Critical Uncertainty Set

Lunar Volatile Commitment and Surface Infrastructure Admissibility

Purpose

This document identifies the uncertainties that remain decision-dominant in lunar volatile exploration and early surface infrastructure commitment.

It does not list every unknown in lunar exploration. It identifies the uncertainties that can still change whether a proposed commitment should be allowed to proceed.

A project may tolerate many forms of uncertainty. It may not tolerate uncertainty that still controls site selection, access geometry, support architecture, excavation planning, ISRU dependency, or long-horizon infrastructure lock-in.

The governing question is:

Which unresolved uncertainties still have the power to change the admissibility of the commitment?

1. Core Principle

Uncertainty is not automatically disqualifying.

Lunar exploration will always proceed under incomplete knowledge. The issue is whether remaining uncertainty is still decision-dominant.

An uncertainty is decision-dominant when resolving it differently would materially change.

- whether a site should be favored,
- whether access should repeat,
- whether power or support should be placed,
- whether disturbance should occur,
- whether excavation should begin,
- whether ISRU dependency is justified,
- whether infrastructure should harden,
- or whether refusal remains credible.

The central rule is:

A commitment cannot proceed while an unresolved uncertainty still has authority over the architecture being committed.

2. Critical Uncertainty Table

Critical uncertainty	Why it matters	Commitments affected	Decision risk if unresolved
Volatile form	Determines whether the resource is frost, adsorbed hydrogen, buried ice, hydrated material, or another state	Excavation, processing, ISRU dependency, site selection	The architecture may depend on a resource form that is not operationally usable
Volatile concentration	Determines whether resource abundance is operationally meaningful	ISRU sizing, processing, logistics substitution, mission cadence	Low-grade material may not justify infrastructure commitment
Spatial continuity	Determines whether the resource is continuous, patchy, localized, or discontinuous	Site hardening, corridor formation, excavation geometry	Infrastructure may harden around a local anomaly rather than a scalable resource

Critical uncertainty	Why it matters	Commitments affected	Decision risk if unresolved
Depth / layering	Determines whether the resource is accessible at practical excavation or drilling depth	Excavation, drilling, power, mobility, thermal planning	Access may require disturbance or equipment beyond the assumed architecture
Accessibility / extractability	Determines whether the resource can be reached and used under lunar operating constraints	ISRU dependency, excavation planning, processing architecture	The resource may exist but remain operationally inaccessible
Regolith mechanics	Determines trafficability, bearing strength, excavation behavior, compaction, and stability	Mobility, landing zones, corridors, excavation, site hardening	Repeated operations may degrade the site or invalidate access assumptions
Thermal stability under disturbance	Determines whether volatile-bearing material remains stable after exposure, excavation, heating, or traffic	Excavation, verification, ISRU processing, storage	Verification or extraction may alter or destroy the target condition
Disturbance response	Determines how drilling, trenching, landing effects, traffic, plume interaction, or excavation change the site	Subsurface access, sampling, corridors, landing zones	Learning may alter the evidence baseline and become commitment-bearing
Terrain and slope constraints	Determine where assets can land, move, operate, survive, and be supported	Site selection, mobility, power placement, logistics	Access convenience may substitute for evidence adequacy
Illumination and power continuity	Determine power availability, survival, operational cadence, and site attractiveness	Power placement, support architecture, site preference	Power advantage may prematurely privilege a site before subsurface adequacy is established
Communications / navigation geometry	Determines coordination, data return, localization, and multi-asset operations	Corridor formation, support architecture, surface logistics	The support geometry may start deciding the site
Scale match between evidence and intervention	Determines whether evidence is adequate at the scale of the action	All commitment-bearing actions	Regional or indirect evidence may be used to justify local irreversible commitment
Fallback-site preservation	Determines whether alternatives remain viable after a first site is favored	Site preference, access, power, logistics, ISRU	The mission may lose practical optionality before evidence becomes decision-grade
Operational repeatability	Determines whether a site can support repeated use, not just first access	Corridors, landing logic, surface infrastructure	A one-time success may be misread as durable site admissibility
Evidence baseline preservation	Determines whether future measurements remain interpretable after disturbance	Drilling, excavation, traffic, plume effects	Post-disturbance evidence may be mistaken for pre-disturbance truth
Governance and refusal authority	Determines whether the mission can still stop, defer, re-site, or re-sequence	All commitment thresholds	Formal authority may remain while practical refusal becomes non-credible

3. Primary Critical Uncertainty Classes

3.1. Resource-State Uncertainty

Resource-state uncertainty concerns what the volatile-bearing material actually is.

Relevant unknowns include:

- physical state,
- concentration,
- continuity,
- depth,
- accessibility,
- host material,
- thermal stability,
- extractability,
- and operational usability.

This uncertainty is central because lunar ISRU depends not merely on the existence of a signal, but on the existence of a usable resource at the right scale, location, depth, and mechanical context.

A hydrogen indication may support exploration. It does not by itself establish that extractable water or operationally useful volatile-bearing material exists.

Decision relevance:

Resource-state uncertainty controls whether a volatile signal can support site anchoring, excavation, processing, logistics substitution, or ISRU dependency.

Admissibility implication:

If plausible volatile states imply materially different ISRU architectures, the commitment remains inadmissible.

3.2. Spatial-Continuity Uncertainty

Spatial-continuity uncertainty concerns whether the resource is continuous enough to support infrastructure.

A site may contain:

- a localized volatile concentration,
- a patchy operational resource,
- a diffuse signal,
- discontinuous deposits,
- or a non-scalable local anomaly.

This matters because infrastructure commitment assumes more than detection. It assumes sufficient spatial coherence to justify repeated access, excavation planning, power placement, and resource-dependent operations.

Decision relevance:

Spatial continuity controls whether a site can become more than a prospecting target.

Admissibility implication:

If the resource may be patchy or non-scalable, site hardening and ISRU dependency should defer.

3.3. Access and Terrain Uncertainty

Access and terrain uncertainty concerns whether a promising location can actually be reached, worked, revisited, and supported.

Relevant unknowns include:

- slope,
- roughness,
- trafficability,
- landing approach,
- traverse feasibility,
- illumination/shadow geometry,
- communications line-of-sight,
- hazard concentration,
- and support accessibility.

A site may be scientifically promising but operationally fragile. Conversely, a site may be operationally attractive because of illumination or access, while remaining weak as a resource commitment.

Decision relevance:

Access and terrain uncertainty controls site preference, corridor formation, support placement, and surface infrastructure sequencing.

Admissibility implication:

Access advantage must not substitute for evidence adequacy.

3.4. Mechanical-Behavior Uncertainty

Mechanical-behavior uncertainty concerns how regolith and near-surface material respond to landing, traffic, excavation, drilling, trenching, compaction, and repeated use.

Relevant unknowns include:

- bearing strength,
- compaction behavior,
- excavation resistance,
- blockiness,
- void risk,
- layering,
- slope stability,
- traffic degradation,
- and tool/material interaction.

This uncertainty is critical because the same site that appears attractive from orbit may behave differently under load, traffic, excavation, or thermal alteration.

Decision relevance:

Mechanical behavior controls whether construction, mobility, excavation, and repeated operations are viable.

Admissibility implication:

If mechanical behavior could invalidate the site or excavation approach, commitment must defer to bounded verification.

3.5. Disturbance-Response Uncertainty

Disturbance-response uncertainty concerns how the act of verification changes the system being evaluated.

Relevant disturbances include:

- landing plume effects,
- rover traffic,
- trenching,
- drilling,
- sampling,
- excavation,
- thermal forcing,
- regolith mixing,
- contamination,
- volatile mobilization,
- and surface compaction.

This is one of the most important lunar uncertainty classes because verification is not neutral. The act of learning can change the local system, alter the evidence baseline, and create pressure to continue.

Decision relevance:

Disturbance response controls whether verification remains bounded evidence acquisition or becomes commitment-bearing action.

Admissibility implication:

Disturbance should proceed only when it reduces decision-dominant uncertainty faster than it creates irreversibility.

3.6. Support-Architecture Uncertainty

Support-architecture uncertainty concerns whether the systems needed to enable exploration begin shaping the commitment before the evidence has earned that role.

Relevant systems include:

- power,
- communications,
- navigation,
- thermal survival,

- mobility,
- logistics,
- staging,
- data relay,
- and local operational support.

Support architecture can quietly privilege one site or corridor. Once support is placed, continued operation at that geometry becomes easier than abandonment.

Decision relevance:

Support architecture controls site preference, access repetition, corridor formation, and practical refusal authority.

Admissibility implication:

Support systems should remain provisional until the site and resource interpretation become decision-grade.

3.7. Scale-Match Uncertainty

- Scale-match uncertainty concerns whether the evidence is resolved at the scale of the proposed action.
- A regional signal may justify regional prospecting.
- It may not justify a landing pad.
- A broad hydrogen indication may justify additional sensing.
- It may not justify excavation geometry.
- A local measurement may justify bounded verification.
- It may not justify site-scale ISRU dependency.

Decision relevance:

Scale match controls whether evidence is adequate for the burden of the action.

Admissibility implication:

Evidence must match the spatial, physical, temporal, and operational scale of the commitment being authorized.

3.8. Governance and Refusal Uncertainty

Governance uncertainty concerns whether the mission, program, partners, or institutions can still refuse, defer, re-site, or re-sequence after a dependency forms.

Relevant factors include:

- partner expectations,
- public site language,
- mission diagrams,
- investment narratives,
- industrial positioning,
- shared infrastructure assumptions,
- and programmatic designation.

This uncertainty matters because formal decision authority can remain intact while practical refusal authority weakens.

Decision relevance:

Governance uncertainty controls whether future decisions remain real or become inherited.

Admissibility implication:

A commitment should not proceed if it would make later refusal non-credible before the evidence burden is met.

4. Decision-Dominant Uncertainty Set

The most decision-dominant uncertainties in the lunar case are:

1. Volatile form and accessibility
   Does the signal correspond to material that can actually be accessed and used?
2. Continuity and concentration
   Is the resource sufficiently coherent and abundant to support infrastructure dependency?
3. Depth and layering
   Can the resource be reached without unacceptable disturbance or architecture shift?
4. Regolith mechanics and trafficability
   Can the site support repeated access, excavation, landing, and surface operations?

5. Thermal and volatile response to disturbance
Does verification or extraction alter the resource condition?
6. Access, slope, and support geometry
Are access and power advantages biasing site commitment before resource adequacy is established?
7. Evidence scale match
Is the evidence resolved at the same scale as the commitment?
8. Fallback preservation
Can the mission still re-site, re-rank, or refuse after the next action?
9. ISRU dependency formation
Is the architecture beginning to depend on unresolved volatile assumptions?
10. Refusal credibility
Will decision authority remain real after the proposed action?

These uncertainties dominate because they can change the commitment decision.

5. Uncertainty-to-Commitment Mapping

Uncertainty	If unresolved, do not authorize
Volatile form	ISRU dependency, excavation commitment, processing infrastructure
Volatile concentration	resource-processing dependency, logistics substitution
Spatial continuity	site hardening, corridor formation, excavation zoning
Depth / layering	drilling, trenching, excavation, subsurface access
Accessibility / extractability	ISRU architecture, processing assumptions
Regolith mechanics	repeated traffic, landing zone preparation, excavation system commitment
Thermal stability	excavation, exposure, heating, processing, storage
Disturbance response	intrusive verification, traffic concentration, repeated landing
Terrain / slope	site fixation, corridor formation, power/support placement
Power continuity	fixed power placement, site preference, survival architecture
Communications / navigation	corridor hardening, repeated operations, surface logistics
Evidence scale match	any commitment exceeding the evidence scale
Fallback preservation	primary site designation, single-site dependency
Governance/refusal authority	programmatic designation, shared infrastructure, public commitment

6. Evidence Adequacy Questions

For each critical uncertainty, the screen should ask:

1. What is currently known?
2. What remains inferred?
3. What materially different states remain plausible?
4. Which commitments would change across those states?
5. What evidence would reduce the uncertainty?
6. Can that evidence be acquired without crossing the commitment threshold?
7. What happens if the uncertainty resolves unfavorably?
8. Can the mission still refuse, defer, re-site, or re-sequence?
9. Does the proposed action preserve or reduce optionality?
10. Has the uncertainty stopped governing the decision?

The final question is decisive:

Has the uncertainty stopped governing the commitment?

If not, the action should defer or be refused.

7. Minimum Uncertainty Reduction Before Commitment

A lunar commitment-bearing action should not proceed unless the following conditions are met:

1. The plausible state set is bounded
   The evidence no longer supports materially divergent interpretations that would require different architectures.
2. The evidence matches the action scale
   Regional, orbital, or indirect evidence is not being used to authorize local irreversible action beyond its resolution.
3. The downside state is survivable
   If the less favorable plausible state proves true, the mission can still recover, re-site, re-sequence, or terminate.
4. Disturbance is bounded
   Verification does not alter the evidence baseline more than it reduces decision-dominant uncertainty.
5. Support remains provisional
   Power, communications, navigation, and logistics do not make one site or corridor the assumed future before admissibility is established.
6. ISRU dependency is not premature
   Resource assumptions have not entered architecture, logistics, or mission sequencing before the resource has earned that role.
7. Refusal remains credible
   The mission can still say no after the action proceeds.

8. Uncertainty Status Classes

Each uncertainty should be classified into one of four states.

Class A — Resolved for the Proposed Action

The uncertainty no longer has the power to change the commitment decision.

Potential output: Proceed within defined bounds.

Class B — Bounded but Still Relevant

The uncertainty remains, but the proposed action is robust across plausible states.

Potential output: Proceed with constraints or continue bounded verification.

Class C — Decision-Dominant

The uncertainty still controls the commitment decision.

Potential output: Defer.

Class D — Blocking

The uncertainty cannot be reduced without crossing the same irreversible threshold, or the proposed action would create exposure the evidence cannot justify.

Potential output: Refuse.

9. Relationship to SIDT

The Subsurface Ignorance Dominance Test applies when unresolved subsurface ambiguity remains capable of changing the admissibility of a proposed commitment.

In this document, SIDT is active when uncertainties such as volatile form, accessibility, continuity, concentration, depth, layering, or regolith mechanics remain decision-dominant.

SIDT is cleared only when plausible remaining states no longer imply materially different decisions about:

- site selection,
- access geometry,
- excavation,
- drilling,
- support architecture,
- ISRU dependency,
- or infrastructure commitment.

If SIDT remains active, the evidence may support exploration, but not commitment.

10. Canonical Statement

A lunar uncertainty becomes critical when it can still change whether the next commitment should be allowed.

The issue is not whether uncertainty remains.
It will. The issue is whether unresolved uncertainty still governs site selection, access geometry, support architecture, disturbance planning, resource dependency, or refusal authority.

Until that uncertainty loses decision-changing power, the admissible path is bounded learning, not infrastructure commitment.

Final rule:

Critical uncertainty must be reduced before commitment or preserved as a reason to defer or refuse.