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PROGRESSIVE PROTOCOL FOR PLANETARY PROTECTION DURING JOINT HUMAN AND ROBOTIC EXPLORATION OF MARS

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ABSTRACT

Current evidence indicates that Mars may harbor biologically viable microclimates. Until proven naturally sterile, such zones will be afforded the fullest protection of NASA's planetary protection policy. Methodical investigation to disprove extant biological activity requires human field science. Traditional human exploration system and operational concepts are "biologically leaky" and cannot guarantee protection, yet fully prophylactic approaches would burden exploration infrastructure for a long time, perhaps unnecessarily. Knowing a reasonable solution could become a precondition for specific mission planning and substantial investment in infrastructure development. A potential solution consists of (1) a framework that undertakes to conclude in stepwise fashion that Mars is sterile, (2) mapping and progressive management of the boundaries of increasingly smaller zones requiring protection, and (3) a protocol that uses robots and humans together to perform this sequential investigation. The end state is either proof of native Mars life, or basis for relaxing planetary protection measures. The method lays groundwork for specific interaction models between field explorers and their robot adjuncts, for an overall Mars surface activity agenda, and for system and equipment requirements to support it.

INTRODUCTION

This paper addresses one central challenge in planning human exploration of Mars: reconciling the conduct of human operations on Mars while biological planetary protection protocols are in force. This reconciliation poses a dilemma, analyzes its constituent issues, and then synthesizes an operational concept that could resolve them.

The ideas developed here were initially outlined in discussions between the author and several colleagues attending the NASA workshop "When Ecologies Collide," held at Pingree Park, Colorado in the summer of 2001. A workshop summary paper[1] briefly introduces the basic concepts in context of the major topics discussed at the meeting. The underlying issues and the zone-management approach to addressing them are also discussed briefly in Chapter 5 of the recent *Safe on Mars* report[2]. Given the present resumption of interest in planning human Mars exploration, the purpose of this paper is to detail the concept, to explore its implications, and to frame more advanced discussion.

PLANETARY PROTECTION DILEMMA

The inherent planetary protection dilemma arises in two stages, technical and programmatic. The technical stage results from a sequence of four issues:

1. Mars may already host microbial life, or be capable of hosting it
2. The operational challenges of investigating the viability of a given microclimate are directly proportional to its viability potential
3. Thorough investigation (i.e., sufficient to establish a conclusion of non-viability) exceeds the capability of foreseeable robotic technology and requires *in situ* field work by scientists
4. Human operational presence at the microclimate may confound the

investigation by compromising the site's biological integrity.

Taken together, these issues mean that the operations required to study the place may ruin the study or even the place itself. A programmatic overlay compounds the dilemma:

5. Without studying potentially viable Martian microclimates, no one can know how viable, extensive, contiguous or interconnected they might be
6. Such "boundary" knowledge is vital for certifying that systems and operational protocols meet planetary protection requirements
7. The NASA Planetary Protection Officer (PPO) must approve all NASA Mars missions prior to launch
8. Lack of a clear plan for obtaining this approval in the end could delay the initial commitment to invest in mission development.

Paradoxically, lack of sufficient knowledge, which cannot be gained except through human exploration, could by our own rules prevent or delay such exploration. The Gordian Knot of this layered dilemma must be untied early to enable mission approval and orderly development.

DISCUSSION OF ISSUES

A brief exploration of the eight issues helps unravel the knot and provide clues to its resolution.

<u>Issue 1 – Mars' viability</u>. The more we learn about Mars, the more real becomes the possibility of its sustaining environments potentially hospitable to life. From tantalizing observation of flow features and novel surface chemistry in the 1970s, we have progressed to evidence of both long-term standing, and geologically recent episodic, liquid water. These data support hypotheses that some microhabitats might remain viable today (i.e., where a favorable combination of hydration, thermal, chemical nutrient and radiation environments could exist below the surface, within rocks, or at hydrothermal or occasional seep interfaces). In 2004, few scientists would assert categorically that Mars is lifeless.

<u>Issue 2 – Most-likely microclimates are the most challenging</u>. We know already that Meridiani Planum might be a promising place to search for evidence of past life. But planetary protection concerns the possibility of extant life, and the places to look for this are far more operationally challenging.

The probability of encountering viable spores or active organisms is inversely proportional to the degree and duration of the environment's dessication, among other parameters. Microclimates where water might enable hospitable conditions include (1) cryptolitho-environments (i.e., inside rocks), (2) occasional seeps inferred from observed flow features in crater walls, (3) subterranean remnants of presumed hydrothermal features, and (4) thaw interfaces of subsurface permafrost zones. On Earth, life has been found in analogs to all four of these microclimates, and many other improbable places[3].

Physically reaching each of these example specialized environments (and studying them in detail once reached) is a classic prescription for human-mediated field science. Environment (1) requires careful selection of target rocks, and responsive sectioning and preparation for analysis. Environment (2) requires lateral drilling into a seep crevasse after rapelling down a cliff face. Environment (3) requires deep drilling in unpredictable substrate after sounding uneven terrain to identify promising drill sites. Environment (4) requires excavation or drilling operations at high latitude, in mixtures of ice, rock, regolith and perhaps mud.

The diverse combination of challenges (e.g., target identification, physical access, visibility and communication, and operational predictability) posed by these and other environments, given their variations in slope, substrate integrity, moisture content and other engineering parameters, put them far outside the risk tolerance envelope historically acceptable for planetary missions, even those costing only ~$\$10^8$. The very sites that must be investigated to disprove biological viability are the hardest of all to investigate.

<u>Issue 3 – Human field science required</u>. Although it is provocative to conceive field robots that could tackle the challenges

posed by such sites, robotic exploration alone is an impractical approach for sustained, thorough investigation of Mars' biological potential. The unforeseeable variability of unique site conditions increases risk of failure for autonomous systems, and in any case few biologists would be willing to rely on such remote operations to select and penetrate the right sites, let alone to conduct the investigations required to conclude that Mars is biologically inert.

Robotic missions, including sample return, could conceivably yield positive results (i.e., biological viability) early. But the planetary protection challenge arises from the more likely opposite scenario: continued absence of evidence of viability. Operations including sample collection, contextual analyses, microbial culturing, and microscopic and biochemical analyses would need to be prosecuted at increasingly challenging sites to build the case for global non-viability. To build that case, the cost-benefit calculus for effective site selection, characterization, access and detailed analysis so strongly favors human-mediated operations that achievable robotic means could not yield robust conclusions within the timeframe of patience for beginning human exploration. Long before we could field robots that match human capability, we would likely plan to put humans onsite anyway.

Issue 4 – Contamination from human activity. But such human presence is exactly what the planetary protection requirements would hope to avoid. Human space systems as traditionally designed and fielded are both "biologically dirty" (they shed viable flora and bio-active chemicals) and "biologically vulnerable" (they inevitably introduce alien material into the habitable environment). Unless strictly controlled in unprecedented ways, these leaky characteristics violate respectively the forward- and back-contamination prevention objectives of NASA's planetary protection policy[4].

Requirements that would preclude these features (e.g., non-venting suits, non-leaking habitat mechanisms, EVA provisions that never allow human contact with native Mars material) have never been incorporated into human space system planning as an integrated set. To do so would change ongoing and anticipated system technology development projects substantially, introducing higher development costs and longer development schedules than currently envisioned. Also, operational protocols dependent on such means would be fragile, since they would be susceptible to disruption in the event of a breach. In such a contingency, even aborting the mission would not undo the breach, a risk the Planetary Protection Officer will account for in his approval evaluation.

Issue 5 – Unknown extent of viable zones. Discovery and characterization of terrestrial extremophiles in recent decades validate the need for caution in presuming sterility of harsh environments, and lack of exchange between hospitable microclimates separated by inhospitable barriers[5]. How much of the extensive permafrost zone might be viable? How might wind mediate the distribution of hardy spores (*a la Deinoccus radiodurans*) whose DNA repair mechanisms can compensate for long exposure to ionizing radiation during periods of dessication[6]? Without *in situ* study, we cannot confidently demarcate the boundary between viable and non-viable zones, the secular or cyclic evolution of the boundary configuration, nor the dynamics of transport mechanisms that may connect discontinuous viable zones.

Issue 6 – Boundary knowledge essential to certify protocols. The absence of foreknowledge regarding zone boundaries means we cannot determine a "safety gradient" for operating in proximity to zones known or thought to be viable. How close is too close? Without models of this gradient, operational planning for human investigations becomes especially problematic. We cannot traceably drive quantitative, verifiable design requirements for systems and their operations procedures. Hence we can neither verify that design and operational protocols will meet planetary protection requirements nor validate that measures thought to be appropriate will actually preclude contamination events.

Issue 7 – Planetary protection approval precedes launch. The PPO's responsibility includes assuring that no action or lack of action by a NASA mission results in an unreasonable or uncontrolled risk of compromising life-seeking science investigations, alien ecologies, human health or the terrestrial ecosystem. The protocols developed so far for robotic deep-space, planetary and sample-return missions are inadequate for human missions to Mars.

However, momentum for human Mars missions has the potential to become an "irresistible force" pitted against the "immovable object" of protection standards whose *raison d'etre* ironically comes to fruition for just such missions. As with space nuclear power, the public will become more aware of planetary protection issues and risks, debate will widen, and attention will focus. It is unlikely that the requirement for PPO launch approval will be relaxed.

<u>Issue 8 – Reasonable plan for obtaining approval precedes program start</u>. Indeed, plans that cannot reasonably be anticipated to obtain such approval are likely to remain unfunded. Absence of a sound requirements basis for precluding an irreversible and irrecoverable event (i.e. a human planetary protection breach at Mars) might lead to an uncomfortable compromise: large, expensive and cumbersome design and operational margins that nonetheless still leave the residual risk unbounded. Such large margins for the purpose of planetary protection would be unprecedented in Mars mission planning. And good project management practice establishes key margins at the beginning of the project and manages them closely throughout its lifecycle. Inability to do this adds one more element of uncertainty to the program plan, diminishing its sustainability.

Our Mars mission planning community is unprepared to commit resource-driving decisions in this area in the foreseeable future. We need a systems engineering framework for resolving this enabling dilemma, deriving a sound basis for reasonable requirements, and formulating a robust mission execution plan.

The framework proposed by this paper is built upon a premise and an axiom.

PREMISE

The premise is that the pragmatic goal of investigating Mars' biological potential is to declare the Mars environment "safe" from "excessive" planetary protection controls as quickly as possible, thus "normalizing" its amenability to traditional concepts for human systems and activities. The simpler the eventual controls can be, the less cumbersome routine operations can be, the less complex operational systems can be, and the less expensive their development and proliferation can be. Simplicity and frugality have inherent value because they maximize the potential for exploration effectiveness. Four scenarios illustrate the logic of the premise.

<u>Scenario 1</u> – Quickly determining that Mars is inherently inhospitable to life would result in the simplest, cheapest requirements for further activity. However, this is the least likely outcome: even the lunar surface environment was able to host terrestrial bacteria in a dormant state. *Streptococcus mitis*, a gram-positive, non-spore-forming bacterium, apparently survived inside a *Surveyor 3* camera on the lunar surface for 2.5 years before being retrieved by Apollo 12 astronauts[7].

<u>Scenario 2</u> – Determining that Mars is naturally sterile, but could be colonized by terrestrial microorganisms, would reduce the future challenge to an ethical debate over the degree to which it is acceptable to allow this to happen. Depending on Mars' natural lethality, containment and transport mechanisms, the few presumed viable spores deposited by the seven mission systems that have either landed or crashed on Mars already, and the many more to come, may have rendered the ethical purity of this debate moot.

<u>Scenario 3</u> – Determining that Mars material is hazardous to human life or imported terrestrial ecologies would require separation technologies appropriate to toxic substances. Although this scenario appears unlikely, we can debate the degree to which intrinsic biochemical lethality would curtail expansionist plans for human activity on the planet. Presumably, science outposts could be managed, but more ambitious visions (e.g., settlement, terraforming) would be dealt a blow.

<u>Scenario 4</u> – Determining that Mars has extant life would be the most momentous and challenging outcome, and would require

prevention of irreversible biological contact pending full investigation of its nature, including biochemical compatibility, ecological compatibility, "second genesis," transgenic potential, and long-term protection strategies.

Unfortunately, caution given our current ignorance relegates us to starting our investigation of Mars' biological potential by presuming the worst case, which is the scientifically exciting but operationally braking fourth scenario. The premise holds that our goal should be to seek to progress carefully but expeditiously from the possibility of the fourth scenario to the certain knowledge of first scenario, so as to facilitate unrestricted future human activities on the planet.

AXIOM

The axiom is that windblown Mars dust will be determined to be ubiquitous and pervasive, globally uniform in being naturally sterile and biologically inert, and will infiltrate any habitat system that is not permanently hermetic.

Global uniformity of natural sterility and biological inertness are what make the dust principle axiomatic – these aspects can never be fully proved, but rather can only be incrementally validated over time. They are nonetheless essential to a pragmatic solution, because they enable the first step of the progressive protocol.

The axiom is required because of dust infiltration. No airlock system yet devised (and there have been many) can preclude all contact between the interior of the human habitable environment and the native Mars environment. The suitlock concept comes closest, but the more dust-exclusionary the mechanism design becomes (e.g., designing the double hatch such that all outer surfaces of the suit and habitat hatches remain mated during all operations), the more prone to operational failure it also becomes.

A better approach is to use robotic precursor missions to perform three sets of tests on windblown dust to satisfaction (i.e., sterility, biological viability as a medium, and bio-compatibility) to determine that (1) small amounts of Mars dust are tolerable within human habitats, and (2) Mars dust is a lethal medium that cannot transport terrestrial microorganisms deep into the native Mars environment. Coupling these results with the global biological uniformity axiom then renders windblown dust anywhere on Mars as dead. This then enables us to define windblown dust as the first zone of our progressive management method.

ZONATION

The "zonation concept" views the accessible Mars environment (including the microclimates induced by human system presence) as a puzzle, whose contiguous pieces are discrete zones – each with distinct biological potential – that are "mutually exclusive and collectively exhaustive."

The windblown dust zone exemplifies the diverse parameters required to characterize a zone: it is dynamically bounded – and therefore can be uniquely defined, mapped and monitored – in the orthogonal dimensions of material composition, physical state, physical space, and time. Compositionally, the dust consists of particulates below the size threshold that permits them to be redistributed by natural winds (i.e., caked dust or "desert varnish" captured and redistributed by boot treads is not part of this zone, nor is dust blasted great distances by artificial explosions or meteorite impacts). The particles are solid and non-consolidated (i.e., particulates that were dust at one time but are now compacted into rock cease to be part of this zone because they can no longer be widely redistributed even by dust devils). The zone includes surficial dust coatings on regolith or rock that might be only microns thick, drifts or fills that might reach substantial depths, and particles suspended in the troposphere. Finally, the conceptual geometrical boundary enclosing this extensive zone varies continuously in the time dimension over timescales from seconds to millennia.

Other zone definitions might include environments such as alluvial deposits, rock interiors, permafrost, crater walls, drill holes, hydrothermal vent pipes, dry lake beds, aquifers, and fissures. Each could be subcategorized (i.e., sub-defined, -mapped, and -monitored) according to specific environmental parameters of potential biological interest (e.g., temperature range and stability, moisture content, exposure to ultraviolet radiation, vulnerability to weather-mediated gardening). Special zones might be defined by the interface boundary between other zones (e.g., any interface between permafrost and subsurface temperature and pressure conditions where ice could melt).

Equally important, artificial zones might include places such as the region around a habitat gas vent or airlock hatch within which terrestrial microorganisms might remain viable, the thermal disruption footprint made by human systems in permafrost, chemical plants, and waste depots, in addition to the obvious zones within habitats and greenhouses. The complex interaction of vented atmosphere and moisture, polymeric materials, and local shielding means that exterior human system surfaces might comprise highly hospitable zones.

The bounding parameters of sites or zones with biological potential can be designated in a variety of ways—either as a location *per se* (e.g. a brine seep) or through a combination of important geometrical (latitude, longitude, depth), geological (material composition and mechanical properties) and environmental (hydration, temperature) features. Such a boundary may vary diurnally, seasonally, or even secularly as Mars exploration operations proceed. Exploration and sample retrieval inside zones with biological potential must maintain strict separation of habitable zone from Mars material. This means that at no time may materials from a non-cleared site be handled in such a way that they contaminate surfaces that will be introduced unsterilized into the habitable zone, and vice versa.

The zonation concept challenges exobiologists to work with other investigative field scientists to (1) define appropriate zone criteria based on both biological potential and field-measurable properties, and (2) generate and maintain a dynamic map of Mars' zones throughout the progressive exploration process.

PROGRESSIVE OPERATIONS PROTOCOL

The progressive protocol uses the dynamic zonation map as the fundamental management tool to assure planetary protection integrity as exploration proceeds. Three models are required to make it work: dynamic definition of the discrete zones, determination of the biological potential of those zones, and transport models of how the zones exchange material and of time-dependent biological viability of material that crosses the boundaries. Using these models together, we can divide the Mars environment into zones within which no human systems may risk intrusion, zones within which human system activities must be carefully managed to avoid contaminating adjacent zones, and zones within which biologically leaky human systems may operate freely. *Safe on Mars* calls these latter regions the "zones of minimal biologic risk" (ZMBR)[8].

Note again the criticality of determining the global uniformity, natural sterility and biological inertness of the first, windblown dust zone: it links any human system on the planet with other easily-accessible zones, planet-wide. If that link itself is biologically viable, then all such easily accessible zones must be determined to be naturally sterile before the first human mission can be allowed. Prosecuting such a research agenda to satisfaction completely robotically is a challenge not traditionally envisioned in Mars mission planning. Validation of the windblown dust axiom is therefore the most critical agenda for robotic precursor missions.

The progressive protocol is a methodical investigation that permits us to incrementally extend a determination of natural sterility, one zone at a time, beginning with the windblown dust zone and working outward into the rest of the Mars environment. As this sequential investigation establishes that each next zone is sterile and/or biologically inert, that zone becomes "safe" to host the operation of biologically leaky human systems without further risk to the biological integrity of other, not-yet-investigated zones. The investigative front progresses until it either subsumes the entire planet or finds life.

A simple image helps visualize this process. Imagine that the windblown dust zone has been cleared for operations by robotic precursors. Next, a local zone of desolate, mid-latitude regolith is similarly cleared for human operations (using the *Safe on Mars* terminology, the ZMBR is expanded). A habitat can now be set up there and operated with confidence that its effluents, attached biota, and local operations will not contaminate more sensitive zones elsewhere on the planet. Conceptually, the habitat operations zone, out to the extent of its potential to contaminate the environment with viable terrestrial organisms, is surrounded by a "black-and-yellow police tape" that cordons it off from the rest of the planet. As progressive investigations determine the inability of surrounding zones to support life, this conceptual "police tape" enclosing the human operations zone moves outward to encompass them as well. When the tape encounters an especially sensitive microclimate (e.g., a drill hole, or a seep), it bypasses both the site and an appropriately wide margin governed by the contamination-potential transport models, leaving them identified as a not-cleared zone. When the expanding tape boundary reaches a similar boundary expanding outward from another human operations outpost, the tapes merge to form one conjoined human operations zone.

Eventually, figure and ground reverse: all of Mars is determined sterile and/or inert except for residual, isolated zones of special interest for biological potential. This approach has two benefits: (1) it rapidly clears the majority of the planet for routine human exploration operations, thereby focusing investigative and protection resources on the sites with highest life potential, and (2) it establishes significant operations infrastructure prior to engaging detailed study of those sites, thus increasing the capabilities available for their orderly study.

Throughout the progressive protocol, the pragmatic goal remains to shrink the residual black-and-yellow-tape enclosures to the vanishing point. As the boundaries tighten – e.g., from a seep site to the seep fissure, to the seep source, to the subsurface zone within the seep itself – the sophistication of instrumentation and the finesse of the operation increase, commensurate with the increasing potential for successful discovery of life signs and the concomitant increase in risk of a planetary protection breach. Imagine the excitement – and extraordinary care required – as field work homes in on such biological hot spots.

ROBOTS AND HUMANS TOGETHER

If human operations cannot be permitted to violate zones not yet cleared, how can they be investigated sufficiently to enable a determination that they are sterile and/or inert? How can the work be done that justifies shifting the black-and-yellow-tape? The answer holds the key to two important questions for technology maturation: (1) the "highest and best use" of robotic technology in human Mars exploration, and (2) the most critical focus for investment in biologically non-leaky human systems.

Robots can act as field scientists' probes outside the cleared zone (i.e., inside the police-tape cordon). Appropriately designed robotic systems can be confidently sterilized prior to use – or between uses – to preclude compromising biological integrity of study zones. In not-cleared zones, initial reconnaissance and sampling can be done robotically to determine whether and how future human activities may be safely permitted in the area. The basic operational concepts will each significantly stretch technology development goals: (1) robotic field assay, and (2) sample retrieval to specially equipped local human facilities for analysis.

Using robots and humans together locally enables five important benefits not available in a meaningful way to the remote robotic approaches used to date or envisioned for the Mars Surface Laboratory (MSL-09) or Mars Sample Return (MSR) missions. Three of these benefits are fundamental capabilities (teleoperation, jury-rigging, and mechanical repair), while the other two are derivative capabilities (tightly responsive and marginal-cost investigations).

<u>Teleoperation</u> of Mars robots from Earth is impractical due to the closed-loop time constant, which is on the order of an hour. But local crews, separated from machines by only meters, or even by over-the-horizon

relays, can achieve a high degree of finesse in controlling them. Whatever level of autonomy can be built into the machines would be dramatically enhanced by having human controllers nearby.

Jury-rigging is the adaptation of equipment designed and qualified for one purpose for another purpose, in response to emergent needs. As the progressive investigation closes in on specific microclimates, their combination of geometry, substrate and other conditions will become unique and unforeseeable. Human crews equipped with even a rudimentary workshop, components and materials can design and build modifications, extensions and syntheses of the robot sensors, mobility subsystems, and effectors that they have on hand. The history of human space flight amply demonstrates the value of this capacity.

Mechanical repair includes mechanical operations on electronic and optical systems as well as mechanisms (as distinct from software loads, which can be installed remotely from Earth). Equipped, local human crews can far exceed the foreseeable capacity of robotic systems to repair themselves or each other. While machines clearly have the advantages of being force-multipliers, specialized sensor-effector platforms, tireless drones, and expendable, humans are unbeatable for keeping the machines healthy and productive.

Tightly responsive investigation is the first derivative benefit. Human interaction has a higher purpose than just making sure the machines work. By being nearby, field scientists can participate immediately in the iterative cycle of data collection, analysis and determination of next steps. Their proximity tightens the responsiveness of science decision-making at the target site. Planetary protection protocols – and physical site properties – may preclude field scientists from using hand lenses or taking their own samples directly, but being able to direct the actions of a suite of robotic tools just meters or kilometers away dramatically increases the efficacy of machine operations compared to remote or autonomous functioning.

Marginal-cost investigation is the second derivative benefit. Once the investment in capability has been made – to enable onsite field scientists and sophisticated robotics to augment them – the additional cost to extend, abort, adapt, repeat, or focus the investigations planned is only marginal. Compare the ratio of opportunity to difficulty of two scenarios. First is a weekly cycle that plans field work, configures robotic tools, takes incremental steps in an ongoing investigation, analyzes results in consultation with experts on Earth, and plans future activities, deployments, or investments. Second is a decadal cycle that plans, develops and launches missions, awaits their successful deployment and data collection, and uses emergent results to influence the final configuration of the next decade's missions. Measured in numerous dimensions (e.g., dollars, time between discoveries, timeliness, sustainment over multiple political administrations, attention span of public support), the costs per unit of new knowledge gained are far lower for the first scenario.

The progressive protocol enables each asset to be used to greatest effectiveness, in a complementary way. Machines do what they do best: sterile operations, first probes, excavation, dangerous access, heavy lifting, monotonous or repetitive actuation, unblinking observation, and transportation. Humans do what they do best: responsive planning, strategic decision-making, pattern recognition, troubleshooting, maintenance, and adaptive innovation. Working collaboratively on both sides of the non-cleared boundary, they accomplish together what neither could alone: rapid cycles of site selection, investigation planning, contextual analysis, sample acquisition and analysis, active and interventionist observation.

Note that scenarios using humans to operate on, rather than just operating, field robots used for the biological investigation of Mars also requires a verifiable capability to sterilize the machines both before and after human intervention. This precludes both forward contamination (sterilizing machines operated on by humans before they are sent into the field) and backward and cross contamination (sterilizing them upon their return prior to being operated on again).

In addition, a new class of "clean" human systems would enable fulfillment of the potential of human presence. The goal of the progressive protocol is not to obviate such clean systems, but rather to limit and focus the need for their use.

We can divide human operations into two types: those required at a base and those required near a site of potential biological interest. While both may require first-time activities, equipment setup and regolith moving, they differ significantly in purpose and detailed requirements. Bases will see heavy and routine operations; large transfers of energy, material, and people; an environment comparatively rich in multipurpose infrastructure; and relative predictability. Science sites will see slow, incremental activity driven unpredictably by discovery and emergent findings (like an archeological dig); focused imports and exports of specialized equipment and experts; and a work environment purposely or necessarily devoid of elaborate infrastructure. Given a site in extremely inaccessible conditions (e.g., a seep site partway down a cliff), we can foresee staged operations: a permanent human base, a forward base near the cliff edge, a zone at the proper level of the cliff face, near the micro-site, that allows human operations, and the micro-site itself in which only sterilized machines may operate under human direction.

The human systems that operate at each of the staged sites have different degrees specificity, finesse, and cleanliness, and different operations protocols. "Science site operations" would be inappropriately slow, cumbersome and expensive for routine base needs, and "base operations" would be biologically inappropriate for science site needs. Some technologies that might be helpful for science site operations include: peel-away or other sacrificial materials; clean-shrouds and casings; mechanism designs that minimize internal corners, re-entrant features and other joints that cannot be reliably cleaned; bake-tolerant equipment and the facilities to bake it sterile; ventless habitable systems; mobility systems that avoid dust generation, sequential-handoff systems, and laboratory modules with glovebox interfaces directly to external environments. These and many more will be supported by technologies that monitor and manage their integrity.

Finally, note that even with the progressive protocol, the main base itself requires special features and procedures, at least at the beginning of the investigative phase. Ingress/egress systems would limit the type and total amount of dust allowed inside the habitable zone – and support procedures to control and clean away the dust that does get inside – since at the beginning only windborne dust is known to be sterile. Once boot-tracked regolith is also known to be sterile, operations rules can be relaxed significantly, driven by engineering and toxicity requirements rather than by the back-contamination risk.

RESEARCH AGENDA

Numerous challenging questions remain: (1) operations concepts that address environments with progressive planetary protection regimes; (2) segmenting requirements based on these concepts to enable equipment and operations to be designed and tested; (3) technologies and innovative design solutions that can meet such requirements; (4) adjunct operations and equipment to complete practical scenarios, e.g. for cleaning and sterilizing rover vehicles, tools, astronaut suits, native material, etc., as the boundary between non-cleared and cleared zones is crossed.

Just as the progressive protocol is a novel organizing framework for the biologically safe investigation of Mars by joint teams of robots and humans, it could be useful for organizing the development and validation of an integrated R&D agenda that enables these Mars surface operations, and for organizing a lunar-based testing program for many of these approaches.

CONCLUSION

Even if precursor robotic missions, including sample return, yield no evidence of biological activity on Mars, doubts will remain for the most sheltered micro-environments. Such places – beneath the weathered rind of rocks, deep inside ancient thermal spring features, in the regolith surrounding episodic fluid flows – are at once the places most compelling to look for evidence of life, most needful of direct human action to be studied, and most likely to pose the risk of a planetary protection breach.

Human exploration systems could be designed to completely preclude any interaction at all between human and putative native ecosystems. This option would be unprecedented for human space system design, departing significantly from heritage experience. It would dramatically increase the cost of human exploration systems beyond baseline planning assumptions. This higher cost would be incurred at the very beginning of the program, yet would be rendered moot *post facto* if Mars is ultimately determined to be biologically inert.

A better option is an operations protocol that uses robots and humans in a carefully sequenced way to incrementally relax the planetary protection constraint as exploration proceeds. This pragmatic approach is based on the following logical argument: (1) we cannot really know Mars' biological status without *in situ* exploration by humans; (2) airlocks inevitably exchange material between the human and native environments; (3) windblown dust is ubiquitous and therefore biologically uniform, and can be determined to be biologically inert; (4) the Mars environment can be divided into "cleared" and "not-cleared" zones, which can be mapped multi-dimensionally; (5) the boundaries between these zones can be managed to preclude operational opportunities for forward or backward contamination in not-cleared zones; (6) robotic penetration, followed by human field investigation, can advance the boundary of the cleared zone, incrementally shrinking the extent of the not-cleared zone until either the entire Mars environment is declared cleared or life is found.

This zonation-based progressive protocol preserves the fundamental principle of "doing nothing irreversible," enables exploration planning to proceed, and results in protection of, and protection from, any extant life that may be found on Mars.

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