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PRINCIPLES FOR A PRACTICAL MOON BASE

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NASA planning for the human space flight frontier is now coming into alignment with goals promoted by other planetary-capable national space agencies. US policy aims to achieve the "horizon goal" of Humans to Mars through significant learning about systems, operations, and partnerships in the cislunar and lunar-surface environment first. 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, followed by human missions to Mars and other destinations". The stage is now set for sufficient 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 evident drivers, and remain absent from most depictions 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 culminates by discussing 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.

We need to engineer today's generation of practical, justifiable, and inspirational Moon base concepts.

I. 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 result was RLSO, the Robotic Lunar Surface Operations study.[1]

Lasting less than a year, and documented just months after the SEI "90-day Study", RLSO was reported to the community in four papers at Space 1990: Engineering, Construction, and Operations in Space.[2-5] It started influencing community discussions about practical Moon base concepts and principles, until the demise of SEI itself in 1992.

RLSO was unique in several regards: 1) it was the first lunar base study driven by a coherent surface operations concept rather than by the design of space transportation missions and vehicles – it put destination activities first; 2) it purposely maximized infusion of autonomy and robotics (A&R), optimizing design features for machine-mediated operations rather than for EVA crew; 3) it made production-scale ISRU (*in situ* resource utilization) key, driving the base content, configuration, and activity cadence; 4) it used quantitative end-to-end operations analysis to size all the base elements, duty cycles, timelines, and construction sequence; 5) it performed quantitative reliability analysis of the base hardware, using a complete MEL (master equipment list) defined to the replaceable-unit level to drive out the logistics requirement for spares; 6) it developed concepts for mobile robots based on energy balance, soil mechanics of regolith, and a comprehensive derivation of activity functions to build and operate a base; 7) it engineered defensible concepts to implement several zeitgeist ideas – production of LLOX (lunar liquid oxygen) from ilmenite ($FeTiO_3$) in fluidized-bed reactors, use of regolith to shield an expandable habitat complex, paving to control dust production, and power management tuned to the mid-latitudes' 2-week lunar night; 8) it 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 mass and mobile power are unlimited compared to lunar surface conditions. The most credible system concept for nuclear power was the just-canceled SP-100 program. Although many thermochemical processes were 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 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 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.

II. 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 the RLSO precursor study (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 including both 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 a round-trip propellant load.
5. Focus operations on establishing base infrastructure, emplacing and shielding a habitat complex, and starting ISRU for propellant production. Crew lunar 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.
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.

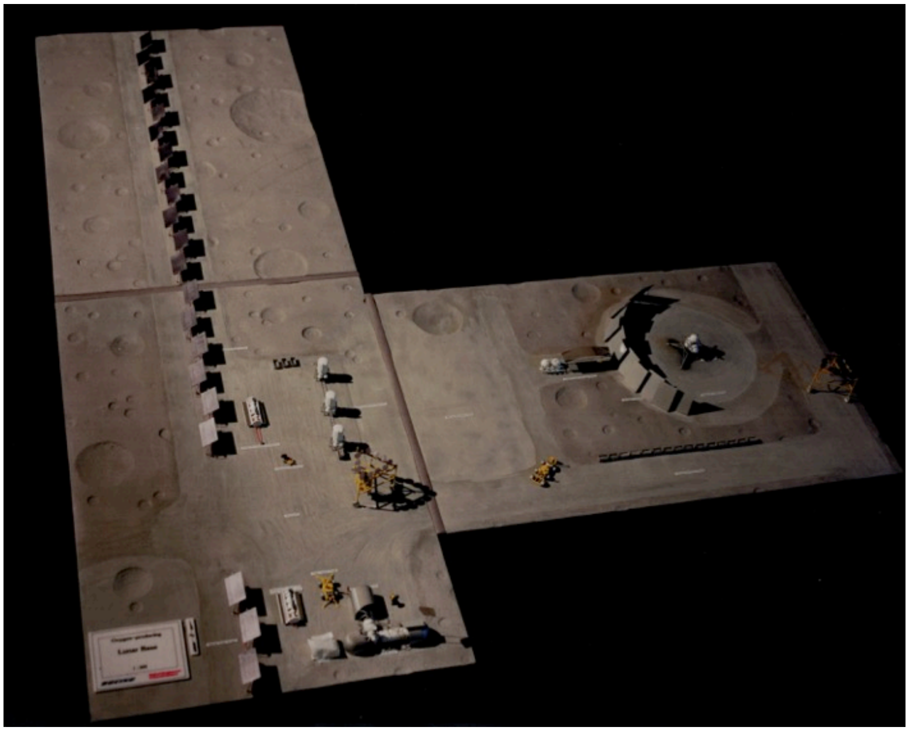

Fig. 1: **Overview of the RLSO lunar base concept:** solar-powered at a mid-latitude mare location, supporting a small shielded habitat complex, and producing enough lunar oxygen for four round-trip flights per year of a reusable lander. *Note: diorama by Raytheon United Engineers and Constructors; diorama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

10. Operate reliably in the lunar environment with minimal need for onsite crew.

III. RLSO POINT DESIGN AND DESIGN-SPECIFIC FINDINGS

This section summarizes features of the RLSO study relevant for contextual understanding of its findings. Figure 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:

- **Primary elements** (Figure 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; and one LLOX storage depot per landing pad.

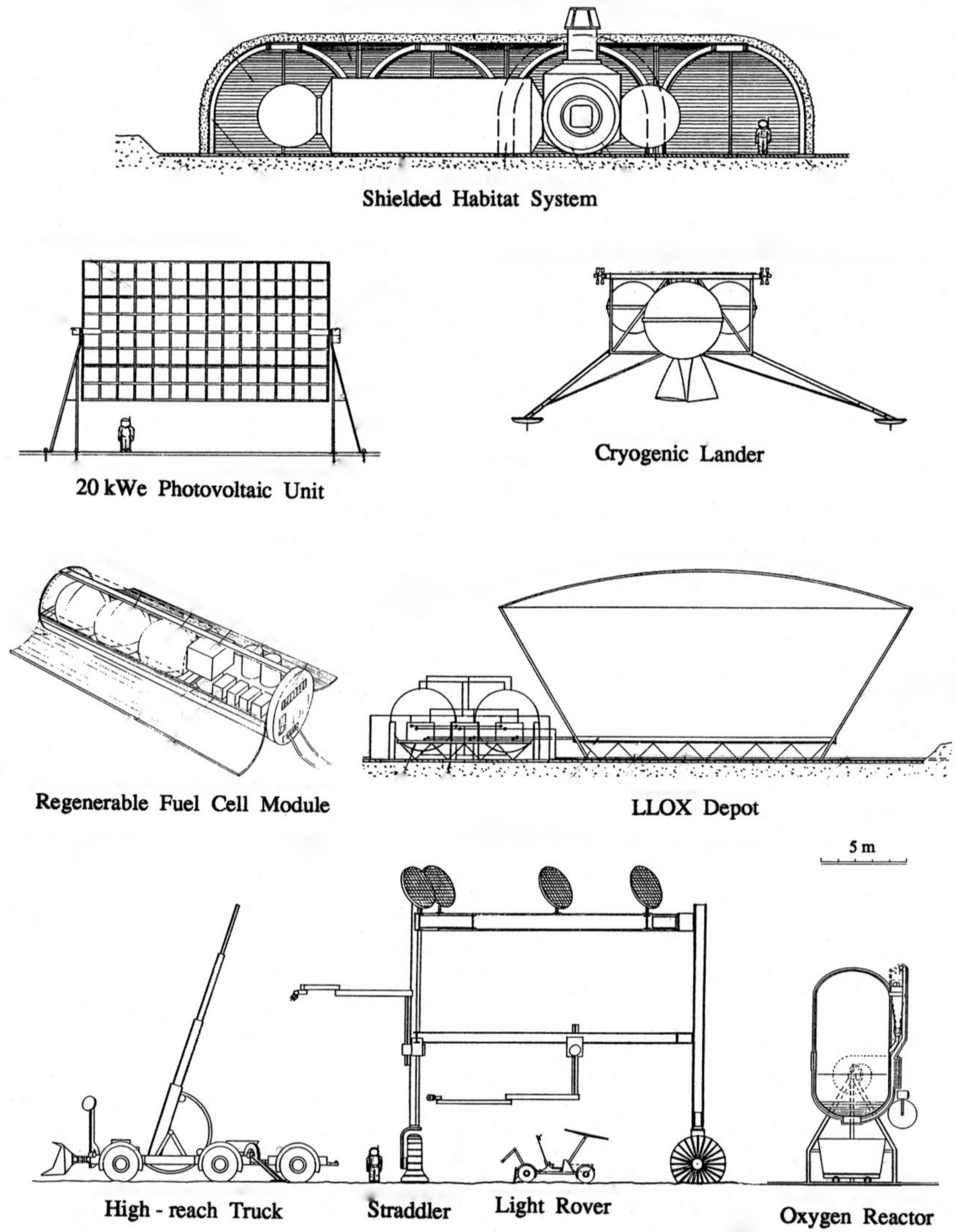

Fig. 2: **Major base elements engineered by RLSO, to scale.** Base inventory comprised one regolith-shielded habitat complex; reusable 30-mt capacity cryogenic lander(s) used quarterly; 24 20-kWe tracking, flat-panel photovoltaic arrays; two regenerable fuel cell modules; one LLOX storage depot per landing 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.

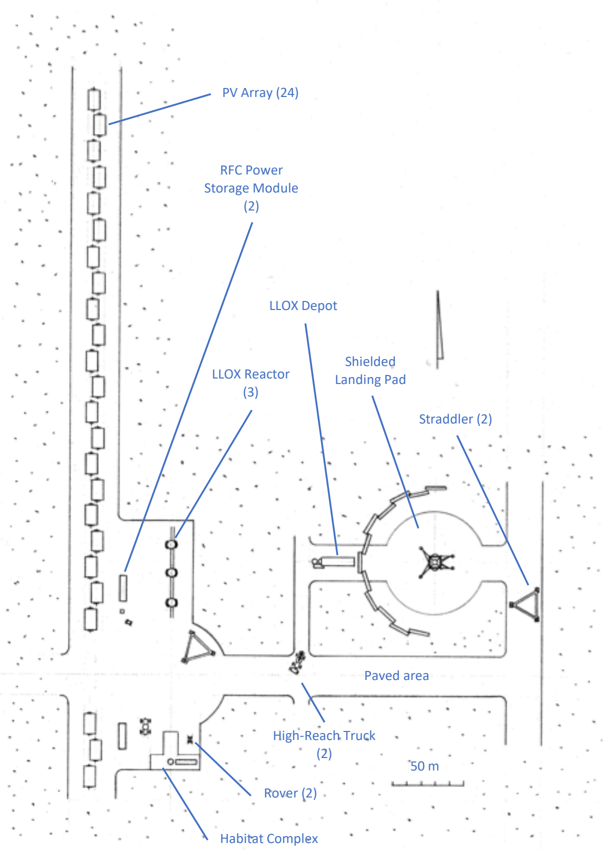

Fig. 3: **Scaled site plan for RLSO lunar base.** Dimensions were tuned iteratively with paving scheme, robot designs and duty cycles, excavation, beneficiation, and LLOX production rates, and buildup sequence.

- **Mobile robots** (Figure 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 waste-heat radiator modules; 12 erectable debris barriers per landing pad; LLOX terminal within each landing pad, plumbed underground to its LLOX depot; 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 (sieved gravel); foundations for heavy elements like the habitat complex (excavated down to 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 including 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 riveted together onsite by the Straddler robot's manipulators, and filled with half a meter of sieved regolith fines. Figure 3 shows the final site plan.

Figure 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 door to position components awaiting repair by shirtsleeve crew; 2) the Straddler itself became a three-legged mobile gantry (Figure 5), and the Lander configuration evolved so the Straddler could drive over it for self-unloading the first landing, handling subsequent Lander cargo, and relocating Landers; 3) hosted by a Straddler, a Miner module (Figure 6) shave-excavated native regolith, displacing rocks and grading the path, grade-sieving and binning the regolith, and 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 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 generates 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.
- Suspending energy-intensive industrial operations during 2-week mid-latitude lunar night minimizes power storage requirements. Stored power for the

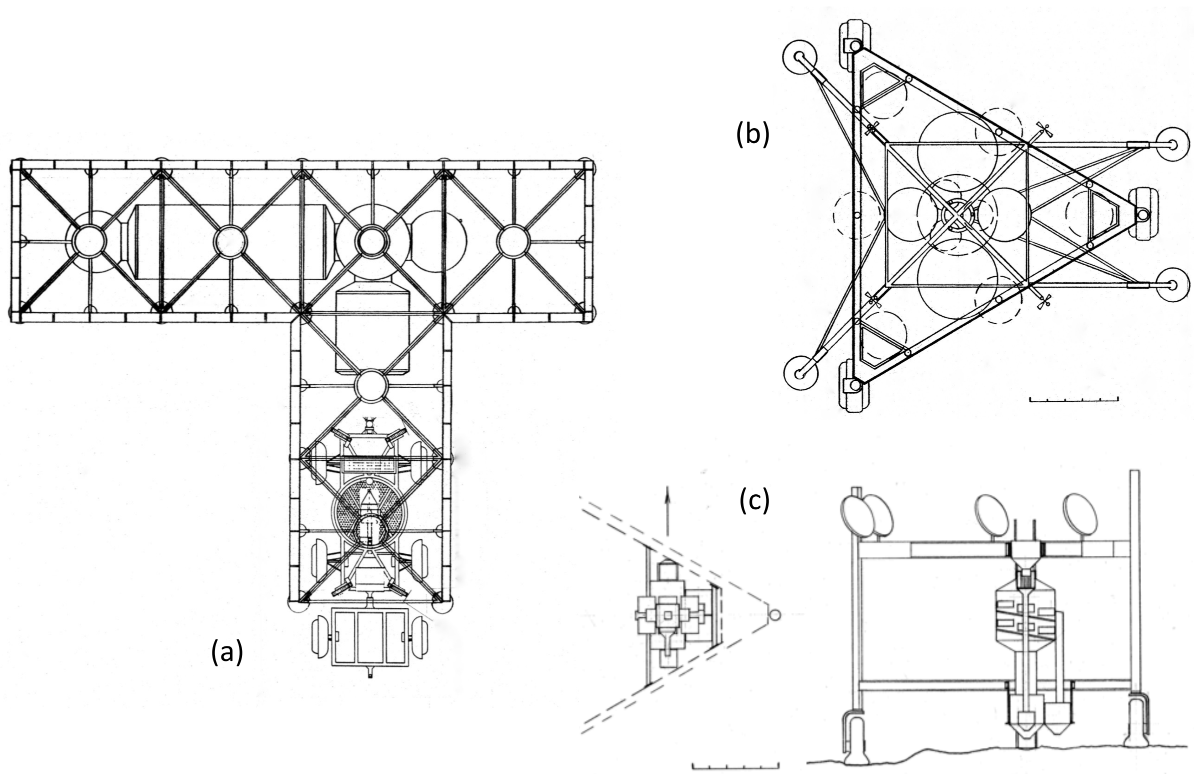

Fig. 4: **RLSO element designs and operations concept were tightly coupled.** (a) High-reach Truck enters radiation shelter to place units for repair inside pressurized workshop module. (b) Triangular Straddler drives over asymmetrical Lander for self-offloading, cargo unloading, and Lander relocation. (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.

336-hr lunar night costs about 1 mt/kWe, with 50%-efficient RFCs. Long lunar nights can be useful for equipment repair.

- Substantial lunar resources could start being used in the transportation architecture within four years of first landing...but only if crew flights are a small fraction of the total (2/15 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.
- R&R is an ongoing task during each lunation. The RLSO reliability analysis yielded an average of 12 failures per lunar daytime period for this simple base concept (about six times better than the reliability performance of mid-1980s manned space flight systems), where 'failure' is defined as off-nominal performance, regardless of severity.
- Supervisory control was enabling for this concept. This type of robot control requires well-characterized workpieces, a predictable environment, and a modicum of onboard sensor and command processing. Supervisory control provides a safe and efficient task execution environment because human operators are relieved of exclusion rules, reflexes, and details for routine operations. The machines need not be particularly intelligent, or to 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.

IV. 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:

Most lunar base operations, most of the time, must be robotic. This almost tautological principle is frustratingly overlooked in common visions of what a Moon base can be, but is vitally important to keep top-of-mind. Fundamentally it is driven by scope, safety, and economics. Scope: commonly anticipated lunar

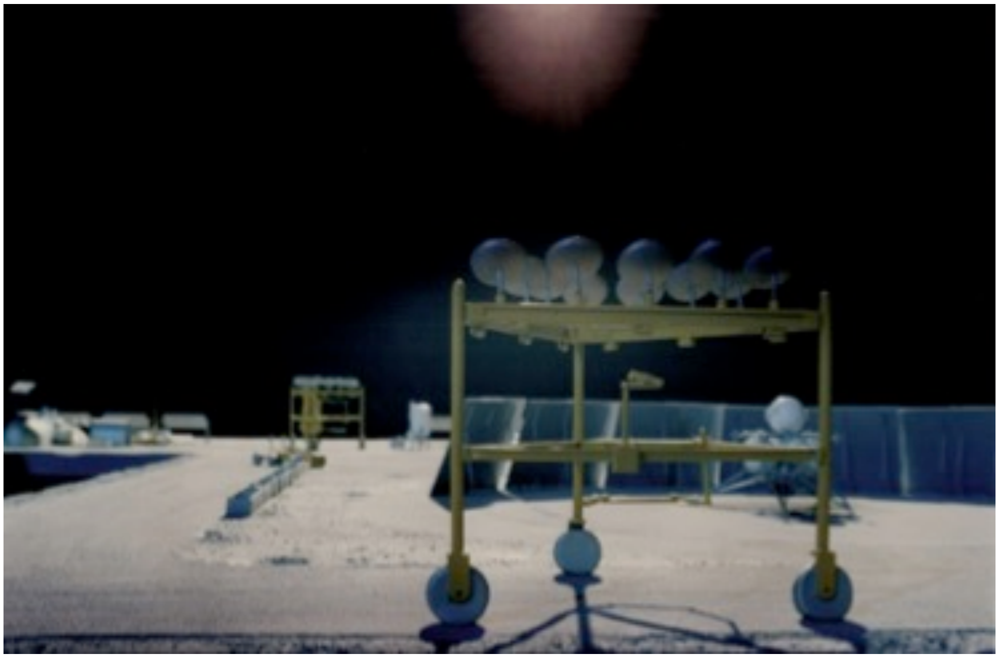

Fig. 5: **Solar-powered Straddler mobile gantry offloads all Lander cargo**, including itself.

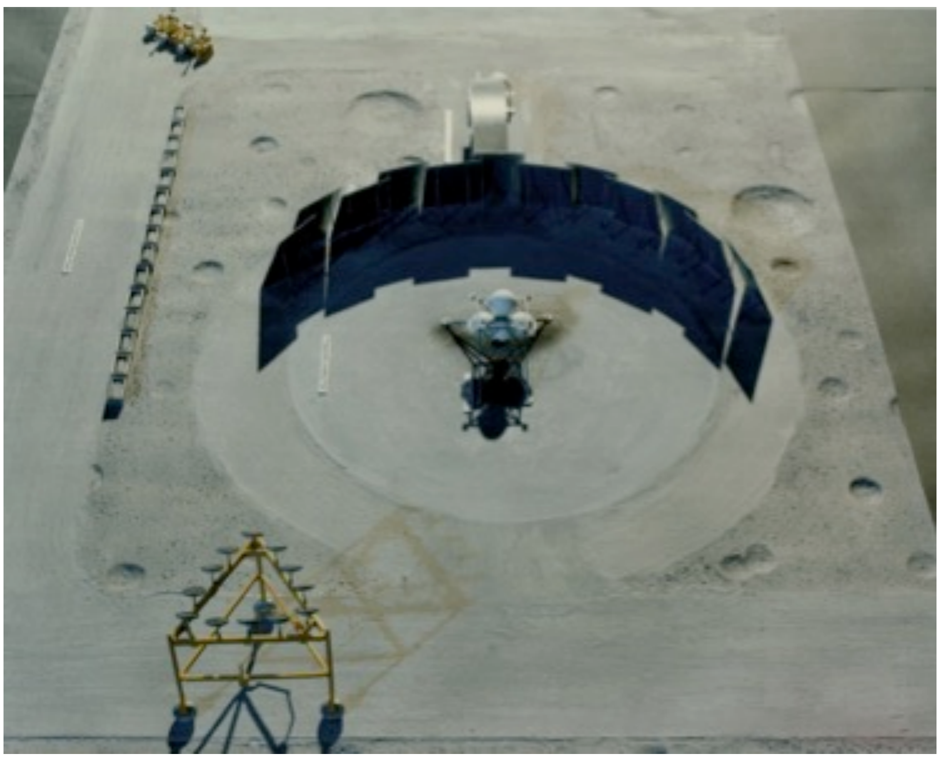

Fig. 6: **Base is shielded** from graveled landing pad by erectable debris deflectors.

base activities create a need for near-continuous action outside a habitat, moving enormous volumes of regolith, and tasks that 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, an enormous investment, would sit idle between intermittent crew visits without capable robots.

Unmanned work systems are the agents that will physically implement lunar surface construction and background operations.

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, road deposition and paving), 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 cargo and relocating landers. Operations are mainly constrained by frequency of lunar transport flights, rather than by capacities 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). Typical concepts 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 generally for direct human operation, 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 more 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 deposited in a 5-cm layer, then compacted by weighted rollers, to make roadbeds and workyard; sand was used to fill the habitat radiation shelter structure; dust was deposited as 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 (defined by RLSO as beyond the 1989 state of the art) 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. 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. Offloading crew tasks 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., + 1/3 for a 10,000-component system with 100x commonality to have 99% reliability over 20,000 hrs). RLSO solved this with a human-robotic partnership: mobile robots conducting EVA remove-and-replace maintenance, and visiting crew conducting sub-component repairs in an IVA workshop.

Seek to minimize the number of different element projects – including mobile robots. The program cost for a lunar base is driven primarily by the number of end-item development projects needed, as each constitutes a separate development procurement. RLSO established a 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. RLSO posited integrated solutions that set a high bar for alternatives:

- **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 Lander flights. 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

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).

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 to be disassembled and reconfigured for base growth. RLSO solved this with a modular, erectable, double-walled vault-shell structure that minimized 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 the 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 just 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 (Figure 7). Night also provided ample IVA time for repairing faulty units.

V. WHAT HAS CHANGED SINCE 1989

Despite the potential for persistent lessons just described, three decades – a whole generation – have elapsed since RLSO. In that time the cultural environment within which major space programs occur has evolved significantly. In the US – whose space-program resources are essential to develop a 30-t capable reusable lunar lander[8] – the society that revered "rocket scientists" in the 1960s is largely gone now, replaced by a directly-connected, cynical population[9] immersed in fragmented information that travels at the speed of Twitter.[10]

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. Among other objectives, absolute chronologies will calibrate ages across the solar system.

Thus we now have better prospects for using the Moon to bootstrap 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, distant rectilinear halo orbit planned for the Gateway) allow mass-efficient transportation, eliminate critical events, and yield favorable geometries for orbit transfer, communications visibility, and visibility 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 would 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. China has roved on the Moon recently, and some commercial companies 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 mechanisms; 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 sociological climate 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 seen 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 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 another planet. ISS is the precedent for Moon Village: multiple actors pursuing individual interests, using interoperable and shared infrastructure.[8]

Also since 1989, 'commercial' activities characterized by infusions of private capital into robotic and human space flight have emerged. 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 have explicitly embraced the Moon as their stepping stone, citing multifaceted rationale: 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.

Thus we now have an existence proof 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 5-mt Blue Moon lander, and the SpaceX BFR, Big Falcon Rocket.

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. 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.

Thirty years of these advances set the foundation for revisiting RLSO with contemporary knowledge, technologies, programmatic drivers, system capabilities, and tools. We now know where to go on the Moon and what resource to tap; we have better flight 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 international policy climate.

We can and should generate sensible, affordable Moon base concepts that can be turned into real projects to that we can begin operating on the lunar surface in meaningful way, as soon as possible. The coming years will doubtless see many suggested concepts. Quantitative operations analysis is key to separating the wheat from the chaff in this field. An affordable and sustainable lunar program requires a viable bootstrapping scheme with system-integrated element designs, including heavy landers. As RLSO put it:

"No matter where it leads, after all, our return to the Moon will begin with one flight."[1]

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