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Lunar Architecture and Urbanism, 2^{nd} ed.

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ABSTRACT

Human civilization and architecture have defined each other for almost 10,000 years on Earth. As the space population grows over time, persistent issues of human urbanism will eclipse within a historically short time the technical challenges of space exploration that dominate current efforts. Although urban design teams will have to integrate many new disciplines (e.g., system engineering, space transportation, solar system science, life support and human systems, space resource utilization, and environmental management) into their already renaissance array of expertise, doing so will enable them to adapt ancient, proven solutions to opportunities afforded by expanding urbanism offworld. Inescapable facts about the Moon set boundaries within which tenable lunar urbanism and its component architecture will eventually develop.

INTRODUCTION

This paper updates the author's original 1988 treatment of the subject.[1] In the 17 years since then, four major changes have occurred: (1) the U.S. has undergone two major cycles of national planning for lunar exploration and Europe has undergone one; (2) the International Space Station (ISS) has been designed, redesigned, built, partially flown, and operated; (3) the space tourism industry has begun to be validated by the emergence of Space Adventures and Virgin Galactic, the X-Prize, and commercial visits to the ISS; and (4) the field of space architecture has attained some professional stature as evinced by university curricula, an AIAA technical subcommittee, and publication of numerous papers. It is time to check the validity of the original thesis.

THE LONG VIEW

Many decades still separate us from any kind of lunar development that could be thought of as urbanism. Indeed current planning puts construction of even the first lunar base at least 15 years away. Why examine a field so embryonic that its likely reality cannot yet be known? Three reasons motivate this analysis.

First, given the proof of Project Apollo, we must recognize that human expansion to other planets is possible. Indeed it is central to the new U.S. Vision for Space Exploration (VSE). As VSE momentum builds, many non-specialists will anticipate lunar development with concepts that imply the character of eventual lunar civilization. Such projections will be most productive and useful if grounded realistically in inescapable facts that will constrain the eventual reality.

Second, those aspiring professionally to design the built lunar environment tend to originate either as space engineers who know little about urban development, architecture and their history; or architects just beginning to learn about actual space environments and the development, testing and operation of space systems. Eventually however, lunar planners will have to be well-versed in both worlds. Preparing rigorously for that combined future will take time; the present analysis is intended as one small step.

Third and most central, setting goals from the start can refine the paths that bridge from present thinking to future history. Tangible ideas regarding what the far future must, might, and should be, can give us a sound basis for making the many incremental decisions along the way toward it. So it is not premature to begin earnest, broad-based discussion of how people will use Earth's Moon. Recognizing end-states of offworld urbanism can both save resources and avoid regret as that urbanism develops over time.

TRAVELING, STAYING AND LIVING – To begin, we draw distinctions among three human activities, each with a special role to play in the growth of space civilization: traveling, staying and living. Space architecture so far has been entirely vehicular, based on components launched from Earth. Atmospheric flight governs their form from the outside in. Like trucks, vans, and the cargo containers they carry, this vehicular architecture only grudgingly allows human activity: it is cramped, noisy, and smelly. The interior human environment of such capsules, shuttles and modules is adapted directly from methods and solutions optimized for atmospheric flight vehicles.

Because vehicles themselves are inappropriate for lengthy habitation, longer-staytime missions based nonetheless on vehicular architecture require either excrescent, retrofitted, or modular approaches. The Space Shuttle exemplifies the excrescent type. Shuttle missions before the *Columbia* accident commonly carried “ab-ware” (Spacelab, SpaceHab) to extend their habitable volume so that seven workers could work for up to two weeks. This enabled, but also required, extensive ground support and preparation for every mission, and was ultimately limited by the capacity and operability of the vehicle itself.

The retrofitted and modular types characterize long-lived orbital stations. Skylab was a retrofit: built as a hydrogen tank but modified into a habitable research lab. Its capacious volume enabled greater spatial differentiation and privacy, but its architecture was limited by what could be designed in prior to its launch. The modular approach is more common: *Salyut*, *Mir* and the ISS have all been of this type. Large habitable volume is obtained incrementally through the accretion of small modules. The contemporary modular architecture does achieve operational efficiency by distilling staying activities from traveling activities (i.e., ISS from *Soyuz* and Shuttle), but is ultimately limited by the dimensions of its units and the complexity of their multiple connections.

A space architecture of linked, pressurized cylinders, even one that sprouts appendages and enormous exterior structures, is still essentially vehicular. Such habitable components on orbit are like train cars parked on a siding. Mission durations exceeding a year prove that, when specialized, such architecture can indeed enable individuals to work and stay in space. But while it is natural and common to envision even future space architecture based on this familiar vehicular vocabulary, only the first stages of permanent construction in orbit, or on planetary surfaces, can sensibly be vehicular. This realization has driven the development of larger, deployable modules like the inflatable TransHab originally developed by NASA and now being matured by Bigelow Aerospace.

ARCHITECTURE AND URBANISM

Submarine and Antarctic environments have been used as paradigms for space. Remote and hostile, all three are intrinsically lethal and require artifice to sustain life, promote efficiency, avoid conflict and encourage conciliation, and prevent disaster. From these urgent needs emerged “human factors engineering,” the discipline of quantifying human behavior in response to the built environment and improving its design as a result. Human factors engineering helps us understand human tolerance of key parameters in hostile settings. This enhances our ability to design an acceptable balance between minimizing resources and maximizing probability of mission success. But Earth’s oceans and poles, from which people generally return within a year, can only model the remoteness of space to a certain point. Long interplanetary flights and planetary outposts blur the boundary between traveling and staying.

Space cannot become a settled, economically viable human domain until people establish their lives there. As the amount of space activity increases, the travel time, expense and risk will eventually make it more practical for people to transform staying in space to living in space. Human living is an exceedingly complex activity that requires much more than passably engineered accommodation because it includes all we do: working, resting, playing, and growing. Designing for living is a vastly messy problem not deeply solvable by supercomputers or with “human factors” alone. People and their behavior cannot be reduced to factors in a numerical model of living. Rather, human living embodies the sum of physical and abstract richness developed over all of human history.

The requirements and effects of environments that support human living are subtle, and continue to be honed over millennia as society evolves. Manipulating those environments with skill and grace demands a fine, multivariate balance that only human experience and wisdom can feasibly provide – in space as on Earth, as far into the future as we can foresee. It demands in fact the practice of architecture.

Architecture is the professional activity of coordinating a set of specialty industries and services to make facilities that enable, enhance, and foster human living. Its product addresses needs that range from the prosaic to the spiritual. To dissect the profession, we first need ways to evaluate its product. Then we can better understand the range of specialties it coordinates.

FIRMNESS, COMMODITY AND DELIGHT – Two millennia ago, the Roman architectural historian Vitruvius proffered a clear, concise and complete statement of the qualities defining good architecture, translated since the 17th century as “firmness, commodity and delight.”[2] This tripolar standard covers anything that architecture can do or be. Firmness refers to structural integrity, appropriate material qualities, proper fabrication and safety. Firmness addresses the question: is it usable? Commodity subsumes all the ways a work of architecture serves the programmatic purpose for which it is built, accommodating the physical and abstract needs of its occupants and environment. Commodity addresses the question: is it useful? Delight is often the diacritical signature of great architecture, and frequently short-shrifted by modern commercial western builders as a separable luxury. Delight addresses subtle but penetrating questions: would people rather use this than other solutions? Will it last? These three ancient principles apply to all ages, modes and styles of architecture. They encapsulate distinct and complementary properties, without any one of which architecture cannot be simultaneously engineering, solution and art.

At its best, architecture projects human values and aspirations; at the very least, it embodies human needs and behaviors. Because it depends on manipulating materials for human use, architecture has been whimsically called the “second oldest profession” (as have business management, taxation and spying, incidentally). Architecture’s purview is extensive and inclusive. All designed interfaces between human beings and their environment, from spoons to highways, gardens to sewers, and buildings too, are elements of architecture. Civic architecture, that which services and embodies human community, is convolved inextricably with civilization.

THE ORIGIN OF URBANISM – Although known human cultural artifacts date back as far as 15,000 B.C., organized civilization arose ten millennia ago as a result of several key inventions: agriculture, abstract writing, money, and urbanism. Natufian hunter-gatherers first began farming cereal when the climate in the Middle East warmed around 8000 B.C.[3] Artifacts of early urban development appear in the record at Jericho in 7500 B.C. and at Catal Hüyük from 6500 B.C.[4]

The earliest applications of writing and urbanism were for commerce; they used formal design to facilitate densely efficient business intercourse. These permanently expressive media, both written and built, became useful also for capturing and stimulating human sensibilities. By transcending mere functionality, the recording arts of literature and architecture were born of writing and building. Down through the millennia since then, civilization and its cultural expressions have continued to define each other iteratively. We cannot imagine “civilization” (from the Latin root *civis*, i.e. citizen) divorced from its created artifacts.

The city is architecture’s grandest product, a built armature within which large numbers of people can arrange discrete but linked lives. As a tool to enable the evolution of increased social complexity, the city must first provide enduring organization, and sustain the individual and collective needs of the people living in it. By simultaneously accommodating most of the conflicting, singular services individual citizens need and desire, cities enable population density. The synergy achieved by that density in turn animates a social organism much larger, more resourceful, and more consequential than any individual could be. The strength, capacity and influence accessible to civic culture is what drives humans together to make cities wherever they live.[5]

An enduring and efficient civilization can achieve great things that advance the reach of the human spirit. But the extreme density encouraged by cities cannot alone guarantee greatness; urbanism often falls far short of both commodity and delight. Disease, exploitation, violence, environmental devastation, and spiritual impoverishment have historically accompanied high concentrations of people. As physical limits are approached, atavistic biological controls resurface in human populations. Certainly there is a significant gap between what is biologically tolerable for the human species and what is spiritually desirable for human civilization. The practice of urban design tries to mitigate the negative aspects of dense populations while leveraging their special benefits.

TRADITIONAL SPECIALITIES - Architecture occupies a central role in building civilization, by integrating and reconciling disparate fields that only create a firm, commodious and delightful environment when combined coherently. Traditional specialties contributing to modern terrestrial architecture include: human activity programming, comparative historical analysis, abstract and representational modeling, psychology, structural engineering, law and regulation, materials testing and development, environmental control engineering, negotiation and contracting, construction management, engineering geology, economics, site engineering, landscaping, and art.

At a larger scale, designers of cities must in addition address mass transportation, civic logistics, waste management, industrial production, crime, commerce, power production and distribution, spectator events, communication networks and media, public recreation, law enforcement, resource conservation, death, park management, health maintenance, environmental protection, and defense.

Architects and urban planners work to satisfy the needs of all these subjects simultaneously by manipulating the proportions, character, symbolism and scale of material assemblages. In so doing they add incrementally to the long history of built human environments. Their core effort – coordination and integration – remains invariant despite material and social features unique to time and place.

ANOTHER CHANCE

Let us now focus on a particular time (the 21st century) and place (cis-lunar space, specifically on and under the surface of Earth’s companion planet, the Moon). Before that time and place, the vehicular nature of space vessels ensures that their design will continue to be influenced by only the barest skeleton – the “human factors” – of the tremendous array of architectural issues. Poised at the threshold of learning to inhabit the most novel environment since the dawn of Man, and having only essayed tentatively into it, we are preoccupied with technical challenges. Keeping people alive and physically healthy still dominates all other challenges of human space activity.

Landing a few people on the Moon, and learning how to keep a few people in orbit continuously, consumed the best engineering effort the 20th century could muster, and is still beyond most nations. Developing a more open-ended, comprehensive, and safe cis-lunar transportation infrastructure now occupies us. Later, growing this to accommodate greater numbers of people and greater distances will open a new level of technical problems by leaving behind the sustenance and protection of Earth. For example, sustaining large groups for long times swings the logistics trade in favor of life support system closure. Long microgravity stays might require biochemical or inertial prophylaxis against deconditioning. Protracted travel beyond low Earth orbit requires shielding against both continuous and acute radiation exposure. And living far away from Earth in confined, artificial environments will challenge psychological health. Solving just these four challenges reliably and elegantly will keep us busy well into this century.

And yet, once those problems are fundamentally solved, they will cease to pose the dominant design obstacle to space civilization. By the time multitudes of people can begin living in space, more ancient architectural issues will have superseded the technical challenges of putting and keeping them there. We will have to establish an offworld urbanism that can provide the spectrum of amenities, stimulation and cultural support that people require of cities anywhere. The urban complexities introduced by hundreds, thousands, or even millions of people living in space will come to dominate everything else. Technically on the verge of enabling astronauts to stay on the Moon, we have barely begun to prepare for solving the total architectural problem eventually engaged by doing so.

PREPARING FOR THE FUTURE – Unconcerted preparation takes three forms. First but least useful are the striking, utopian images that characterize the 20th-century space colonization literature, both in studies and hotel company promotions.[6] These paint pictures of space civilization by projecting forward isolated details that may reveal more about their creators' parochial interests than they do about life in space. They can be inspirational, but are of limited help for planning because, like television science fiction operas, they tend to gloss over intervening practicalities.

Second and more provocative are the uncounted ideas explored in vignetted detail by science fiction writing and cinema. As the 20th century progressed, the SF audience became educated and sophisticated by developments in contemporary technology, and the genre produced a branch founded specifically on physical feasibility. The realistic and more fanciful stories both bring to the study of human futures the important advantage of having been conceived by writers generally driven to explore implications and meaning, rather than ways and means. In aggregate, they can help stimulate and caution our planning.

Third, the profession of terrestrial architecture is unwittingly well prepared for solving many of the eventually important problems of living in space. Dedicated architects and urban planners, supported by the professional heritage of millennia of experience, can help us focus on key issues, avoid the mannerist traps of simple visions, tap the wealth of futures concepts, and begin thinking seriously about viable and inspiring cities in space.

NEW SPECIALTIES – Space engineering adds a new set of tools to the ancient panoply of architectural practice. Lunar urbanism will follow the human needs of its citizens according to principles that new technologies, new environments, and new ideas are unlikely to change deeply. Engineering realities of building on the Moon will provide the language, but not the basic message, of lunar urbanism.

Offworld urban design will require attention to all the traditional architectural and planning subjects listed earlier, plus: advanced and closed life support; radiation management; reduced-gravity biology; space mining; biomass production; and material recycling. These are all in addition to the full complement of disciplines specific to spacecraft engineering, including: astrodynamics; propulsion; power production and distribution; structures and mechanisms; pressure containment; vibration and noise control; thermal management; guidance, navigation and control; command and data handling; autonomy; and reliability, safety and mission assurance. Planetary architecture must further address unique considerations including: launch and landing; alien engineering geology, weather, diurnal cycle, and gravity level; and wilderness management. To establish a mature and noble lunar urbanism, offworld urban designers will have to master many subjects.

That sudden technical and environmental enrichment of the architecture profession heralds a great step forward for human civilization. For the ten millennia of its history, architecture has operated within a familiar, fixed range of conditions governed by the cradle of Earth. The space environment bursts that ancient design boundary, substituting a new set of freedoms and restrictions. Traditional planetary constants become parameters. The easy dialogue between indoors and outdoors that humans have always enjoyed vanishes; interior "exteriors" must arise since the actual exterior is lethal. The harsh rules of space, and its startling allowances, define a new relationship between people and the natural environment.

NEW CHALLENGES – By being forced to rethink human living off Earth, we can remake urbanism if we proceed carefully, starting afresh with the 10,000-year history of civilization as practice. Space proffers the most emphatic environmental transformation our species will undergo, and the Moon provides a unique chance to experiment. The promise of a pristine realm affording utterly new opportunities fuels the designer's incessant hope: improving the human condition by creating a new standard of firm, commodious and delightful urbanism. Perhaps the clarity with which we will have to treat human living on an alien world can even teach us how to live more lightly on Earth.

Given time and trial, of course, the fuzzy problems of lunar human living would approximately sort themselves out, as they have done on Earth. But we may hope that foresight can limit missteps through planning, even though space is an utterly novel domain. We should aim to design on the Moon an urbanism better than any yet created on Earth. And with today's accelerating rate of material progress, we must aim to do it hundreds of times quicker than the leisurely ten millennia we had here. Otherwise the material, human and environmental cost will be higher than we would wish in retrospect.

LUNAR REALITY

Having defined the scope of architecture and urbanism, and established why expansion into space will open new paths for their evolution, we can look more closely at their necessary expression on the Moon. The abundance of misleading images of lunar communities means that certain basic principles remain unobvious, so it may be helpful to outline the most probable rules that will constrain lunar architecture. Rather than attempt to portray arbitrary details that might characterize one possible future, we instead limn fundamental factual boundaries that contain all the possibilities. Not all these facts will dominate lunar life until real urban growth supplants the first vehicular and outpost phases. Nor will they necessarily remain dominant for more than a few centuries, as they cannot account for unpredictable material progress. But they will likely circumscribe the first several generations of lunar architecture and urbanism.

DENSE POPULATION – Lunar urbanism will be densely populated at virtually all stages of its evolution. In most places on Earth, the costs of spreading out in single-family dwellings are either low enough or external enough that homesteading appears natural, even when unnecessary for farming. On the Moon, however, every cubic meter of habitable volume must be imported, assembled, sealed, poured or hewn, and sustained indefinitely – reverting otherwise to its native, lethal state. Resources for construction and life support would not often be dissipated on any configuration but the densest of city constructions. Lunar society will be almost fully urban.

LOCAL MATERIALS – The overwhelming majority of lunar civilization will depend on indigenous manufacturing. Offworld imports will inevitably be rate-limited. Common objects will be made locally, not because supplying them from space is impossible but because it is impractical by comparison. A specialized computer might be imported, but the chair in which the programmer sits, the room in which she works, the snack she munches, the scrap paper on which she doodles, and the light by which she sees, must all somehow be produced on the Moon.

This pervasively local origin of the bulk artifacts of lunar culture, with its corollary need to fashion a human environment from the bottom up, will excite and occupy designers for generations, and prevents us incidentally from accurately picturing it yet. But some conclusions are unavoidable. For example, simplicity will favor human-powered interior transportation: lunar city-dwellers are more likely to ride bicycles than electromagnetically-levitated monorails. If a few kilograms of composite can provide mobility and exercise unobtrusively, elaborate centralized transit systems are likely to be justified only for inter-urban traffic.

Ubiquitous products will be made as quickly, simply, and cheaply as possible from available resources. We can expect most surface buildings to be made primarily of lunar concrete reinforced with local metal rebar or glass fibers, serving both structural and shielding needs with minimal industry. We can expect iron and alloys of titanium and aluminum to be used as commonly as are steel and plastic on Earth. And we can expect glass to be everywhere – among the easiest materials to fabricate from lunar sources, glasses of varying purities will comprise everything from tunneled cavern linings and architectural elements, to structural and optical fibers. This might well mean a built landscape dominated by poured, masonry, fired and vitreous materials. Again, these are not all the Moon makes possible, but they will be the most expedient and therefore likely to be the most common.

HERMETIC INTERIOR ENVIRONMENT – Lunar architecture must be an interior architecture. Heavily shielded havens are required during solar proton events (SPE, or flares). And cosmic rays (which Earth's atmosphere attenuates) irradiate the lunar surface semi-isotropically and continuously; the best long-term countermeasures are not yet known. It may well be that, when not actually working in the space environment, people living there will voluntarily limit their unshielded exposure. The image of miraculous, crystalline pressure domes scattered about planetary surfaces, affording a suburban populace with magnificent views of raw space, is a baseless, albeit persistent, modern myth. Such architecture would bake the inhabitants and their parklands in strong sunlight while poisoning them with space radiation at the same time.

However, the natural landscapes of the Moon's surface and the antisolar sky will be especially attractive to human sensibility, just because they are natural. A lunar lifestyle may evolve that restricts recreational viewing to special times, perhaps spurring ritual behavior and special surface architectures for that purpose. Primarily or effectively subterranean then, lunar cities would be heavily top-shielded by concrete superstructures, by regolith overburden, or perhaps even by areas of untouched wilderness overlying tunneled city caverns. The natural and engineered planetary surface will be the single most important architectural interface on the Moon.

That interface must also include a continuous hermetic boundary capable of containing atmospheric pressure. While the enclosures inside lunar cities can be structurally rather conventional, every square meter of the actual city wall must withstand over 100,000 newtons of force exerted by the air within it. Indeed, a regolith overburden with sufficient weight to counteract this pressure would exceed by many times the thickness required for safe radiation shielding alone. Thus pressurized, lunar cities will in effect be grounded spaceships; no other single feature argues more strongly for an economical, underground urbanism there.

Lunar life need not be troglodytic, though. Many ages of architecture, three of which provide contrasting programmatic examples, have been conceptually or explicitly interior. Roman urbanism was conceived and executed as a sequence of controlled volumes and views that regarded all the natural landscapes it overran, from the Middle East to the British Isles, as alien. Turning inward away from natural features, Romans imposed the same planning schemes everywhere, creating their own universe around themselves, civilizing it with gods of their convenience, and arranging in it the ordered landscape of their choosing.[8,9] Virtually all outdoor spaces in Roman cities functioned as urban "rooms" within which the public rituals of Roman society could be played out. The Roman invention of concrete allowed enclosed volumes of a truly public scale never before seen, and the legacy both of those volumes and of the street facades that surfaced and announced them remains alive today.[10,11] From Roman urbanism, we learn that necessarily interior lunar urbanism can nonetheless be grand and theatrical, and promote civic life.

In the western medieval millennium following the Roman Empire, northern cold and frequent, local warfare among independent fiefdoms conspired to produce a genuinely interior environment. Often little more from the outside than a densely shielded pile, medieval architecture peered out of halls and chambers through tiny slits recessed in thick masonry walls.[12,13] The intellectualism of Christianity encouraged introspection, and even ornament shrank largely off the stone architecture to cloak the people instead.[14,15] To the east, the old Roman extravagance became Byzantine piety, still with enormous and lavishly ornamented interior spaces but now in the service of religious mystery rather than a secular civic public.[16] Eventually belief inspired the west to refine its masonry construction technology to recover volume, stretching the old Roman basilica form upward and flooding it with light from above. Gothic religion came to sustain an interior architecture as potent, grand and influential as anything Roman.[17,18] From medieval architecture, we learn that interior lunar urbanism can use precious but dangerous external views sparingly, yet still be emotionally and spiritually inspiring.

Most familiarly, 20th-century North America evolved the inclusive interior shopping mall to compensate the automotive dispersion of population. Wrapped within parking lots and structures, the mall's manufactured interior landscape entertains and stimulates temporary pedestrians along intersecting, faux-outdoor streets of retail facades. Roman-like consistency of style makes Toronto and Los Angeles essentially the same.[19] From capitalism-driven mall architecture we learn that interior lunar urbanism can create an "interior outdoors," be transient and adaptable, and even feel familiar.

Civic pride, protectionism, spiritualism, and commercialism, some of the most well-known built expressions of which we have just briefly reviewed, will be among the old and new motives guiding lunar civic building. Referring eclectically to the rich human past, a pluralistic 21st-century lunar culture will embody its own aspirations in the public interiors it builds. But all types of lunar interiors will share two distinctive differences from Earth's.

REDUCED-GRAVITY PROPORTIONS – First, lunar architecture must accommodate a larger scale of human movement. Although details await experience, the stride of a natural human gait in lunar gravity will be longer and rise higher than on Earth. (Note that the side-to-side, bounding gait used by Apollo astronauts was likely governed by rigid, bulky space suits as much as by lunar gravity, so these videos may not be a helpful design guide.) Human factors will have a new problem to solve: the proper dimensions of standard ceiling heights, doorways, and corridor widths.

Second, interior supporting structures, governed as always by economy, will be much more slender on the Moon than on Earth. For example, concrete columns, beams and ribs can be less massive than we are used to. Lunar architecture will tend to be lighter and seem more expansive despite its pressurized closure, its exterior shielding, and its urban crowdedness. The reduced weight-bearing requirement, when coupled with the easy availability of reduced iron in lunar regolith, may lead to a renaissance of cast-iron structural members.

NON-STERILE ENVIRONMENT – Like terrestrial life, lunar life will be non-sterile. Human beings are elaborate ecological hosts, having evolved in the septic biosphere of Earth a vast web of symbiotic, commensal, and parasitic interactions with microscopic organisms. Our understanding of these relationships is still too shallow, and utter sterilization too impractical anyway, for us to plan seriously a sterile offworld human ecology. Indeed, the biological "dirtiness" of humans poses a serious challenge to planetary protection considerations for places like Mars that may be hospitable to native or imported life.[20] Inside the hermetic confines of a lunar city, pathogen management will be a difficult but real problem, both for preventing hazardous infections and ensuring beneficial inoculations.[21]

Lunar cities themselves will host life as well. For example, bacteria that metabolize by corroding metal, and can live in environments extreme in temperature, pressure, radiation, and toxics, will exploit niches in space. Although it is conceivable that all lunar plants could be germinated and raised in sterile media, healthy plant ecologies probably require genuine soil cultures imported from Earth. In any case, just one smuggled culture could irreversibly inoculate the lunar plant community anyway. Similarly, feral pets and research animals will eventually co-inhabit lunar cities. While Norwegian rats, pigeons, and sparrows should be avoidable, it is unlikely that a secret, intentional release of fertile lab rodents will never occur. And it appears highly unlikely that offworld urbanism could grow without bringing along hardy stowaway organisms like the cockroach. Expansion will be too fast, and quarantine too porous, to preclude eggs and spores of vermin from colonizing the Moon with us.

IRREPLACEABLE WILDERNESS – Finally, the Moon must be a place of unprecedented demarcation between wilderness and human use. The ancient architectural form of the "town wall" will recur on the Moon – not to protect inhabitants from outside dangers, but rather to keep routine human activity from inexorably overrunning the native lunar landscape. Fragile though the Earth's biosphere may be in the face of modern development, its ultimate resilience has spoiled us. The encroachment of living things, relentless weathering, and finally even the implacable tectonics of Earth's geology render most signs of human action here into transience. Left alone, even denuded forests and ravaged desert ecostructures can eventually recover.

The inanimate lunar wilderness, however, is truly fragile and effectively irrecoverable. At least millions of years are required for micrometeorite "gardening" to remake just centimeters of regolith. The forces that reclaim strip mines and ruins on Earth simply do not exist on the Moon; the first trek through a pristine region of the Moon's unique "magnificent desolation" ruins its ineffable wilderness value practically forever. Surface exploration, strip-mining, construction, and recreation will be facts of human activity on the Moon. But so, sooner or later, will be human demands for utter preservation of untouched wild regions. Wilderness appreciation cannot be participatory on the Moon the same way it is on Earth. The solace and emotional renewal afforded by passively contemplating wilderness will induce radically new forms of urban design, specialized architectures, and art, to accommodate that human need on the Moon. The Moon's small size (about the same area as Africa) increases the urgency of preventing total surface development; however, it also creates a close horizon that will help to isolate areas visually.

CONCLUSION

The few salient characteristics of lunar architecture and urbanism discussed here grow directly out of facts as intrinsic to the Moon as weather is to the Earth. By accepting them as boundary conditions, we can project the built human lunar environment more aptly. Many types of people – including designers, authors, illustrators, engineers, explorers, leaders, and planners – are inspired by thinking about living in space and on the Moon. We should inject as much realism as possible into their thoughts. Rigorous designs can be even more exciting and romantic than specious fantasies, and are more helpful for shaping our collective vision of the future. By starting from a few accurate principles – that lunar urbanism will be densely populated, hermetic, interior, kinesthetically expansive, visually lightweight, and based on indigenous materials; that it will be non-sterile; and that lunar wilderness will become irreplaceably precious – those who do plan can contribute meaningfully to the responsible realization of one of the grandest projects ever imagined in human history.

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