Space Bioindustrial Architecture: A Claim-Control Methodology for Low-Resupply Lunar and Martian Settlement Capability

Abstract

Future lunar and Martian surface architectures require defensible methods for determining when specific systems can be counted as maintained settlement capability rather than merely as mission support, technology demonstration, or scientific promise. Existing space-systems engineering, verification and validation, reliability, life-support, bioregenerative, and assurance-case methods are necessary for this task, but they do not by themselves define when an exact low-resupply capability package earns infrastructure credit, when it must be refused, or what gaps must be closed before reconsideration. This article introduces the Space Bioindustrial Architecture (SBA), a claim-control methodology specified around registry records: controlled records of case assumptions, package versions, evidence, authority boundaries, claim states, gaps, and requalification triggers. SBA evaluates declared cases, exact claims, complete capability packages, evidence sufficiency, authorized boundaries, lifecycle burden, interruption recovery, baseline displacement, and formal claim states. The method is demonstrated through PBR-001, a workbook-executed reference case evaluating a PBR@LSR-derived *Chlorella vulgaris* lunar photobioreactor package for a four-crew, 28-day lunar South Pole early-habitation case, with physicochemical ECLSS retaining crew-safety responsibility. Although the candidate is scientifically credible and warrants evaluation, SBA assigns 0 kg accepted oxygen, 0 kg accepted biomass, no avoided import, no established baseline displacement, no lifecycle-qualified contribution, and no countable infrastructure credit. Its formal evaluated claim state is Refused, with a retained experimental evidence-building role. SBA's contribution is therefore not automatic acceptance or technology rejection, but disciplined control of the boundary between plausible technologies and countable settlement infrastructure.

Keywords: lunar settlement; Mars settlement; bioregenerative life support; assurance case; claim control; configuration management; photobioreactor; low-resupply architecture; infrastructure credit; space systems engineering

1. Introduction

Human return to the lunar surface and prospective human operations on Mars are usually framed through missions, vehicles, habitats, logistics chains, payload delivery, in-situ resource utilization, and environmental-control and life-support systems [1-4]. These are indispensable categories. They describe how crews are transported, supported, protected, and supplied. They do not, however, settle a narrower question that becomes increasingly important as surface activity extends in duration and ambition: when may a specific system, subsystem, biological process, or bioindustrial package be counted as durable low-resupply settlement capability?

Crew presence is not the same as settlement capability. A crew can occupy a surface habitat while relying on Earth resupply, conservative physicochemical ECLSS redundancy, pre-positioned consumables, abort options, and mission-specific support assumptions. That posture may be necessary during early exploration. It should not be confused with a maintained capability to regenerate air, recycle water, produce food, convert waste, synthesize materials, provide medical bioproduction, buffer ecological function, or filter habitat environments under reduced resupply conditions. Settlement capability requires a controlled claim that a particular package, under declared operating assumptions, produces an accepted contribution that can be authorized, sustained, recovered, and counted.

This article addresses that countability problem. Photobioreactors, algal systems, biological waste conversion pathways, biomanufacturing systems, food-production modules, microbial monitoring systems, filtration architectures, and other closed-loop concepts may all be relevant to long-duration surface habitation [5-10]. Relevance, however, does not establish infrastructure credit. A candidate may be relevant to air regeneration without displacing accepted oxygen import. It may produce biomass without that biomass being accepted as food, feedstock, medical input, or material contribution. It may operate experimentally without being authorized to carry crew-safety responsibility. It may restart after interruption without restoring the exact claim that was previously evaluated.

The Space Bioindustrial Architecture (SBA) is proposed as a methodology and reference architecture for registry-specified claim control of low-resupply lunar and Martian settlement-capability packages [11]. SBA does not replace NASA systems engineering, verification and validation, reliability and maintainability analysis, ECLSS design, digital engineering, assurance cases, planetary protection, biosafety review, or mission authority. It depends on the artifacts and disciplines produced by those methods. Its function is different: to govern what can be counted. Prior art helps populate the architecture; the architecture governs whether an exact claim, attached to a complete package and bounded case, is accepted, conditioned, deferred, refused, quarantined, retired, or retained only for a non-credit-bearing role.

In this article, a registry is not a deployed software product or agency system of record. It is the controlled record structure required to keep a settlement-capability claim tied to a declared case, exact package version, evidence base, authority boundary, formal claim state, gap entries, retained roles, and requalification triggers. SBA v1.0 is therefore registry-specified rather than registry-implemented: it defines the objects and decision logic an operational registry would need, while the present reference case is executed through workbooks and the OSF reference architecture. [11]

The article makes one central claim: SBA defines a registry-specified method for determining when exact low-resupply lunar or Martian settlement-capability packages may be counted as infrastructure, when they must be refused or conditioned, and what capability and assurance gaps must be closed before reconsideration. The method is illustrated through PBR-001, a workbook-executed reference case evaluating a PBR@LSR-derived *Chlorella vulgaris* photobioreactor package for a four-crew, 28-day lunar South Pole early-habitation case. PBR-001 is useful precisely because it is not an easy positive case. The candidate is scientifically plausible and strategically relevant, but the evaluated package does not establish accepted oxygen, accepted biomass, avoided import, baseline displacement, lifecycle-qualified contribution, or countable infrastructure credit. SBA therefore refuses the infrastructure claim while retaining the candidate for contained experimental and evidence-building roles.

Refusal is not technology dismissal. It is a controlled claim state that preserves the distinction between scientific credibility and settlement infrastructure. In a domain where premature credit can distort mission planning, safety margins, logistics assumptions, and development priorities, disciplined refusal can be as valuable as acceptance. SBA v1.0 therefore defines both a boundary of countable settlement capability and a ledger of gaps that future development can address.

2. Decision Gap and Bounded Novelty

SBA is deliberately conservative in its novelty claims. It does not claim to invent systems engineering, assurance cases, configuration control, verification and validation, reliability analysis, bioregenerative life support, photobioreactors, environmental control, biosafety, planetary protection, or evidence management. Those areas have substantial technical and institutional histories in life-support baseline analysis and equivalent-system-mass reasoning [5-6], bioregenerative and photobioreactor research [7-10,12-13], NASA systems engineering, configuration, reliability, and digital-engineering practice [14-18], assurance-case practice [19-22], and planetary-protection and biosafety governance [23-26]. SBA's novelty lies in combining these families of practice into a specific decision architecture for settlement-capability countability.

This bounded novelty posture is important for reviewer interpretation. The paper does not argue that existing mission-engineering or assurance processes are deficient in their own terms. It argues that the transition from mission support to countable settlement capability requires an additional decision layer. That layer is not a new technology-readiness scale, not a substitute for certification, and not a generalized governance framework. It is a method for controlling the claim that a particular package changes the settlement architecture under specified assumptions.

The decision gap arises because existing methods often answer adjacent questions. Systems engineering can define requirements, interfaces, verification plans, hazards, design baselines, and configuration-controlled artifacts. V&V can test whether a system satisfies specified requirements and whether the right system has been built for the intended use. Reliability, maintainability, and safety methods can characterize failures, redundancy, maintenance burden, and acceptable risk. ECLSS and life-support analyses can quantify consumables, oxygen, carbon dioxide, water, food, waste streams, equivalent system mass, and candidate closure pathways. Assurance cases can structure arguments that a system is acceptably safe, secure, reliable, or fit for purpose. Digital engineering and configuration-management practices can preserve model, artifact, and design-state traceability.

These methods are necessary, and SBA is designed to ingest their outputs. But none of them, by itself, settles the narrower claim-control question: when does an exact package become countable settlement infrastructure under a declared low-resupply case?

The gap is clearest when a technology moves from plausibility to planning credit. For example, engineering evidence may show that a subsystem functions, yet mission planners still need to know whether the package may reduce a manifest, displace redundancy, alter crew-safety responsibility, or be treated as maintained infrastructure. SBA makes that planning-credit step explicit rather than allowing it to occur implicitly through optimistic interpretation of prior art.

SBA addresses this gap by making the evaluated claim itself the unit of control. The architecture does not begin with a technology class and ask whether it is significant. It begins with a declared case, an exact claim, and a complete package. It then asks what output is theoretically produced, what gross output is measured, what output is validated, what output is accepted by an authorized boundary, whether accepted output avoids an import, whether avoided import displaces a defined baseline, and whether the resulting contribution remains positive after lifecycle burden, interruption, recovery, and continuity conditions are considered. This sequence prevents premature conversion of plausible output into infrastructure credit.

The architecture also distinguishes admission from credit. A candidate may be admitted for evaluation because it is scientifically credible, strategically relevant, or potentially important to one or more settlement requirement domains. Admission means the candidate is worth structured evaluation; it does not mean the package is countable. Similarly, stage relevance does not establish stage placement, stage placement does not establish advancement, and advancement does not establish infrastructure credit. These distinctions are especially important for biological and bioindustrial systems, where laboratory plausibility, analog performance, controlled demonstration, habitat integration, mission authorization, and settlement contribution may diverge.

The distinction between candidate credibility and claim sufficiency is central. External photobioreactor and Chlorella vulgaris literature may support photosynthetic oxygen generation, biomass production, and bioregenerative life-support relevance [8-10,12-13]. It cannot, by itself, establish that a specific lunar photobioreactor package in a specific early-habitation case can displace oxygen imports, accept biomass, close lifecycle burdens, demonstrate interruption recovery, or earn infrastructure credit. Those are exact-package claims requiring declared assumptions, complete package boundaries, comparator baselines, accepted-output rules, and authorized claim-state assignment.

The nature of SBA's contribution is clearest where the answer is negative but not dismissive. A conventional technology assessment might conclude that a candidate is promising but immature. A systems-engineering review may identify additional requirements, tests, or interface definitions. By contrast, SBA converts such partial findings into a claim-control result: the package may be refused for countable infrastructure credit while still retaining an evidence-building, burden-characterization, interface-development, validation-method, or a future-reconsideration role. This turns blanket refusal into a constructive planning artifact.

3. SBA Methodology

SBA evaluates settlement capability through a sequence of controlled constructs: declared case, exact claim, complete capability package, requirement-domain relevance, output-to-contribution chain, assurance checkpoints, registry record, gap register, and formal evaluated claim state. The architecture is operationalized in the full OSF reference system through a canonical 24-instrument design basis and workbook-executed cases, but the manuscript-level method can be summarized as a workflow: define the case, constitute the claim, bound the package, map domain relevance without yet granting credit, trace outputs through contribution, apply assurance checkpoints, assign a claim state, and record the gaps and requalification triggers [11,27-28]. Figure 1 summarizes the claim-control architecture that organizes this workflow.

The workflow should be read as a claim-adjudication procedure rather than a description of a biological or engineering design cycle. It asks first what is being claimed, then what package and case make the claim meaningful, then what evidence and authority would be required to count the contribution. This ordering is deliberate. It prevents a candidate's scientific or engineering appeal from determining the claim before the package boundary, comparator, lifecycle burden, and requalification conditions have been stated.

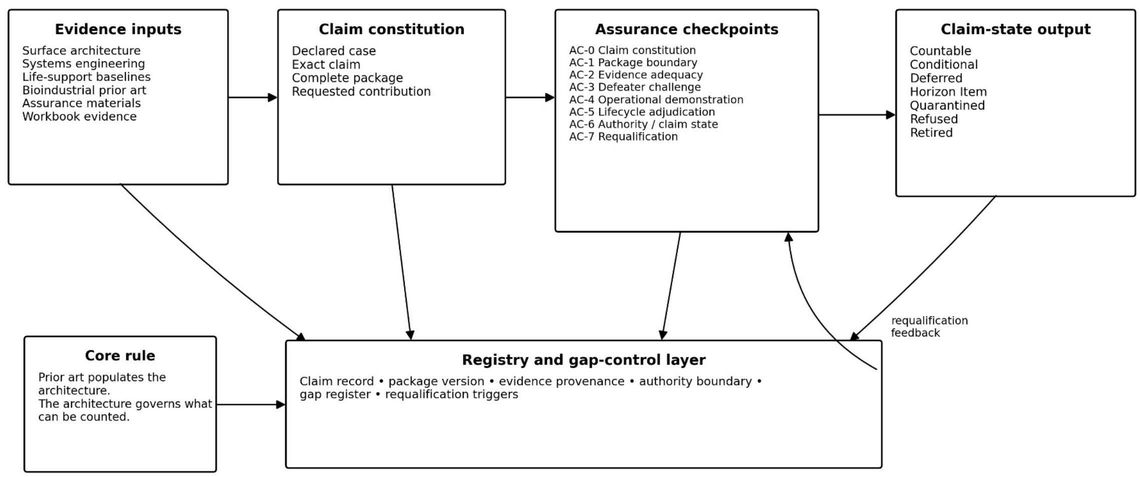

Figure 1. SBA claim-control architecture for low-resupply settlement capability. Mission assumptions, prior art, engineering evidence, assurance materials, and workbook evidence are converted into an exact package-specific claim record. The claim passes through AC-0 through AC-7 before a formal evaluated claim state is assigned. Registry control preserves package version, evidence provenance, authority boundary, gap-register entries, and requalification triggers.

The declared case specifies the context in which the claim is evaluated, including factors such as crew scale, duration, location, operating environment, baseline architecture, assumed responsibilities, boundary conditions, and comparator posture. Without a fully declared case of this kind, the same technology can appear stronger or weaker depending on unstated assumptions. A photobioreactor may be evaluated differently for a laboratory experiment, a free-flying platform, an analog habitat, an early lunar sortie, a 28-day lunar South Pole habitation case, or a long-duration Mars surface settlement. SBA therefore treats the case declaration as an essential part of the claim, not as incidental background.

The exact claim specifies the package, conditions, accepted outputs, displaced imports or baseline functions, authority boundary, lifecycle envelope, and claim state sought. SBA refuses evaluation of broad statements such as 'algal systems support life support' or 'bioregenerative systems reduce resupply' and is constrained to evaluating package-specific claims.

The complete capability package includes the hardware, biological material, feedstocks, inputs, energy, water, crew time, maintenance tools, controls, sensors, containment provisions, spares, interfaces, data products, operating procedures, validation methods, recovery procedures, disposal pathways, governance assumptions, and authority conditions required for the claim. This package boundary is essential because low-resupply settlement contribution depends not only on output but also on burden. A system that produces useful material while consuming large quantities of power, water, crew time, consumables, or logistics support may fail to establish a net contribution.

Requirement-domain relevance is mapped, but not credited automatically. SBA recognizes eight settlement requirement domains: air regeneration, water recycling, food production, waste conversion, materials synthesis, medical bioproduction, ecological buffering, and environmental filtration. These domains organize the architecture's view of settlement capability, but they are not themselves capability packages. Domain relevance alone is therefore insufficient for infrastructure credit.

This rule prevents a common category error in settlement planning. A candidate can be relevant to several domains at once and yet not be countable in any of them. A photobioreactor, for example, may be relevant to air regeneration, food production, waste conversion, ecological buffering, and environmental filtration. Nevertheless, SBA does not treat such multi-domain relevance as cumulative credit. Each asserted contribution must be separately bounded, accepted, authorized, and compared against the baseline before it can be counted.

The output-to-contribution chain distinguishes theoretical output, gross output, validated output, accepted output, avoided import, baseline displacement, and lifecycle-qualified contribution. The chain is deliberately strict. Gross oxygen is not automatically accepted oxygen. Accepted oxygen is not automatically avoided oxygen import. Avoided oxygen import is not automatically baseline displacement. Baseline displacement is not automatically lifecycle-qualified contribution. At each step, the claim can be reduced, conditioned, deferred, refused, or assigned to a retained non-credit-bearing role.

SBA then applies AC-0 through AC-7: Claim Constitution; Package and Boundary Completeness; Argument and Evidence Adequacy; Defeater Analysis and Independent Challenge; Exact-Package Operational Demonstration; Comparator and Lifecycle Adjudication; Authority and Claim-State Assignment; and Operational Continuity and Dynamic Requalification. Each of these checkpoints is a claim-control gate.

This distinction also keeps SBA from duplicating assurance-case practice. Assurance cases organize claims, arguments, evidence, and defeaters for safety, reliability, security, or fitness-for-purpose claims. SBA can ingest those arguments, but it asks a different final question: whether the evidence supports infrastructure countability in a declared low-resupply settlement case. A strong assurance case for experimental operation may still coexist with a refused infrastructure claim if accepted output, baseline displacement, or lifecycle-qualified contribution is absent. [19-22]

Registry control preserves the claim, package, evidence, authority, boundary conditions, assumptions, versions, decisions, gaps, and claim states as controlled objects. This matters because settlement capability is configuration-sensitive. A claim accepted for one package version, operating envelope, crew scale, baseline architecture, biological strain, lighting regime, containment boundary, validation method, or safety responsibility may not survive a material change. The gap register records the missing evidence, package incompleteness, unclosed burden, unresolved defeater, absent authority, failed recovery condition, or safety limitation that prevents or constrains countability. [11,29-32]

SBA uses seven formal evaluated claim states: Countable, Conditional, Deferred, Horizon Item, Quarantined, Refused, and Retired. Retained experimental, evidence-building, or hybrid roles are permitted roles, not additional formal states. This separation allows SBA to be strict about countability without being dismissive about development value. Table 1 summarizes the core constructs, and Table 2 summarizes the assurance checkpoints. [11]

In practical use, the method is iterative but not circular. A package may fail AC-1 because the boundary is incomplete, return to package definition, and then proceed again. It may pass AC-2 for scientific plausibility but fail AC-5 for lifecycle contribution. It may be refused for the declared early-habitation case while remaining a horizon item for a later settlement architecture with different baselines and authorities. The architecture therefore supports disciplined revision without allowing revision itself to count as claim closure.

Table 1. Core SBA constructs for settlement-capability claim control.

Construct	Function in SBA	Boundary rule
Declared case	Defines the mission or settlement context in which the claim is evaluated, including crew scale, duration, location, operating assumptions, baseline architecture, and comparator posture.	A claim cannot be evaluated apart from the case in which it is asserted.
Exact claim	Specifies the package, function, output, accepted contribution, boundary, and state sought.	Broad technological relevance is not an exact claim.
Complete capability package	Includes hardware, biological material, inputs, energy, consumables, controls, sensors, crew operations, maintenance, validation, containment, interfaces, recovery provisions, disposal paths, and authority conditions required by the claim.	A module or process is not automatically a complete package.
Requirement-domain relevance	Maps the package to one or more settlement domains: air regeneration, water recycling, food production, waste conversion, materials synthesis, medical bioproduction, ecological buffering, and environmental filtration.	Domain relevance does not confer infrastructure credit.
Output-to-contribution chain	Traces theoretical output through gross output, validated output, accepted output, avoided import, baseline displacement, and lifecycle-qualified contribution.	Intermediate conversions must be justified; output is not contribution.
Authorized capability boundary	The boundary within which an accepted contribution may be counted for settlement capability.	Capability cannot be counted outside the authorized boundary.
Gap register	Controlled record of missing evidence, incomplete package elements, unresolved defeaters, absent authority, unclosed burdens, or failed recovery	Gap closure permits reconsideration but does not automatically restore the claim.

	conditions.	
Formal evaluated claim state	One of seven claim states: Countable, Conditional, Deferred, Horizon Item, Quarantined, Refused, or Retired.	Retained experimental or evidence-building roles are roles, not additional formal states.

Table 2. SBA assurance checkpoints AC-0 through AC-7.

Checkpoint	**Name**	**Claim-control question**	**Not equivalent to**
AC-0	Claim Constitution	Has the evaluated claim been stated exactly enough to be assessed, including case, package, requested contribution, boundary, and desired claim state?	A mission objective, technology description, or research hypothesis
AC-1	Package and Boundary Completeness	Is the complete capability package defined, including interfaces, inputs, burdens, controls, containment, operations, maintenance, validation, and authority dependencies?	A module description or subsystem bill of materials
AC-2	Argument and Evidence Adequacy	Does the evidence support the exact claim rather than only generic plausibility or domain relevance?	Literature support alone, technology maturity alone, or workbook completion alone
AC-3	Defeater Analysis and Independent Challenge	Have foreseeable defeaters, counterclaims, safety concerns, burden reversals, interface failures, and dependency failures been identified and challenged?	Internal advocacy review or informal risk discussion
AC-4	Exact-Package Operational Demonstration	Has the same package, or a justified equivalent configuration, demonstrated the claimed function under conditions adequate for the declared case?	Component test, analog relevance, or non-equivalent prototype performance
AC-5	Comparator and	Has accepted output been	Gross output estimate or

	Lifecycle Adjudication	compared against baseline import or baseline function after lifecycle burden, maintenance, interruption, recovery, and continuity effects are considered?	equivalent-system-mass calculation alone
AC-6	Authority and Claim-State Assignment	Is there an authorized basis for assigning Countable, Conditional, Deferred, Horizon Item, Quarantined, Refused, or Retired status?	Technical recommendation without authority boundary
AC-7	Operational Continuity and Dynamic Requalification	Are configuration changes, interruptions, recovery events, degradation, evidence updates, and boundary changes controlled so that the claim remains valid or is requalified?	Initial acceptance, safe shutdown, or restart alone

4. Assurance Checkpoints and Registry Control

SBA depends on assurance checkpoints because settlement-capability claims are decisions about what may be counted, under what boundary, with what evidence, and subject to what continuing conditions. A low-resupply capability package can affect mission logistics, safety margins, contingency planning, resupply assumptions, surface infrastructure design, crew operations, and development priorities. The architecture therefore requires more than a technical description. It requires a controlled route from claim constitution to formal claim-state assignment.

AC-0 through AC-2 establish the claim and its evidentiary basis. AC-0 requires the declared case, package, requested contribution, authority boundary, comparator baseline, and desired claim state to be stated exactly enough to evaluate. AC-1 requires package and boundary completeness, including inputs, interfaces, burdens, controls, containment, operations, maintenance, validation, and authority dependencies. AC-2 asks whether the evidence supports the exact claim rather than only generic plausibility. Evidence that *Chlorella vulgaris* can photosynthesize or that photobioreactors are relevant to bioregenerative life support may justify evaluation without establishing accepted lunar oxygen, avoided import, or lifecycle-qualified contribution for a specific package.

AC-3 through AC-5 test the claim against failure modes, demonstrations, and comparator burdens. AC-3 records foreseeable defeaters: incomplete package boundaries, energy or water burdens, contamination risks, fragile biological operating envelopes, uncertain restart behavior, crew-time burden, unvalidated output quality, inadequate measurement, lack of authority, non-equivalent demonstrations, baseline mismatch, safety incompatibility, or configuration drift. AC-4 asks whether the exact package, or a justified equivalent configuration, has demonstrated the claimed function under conditions adequate for the declared case. AC-5 asks whether accepted output has become avoided import, baseline displacement, and lifecycle-qualified contribution after burden and recovery are adjudicated.

AC-6 and AC-7 connect technical analysis to authority and continuity. AC-6 separates validation from authorization by requiring an authorized basis for assigning Countable, Conditional, Deferred, Horizon Item, Quarantined, Refused, or Retired status. AC-7 prevents countability from persisting by inertia after configuration change, degradation, contamination, biological drift, replacement of parts, altered mission duration, changed baseline architecture, interruption, or recovery. Safe shutdown is valuable, but it is not autonomy. Restart is valuable, but it is not restored countability unless the claim is still valid or has been requalified.

This makes SBA particularly relevant to biological and bioindustrial systems. Biological packages are not static artifacts. Strain performance, contamination state, culture health, growth media, sensor calibration, gas exchange, lighting, and crew procedures can each effectively change the package that is being operated. Registry control is therefore not merely documentary. It protects the link between the evaluated package and the package being counted.

Registry control is the information architecture that preserves these decisions. In SBA v1.0, the method is registry-specified: it defines the objects, relationships, state logic, evidence roles, authority dependencies, gap records, and requalification triggers that an operational registry would need to maintain. The v1.0 reference cases and workbooks demonstrate this logic, but they are not a deployed institutional registry or agency system of record. [11,29-32]

A registry-controlled claim record includes the declared case, exact claim, package version, boundary assumptions, evidence artifacts, argument structure, defeaters, adjudication notes, output quantities, accepted-output decisions, comparator baseline, lifecycle burdens, authority basis, formal claim state, retained roles, and gap-register entries. It must also preserve provenance and configuration. Without this control, a developer may cite evidence from one package version while counting another, a mission planner may treat experimental output as accepted contribution, or a preliminary result may survive after its assumptions have changed.

The registry-specified posture also clarifies SBA's implementation limit. Version 1.0 defines the record structure and decision logic that an operational registry would need, but it does not claim to instantiate the institutional authority that would make a flight or settlement decision. This distinction is methodologically conservative. It allows the paper to define a rigorous architecture without implying that an OSF workbook or academic reference system can certify hardware or authorize mission responsibility.

Importantly, the gap register can convert negative or limited decisions into structured development information. A refused, deferred, conditional, quarantined, or retired claim should not disappear into an undifferentiated category of immaturity. The missing element might be package completeness, exact-package demonstration, accepted-output criteria, lifecycle-burden closure, interruption recovery, biosafety control, planetary-protection compatibility, authority, or requalification basis. Once recorded, a gap can be assigned to evidence generation, design revision, interface development, validation-method development, or authority clarification.

The registry and gap register also reduce a recurrent institutional risk: different communities can use the same word, such as 'capability,' 'validated,' 'operational,' or 'autonomous,' while meaning different things. SBA does not resolve that ambiguity by imposing a universal vocabulary on all space engineering. It resolves it within the claim record. Each term is anchored to a declared case, package version, evidence state, authority boundary, and formal claim state.

5. Lifecycle-Qualified Contribution

The central quantitative and conceptual discipline of SBA is lifecycle-qualified contribution. A low-resupply settlement architecture cannot count a package merely because it produces a desired output. It must ask whether the output is accepted, whether it displaces an import or baseline function, and whether the resulting benefit survives the package's full lifecycle burden. This requirement is especially important for biological and bioindustrial systems because their apparent outputs may be offset by mass, energy, water, crew time, monitoring, containment, contamination control, replacement, recovery, and validation burdens.

The logic is compatible with, but not reducible to, equivalent-system-mass reasoning. ESM and related life-support metrics are essential for comparing mass, volume, power, cooling, crew time, and logistics burdens, but SBA asks an additional claim-control question: whether the resulting contribution is accepted and authorized as infrastructure in the declared case. A favorable mass-equivalent result would not by itself establish countability, and even an unfavorable burden result may still leave a package with a valuable evidence-building role. [5-6,33-34]

SBA therefore distinguishes output from ultimate contribution. Output is what a system produces. Contribution is what the settlement architecture can count after authorization, comparator displacement, and lifecycle adjudication. A reactor may produce oxygen, but if that oxygen is not accepted for crew-support use, it is not accepted oxygen.

The output-to-contribution chain begins with theoretical output. Theoretical output may be derived from stoichiometry, models, laboratory rates, published studies, or declared assumptions. It bounds what might be possible, but it is not a claim result. Gross output is measured or estimated production before claim-specific acceptance. Validated output satisfies measurement and quality criteria. Accepted output is validated output accepted by the authorized boundary for the claimed settlement function. Only accepted output can enter avoided-import analysis. Figure 2 summarizes the conversion sequence and the associated gap-register exits.

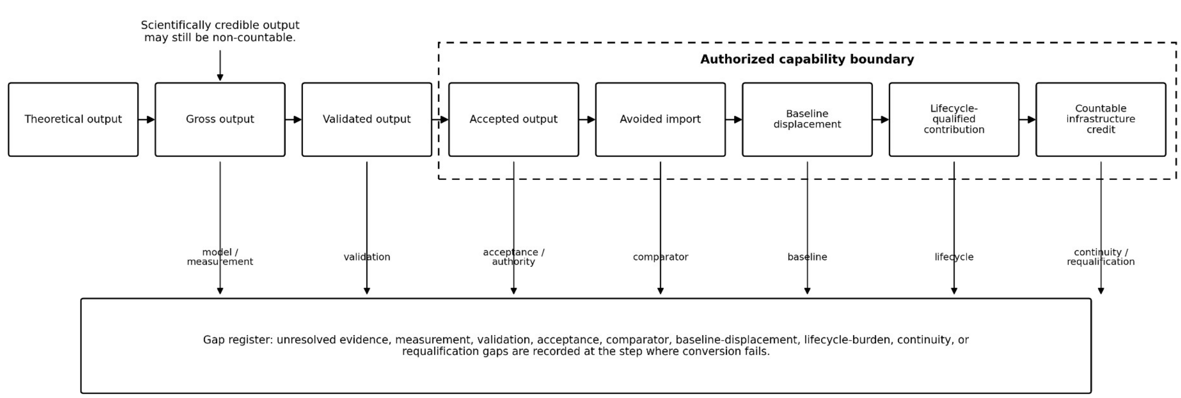

Figure 2. Output-to-contribution chain and authorized capability boundary. Theoretical or gross output must become validated output, accepted output, avoided import, baseline displacement, and lifecycle-qualified contribution before it can be counted. At each step, unresolved evidence, authority, comparator, lifecycle, or continuity gaps are recorded in the gap register. Scientific credibility may justify evaluation, but only accepted contribution within an authorized boundary can receive infrastructure credit.

Avoided import is narrower than accepted output. The architecture must show that accepted output reduces an import, consumable, spare, function, or baseline capacity that the declared case would otherwise require. For oxygen, accepted oxygen must be credited against a defined oxygen provision. For biomass, the biomass must be accepted for a defined use, such as food, feedstock, medical production, material input, or another authorized function. If the baseline system retains all responsibility and consumables because the candidate package is experimental, the candidate may produce output but avoid no import.

Baseline displacement is the next threshold. A conservative mission may carry the full baseline provision despite expected experimental production. A biological system may be permitted to operate only as a research payload, with no effect on mission consumables, crew-safety responsibility, or logistics planning. In such a case, the package may generate learning value but no infrastructure credit. SBA requires a defined baseline displacement before contribution can be counted.

Lifecycle-qualified contribution then subtracts or adjudicates the package's burdens and continuity requirements. These include launch mass, working mass, water inventory, nutrients, gases, energy, thermal-control requirements, spares, crew time, monitoring, cleaning, sterilization, microbial-control burden, containment, waste handling, data systems, maintenance, failure response, safe shutdown, restart, and end-of-life disposal. They also include authority burden, validation burden, training burden, interface burden, operational complexity, risk-coupling to crew safety, and dependency on other infrastructure.

Interruption and recovery are part of the same logic. Settlement capability must be maintained or recoverable under credible disruption. Biological systems can be especially sensitive to interruptions in lighting, temperature control, mixing, gas exchange, nutrient supply, contamination control, water quality, and monitoring. Safe shutdown is not autonomy, and restart is not restored countability. The claim record must specify what happens after interruption, what evidence supports recovery, and whether the package must be requalified before its contribution can again be counted.

This logic applies across the eight settlement requirement domains. In air regeneration, produced oxygen must become accepted oxygen and displace a baseline oxygen provision. In water recycling, recovered water must meet quality, safety, availability, and authorization criteria. In food production, biomass must become accepted food or feedstock rather than merely edible or potentially nutritious matter. In waste conversion, materials synthesis, medical bioproduction, ecological buffering, and environmental filtration, the same principle applies: domain relevance begins evaluation but does not confer infrastructure credit.

The strictness of the chain is especially important when a candidate is described as 'closing a loop.' Closure is not established merely because a material is recycled or a consumable is produced. The package boundary must include the inputs that make the loop function, the burdens that keep it operating, the validation that makes the output acceptable, and the authority that allows the output to displace a baseline. SBA therefore allows partial closure, experimental closure, conditional closure, and countable closure to remain distinct.

Lifecycle-qualified contribution is not intended to make biological systems fail by default. Rather, it gives them a precise path to credit. A biological package that genuinely displaces imports, reduces resupply burden, provides robust recovery, integrates safely with habitat systems, and maintains contribution over time should receive credit in proportion to the accepted claim. SBA's strictness protects credible future claims from being diluted by premature or overbroad assertions.

This is why SBA treats contribution as a relation among package, baseline, authority, and time. A contribution is not merely a material quantity. It is a material or functional displacement that remains valid under the declared operating assumptions and requalification rules. This matters for early surface systems because a package may be allowed to operate, allowed to generate data, and allowed to produce useful byproducts without being allowed to reduce what the mission must carry or what the baseline system must guarantee.

6. PBR-001 Reference Case

PBR-001 demonstrates the SBA accreditation process by applying the architecture to a scientifically credible but non-countable biological candidate. The case evaluates a PBR@LSR-derived Chlorella vulgaris lunar photobioreactor reference package for a four-crew, 28-day lunar South Pole early-habitation case, with physicochemical ECLSS retaining crew-safety responsibility [10,12-13,35-36]. The case is not a NASA-selected lunar system, flight article, certified design, replacement for baseline ECLSS, operational registry execution, or mission-authority decision. It is a workbook-executed reference case used to test SBA's claim-control method.

The candidate is credible by nature. Photobioreactors and algal systems have long been investigated for bioregenerative life-support relevance, including photosynthetic oxygen production, carbon dioxide processing, biomass generation, and potential integration into closed or partially closed habitat resource loops [8-10,12-13]. Chlorella vulgaris is a familiar candidate organism because of its photosynthetic productivity, cultivation history, and relevance to oxygen and biomass studies. These sources support candidate credibility and justify evaluation.

Under the SBA accreditation process, however, candidate credibility is not the basis for infrastructure credit. External photobioreactor literature supports scientific plausibility, technology lineage, photosynthetic mechanism, and bioregenerative relevance. It does not establish that the specific PBR-001 package, in the declared lunar early-habitation case, produces accepted oxygen, accepted biomass, avoided import, baseline displacement, lifecycle-qualified contribution, or authorized settlement infrastructure credit. Those findings belong to the SBA evaluation and the PBR-001 workbook.

The declared PBR-001 case uses a four-crew, 28-day mission denominator. The mission oxygen denominator is 99.68 kg O_2, and the mission metabolic carbon dioxide quantity is 120.96 kg CO_2. PBR-001 evaluates a declared 10% carbon dioxide processing case, corresponding to 12.096 kg CO_2. Under the case assumptions, this yields a theoretical oxygen upper bound of 8.797 kg O_2. The working-liquid lower-bound range is 20-80 kg, the electrical-demand range is 168-1,344 kWh, and gross biomass sensitivity is 2.24-4.48 kg [35].

The denominator structure matters because it disciplines the scale of the claim. Consistently with SBA criteria, PBR-001 does not ask whether Chlorella-based systems could eventually contribute to life support in some future settlement. It asks instead whether the declared package, against a four-crew, 28-day early-habitation denominator, earns credit in this case. The 10% carbon dioxide processing scenario is therefore an evaluation boundary, not a general prediction of photobioreactor settlement value. [35]

These quantities prevent two common errors. The first is to treat theoretical oxygen as accepted oxygen. The second is to treat biological output as infrastructure credit without adjudicating burden, boundary, baseline, and authority. The 8.797 kg O_2 figure is a theoretical upper bound under the declared 10% CO_2-processing case. It is not accepted oxygen. The biomass range is a gross sensitivity result. It is not accepted food, accepted feedstock, accepted medical input, or accepted material contribution. The working-liquid and electrical-demand ranges are package burdens that must be weighed before any lifecycle-qualified contribution can be assigned.

The PBR-001 evaluation therefore stops before contribution. The candidate has theoretical oxygen potential and gross biomass relevance, but the evaluated package does not establish accepted oxygen within the authorized capability boundary. Because accepted oxygen is 0 kg, avoided oxygen import is 0 kg. Because avoided import is 0 kg, baseline displacement is not established. Because baseline displacement is not established, lifecycle-qualified contribution is not established. The same logic applies to biomass: gross biomass sensitivity does not become accepted biomass, and accepted biomass is 0 kg. The package therefore earns no countable infrastructure credit. [35]

This stopping point is the core methodological result of the reference case. SBA does not need to show that the package is useless in order to refuse the claim. It only needs to show that the chain from theoretical output to countable contribution has not been completed. In PBR-001, that failure occurs before accepted output and therefore before avoided import, baseline displacement, and lifecycle-qualified contribution can be assigned. [35]

This result is not a judgment that photobioreactors are unimportant, that *Chlorella vulgaris* is scientifically weak, or that biological life-support systems have no future settlement role. It is exclusively a judgment about the exact claim in the declared case. Scientific credibility justified the original evaluation. Evidence sufficiency controlled the final claim. The PBR-001 package is refused because the evaluated package does not establish accepted contribution, avoided import, baseline displacement, lifecycle-qualified contribution, or authority to count as settlement infrastructure.

The safety and responsibility boundary is decisive. PBR-001 is evaluated with physicochemical ECLSS retaining crew-safety responsibility. The photobioreactor is not credited as a replacement for baseline life-support responsibility. Even if the package produces oxygen experimentally, it does not thereby assume authorized crew-safety function. A biological system that can be shut down safely, restarted experimentally, or operated as a contained research package has not necessarily demonstrated operational autonomy or infrastructure-grade contribution.

The operational-readiness result is Experimental Operations Only. PBR-001 may be retained as a contained experimental or hybrid evidence-building package for interface development, burden characterization, interruption testing, validation development, and future capability building. This retained role can support development of lighting regimes, growth protocols, gas-exchange interfaces, microbial-control methods, crew-operation procedures, sensor packages, containment strategies, failure detection, restart procedures, and integration models. But retained role is not a formal evaluated claim state and does not confer infrastructure credit. [35-36]

This role/state separation is one of the reasons PBR-001 is a strong demonstration case. It shows how the architecture can preserve full technology-development value while denying planning credit. A less precise framework might either overstate the package as partial life support or dismiss it as immature. SBA instead locates the package in a controlled experimental role and records the specific gaps that must be closed before reconsideration.

The formal evaluated claim state is Refused. In SBA, Refused means that the evaluated claim does not earn the requested infrastructure credit under the declared case. It does not mean the candidate is scientifically dismissed or permanently excluded. For PBR-001, the gap register includes accepted-output validation, authorized oxygen or biomass acceptance, baseline displacement, lifecycle-burden closure, exact-package operational demonstration, interruption and recovery qualification, and authority to assign any future countable or conditional claim state. [35-36]

PBR-001 therefore illustrates the distinctive value of SBA as a claim-control methodology. Without SBA, a reviewer might see a credible photobioreactor lineage, a stoichiometric oxygen figure, and a biomass estimate and conclude that the system contributes some fraction of settlement life support. SBA prevents that premature conversion. The result is stricter but more useful: the package receives no present infrastructure credit, yet it remains developmentally valuable in a controlled retained role. Table 3 summarizes the reference-case findings.

Table 3. PBR-001 reference-case summary. [35-36]

Evaluation item	**PBR-001 result**
Case	Four-crew, 28-day lunar South Pole early-habitation case
Candidate package	PBR@LSR-derived Chlorella vulgaris lunar photobioreactor reference package
Crew-safety responsibility	Physicochemical ECLSS retained
Mission oxygen denominator	99.68 kg O_2
Mission metabolic carbon dioxide	120.96 kg CO_2
Declared CO_2-processing case	10% of mission metabolic CO_2
Declared CO_2 processed	12.096 kg CO_2
Theoretical oxygen upper bound	8.797 kg O_2
Working-liquid lower-bound range	20-80 kg
Electrical-demand range	168-1,344 kWh
Gross biomass sensitivity	2.24-4.48 kg
Accepted oxygen	0 kg
Accepted biomass	0 kg
Avoided import	0 kg
Baseline displacement	None established
Lifecycle-qualified contribution	Not established
Countable infrastructure credit	None
Operational-readiness state	Experimental Operations Only
Formal evaluated claim state	Refused
Retained role	Contained experimental or hybrid evidence-building package for interface development, burden characterization, interruption testing, validation development, and future capability building

7. Discussion

SBA addresses a problem that becomes increasingly important as lunar and Martian surface architectures move from short-duration exploration toward sustained low-resupply capability. The problem is whether exact packages, in declared cases, can be counted as maintained infrastructure. Settlement architectures demand a disciplined distinction between promise and credit, output and contribution, experiment and baseline displacement, and technical validation and authorized responsibility.

The architecture's first contribution is exactness. Space-system discussions often move between technology classes, mission concepts, subsystems, demonstrations, and future settlement aspirations. SBA requires the claim to specify the declared case, package, output, accepted contribution, comparator baseline, authority boundary, lifecycle burden, and formal claim state. This reduces ambiguity and makes countability a property of a versioned package in a bounded case rather than a property of an underspecified technology class.

The second contribution is package completeness. Low-resupply settlement capability is often constrained less by isolated process feasibility than by integration burden. For biological and bioindustrial systems, the organism or reactor is rarely the whole capability. Lighting, gas exchange, nutrient supply, microbial control, contamination management, sensors, procedures, and failure response may determine whether the package contributes or becomes a burden. SBA forces these dependencies into claim visibility.

The third contribution is constructive refusal. A refused claim is not necessarily a dismissed technology. It is a determination that the evaluated claim does not earn the requested infrastructure credit under the declared case. PBR-001 illustrates the point: the photobioreactor lineage justifies evaluation, but the package does not establish accepted oxygen, accepted biomass, avoided import, baseline displacement, lifecycle-qualified contribution, or infrastructure credit. Refusal protects the integrity of the settlement-capability ledger while preserving a retained role for evidence-building.

The fourth contribution is the gap register. A conventional negative evaluation may leave developers with a general impression that a system is immature. SBA records the specific reason the claim cannot be counted: package incompleteness, lack of exact-package demonstration, missing accepted-output criteria, absent authority, unresolved comparator, baseline-displacement failure, burden closure, interruption recovery, biosafety control, planetary-protection compatibility, or requalification basis. This converts refusal, deferral, quarantine, or conditionality into actionable development information.

The fifth contribution is dynamic requalification. Settlement capability is not static. It can change when the package changes, when the biological strain changes, when operating procedures change, when mission duration changes, when the baseline architecture changes, when evidence is superseded, when contamination occurs, when interruption occurs, or when authority boundaries shift. AC-7 prevents countability from persisting by inertia after the conditions that supported it have changed.

SBA is intentionally complementary to NASA and other institutional methods. It does not replace mission authority, safety certification, engineering review, V&V, assurance cases, ECLSS design, planetary protection, biosafety review, or configuration management.

For implementation, this suggests a staged institutional path. Early adopters could use SBA as a workbook-based review discipline, then as a registry-backed evidence and gap-tracking system, and eventually as an interface between engineering artifacts, assurance cases, life-support analyses, and authority decisions. Each stage would need its own governance controls. The present paper specifies the method and reference architecture, not those institutional deployments. [11,27-28]

The limits of SBA v1.0 are important. The architecture is registry-specified, not an operational institutional registry. It defines the objects, relationships, evidence roles, authority dependencies, claim states, gap logic, and requalification triggers that a registry would need to implement, but it does not deliver deployed software or an agency system of record. PBR-001 is workbook-executed, not an operational registry execution. SBA also does not certify technologies, select flight hardware, assign NASA authority, resolve mission design, or replace engineering judgment. Its output is a controlled claim-state result, not a mission decision.

The PBR-001 result should be read within that boundary.

The broader implication is that low-resupply settlement capability should be managed as a controlled ledger rather than as a narrative of technological promise. The ledger must say what is countable, under what case, in which package version, with what accepted contribution, against which baseline, under whose authority, and subject to which requalification conditions. It must also say what is not countable and why. SBA v1.0 supplies a reference architecture for that ledger.

This ledger framing also explains why a negative case is not secondary to the paper. A methodology for settlement capability must be able to reject attractive claims without losing useful development information. PBR-001 performs that function: it establishes a refusal while preserving a retained experimental pathway. The result is an evaluated boundary, not a final verdict on the technology family.

This reviewer-facing point is worth emphasizing. A methodology article can be judged not only by whether it produces a positive case, but by whether it prevents a false positive. PBR-001 serves as a stress test because the candidate has enough scientific credibility to tempt over-crediting. SBA's refusal result shows that the method can accept relevance, preserve development value, and still deny infrastructure credit when the evidence chain is incomplete. That is perhaps the paper's strongest demonstration of methodological control.

8. Conclusion

Sustained human activity on the Moon and Mars will require more than missions, demonstrations, and promising technologies. It will require disciplined methods for determining when specific systems can be counted as low-resupply settlement infrastructure. The Space Bioindustrial Architecture addresses this need by defining a registry-specified claim-control methodology for exact settlement-capability packages.

SBA begins with a declared case and exact claim, requires a complete capability package, maps but does not over-credit requirement-domain relevance, traces output through accepted contribution, applies AC-0 through AC-7, records evidence and authority in a registry-specified claim structure, assigns one of seven formal evaluated claim states, and preserves unresolved issues in a gap register. This structure distinguishes crew occupation from maintained settlement capability, candidate modules from complete packages, domain relevance from authorized contribution, gross output from accepted output, validation from authorization, safe shutdown from autonomy, and refusal from technology dismissal.

The PBR-001 reference case demonstrates the method. A PBR@LSR-derived *Chlorella vulgaris* lunar photobioreactor package is scientifically credible and relevant to bioregenerative life-support development. Under the declared four-crew, 28-day lunar South Pole early-habitation case, however, it establishes 0 kg accepted oxygen, 0 kg accepted biomass, 0 kg avoided import, no baseline displacement, no lifecycle-qualified contribution, and no countable infrastructure credit. Its formal evaluated claim state is Refused, while its retained role is contained experimental or hybrid evidence-building.

This result illustrates SBA's most distinctive value. The architecture does not collapse promise into credit or refusal into dismissal. It provides a controlled boundary around what can be counted and a structured ledger of the gaps that must be closed before additional packages can be reconsidered. The full architecture, reference instruments, and workbook-executed PBR-001 case are provided in the OSF reference architecture, version 1.0, which functions as the extended academic reference system for this compressed manuscript argument. SBA v1.0 defines the current boundary of countable settlement capability and the systematic ledger of gaps that must be closed to move additional packages across that boundary. [11,27-28,35-36]

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