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Principles for a practical Moon base

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ABSTRACT

NASA planning for the human space flight frontier is coming into alignment with the goals of other planetary-capable national space agencies and independent commercial actors. US Space Policy Directive 1 made this shift explicit: "the United States will lead the return of humans to the Moon for long-term exploration and utilization". The stage is now set for public and private American investment in a wide range of lunar activities.

Assumptions about Moon base architectures and operations are likely to drive the invention of requirements that will in turn govern development of systems, commercial-services purchase agreements, and priorities for technology investment. Yet some fundamental architecture-shaping lessons already captured in the literature are not clearly being used as drivers, and remain absent from typical treatments of lunar base concepts. A prime example is general failure to recognize that most of the time (i.e., before and between intermittent human occupancy), a Moon base must be robotic: most of the activity, most of the time, must be implemented by robot agents rather than astronauts.

This paper reviews key findings of a seminal robotic-base design-operations analysis commissioned by NASA in 1989. It discusses implications of these lessons for today's Moon Village and SPD-1 paradigms: exploration by multiple actors; public-private partnership development and operations; cislunar infrastructure; production-quantity exploitation of volatile resources near the poles to bootstrap further space activities; autonomy capability that was frontier in 1989 but now routine within terrestrial industry. It outlines new work underway to close these gaps; and articulates conclusions that can guide future work.

1. Introduction

In 1989, before President George H. W. Bush announced SEI (the Space Exploration Initiative) on the steps of the US National Air & Space Museum, the Advanced Robotics office at NASA Ames Research Center commissioned the Boeing Company, Advanced Civil Space Systems, to "examine options for (and characterize the benefits and challenges of) performing extensive robotic site preparation of planetary base and scientific sites, and lunar and Mars propellant production facilities." The major result was RLSO, the Robotic Lunar Surface Operations study [1].

Lasting less than a year, and reported just months after the SEI "90-day Study", RLSO was presented to the community in four papers at Space 1990: Engineering, Construction, and Operations in Space [2–5]. It started influencing community thinking about lunar basing, until the demise of SEI in 1992.

RLSO was unique in several regards: 1) put destination activities first, as the first lunar base study driven by a coherent surface operations concept rather than by the design of space transportation vehicles; 2) purposely maximized infusion of autonomy and robotics (A&R), optimizing all design features for machine-mediated operations rather than for EVA crew; 3) made production-scale ISRU (*in situ* resource utilization) key, which in turn drove the base definition, element configurations, and activity cadence; 4) used quantitative end-to-end operations analysis to size all the base elements, duty cycles, timelines, and construction sequence; 5) performed quantitative reliability analysis of the base hardware, using a complete MEL (master equipment list) defined to the replaceable-unit level, to deterministically calculate the logistics requirement for spares; 6) developed concepts for mobile robots based on energy balance, soil mechanics of lunar regolith, and a comprehensive decomposition of the activity functions needed to build and operate a base; 7) engineered defensible concepts to implement several zeitgeist ideas – production of LLOX (lunar-sourced liquid oxygen) from ilmenite ($FeTiO_3$) in fluidized-bed reactors, use of regolith to shield an expandable habitat complex, paving to control dust, and power management tuned to the mid-latitude 2-week lunar night; 8) was the first study team to blend advanced field robotics experts with Apollo surface experience in an aerospace concept engineering environment.

In 1989, the only accessible exemplars for planet-surface machine performance data were the three Apollo Lunar Roving Vehicles and the two Viking Mars landers. Advanced surface operations concepts typically took equipment designs from terrestrial applications, where reaction mass, diesel power, and hydraulic actuation are common. The most credible system concept for nuclear power was the just-canceled SP-100 program. Of many thermochemical processes posited for extracting oxygen from dry lunar minerals, the modal approach was hydrogen reduction of ilmenite.

RLSO sought to determine which functional activities must or could be allocated to a coordinated set of mobile robots, so as to resolve key

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puzzles such as: how much of an operational, habitable, resource-producing lunar base could be assembled before crew arrive?

"*Permanent human presence on the Moon is challenging to bootstrap. We need facilities on the Moon to support the people, but we would seem to require people to construct the facilities. It is certainly possible to devise incremental operations scenarios to resolve this dilemma, but they require off-nominal circumstances. For example, expecting an initial crew to set up a permanent radiation-sheltered habitat on the lunar surface requires either: relying with no backup on an unproven temporary sheltering scheme if a solar flare occurs before set-up is complete; accepting the risks and programmatic effects of the crew aborting to their orbiting, shielded transfer vehicle; or accepting the performance penalty of burdening their lander with a heavy storm shelter. Incidentally, neither approach avoids the need for large, strong robots (whether "driven" or autonomous) to do the construction, nor the cost in lunar surface crew time to perform and oversee the task. Similarly, waiting to begin production of LLOX propellant (the heaviest single component of cryogenic spacecraft and therefore a prime candidate for ISRU) until a large local crew can get the production going, precludes economic payback early in the manned program. LLOX use should optimally begin within just a few years of the first landing; pushing the return farther into the future is prohibitive for private investment and costly for governmental programs.*" [1].

The RLSO study yielded the conceptually transformational findings described below, setting the stage for approaches twenty years later like NASA's Mars design reference architecture DRA 5.0, in which infrastructure assets would be robotically landed, assembled, and operated to produce return propellant before a crew even launched from Earth [6].

Several of the principles driving RLSO and learned from it are freshly applicable to today's planning environment, which anticipates diverse lunar surface activities by multiple actors.

2. RLSO study framework

The relevant RLSO Study Guidelines were:

1. Make equipment conducive to both robotic and human operations. Adopt the specific system design recommendations developed in a predecessor study for orbital assembly of human-scale deep space vehicles by robots [7].
2. Drive out potential robotics requirements by minimizing the need for onsite human crews. Maximize opportunities for machine autonomy, then supervisory control, and finally teleoperation, in that order.
3. As a guideline, presume a 4/yr landing cadence comprising a mix of cargo and crew missions.
4. As a reference, presume a reusable, single-stage LOX/hydrogen lunar lander capable of delivering 30 mt of cargo to the surface and returning itself to LLO (low lunar orbit), or of landing up to eight crew with supplies for 30 d and returning them to LLO, with one round-trip propellant load.
5. Focus operations on establishing base infrastructure, emplacing and shielding a habitat complex, and starting ISRU for propellant production. Crew exploration science would start after buildup, once the base reached steady-state operations.
6. Baseline solar power if possible.

The performance goals for autonomy and robotics were:

1. Offload, possibly move, and service reusable lander vehicles.
2. Perform necessary site reconnaissance and preparation.
3. Excavate, beneficiate, and transport native lunar regolith.
4. Install necessary site utilities like power cables, fluid lines, and roads.

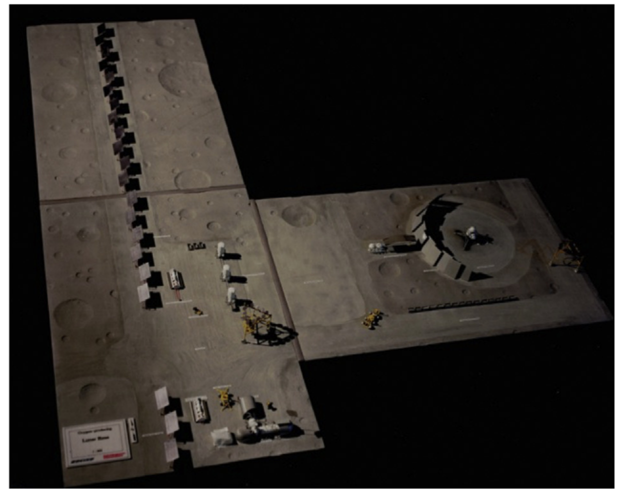

Fig. 1. Overview of the RLSO lunar base concept: solar-powered at a mid-latitude mare location, supporting a small shielded habitat complex, and producing enough lunar oxygen for four round-trip flights per year of a reusable lander. *Note: diorama by Raytheon United Engineers and Constructors; diorama photographs by the Boeing Company.*

5. Construct a landing facility with blast-debris countermeasures.
6. Emplace and shield with regolith a habitat system capable of later growth.
7. Deploy a modular solar/RFC (regenerable fuel cell) power plant.
8. Emplace and operate a chemical plant to produce LLOX.
9. Perform R&R (remove-and-replace) maintenance on all base elements.
10. Operate reliably in the lunar environment with minimal need for onsite crew.

3. RLSO point design and design-specific findings

This section summarizes features of the RLSO study relevant for contextual understanding of its findings. Fig. 1 shows an overview of the entire base. The four Space 1990 papers describe in detail the study and its analyses, robotics-optimized engineering concepts for the reference base elements, and development of the study-specific site plan.

"*Our base concept uses solar power. Its primary industry is the production of liquid oxygen for propellant, which it extracts from native lunar regolith. Production supports four lander flights per year and shuts down during the lunar nighttime while maintenance is performed. Robots replace malfunctioning components with spares and bring faulty units to a pressurized workshop. The base supports and shelters small crews for man-tended visits, during which the crew repairs the backlog of defective components, oversees operations and performs experiments. A simple set of three vehicle types performs all mobile operations, including site surveying, lander offloading, mining, beneficiation, excavation, paving, construction and assembly, surface transportation, waste deposition, maintenance, and scientific exploration. Resource mining and site preparation are two ends of the same process. Machines use automated task control, supervised by human crews in space and on Earth, and backed up by extensive Earth-based engineering support and the alternative of teleoperation. The base integrates almost 400 mt of equipment (including spares) brought from Earth, together with native lunar materials, to transform a virgin lunar site into an efficient research and production facility, in just four years. What makes such a concept tenable is the methodical incorporation, from the very beginning, of realistic abilities and constraints, and rigorous quantitative consistency throughout the scenario.*" [1].

The RLSO base inventory divided into four types:

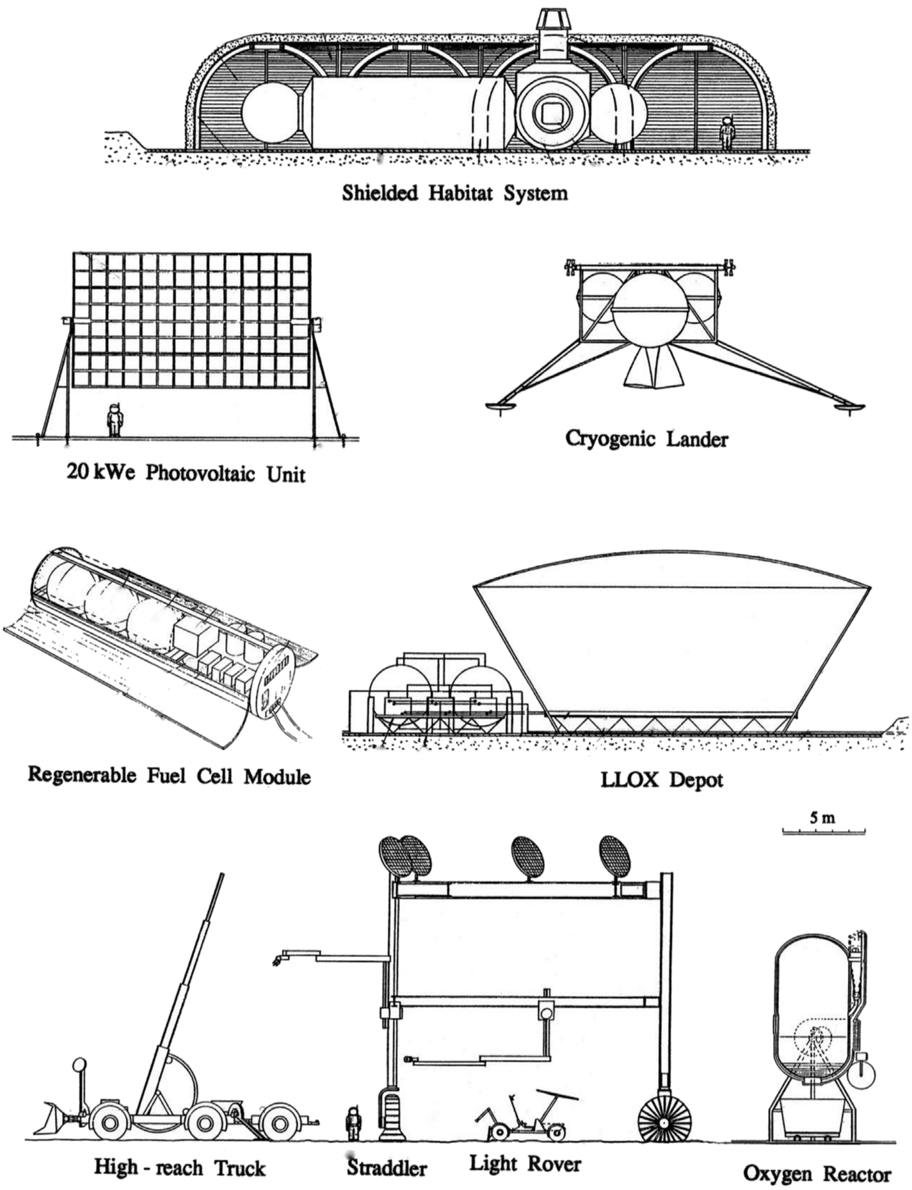

Fig. 2. Major base elements engineered by RLSO, to scale. Base inventory comprised one regolith-shielded habitat complex; reusable 30-mt capacity cryogenic lander(s) used quarterly; 24 20-kWe tracking, flat-panel photovoltaic arrays; two regenerable fuel cell modules; one LLOX storage depot per landing pad; three fluidized-bed ilmenite-reduction reactors producing LOX; two each of three types of mobile robots – Straddler mobile gantry, high-reach manipulator Truck, and fast light Rover.

- **Primary elements** (Fig. 2) – one regolith-shielded habitat complex; up to three reusable 30 mt capacity cryogenic landers, supporting a quarterly flight rate; 24 20-kWe power plants – tracking, flat-panel photovoltaic arrays; two 20-kWe regenerable fuel cell modules; three fluidized-bed ilmenite-reduction reactors producing LOX; one LLOX storage depot per landing pad.
- **Mobile robots** (Fig. 2) – two each of three types of mobile robots – Straddler mobile gantry, high-reach manipulator Truck, and light Rover compatible with human driving speeds.
- **Utilities** – eight ganged waste-heat radiator modules; 12 erectable debris barriers per landing pad; LLOX terminal within each landing pad, plumbed underground to its respective LLOX depot outside the debris zone; guidance beacons; vapor and fluid lines; power switching substation; power, data, and grounding cables; networked sensor posts; lights; 22 material hoppers; end effectors and tools.
- **Siteworks** (structures made of regolith) – spaceport with paved landing pads (compacted sieved gravel); foundations for heavy elements like the habitat complex (exposed, naturally consolidated regolith); open workyard (among the habitat complex, power storage modules, and LLOX plant) and connecting roads, paved with 5 cm of sieved gravel; gangue deposition berms.

The minimal reference base concept included one landing pad, one reusable lander, and a spartan habitat complex comprising only a single hab/lab module, a workshop module, two airlocks, and cupola. The habitat shielding scheme was an open architecture of corrugated aluminum prefabricated vault sections, nested for transport, then erected and pinned together onsite by the Straddler robot's manipulators, and filled with half a meter of sieved regolith fines. Fig. 3 shows the final site plan.

Fig. 4 demonstrates the highly coupled nature of the RLSO element designs and concept of operations: 1) the shielded vacuum hangar covering the workshop module accommodated the Truck, which could reach inside the workshop hatch to position components for repair by

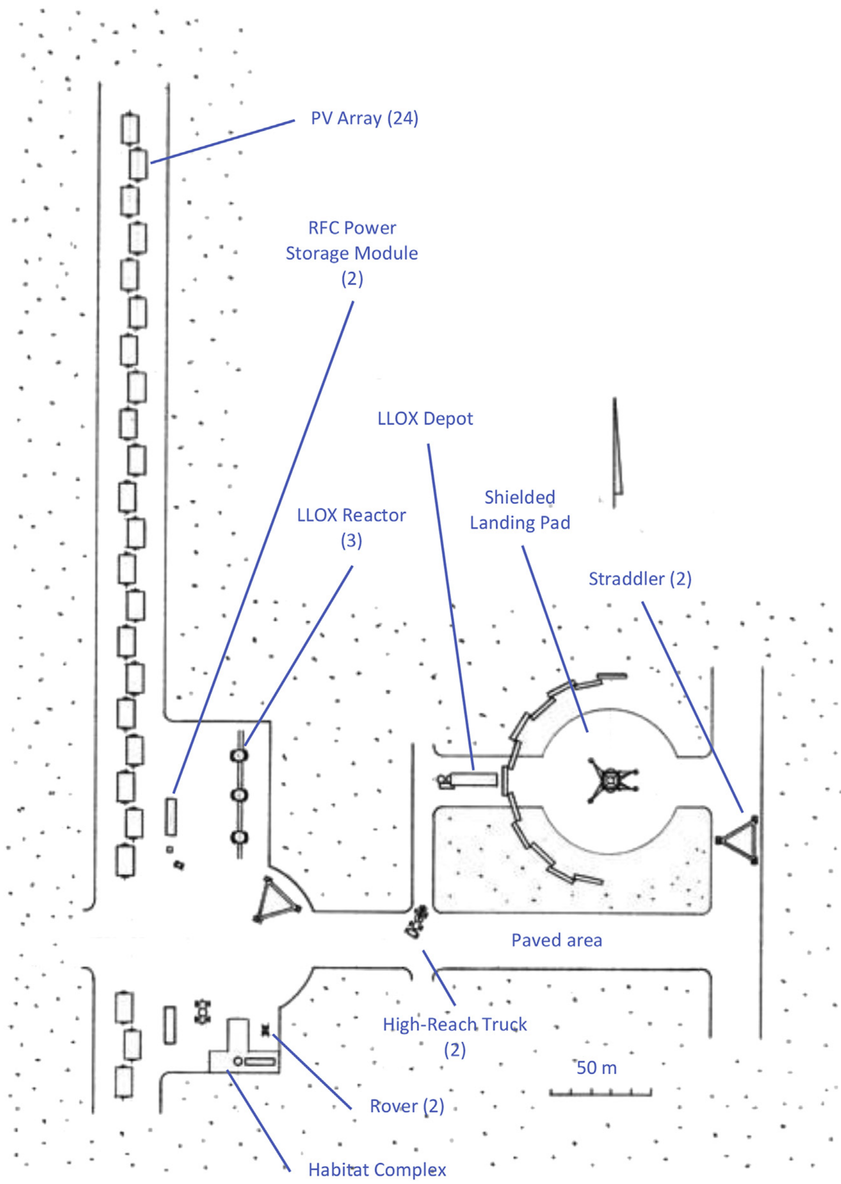

Fig. 3. Scaled site plan for RLSO lunar base. Dimensions were tuned iteratively with paving scheme, robot designs and duty cycles; excavation, beneficiation, and LLOX production rates; and buildup sequence.

shirtsleeve crew; 2) the Straddler evolved to a three-legged mobile gantry (Fig. 5), while the Lander configuration evolved so the Straddler could drive over it for self-unloading upon first landing, handling subsequent Lander cargo, and relocating Landers; 3) hosted by a Straddler, a Miner module shave-excavated native regolith, displacing rocks and grading the path, grade-sieving and binning the regolith, and magnetically beneficiating the ilmenite feedstock. Other examples are detailed in the study report.

The point-design concept yielded several interesting concept-specific findings:

- Fifteen 30-mt deliveries are required to build the base: seven for the LLOX industry, three for the habitat complex, three for mixed-use equipment, and two for eyes-on crew presence and checkout of the buildup operation.
- Four flights per year are appropriate early in the base buildup. However, more frequent flights later could avoid excessive downtime, and more fully utilize the redundant robots. Flexibility in launch cadence would enhance both surface operations efficiency and scenario reliability.
- Three types of mobile robot (light, crew-adaptable Rover; medium high-reach Truck; large Straddler mobile gantry) emerged as a minimal but sufficient set. All were found to be widely useful beyond the baseline scenario.
- Construction of this small base would generate enough ilmenite feedstock to provide LLOX for four round-trip lander flights per year. The excavation and beneficiation required for construction dominate the requirement for generating LLOX feedstock: even harvesting gravel for simple paving yields over a year's supply of ilmenite feedstock. The operations concept and element sizing were tuned to match the paving requirement with the LLOX production rate (Fig. 6).
- Suspending energy-intensive industrial operations during the 2-week mid-latitude lunar night minimizes power storage requirements. Storing power for 336 h with 50%-efficient RFCs costs about 1 mt/kWe. Long lunar nights can be used by crew to repair equipment.
- Substantial lunar resources could start being used in the

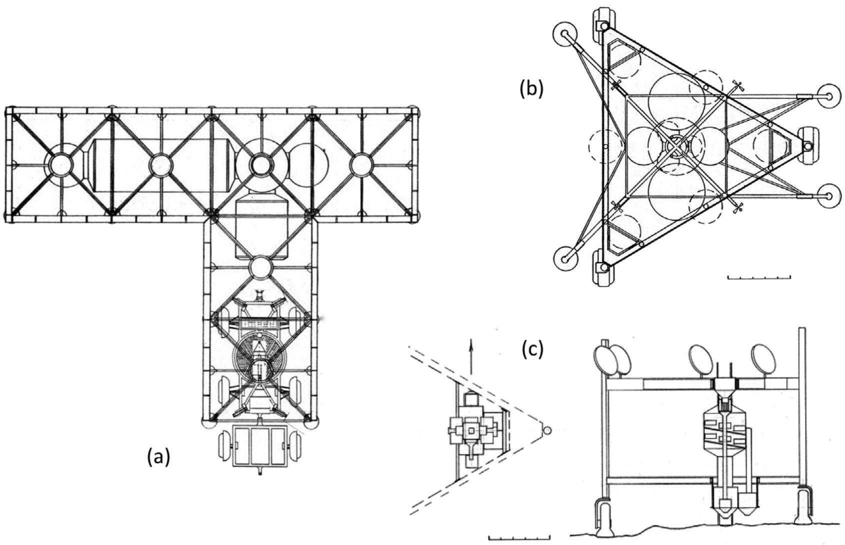

Fig. 4. RLSO element designs and operations concept were tightly coupled. (a) High-reach Truck enters radiation shelter to place units for repair inside pressurized workshop module. (b) Triangular Straddler drives over asymmetrical Lander for self-offloading, cargo unloading, and Lander relocation. (c) Straddler-hosted Miner shave-excavates at creeping speeds, bins regolith components by size, and magnetically beneficiates ilmenite feedstock. Common scale bar is 5 m.

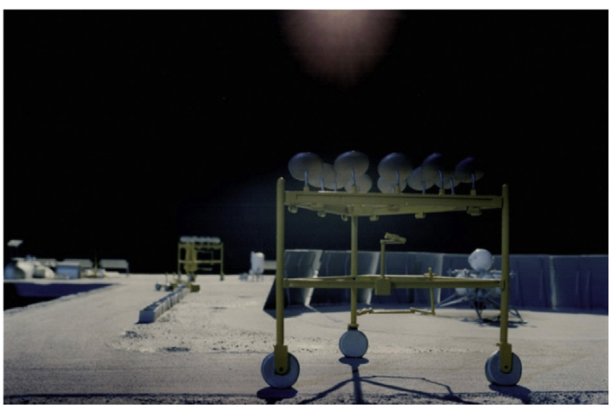

Fig. 5. Solar-powered Straddler mobile gantry offloads all Lander cargo, including itself.

Fig. 6. Gravel paving and debris deflectors allow landing pads to be close to the rest of the base, minimizing road construction and robot driving time at creeping speeds.

transportation architecture within four years of first landing … but only if crew flights are kept to a small fraction of the total (2 of 15 in RLSO) and human presence is not continuous.

- Unmargined schedules show that time from first landing to habitability is at least 1.5 years, and to first LLOX production is at least 2.75 years.
- Robotic R&R is an ongoing task. The reliability analysis yielded an average of 12 failures per lunation for this simple base concept (about six times better than the performance of mid-1980s human space flight systems, the reference at the time), where ‘failure’ is defined as off-nominal performance, regardless of severity. This manageable failure rate depends on designing for maintenance at a replaceable-unit level.
- Supervisory robot control is enabling for the RLSO concept. This requires well-characterized workpieces, predictable environments, and a modicum of onboard sensor and command processing. Supervisory control provides safe and efficient task execution because human operators are relieved of exclusion rules, reflexes, and routine operation details. The machines need not be particularly intelligent, or even run a complete system or operations model. Given a well-constrained environment (a navigable lunar base) and well characterized tools and parts, a three-tiered machine control hierarchy is sufficient: nominally automated task control, routine supervised autonomy, and occasional teleoperation.

4. Principles for a practical Moon base

RLSO also yielded several findings that are not inherently limited to its point design, and which therefore could be foundational principles for a practical Moon base. Using RLSO as a point of departure, they can be cast for today's lunar basing needs:

Most lunar base operations, most of the time, must be robotic. This almost tautological principle appears secondary given a focus on “human lunar exploration”, but is vitally important to keep top-of-mind. It is driven fundamentally by scope, safety, and economics. Scope: commonly anticipated lunar base activities create a need for near-continuous action outside a habitat, moving enormous volumes of regolith, and tasks that easily exceed human capacity in strength, reach, steadiness, patience, distance, and time. Safety: heavy labor in EVA suits (extravehicular activity) is impractical from a crew safety standpoint. Even many tasks for which EVA is used on ISS cannot be ported into the 1/6 g lunar environment. “Guys in suits with shovels” is not a useful paradigm for practically any task required for lunar base construction. Economics: a Moon base would be an enormous investment, sitting idle between intermittent crew visits without capable and tireless robots. Robotic work systems are the agents that will physically implement surface construction and background operations at a habitable lunar base.

Substantial base infrastructure can be constructed, and base operations conducted, despite only a few short, intermittent crew

visits. RLSO engineered operations concepts for all activities, from the first landed site survey, through all base buildup tasks (construction and assembly), to tasks supporting steady-state operations (industrial-scale ISRU and R&R maintenance).

No EVA task was found to be beyond reasonable robotic capabilities, a watershed finding. A key enabler is site preparation (surveying, grading, rock removal, navigation beacon emplacement, and paving deposition), to make the routine operating environment predictable. Still, RLSO reserved two out of the fifteen landings for crew visits, to accommodate eyes-on attention to unforeseeable circumstances and provide the opportunity for onsite operations learning, a core objective of human lunar activity.

Lander cargo capacity, configuration, and flight rate fundamentally affect base element design. Capacity determines the largest unit transportable intact to the surface. Configuration constrains the nature of similar-scale surface mobile robots for offloading such cargo and relocating landers. Operations are mainly constrained by frequency of lunar transport flights, rather than by capacity of the robotic equipment (i.e., despite an operations concept designed around "creeping speeds"). These factors argue strongly against designing the Lander separately from the rest of the base elements.

Moving a crippled lander is the bounding requirement for cargo mobility on the surface. The cargo lander must be designed together with a surface cargo mobility solution for every base element (i.e., schemes that "drop" payload on the surface solve only part of the systems problem). Concepts typically neglect to consider the lander itself as one of these elements. Routine traffic to and from a base means there will be off-nominal landings. Even "five nines" aircraft occasionally suffer hard landings, failed landing gear, or other anomalies that damage the vehicle and/or leave it in a state and location that compromises subsequent ground activities. Abandoning damaged or derelict landers in place is not a viable alternative.

A&R considerations are driving requirements for all base elements. Element concepts should be zero-based for A&R because it cannot easily be retro-engineered into legacy concepts or approaches. Allocation of functions throughout the WBS (work breakdown structure) for every item at the base should be done so that the components most likely to fail in use can be removed and replaced robotically to restore functionality without crew EVA. Unlike on ISS, crew-mediated fallbacks for R&R maintenance are not straightforward on the lunar surface due to the presence of weight.

A detailed three-dimensional sitemap, including subsurface characterization at 10 cm resolution, is important for predictable robotic surface operations and informed base layout. A lunar base is a significant long-term investment, justifying rich precursor knowledge. For a polar volatiles extraction base, this should occur in three phases: 1) contingent site selection based on orbital data, already largely in hand, for prospecting (ice signature) and reconnaissance (topography, rockiness, insolation cycle); 2) *in situ*, mobile prospecting for site certification – landing zones; resource abundance, patchiness, and depth; local features and topography; trafficability and geotechnical assay; demonstration of resource recovery; 3) raster rover mapping with GPR (ground penetrating radar) to allow detailed site planning; and deployment of laser and radio surface-navigation beacons to prepare for the first large Lander, carrying the first large mobile robot.

High-power (> 10 hp) vehicles are not necessary for an early base to produce LLOX at 100 t/yr rates. On the Moon, mobile-robot energetics favor creeping speeds and 'shaving' excavation – not the terrestrial construction paradigm. Actuators must be electric, and mobile power must be either regenerable (onboard batteries or fuel cells) or beamed in. In addition, lunar regolith below 20 cm depth is naturally highly compacted. So heavy work (e.g., grading, mining, habitat complex construction) should use creeping speeds (from 30 cm/s down to barely perceptible motion). Albeit too slow for human operators, this speed regime is highly amenable to robotic control. The terrestrial earthmoving paradigm (e.g., diesel-powered, hydraulics-actuated front-end loaders) does not fit lunar native or engineered conditions. Shaving excavation, albeit perhaps mesmerizing to watch, is deterministic and supports a timeline consistent with an affordable early landing rate.

Paving routine traffic routes is the driving requirement for construction timelines. Roadbeds minimize the probability of driving or handling mishaps, so grading is essential to make a predictable operating environment. Half the lunar regolith is as fine as cake flour, and this dust is a well-recognized challenge: pervasive, electrostatically "sticky", and highly abrasive. Creeping mobility would minimize dust kick-up, but crew driving (of small rovers, for example) is likely to be a persistent, bothersome source of dust deposition unless managed by paving. Largely to explore how this might be done, RLSO developed a paving scheme consistent with the shaving excavation technique adopted and the regolith beneficiation needed anyway to produce ilmenite feedstock for the LLOX reactors. This scheme shaved down to a 20-cm average depth, leveling the landscape while removing rocks, and gravity-sieving the excavated material into gravel, sand, and dust (ilmenite-bearing grains were magnetically separated during sieving). The valuable gravel was then redeposited in a 5-cm layer and compacted by weighted rollers, to make roadbeds and workyard; sand was used to fill the habitat radiation shelter structure; dust and gangue were deposited to build an eventual berm between landing pads and the rest of the base. Erectable debris deflection shields allowed the landing pads to be a short distance from the base, which in turn minimized road construction material and time. The 5-cm paving thickness matches the excavation rate, LLOX production rate, element sizing, and base buildup sequence.

Hierarchical supervisory control is enabling, but full autonomy is not. Advanced autonomy (beyond the 1989 state of the art for RLSO) is not required even for a fully robotic base with multiple mobile machines performing complex simultaneous tasks. (RLSO proposed a hierarchical control architecture that performs high-level command scripts, yet allows teleoperation down to the level of every motor, either locally by crew or from an operations team on Earth, in off-nominal circumstances.) This is a remarkable result, compared to today's state of the art in robot control. A robotic lunar base ought to be quite feasible. Networked entertainment and crowd-engaged operations offer new possibilities not envisioned in 1989.

~15% of delivered mass is required for spares inventory. For a design philosophy of unit-replaceable components (consistent with a robotic R&R servicing operations concept), this value is not surprising. However, RLSO derived it using a quantitative reliability analysis at the unit-replacement level for the entire base MEL. The result was incorporated into the logistics delivery manifest to construct an initial, habitable, LLOX-producing base: thirteen 30-mt cargo landings and two crew visits.

Habitat systems and other complex components should not be buried directly with regolith, as this would preclude or severely compromise any future maintenance activities. Passive line runs (e.g., fluid, vapor, power, grounding) and passive structure elements (footings) can be buried directly, but inspection, operation, or maintenance points like valves, connectors, joints, and active components should be at least a half meter above the ground. Using regolith for radiation shielding means building and filling a superstructure, not simple burial.

Crew time is valuable; EVA time is even more valuable. Shifting tasks from crew to robots has positive value. Human time should be focused on investigative activities (pure and applied science), developmental activities (qualifying processes with pilot equipment, monitoring expansion of the robotic operating envelope), and complex equipment servicing and repair (inspection, evaluation, and repair of robotically removed components). An essential element of a human-tended base is a shirtsleeve workshop module in which sealed components can be cleaned, opened, serviced, and restored to functionality.

"Our operations concept stresses those aspects of lunar operations least understood so far: machine capability, surface system equipment design,

day-to-day work schedules, and reliability. The concept exploits machines wherever and whenever they may be appropriate, with the goal of preserving valuable crew time for supervision, dexterous repair, long-range planning, adjustment, experimentation, and discovery. The minds and hands of the crew are thus complemented by the strength, reach, consistency, untiring operation, and relative immunity to the EVA environment of machines. With that combination, the base can run smoothly, produce efficiently, and expand quickly, while our human understanding grows and our foothold in space firms." [1].

Repair at the sub-component level is essential (e.g., replacing a failed chip on a circuit card; replacing a leaking seal in a valve) to avoid an overwhelming requirement for spare components (e.g., another third of the total mass of a 10,000-component system with 100x commonality to have 99% reliability over 20,000 h). RLSO solved this with a human-robotic partnership: mobile robots conduct EVA remove-and-replace maintenance, then visiting crew conduct sub-component repairs in an IVA workshop, to return failed units into service.

Seek to minimize the number of different elements – including mobile robots. The overall program cost for a lunar base is strongly driven by the number of end-item development projects, because each constitutes a separate procurement. RLSO demonstrated a conceptual benchmark of just three types of mobile robots to perform all base functions.

Directly tackle the well-known challenges. The lunar-base concept literature describes several 'thorny' system-level issues that credible concepts will resolve. By positing integrated solutions for these, RLSO set a high bar for alternative schemes:

- **Protecting base assets from Lander jet debris.** Surface particulates sprayed outward by rocket exhaust travel ballistically in vacuum, posing a hazard to the base from repeated landings and takeoffs. Yet putting the landing zone far from the base imposes significant costs in paving and time to transport cargo. The landing flight path angle is much shallower than for ascent, so RLSO solved this by putting the base west of the landing approach and pad, shielded from it by a bank of debris deflector panels.
- **First-landing problem.** Cargo offloading, element positioning, and surface mobility are tightly coupled problems, made harder by the need for an offloader to offload itself first. RLSO solved this with the Straddler mobile-gantry concept.
- **Regolith radiation shielding.** Loose regolith material used for shielding must be contained in a superstructure to preserve dust-free inspection and maintenance access around a multi-$B habitat system, and so it can be disassembled and reconfigured as the habitat complex grows. RLSO solved this with a modular, erectable, double-walled vault-shell structure that minimized the shielding's footprint, transported volume, assembly complexity, and regolith handling.
- **Dust control.** The fines fraction should be either removed from routine traffic routes and work spaces, or stabilized. RLSO solved this by removal: leveraging the necessary grading and ilmenite-beneficiation operations to separate gravel as a key resource for re-deposition. Without testing it is unclear whether this scheme, or a stabilization approach like microwave sintering, would be best.
- **Surviving the night.** A big advantage of polar sites is that the sun is at the horizon and the day-night ratio is controlled by topography; extreme temperature cycling and long nights can be avoided. By contrast, mid-latitude sites are constrained to 14 days of sun alternating with 14 days of night. Power storage to bridge such a duration is costly and complex. RLSO solved this by designing the operations cadence to limit heavy power consumption at night to primarily the habitat system. LLOX generation, a batch process anyway, ran in daytime only; the reactors passively cooled during the night, then were emptied, refurbished, and filled with feedstock for the next day's cycle (Fig. 7). Night also provided ample IVA time for repairing faulty units.

These foundational RLSO principles are not generally reflected by subsequent NASA concept work; cis-lunar transportation astronautics continues to be the major source of driving requirements. The major effort, the mid-2000s Constellation architecture, was typical in this regard. ESAS (Constellation's opening exploration systems architecture study) extensively traded propellant options, transportation architectures, radiation effects on crew, and lander vehicle configurations, but its attention to surface operations was superficial [8]. "The emphasis will be on EVAs". "Global access, anytime return" and long-distance science and sample collection sorties drove its surface mission objectives, including how its robotic assets would be used between crew missions. No driving requirements were developed for the buildup or sustainable operations of a resource-producing base; outpost site planning was limited to schematic diagrams implying pinpoint proximate landings and EVA-mediated assembly. A "scissor-jack truck" was assumed for offloading large payloads, but described as "not conducive to lunar surface assembly operations." Requirements for site preparation, infrastructure and logistics, and resource operations all remained unquantified despite a stated goal to "transition ISRU from demonstration to production." Only one fifth of one chapter was devoted to surface activities, and half of that material focused on exploration science and "Mars forward" objectives; RLSO was not cited.

One RLSO concept was echoed in that era, by JPL's ATHLETE mobile-robot concept [9,10]. Like the Straddler, ATHLETE was conceived as a multipurpose robot to support diverse surface operations scenarios, in this case ranging from exploration to construction. However, the exploration requirement drove its all-terrain design, whereas the Straddler concept was optimized for methodical preparation of a flat site, subsequent base construction, and routine base operations.

Late in Constellation, a NASA team developed detailed surface concepts and basing scenarios, albeit driven by the objective of long-distance exploration. In that research, the all-terrain ATHLETE and its derivatives enabled the "Lunabago" scenario [11], a version of the Habot concept that relocates itinerant base assets between crew sorties [12]. This total mobility approach is the antithesis of a resource-producing base that requires permanent infrastructure.

5. What has changed since 1989

Three decades – a whole generation – have elapsed since RLSO. In that time the cultural context for major space programs has evolved significantly. In the US – whose space-program resources are essential to develop a 30-t capable reusable lunar lander – the society that revered "rocket scientists" in the 1960s is largely gone now, replaced by a directly-connected, cynical population immersed in fragmented information that travels at the speed of Twitter. [13,14].

Against that backdrop, significant progress has occurred in five areas:

Knowledge. A half-dozen scientific missions have revealed a Moon Apollo never knew. Today we know the Moon holds a large inventory of polar volatiles, in various forms: adsorbed solar wind, accumulated crystalline water ice and even surface frost in some PSRs (permanently shadowed regions), and perhaps deep ice from ancient cometary impacts. The science community has also developed a prioritized list of about two dozen key investigation sites around the lunar globe, with implications for both lunar science and science across the solar system [15].

Thus we now have better prospects for using the Moon to bootstrap both scientific and human offworld achievements. Scientifically, the stage is set for a robust lunar program.

Technologies. Our ability to navigate within the two-body Earth-Moon system has also advanced significantly. Two enabling technologies not yet in common use at the time of RLSO are low-thrust trajectories and electric propulsion. Non-Keplerian orbits (e.g., the DRHO,

Fig. 7. Hydrogen reduction of ilmenite is a batch process, run with photovoltaic power during the two-week lunar day. The sealed reactors (right) cool down during the long night, are opened, emptied by the high-reach Truck, and readied with a new batch of feedstock. Oxygen product is piped to a liquefaction and storage depot adjacent to the landing pad (left).

distant rectilinear halo orbit planned for a Gateway node) allow mass-efficient transportation, eliminate critical events, and yield favorable geometries for orbit transfer, communications visibility, and overflight of the lunar surface. And electric propulsion allows mass-efficient transfer of cargo between low Earth orbit and the lunar vicinity, relocation of infrastructure (like the Gateway itself) into new orbits, and efficient gradual spinup and spindown of potential artificial-gravity stations. One significant consequence is an imminent commercial, competitive business sector able to deliver payloads from Earth to the Moon.

The A&R capabilities posited for the Moon by RLSO in 1989 have since found widespread terrestrial application, particularly in factory settings but also in exploratory missions like seafloor science. Networked mobile computing has now pervaded the consumer economy. And artificial intelligence milestones indicate an exponential transition into a future of machine autonomy. Where RLSO invoked scripts in a controlled environment, today an RLSO2 might presume learning and adaptive behaviors.

Since RLSO, three generations of Mars rover have yielded a significant foundation of design and operations experience for planet-surface mobile robots. In addition, China has roved on the Moon twice recently, and some commercial teams aim to do so soon.

Relevant new technologies are also emergent. Three that could be transformational for lunar surface operations are: 1) kilopower fission power plants – new since the 1970s, NASA and DOE (Department of Energy) tested the KRUSTY developmental space fission reactor to 800 W in 2017; 2) BMG, bulk metallic glass, unknown in 1989, may enable strong, durable, regolith-resistant mechanism components; 3) 3D printing, already widely thought useful for constructing lunar habitat radiation shielding and roadbeds.

With better ways of getting to the Moon and deploying infrastructure there, a societal context that expects machine agency, and transformational technologies maturing, the technological stage is set for a robust lunar program.

Programmatic and technical context. In 1989, the Space Station Freedom Phase C/D contracts had just been awarded. Thus began a five-year period of political close-calls, dramatic reformulation in collaboration with Russia, and program restructuring, all culminating in the International Space Station. Assembly began in 1998 and took a decade. The most impressive peacetime high-tech human endeavor in history, ISS demonstrated and exercised many enabling capabilities including: 1) on-orbit integration of habitable vehicle segments that had never touched each other on Earth; 2) continuous operation, maintenance, and utilization of a scientific microgravity laboratory for over 20 years; 3) human-mediated outfitting, retrofitting, and adaptation of infrastructure in space; 4) operation of a 100-kW power system in space; and 5) hosting of up to 16 crew (peak, during Shuttle crew-exchange missions). Perhaps of equal importance, ISS has demonstrated international collaboration – five principal space agencies and crew from 18 countries to date – for building and operating ongoing, elaborate space infrastructure. ISS demonstrates that human space flight is ready for the next level: another cooperative project, this time on a planet. ISS is the precedent for Moon Village: multiple actors pursuing individual interests, using interoperable and shared infrastructure [16].

Also since 1989, emergent 'commercial' activities are infusing private capital into robotic and human space flight. These generally fall into four categories: 1) new companies, with traditional business models but disruptive technologies that lower costs, e.g., SpaceX reusable boosters; 2) billionaire philanthropists committing personal fortunes to open space, e.g., Richard Branson, Jeff Bezos, Yuri Milner; 3) a proliferation of entrepreneurial startups pursuing multi-customer markets from small to large, e.g., CubeSats, expandable modules, and commercial lunar landing services; 4) speculative business plans aiming at highly disruptive opportunities, e.g., asteroid and lunar mining. Together they lay out a rich menu of potential actors, including both providers and customers – space agencies are no longer the only path forward.

Finally, policies always evolve. For most of the past decade, all spacefaring agencies save NASA explicitly embraced the Moon as their stepping stone, citing multifaceted rationales: a stretch within reach, a peaceful high-tech economic engine, a marker of stature both internally and within the community of nations, and hegemony in the 'high ground' of high orbit. ESA policy promotes a Moon Village approach, where all actors – including China – co-develop and even mutually rely on each other's capabilities and assets. With SPD-1 (Space Policy Directive 1), US policy has pivoted to explicitly acknowledge the need and value for routine cislunar human space flight operations, establishment of nodal transportation infrastructure at the Moon, and experience operating systems on the lunar surface as foundational for deeper space objectives.

We now have existence proofs for productive international partnerships on the high frontier; a diverse and growing commercial space business environment; and conducive policies around the world. The programmatic stage is set for a robust lunar program.

Flight systems in development. In 1989, Soyuz and Shuttle were flying, Mir was orbiting, and only Mir-II and Space Station Freedom were in development. Today we have a far richer set of capabilities to consider. United Launch Alliance and SpaceX are human-rating their operational rockets; Dragon and Cygnus are commercially servicing the International Space Station; Crew Dragon and Starliner-100 are about to start commercial ISS crew exchange. SpaceShip Two and New Shepherd are about to test the suborbital tourism market. NASA is deep in development of large, deep-space capable, human-rated systems: SLS, Orion, and Gateway. A half-dozen small-capacity lunar landers are in private development, stimulated originally by the Google Lunar X-Prize. And large-capacity systems are in development by leading private actors: Blue Origin's multi-ton Blue Moon lander, and the SpaceX Starship.

Modern lunar base architectures need to consider how this plethora of system capabilities, and diversity of actor motivations, can be combined. Today, realistic scenarios can be built upon disruptive technologies and fractionated transportation support, but are also constrained by the 'initial conditions' they establish (e.g., Gateway DRHO as a node). The transportation stage is being set for a robust lunar program.

Analysis and communications tools. RLSO calculations and configurations were done by hand and illustrated by physical diorama, in a work environment before spreadsheets, CAD (computer-aided design), the internet, email, cell phones, Bluetooth, or the cloud. Since then advanced tools have revolutionized the effectiveness of pre-Phase A aerospace concept engineering. Performant desktop computers allow rapid quantification of options and sizing of system concepts. Model-based systems engineering quantifies interfaces to allow flexible parametric capture of complex-system behavior. And CAD allows accurate reconciliation of designs, direct integration of performance attributes with geometry, visceral understanding, and analytical and cinematic rendering.

Thus the stage is set to define, analyze, understand, evolve, and broadly communicate technically defensible options for a robust lunar program.

6. RLSO2

A team including members of the original RLSO study team is conducting an RLSO2 study, for a fresh look given the advancements in knowledge, technology, programmatic context, flight system developments, and design/analysis tools described in the previous section.

The RLSO2 study follows the original RLSO statement of task verbatim, but with contemporary assumptions: 1) harvesting of water ice at a polar base, rather than hydrogen reduction of ilmenite at a nearside mid-latitude base; 2) use of a DHRO Gateway transportation node; 3) logistics scenarios incorporating lander downmass capacities in three ranges: 10s, 1000s, and 10,000 s kg.

Base siting analysis is informed by the Traverse Planning Tool developed by the erstwhile Resource Prospector pre-project; datasets from multiple LRO instruments are synthesized into a time-varying, latitude-longitude-specific illumination model, making insolation and power storage duty cycle a variable dependent on base location and element geometry.

Three resource and base siting schemes of interest are: 1) entire base located in a PSR (permanently shadowed region), where the ice resource has highest concentration but the operating temperature is ~100 K; 2) resource recovery located in a PSR with base habitat located in a nearby PLR (persistently lit region); 3) entire base located in a PLR, where the ice resource has lowest concentration but large traverse distances are avoided.

Even early results help to clarify the tradespace. For example, solar power trades favorably in all cases – not because polar regions allow nights lasting only hours-to-days, but rather because production-scale ISRU requires of order 10^2 kWe. Arrays simply scale better than do kilopower nuclear plants, and require far simpler setup. Also, as a resource, lunar ice may be more enticing than practical: paleo-ice, if it exists, lies significantly buried, necessitating extensive excavation even to reach; near-surface ice also requires some excavation to reach, and is a very low-grade "ore" compared to ilmenite, which is widespread.

RLSO2's quantitative operations model analyzes the system-level performance of alternative methods for extracting water from < 5 wt% ice-fraction regolith; for transmission of electrical power over km-scale distances; for transportation of material and materiel; and for constructing roadbeds and radiation shelters. This evolutionary model provides a basis for evaluating a wide range of proposed process and element concepts.

7. Conclusions

Thirty years of advances set the foundation for revisiting RLSO with contemporary knowledge, technologies, programmatic drivers, system capabilities, and tools. We now have to understand a new set of locations and resources; we have better technologies and far better capacity to design and analyze options; we have a wide range of lunar transportation systems in development, and diverse interested actors; and we have a conducive commercial and international policy climate. An RLSO2 study has begun, to determine which of the original findings may remain applicable in the modern context.

Several of the principles generated by RLSO appear invariant, suggesting that they can guide current work. The coming years will doubtless see many concepts proffered: some entrepreneurial [17], some using the Gateway as a point of departure, and others arising from "Moon Village" activities. Only quantitative operations analysis can separate the wheat from the chaff in this diverse field. Pragmatism – as measured by concept coherence, stepwise capacity buildup, and efficiency and sustainability – is essential if meaningful lunar surface operations are to start any time soon.

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