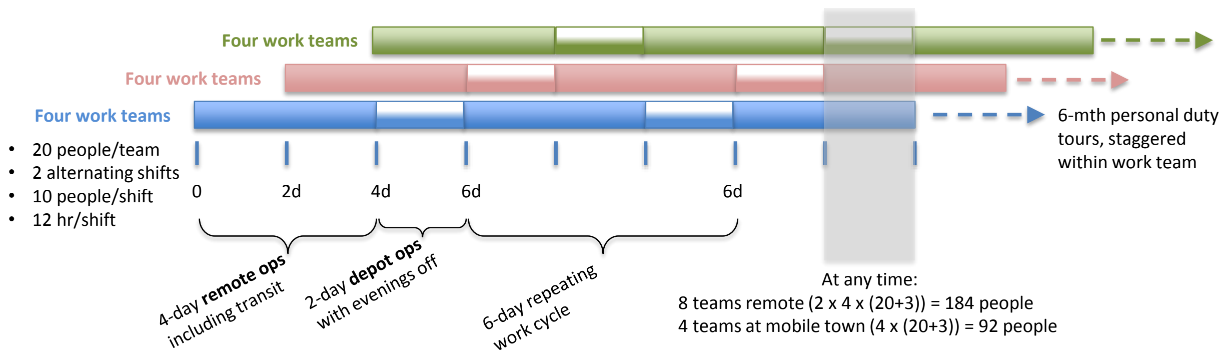

Figure 2. Staggered shifts result in 80 worker-shifts continuously in situ at SPS plants, plus 40 worker-shifts continuously at ORU depot.

IV. Living-Based Needs

The habitation functions in the SPS portion of Table 1 support three populations: (1) professional space workers conducting the SPS industrial operations discussed in the previous section; (2) professional space workers providing support services to them; and (3) a small number of high-paying tourists visiting "the action" in GEO. Distinctions among the three are fundamental to the amount and nature of Space Architecture associated with SPS. The first and second groups comprise a total of up to hundreds of highly paid professionals; on orbit for months; tolerant of compact and Spartan accommodations. The third group would be quite different: the elite tier of a broader, elastic passenger-travel market.

A. Professional SPS Workers

The raison d'être of human space flight associated with SPS industrialization arises from two types of activity: (1) direct demonstration, characterization, assembly, verification, commissioning, monitoring, routine maintenance, and emergent remediation of operational SPS systems; and (2) development, performance verification, local supervisory control, and ongoing repair and optimization of robots that do most of the SPS work.

The reference operations scenario assumes aggressive automation and robotics, and thus a very low ratio of humans to SPS infrastructure. Up to hundreds of SPS workers would be resident at any given time in a mobile GEO town, deployed on "traveling" work shifts lasting up to a few days. Living-based needs not already addressed above arise from the habitation and community facilities serving as the mobile-town "home base" for these workers.

Habitation functions can be divided into primary and secondary drivers. Primary drivers are: sleeping, hygiene, eating, resting, exercise, small-group entertainment, and medical care. Secondary drivers are: private communication, sex, and hobbies. For six-month tours of duty in remote locations the secondary drivers can be accommodated by facilities needed anyway for the primary drivers. For example, hobbies like reading, watching TV, playing music, and tinkering with hardware or software are easily accommodated by facilities needed for other purposes. Private communication (e.g., with family on Earth) can even be accommodated in public places, as contemporary usage of smartphones and earbuds shows.

For the primary drivers a combination of private and shared chambers is required. Living-accommodation approaches could range from Spartan (barracks) to sufficient (dormitory) to comfortable (apartments). Economic pressures mediate against the "high end," while an industrial, non-military organizational model mediates against the "low end." Accommodations for terrestrial work crews in extreme environments provide a rough template. For example the upper Midwest oil-shale boom has led to the rapid growth of temporary-worker "man camps." Habitation architecture and sociology are diverse; some workers live individually in tents and RVs adjacent to communal hygiene setups; many economize by sharing rented trailers (e.g., 12 cots in a double-wide); and those willing to pay up to ~$400/month to their employers for room and board live in special-purpose buildings. The 1250-bed Tioga Lodge, a hermetic, environmentally-controlled station designed for North Dakota climate conditions, has private rooms along a 300-m corridor, and contains TV lounges, fitness center, barber shop, tanning booth, hot-tub spa, and 24-hour commissary.[7] The typical room is equipped with single bed, small desk, one chair, TV, DVD player, and lavatory, and shares a "Jack and Jill" shower/commode room with the adjacent cabin (Fig. 3). The "VIP/Executive" room type is essentially the same, but with full-size bed, more storage, and private ¾ bath. Experience indicates a sparse and prioritized set of architectural care-abouts: good food, comfortable bed, security, and privacy.

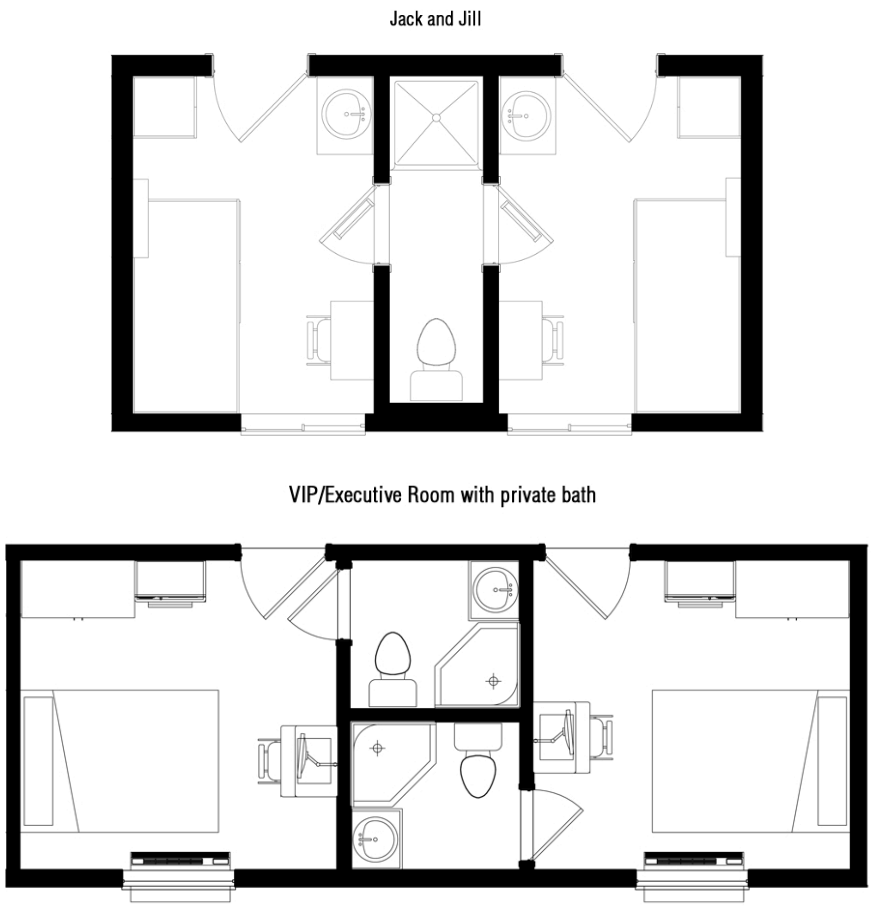

Figure 3. Very small private cabins are standard for company housing in remote work towns on Earth (Tioga Lodge built by Target Logistics, www.TargetLogistics.net)

Oil-drilling man camps are not a perfect template for a GEO SPS industry, as indicated even by their nickname. Oil work is physically demanding far beyond what space-worker safety would permit (stories by Robert Heinlein notwithstanding), so there is no particular reason to posit a skewed sex ratio for GEO workers. Also, whereas many young oil-boomers are lured by $4000/week salaries to skip or defer college, it seems reasonable that most space workers would need advanced education first, due to the technical complexity of the systems they would operate, maintain, and be sustained by. Higher average education level and a more normal population mix would make the sociology of a GEO industrial community noticeably different from an oil camp.

Finally, the work-shift structure of the reference GEO scenario (six-month duty tours; with a cycle of 4 days on at a worksite, 2 days off at the mobile town) is quite different from the daily rhythm of oil workers (up to years-long duty tours; with a cycle of two weeks on, one week off; and work shifts up to 16 hr/day, seven days a week but returning to a private room for each sleep period). An economic model that left private chambers unoccupied more than 70% of the time would make no sense for GEO. A more reasonable model would multi-assign time-shared rooms to staggered work shifts; for example, one room could support three workers (one each from the blue, red, and green teams in Fig. 2) rotating through their respective 4-on/2-off cycles, given provisions for secure personal stowage and semi-daily housekeeping service. Interior architecture that could be re-personalized visually and sonically, every two days as the occupant changed, would be a welcome enhancement.

Medical care requires a surgery-capable infirmary. Constant population turnover and tight living conditions imply a steady flux of viral respiratory infections. In addition, many other conditions requiring urgent care could be expected to occur or emerge during six-month duty tours, e.g., chronic musculoskeletal strains, fungal skin infections, dental caries and trauma, minor or major injuries, kidney stones, and appendicitis. Provisions for routine examination, blood-work, imaging diagnostics, cytology and pathology, observation, and isolation would be required, along with two capabilities for which there is no precedent in space travel: in situ surgery, and stabilization for evacuation to Earth. Solutions for appropriate protocols, techniques, equipment, certification, and training comprise a novel field of research and development essential for sustaining worker populations in GEO.

The remaining habitation functions go beyond the personal realm, into the full social arena: communal meals, large-group entertainment, sports, and assembly. A mess hall can provide a multi-purpose architecture-program solution, supporting routine group meals as well as episodic entertainment events (e.g., movies, theater, music performances) or other assemblies for procedural or safety coordination.

Apart from muster drills and management-assembly events expected for any complex operation, habitation beyond the geomagnetosphere would require safe-haven provision for solar flares (ALSPE, anomalously large solar proton events). Low-atomic-weight, particularly hydrogenous, materials are required for shielding, so the most effective and efficient solution from a shielding standpoint, as well as from the practical standpoint of sustaining the shielded population for days, would be to use the mess hall as a storm shelter, surrounded by the town's water, food, and waste resources as primary shielding. In close quarters, the occupants themselves would provide effective secondary self-shielding.

Sports at an SPS town would likely include free-fall equivalents of recreational pickup basketball or soccer games. In terrestrial industrial towns a soccer pitch is straightforward to configure; in space an equivalent facility would be far more expensive to build and maintain. In addition, recreational sport would likely go beyond team competitions and spectator entertainment to include the workout gym. Again the terrestrial industry-town precedent does not quite match. Oil roughnecks already expend significant physical activity by working long shifts of heavy labor for days on end, so a hotel-type fitness center is sufficient to accommodate the small cohort that wants recreational workouts. But SPS workers would not be an analogous population: roboticists, technicians, and space-system engineers can reasonably be expected to want the equivalent of a terrestrial sports club that offers diverse equipment, group-exercise classes, and daily social interaction. Furthermore, presuming no biochemical prophylaxis is developed for microgravity deconditioning, daily exercise on orbit would remain essential to maintain health for the duration of a duty tour, as it is today on ISS. A large population engaging in significant daily exercise time naturally fits a social architecture solution.

Provisions for leisure gathering would also be required. The model is a lounge, where people can congregate off-hours to talk, unwind, socialize, watch sports or other entertainment in a social setting, or be "alone in a crowd" as an alternative to spending time in their private quarters. Social use of intoxicating substances is untested in the hazardous environment of Space Architecture (apart from occasional, ceremonial use of vodka by international crews reported anecdotally). Company-managed facilities like Tioga Lodge have a no-alcohol policy.

B. Operations Staff

A large, continuous work population in GEO needs support services to keep them productive. Although these needs may be grouped in various ways, the following breakdown serves for estimation purposes: Professional (physicians, dentists, nurses, physical therapists, counselors); Hospitality (restaurant, food culture, housekeeping); Transportation (flight crew, flight-system technicians); Service (laundry, groomers, retail); Facilities (managers, administrators, security, systems technicians).

A key issue is the sociological relationship between the SPS-worker and operations-staff cohorts. While both are subject to the same environmental risks (space flight, radiation, microgravity, intrinsic medical emergency), similar duty-tour constraints and turnover, and the same basic economics of human space flight, they nonetheless differ in specific ways. First, SPS workers would likely incur higher occupational risks from worksite commutes, more-frequent EVA, less-thorough radiation sheltering, and possibly exposure to job-specific materials and energies. Second, they would generally comprise a homogeneous cadre of high-tech workers. While physicians would be at least comparable socioeconomically, housekeepers and barbers would not. The operations staff comprise a diverse cadre, so it is reasonable that societal stratification could develop.

Architecture to support the two populations would inevitably embody the social-engineering choice of how to address this cohort distinction: how much to optimize for it, blur it, or balance these two poles. The present analysis assumes the Architecture should blur the distinction as much as possible. This approach avoids Balkanizing the small total population and promotes opportunities to form relationships throughout overlapping, fairly short duty tours.

Derived requirements for SPS-worker and operations-staff living—Architecture implications of such a total-population sociology include: (1) fairly homogeneous range of living accommodations; (2) intermixing of accommodations assignments to avoid formation of occupation-based ghettos; (3) communal access to the shared services listed earlier, by both SPS workers and the service workers supporting them; and (4) assembly facilities large enough to accommodate the total population.

If biased toward economy, the minimal set of multi-function solutions in Table 2 could accommodate the functions outlined for the two town populations. Functions share facilities in the time domain: (1) private cabins for work crews and their transportation crews are shared one off-shift at a time so the town requires only enough rooms for one-third the SPS work-crew; (2) the largest single space in the complex is used for cafeteria meals, solar-flare storm shelter, muster, other assembly functions, communal cultural recreation (e.g., theater, watching the Super Bowl), and athletic events like team sports; (3) the recreation lounge is divisible into private-party rooms where meetings, celebrations, or even cooking might occur. The reference scenario asserts that such aggressive multi-use is possible through clever design of microgravity outfitting. For example, no one really knows yet what a microgravity team sport would be—one can envision a form of soccer as a test case. So microgravity-restraint seating and tables that could be stowed, together with appropriate materials for sport clothing and balls, and finishes and mechanical systems resistant to impacts and scuffing, could allow the use of a single volume for meals at mealtime and games in between.

The habitation program specified by Table 2, albeit built up from the functional analysis in the preceding sections, feels familiar—essentially it is the same program as a contemporary multi-service hotel. Consider: hundreds of rooms; lobby with bar, lounge, restaurant, and administrative offices; promenade with small stores, business center, and health club/spa; divisible meeting rooms. Compared to this terrestrial model the key differences are: the mobile town program has fewer "guest" rooms; larger sports club; a surgical hospital; adjacent industrial work area and bus depot; and of course less volume and luxury per occupant. Nonetheless the terrestrial-hotel program can point the way to successful topological arrangements that rest on well-understood human-behavior precedents, as designers begin to consider SPS industrialization.

C. GEO Tourists

A GEO-tourism population model consistent with other assumptions in Table 1 would total only some tens per year, a few at a time; visiting for days; paying highly for an integrated adventure-travel experience; and expecting amenities commensurate with the ticket price. For SPS workers EVA would be a risk necessitated by their job; for adventure travelers it would be a pricey but popular recreational option.

In the context of a thriving, continuous LEO passenger-travel market, GEO tourists would be the deep-space, adventure-travel vanguard. As a contemporary analogue consider two ways to visit Machu Picchu in the Peruvian Andes. The most common way is to fly to the mountain city of Cuzco, take a train 112 km down the Urubamba River to the resort town of Aguas Calientes, then use daytime, hourly bus service to cross the river and climb switchback roads to a parking lot built just outside the ancient city. The pricier, riskier, "more authentic" way also goes through Cuzco, but actually starts in the Sacred Valley of the Incas, at the river town of Ollantaytambo at Kilometer 88 on the rail line. Arriving after months of conditioning, adventure travelers hike the Inca Trail itself – four days, 36 kilometers, over three 4200-m mountain passes, sleeping in tents, chewing coca leaves to blunt the effects of altitude sickness, and arriving finally at the Sun Gate above the ancient city. Both ways are tourism; only the second is adventure travel.

"Amenities" for adventure travelers, albeit required, are significantly different from those for mass-tourism markets. Unique and fun things to do, authenticity, and a degree of rarity are essential; many creature comforts are not. Indeed some deprivation and risk are desirable, if authentic—a badge of honor for the adventure traveler. Social bonding that occurs via emotionally memorable activities and communal meals often leads to long-term friendships; and the adventure traveler comes away with a sense of achievement quite unlike the "been there, took pictures" mass-tourism experience.

Derived requirements—Tourism associated directly with GEO industrialization would begin as adventure travel. Small groups might arrive in dedicated vehicles at a GEO worker town for a few-day visit. The tourism support crew would be embedded with the tourist group throughout their trip, as is typical for terrestrial adventure travel. Activities would include acclimatization and training; tour-group communal meals; overview tours of industrial operations including maintenance shops, command centers, and onsite work; physical adventures including excursions to work sites and EVA; and private time—with a view of the soccer-ball Earth—for rest, contemplation, and sleep. The trip and the place would provide the signature experience; and the local industrial workers would be like actors on a stage. Limited socialization might occur at special social events, for example.

Derived requirements for a small adventure-travel population thus impose only quantitative capacity adjustments to the facilities already needed by the SPS-worker and operations-staff populations.

Table 2. Minimal physical facilities accommodate living-based requirements for 400-person mobile-town.

Function	Assumptions	Reference Architecture Solution
Habitation (SPS workers)	• Total population 240, divided into 12 20-person work teams, 8 of them in the field at any given time • Plus 3 flight crew per work team • 6-month duty tours, staggered • Work schedule: 4 days on at remote worksite, 2 days off at mobile town • Predominantly single relationship status	**92 small hotel chambers** (80+12=92 cabins), single-occupancy, hot-bunked in rotation by three workers • Secured private stowage of personal effects while working • Cabins personalized electronically (visual and sonic environment)
Habitation (ops staff)	• Total resident population 60 (3/4 as large as resident worker population) • Plus margin of 40 (intermittent flight crew and other visitors from Earth) • 6-month duty tours, staggered • Some couples	**100 small "residence hotel" chambers** (equivalent single-occupancy cabins) • Conjoined for couples
• Communal meals • Storm shelter • Muster/ assembly • Group entertainment • Microgravity team sports	• Town population needs a forum space for assembly of many types • Large facility must be schedule-multiplexed to economize • Sized to accommodate total town population for multi-day solar flare • Disparate functions (eating vs. microgravity team sports) can share one space given clever design	**Large multipurpose chamber** • Deployable/reconfigurable outfitting, furnishings, & visual/sonic environment • Primary use: communal meals for ≤200 • Secondary use: assembly and recreation including "ball court" with teams and spectators • Contingency capacity: multi-day storm shelter for ≤350 • Ancillary facilities: cafeteria kitchen, food storage, waste processing, stowage for multi-purpose outfitting and furnishings
• Lobby • Lounge • Media room • Small parties	• Population numbering over ~50 needs some type of commons for casual meetings • Spaces for communal relaxation and media entertainment must be available at all times • Semi-private gathering places needed at scales between full-population and private-chamber	**Moderately-large multipurpose chamber** • Informal social mixing space outfitted with reconfigurable furnishings • Partitions to divide intermediate-size chambers for private functions for ~10, 20, 40 people • Ancillary facilities: bar, stowage
• Sport club • Spa • Clinic • Surgery	• Multiple hours per day of physical exercise critical to manage microgravity deconditioning • Prime opportunity for social interaction • "Creature comforts" become popular amenities in remote setting • Routine medical/dental/pharmacy care • Capability for stabilization and microgravity surgery	**Physical health complex** • Moderately-large workout chamber outfitted with strength, cardio, and physical-therapy equipment • Intermediate-size group-exercise chamber, flexible outfitting and equipment • Locker/shower chambers (male/female), steam/sauna chambers, massage chambers • 3 examination chambers outfitted for routine medical/dental care and diagnostics • 2 semi-private hospital chambers for isolation/ observation/recovery • Surgical chamber • Ancillary facilities: hygiene, stowage, mechanical
• Retail	• Minimum services: grooming, laundry, personal items • Private enterprise	**Storefront chambers** • Conveniently located • Secure storage
• Administration • Coordination • Facilities management	• Large complex with diverse activities and large transient population has significant onsite administrative overhead	**Operations center** • Service counter, offices • Ancillary facilities: maintenance, housekeeping, meeting

V. Capability Gaps and Technology-Development Agenda

The human space-flight industrial community is far from prepared to support industrialization of GEO by a mid-21st energy industry. The capabilities, capacities, and technologies needed are not principally aligned either qualitatively or quantitatively with current trends in government space-flight investment.

Using the reference scenario as a benchmark, the SPS capability gap can be binned into two types: (1) those to overcome to intrinsically enable large-scale SPS launch and operation; and (2) those to overcome for HSF to support an SPS enterprise. Table 3 summarizes both types for reference; however only the latter type, relevant for SPS Space Architecture, is discussed here.

U.S. government HSF plans in 2012 include development of an integrated flight system comprising an evolutionary-capacity SLS (space launch system) and Orion (crew vehicle), capable together of reaching GEO and supporting some assembly and servicing operations there. The SLS/Orion system is envisioned to open a deep-space HSF future that reaches Mars someday. Its design reliability reaches into the low end of the range proposed here for HSF to support SPS industrialization (loss-of-crew events limited to at most 10^{-3}). Furthermore both stages of the SLS core are based on LOX/LH_2 propulsion (the exhaust is water vapor). Developmental flights will use Shuttle-era SRBs but the eventual booster propulsion has not been selected; LOX/LH_2 for that element as well would make the SLS a fully "green" launch system. In addition, as has been known since the 1970s, a flyback configuration for those boosters could lead to a reusability rate compatible with SPS cargo launch requirements. However, these booster choices are not assured.

Beyond the issue of launch, the government transportation architecture is silent regarding other systems essential for SPS industrialization: highly-reusable orbit transfer tug; habitable operations bus compatible with it, with capacity for two-dozen people for several days; berthing mechanisms that can function reliably and continue to seal well after thousands of usage cycles; large-power electric-propulsion stages for orbit-shifting and station-keeping of SPS platforms and inhabited stations. A few technology investments are underway that could lead to such systems (e.g., on-orbit cryogenic propellant transfer and storage; electric propulsion in the multi-tens kW range); and significant concept momentum exists already for a two-person EVA/EVR operations vehicle sometimes called the MMSEV. Developing any of these systems to reach operational capability is not assured either.

Table 3. SPS capability gap defines a technology-development specification that could frame a coherent strategic future for human space flight, linked directly to timely terrestrial priorities.

SPS-intrinsic (broad categories, for reference only)	HSF-enabling (per reference scenario)
• **Advanced space robotics**—Capable of primarily autonomous positioning, assembly, verification, operation, inspection, troubleshooting, and ORU replacement of SPS system modules. Capable of self-diagnosis, mutual servicing and ORU replacement of robots. • **SPS system architecture**—Reliable, continuous operation of a large formation fleet of large, lightweight, high-power, deep-space space platforms • **Modular SPS subsystems**—Platform architecture comprising thousands of identical, interchangeable, solid-state PV-to-μwave panels; thousands of structural elements; thousands of aimed thin-film reflectors; integrated functions for station-keeping, GNC, telecommunications, onboard power, and fault management • **Cost-efficient "green" launch to GEO**—High-rate, low $/kg launch of SPS elements without toxic or climate-impacting effluent • **2.45-GHz transmission protocols**—Technical and treaty resolution of health, heating, and radio-interference impacts of high-flux trans-atmospheric power transmission and ground reception	• **Reliable human launch/return**—LOC likely 10^{-3} for a quasi-commercial industry that exchanges ~600 people/year in GEO • **GEO operations**—ISS-class EVA/EVR operations at GEO; storm-shelter protocols for solar flares; routine orbit transfer • **Highly-reusable in-space vehicles**—SPS work buses for daily "commute" and proximity operations between SPS platforms and mobile town; 10^3 startup cycles, routine replenishment of consumables including propellant; capacity 20 passengers + 3 crew • **Multi-use berthing mechanisms**—Certified for 10^2 to 10^3 × cycles experienced by ISS CBM and APAS subsystems • **Large habitable volumes assembled and verified in situ**—Able to accommodate assembly of 50–400 people; and contingency storm-shelter of same number for multiple days • **Kitchen science**—Genuine cooking; food growth and processing; kitchen-waste recycling • **Surgery**—Equipment, procedures, and experience for open surgery including organ restraint and fluids management

Radiation shielding using water, food, and other low-Z materials has been conceived but not tested, implemented, or incorporated into advanced concepts for space habitats. Solving this challenge is on the path to Mars, as is better mitigation of microgravity deconditioning, remote surgery in microgravity conditions, and more-practical EVA systems. But kitchen science, as meant here, is not part of the government plan. Better techniques for stabilizing packaged food, for longer durations, is an investment area; but outright growth, harvesting, preparation, and cooking of food in situ is non-essential for small expeditionary crews of civil servants. Experience in frontier industrial towns on Earth demonstrates, however, that the quality of food is the top factor for maintaining workforce morale; for SPS industrialization and life in a GEO town, kitchen science would be enabling.

By far the greatest technical impediment to legitimate, sociologically healthy in-space communities is having no demonstrated way of building and certifying, on orbit, habitats with volume far exceeding what can be launched intact from Earth. Government investment in habitat technology aims to develop deployable/inflatable vessels, with functional subsystems already integrated and verified pre-launch, for Mars-transit and planet-surface applications to support small expeditionary crews. No work is currently funded that could lead to chambers like the partitionable lounge, sports club, or mess-hall/storm-shelter proposed in Table 2. Various schemes have been proposed (e.g., e-beam welding of precision prefabricated metal segments launched stacked; assembly and adhesive-sealing of panels restrained by a post-tensioned web; vacuum-sputtering of a one-piece metal shell inside a weakly-inflated mandrel). Some or all might work, but no development is underway.

The SPS mobile-town Architecture program was compared earlier to the program for a terrestrial multi-function hotel. Interestingly some of the habitation technologies not on the government investment path to Mars, like large volumes, multi-cycle berthing, and kitchen science, are also required for long-term growth of an elastic space passenger-travel market in LEO. Some of the government-exploration needs and the commercial tourism needs are complementary; added together the exploration and tourism initiatives can develop some, but not all, of the HSF capabilities and systems required to industrialize GEO.[2]

VI. Further Analysis

The present analysis is intended only to frame an under-studied design problem in Space Architecture: human space-flight support of GEO industrialization of SPS at a scale that could make a difference for the future of human civilization and Earth in and beyond the 21st century. The reference scenario presented is self-consistent, and to first order is coherent with a particular SPS operations scenario, so as to promote dialogue in the topic area. However several pivotal parameters require revision as SPS scenarios continue to be developed:

1) Practical "ratio" of onsite human activities to autonomous robotics: for assembly, operation, and servicing of SPS platforms
2) Geography of an operational SPS fleet in GEO: clustering, mutual spacing, out-of-plane orbit geometries
3) Co-optimized transportation scenarios: Earth-GEO launch of SPS cargo, Earth-GEO-Earth exchange of people, local access to SPS platforms, relocation around GEO
4) Work schedule and its relationship to facility occupancy: platform revisit rate, activity-based and transit-based shift cycle constraints, duty weeks and duty tours, facility capacity and overcapacity
5) Rate of scale-up from demonstration, to niche augmentation, to committed baseband power, to national-scale supply.

As these factors are analyzed in greater depth and other coherent combinations evolve, more design reference scenarios will arise, leading to derived requirements for Space Architecture different from those outlined here. However the capability gaps and their associated technology-development agenda should be expected to remain roughly stable as more detailed scenarios are developed.

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