Criteria for Lunar Outpost Excavation

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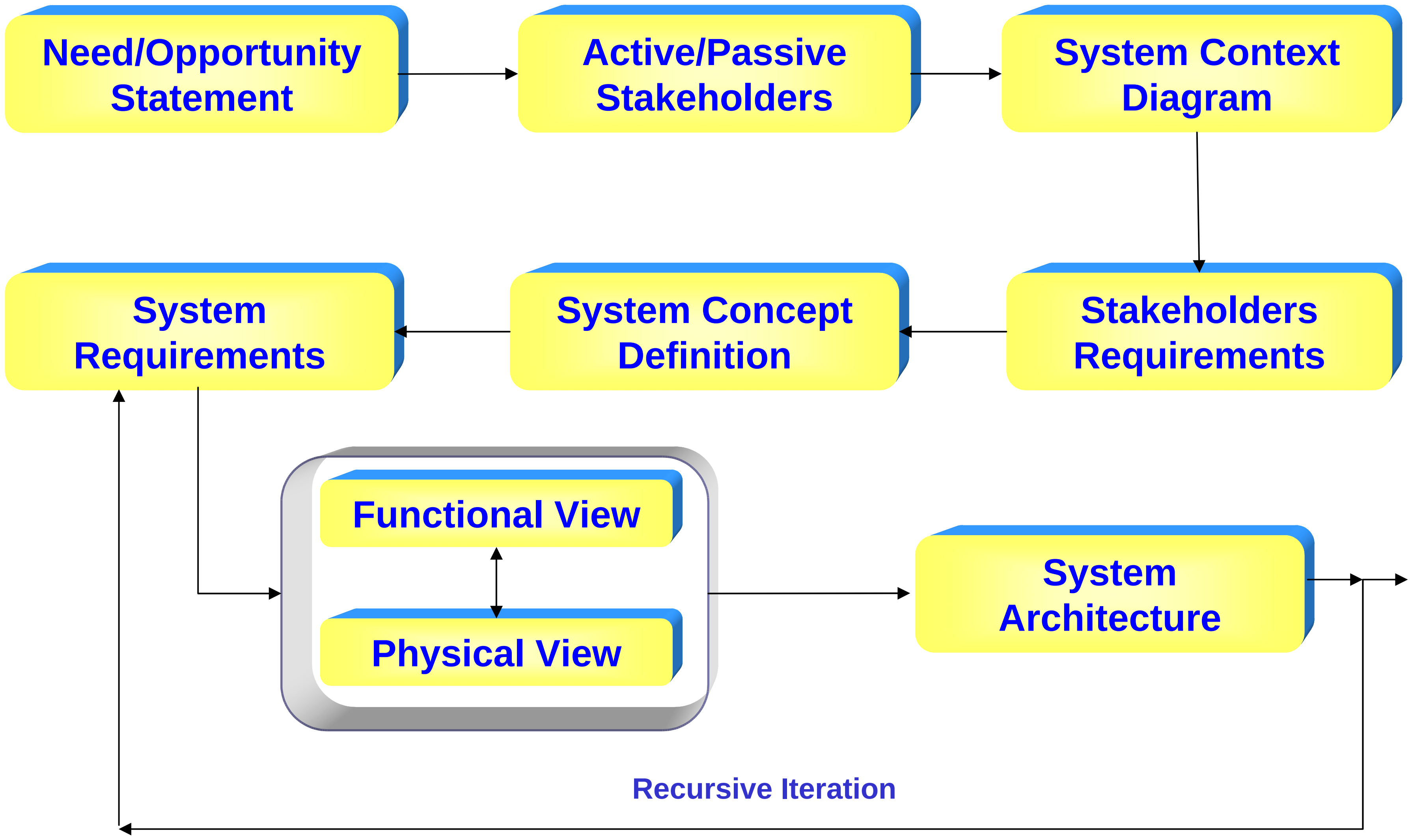
Agenda

- Systems Engineering Approach to Lunar Outpost Excavation
- Exploration Architecture & Constellation Program Requirements
- Lunar Outpost Architectures: LAT I and LAT II
- Types of Lunar Excavation
- Excavation Tasks for a NASA Lunar Outpost
- Manifest / Concept of Operations
- Excavation Requirements – Option 1
- Excavation Requirements – Option 2
- Key Performance Parameters
- Regolith Properties
- Excavation Concept Evaluation Criteria
- Conclusion

Typical Systems Engineering Process



Space Opportunities

- John F. Kennedy,1962

"I believe that this nation should commit itself to achieving the goal,
before this decade is out,
of landing a man on the moon and
returning him safely to the earth.

- George W. Bush, 2004

"…return to the moon by 2020,
as the launching point for missions beyond,
with the goal of living and working there for increasingly extended periods of time."

Vision for Space Exploration Requirements (Strategic)

Based on results from the Vision for Space Exploration (VSE), 5 of the top 40 requirements for returning to the Moon are directly related to ISRU.

- Develop and validate tools, technologies and systems to extract and process resources on the Moon, with extension to other exploration destinations.
- Produce propellants, life support and other consumables from lunar resources
- Characterize and quantify the resource potential of the Moon.
- Demonstrate ISRU technologies and systems to reduce risk for mission integration and commercial development.
- Investigate and develop technologies and systems that effectively utilize lunar resources and products.

Objectives for Lunar Exploration & Beyond

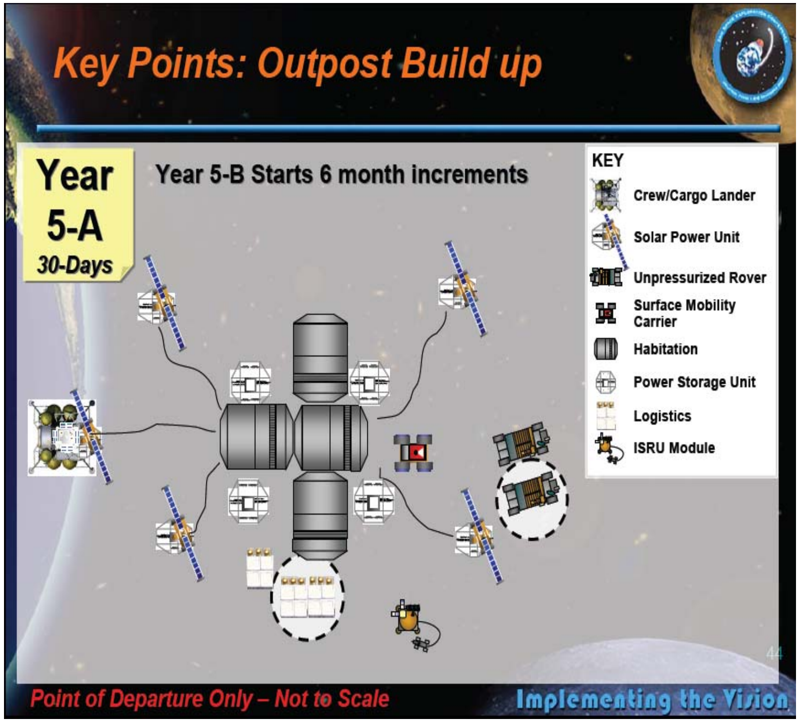
- [EARD-Ex-0004] The Exploration Architecture shall demonstrate resource extraction from in-situ materials during lunar missions. [CA0006-HQ]
- *Rationale:* Establishes the priority of extraction and use of resources from the lunar environment. Extraction and utilization demonstrations can serve as a first step in utilizing lunar resources (if desirable), or in demonstrating a capability that may be further exploited during human missions to Mars.

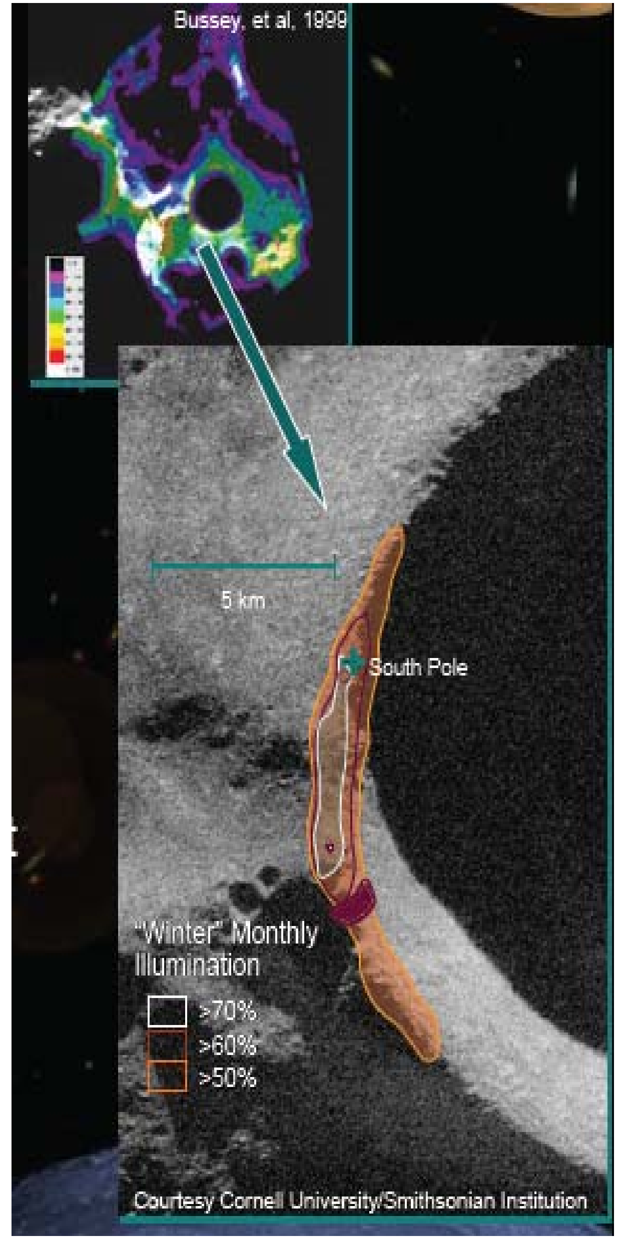
- [CA0006-HQ] The Constellation Architecture **shall provide the capability to demonstrate resource extraction and utilization from in situ materials** during lunar missions.
- *Rationale:* Establishes the priority of extraction and use of resources from the lunar environment. Extraction and utilization demonstrations can serve as a first step in utilizing lunar resources (if desirable), or in demonstrating a capability that may be further exploited during human missions to Mars

Supportability & ISRU Consumable Production

- [EARD 3.2.7.6 Supportability] "… **Using in-situ surface resources to produce propellants, breathing gases, and possibly consumable water could significantly reduce the mass that must be delivered to planetary surfaces**.
- [CARD 3.1.3.6.7 Supportability]: The logistics footprint required to support exploration missions must be minimized… …**Utilization of in-situ surface resources for production of propellants, breathing gases, and possibly consumable water could significantly reduce the mass that must be delivered to planetary surfaces**…
- [EARD 4.1.1.1.3 Stockpiling and Outpost Completion]: "… ISRU will begin to come online near the end of this phase, reducing the reliance on consumables from Earth.
- [CA0353-PO] **Draft** The Constellation Architecture shall be capable of utilizing predeployed surface infrastructure.
  - *Rationale:* The Constellation Architecture **elements will be able to utilize functionality contained within pre-deployed infrastructure** to meet outpost mission requirements. Pre-deployed mission assets could include surface infrastructure such as habitats, power systems, **in-situ resource utilization equipment**, exploration elements, and landing navigation beacons.
- [EARD 4.1.2.1.4.1 In-Situ Resource Utilization]: The outpost will **operate ISRU elements to allow for extraction of water and oxygen from the lunar surface**. Production units, transportation capability, and storage facilities are all necessary for the extraction of consumables from the surface. The lunar outpost will leverage the extracted resources to supplement its water and oxygen requirements. NASA may identify other uses for lunar resources as well.
- [EARD-Cx-0008] **By 2023, the Constellation Architecture should provide from lunar in-situ resources, no less than 1 metric ton of oxygen per year.**
- [EARD-Cx-0011] **By 2027, the Constellation Architecture should produce no less than 10 metric tons of oxygen per year using lunar in-situ resources.**

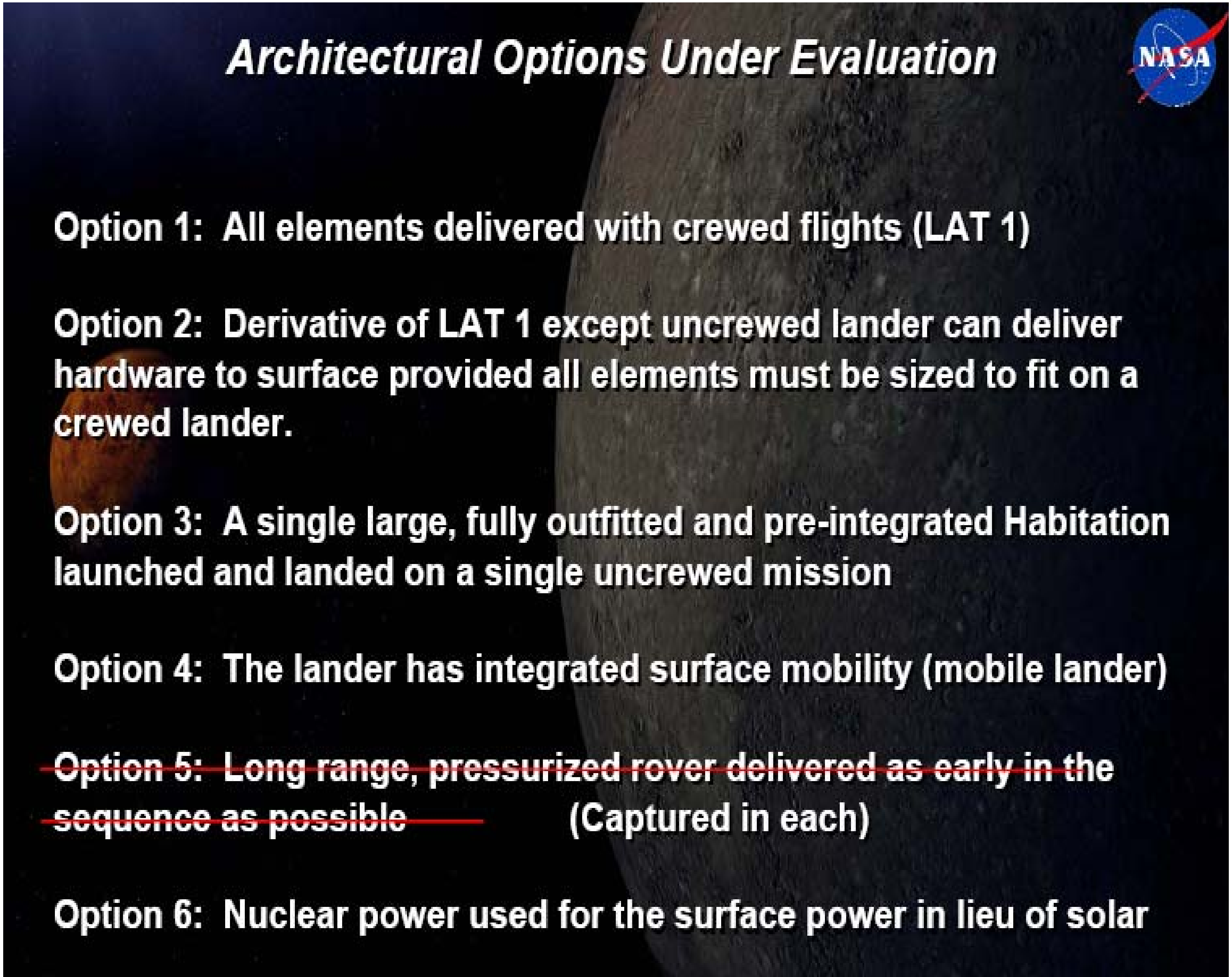
LAT I Architecture – December 2006





- Human lunar missions will be used to build an outpost at a polar site
- The ability to fly human sorties and cargo missions with the human lander will be preserved
- Initial power architecture will be solar with the potential augmentation of nuclear power at a later time

LAT II Architecture – September 2007



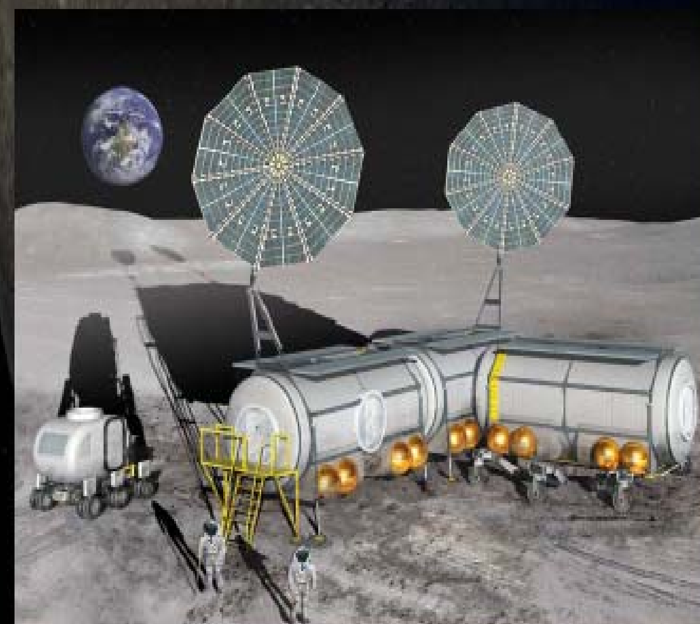
LAT II Architecture – September 2007

Hybrid Approach to Options

A flexible architecture incorporating best features and lessons learned from all the Lunar Architecture Team options

Surface Architecture - Discrete elements sized smaller than the monolithic unit, but larger than the mini-hab concept

- Cargo lander needed for robustness
- Outpost built up from only 2 or 3 of these elements
- Assembly facilitated from separate surface mobility system
- Make maximum use of delivered hardware to minimize the bone yard



LAT II Architecture – September 2007

Hybrid Approach to Options (cont.)

Capability for global access and extended range surface exploration is essential

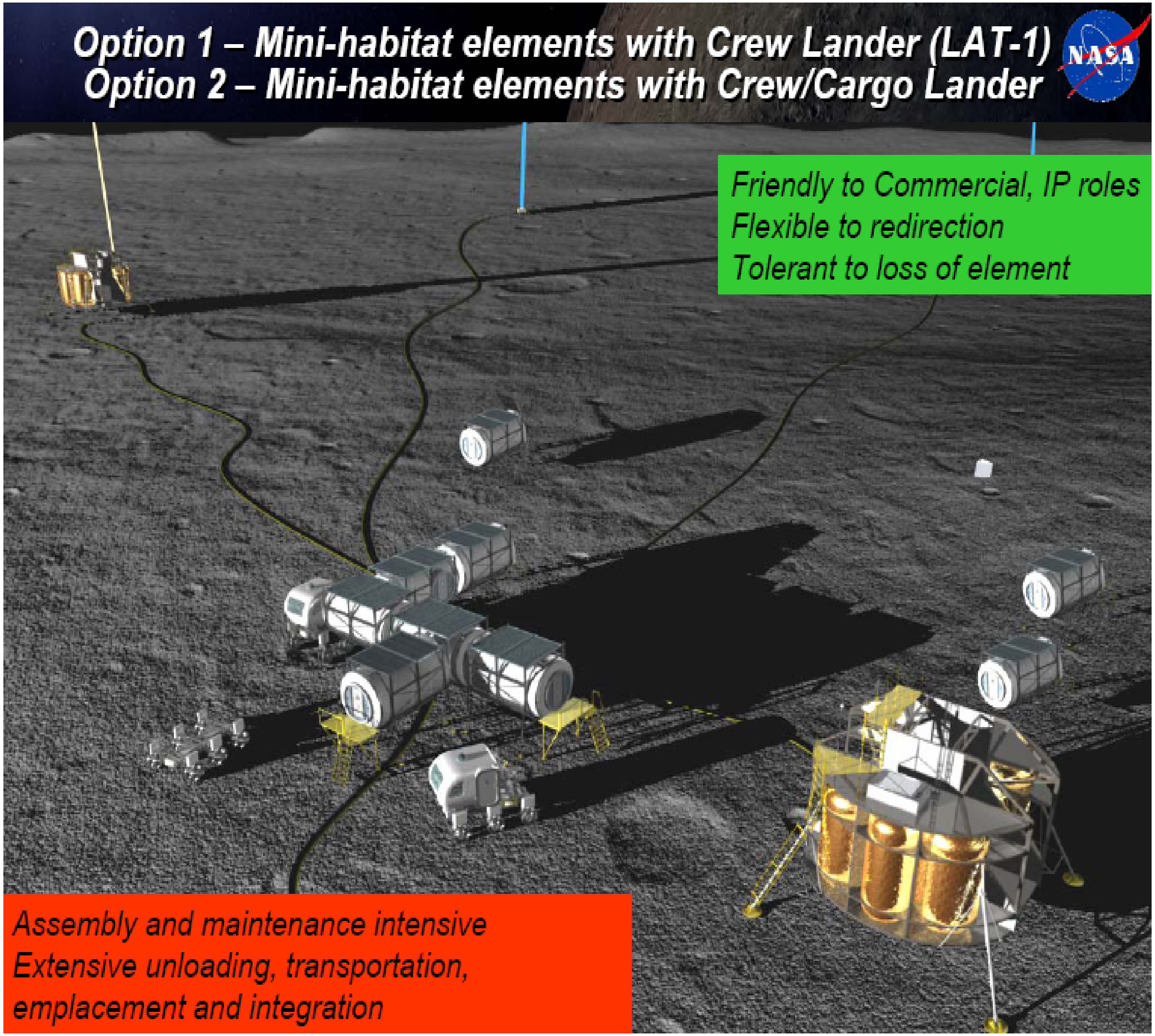
- **Surface Mobility**
  - Early delivery of small, agile pressurized rover that carries SPE protection, suit lock (not like Apollo)
  - Utilize common elements from surface carrier where possible (e.g. wheel/motor units)

38

Lunar Outpost Excavation Study

- Examined LAT I Architecture
- Examined LAT II Architecture
- Study is based on LAT II, Option 1 & Option 2 only
- Too many options to examine them all
- Functional Decomposition by Mission Manifest (Reference EARD Rev G 122106)
- Identified Lunar Outpost Elements
- Developed an associated notional Concept of Operations (ConOps)
- Identified discrete Excavation tasks in the ConOps
- Examined the total excavation needs by task
- Proceeded with a chronological identification of excavation needs
- Delivered results to ISRU Systems Modeling team for systems level analysis
- Determined Mars Forward Links

LAT II Architecture – September 2007



Regolith Excavation & Material Handling
Overview

Develop Capabilities for Lunar Regolith Excavation and Material Handling, Sized for Efficient Lunar Outpost Operations


Excavation for O_2 Production

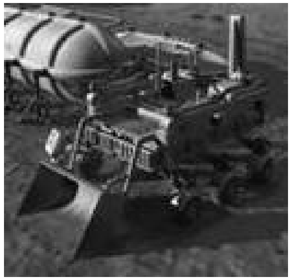
- Excavate, collect and deliver unconsolidated surface regolith for use as feedstock in *oxygen production* and *solar-wind volatile* extraction.


Excavation for Volatiles

- Excavate, collect and deliver consolidated subsurface regolith for *polar-volatile extraction* in permanently shadowed polar craters.


Mining Polar Water

- Excavate, collect, contour and stabilize surface and subsurface regolith for *lunar site preparation* including burying habitat and reactor modules, construction of berms, launch/landing surfaces, roads, etc.


Excavation for Site Prep

- Remove processed regolith from oxygen or volatile extraction plants.

This study addresses Excavation for O2 Production, Polar H2O & Site Preparation Only

Regolith Excavation Study

- <u>Excavation Criteria are determined by:</u>

- Lunar Outpost Configuration, ConOps and Associated Elements
- Excavation Tasks and Outpost Needs
- Lunar Environment
- Space Transportation Architecture and Capability
- Supportability and Life Cycle Requirements

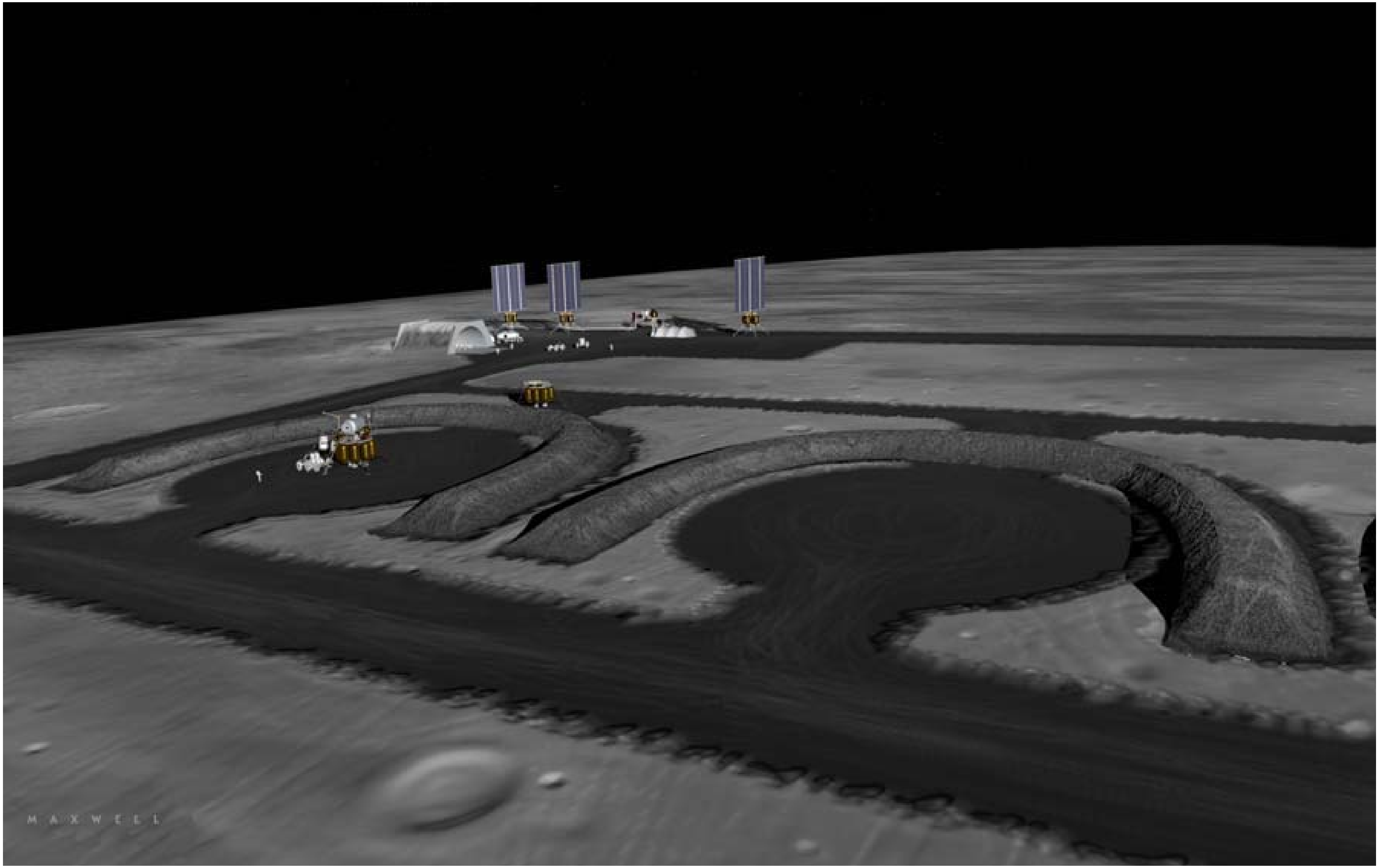
<u>The steps followed in this study to evaluate the specific criteria were:</u>

- Specify the excavation tasks by careful study of the lunar outpost development plans.
- Determine the functional requirements for excavation.
- Develop a list of criteria for ranking alternative excavation concepts.
- Organize the criteria with a hierarchy.

Excavation Tasks

- Regolith Mining for O2 Production
- H2O Ice/Regolith Mining from Shadowed Craters
- Landing / Launch Pads
- Blast Protection Berms
- Electrical Cable Trenches
- Utility Roads / Clearing Obstacles
- Foundations / Leveling
- Trenches for Habitat & Element Burial
- Regolith Shielding on Roof over Element Trenches

Artist's Landing Pad Concept



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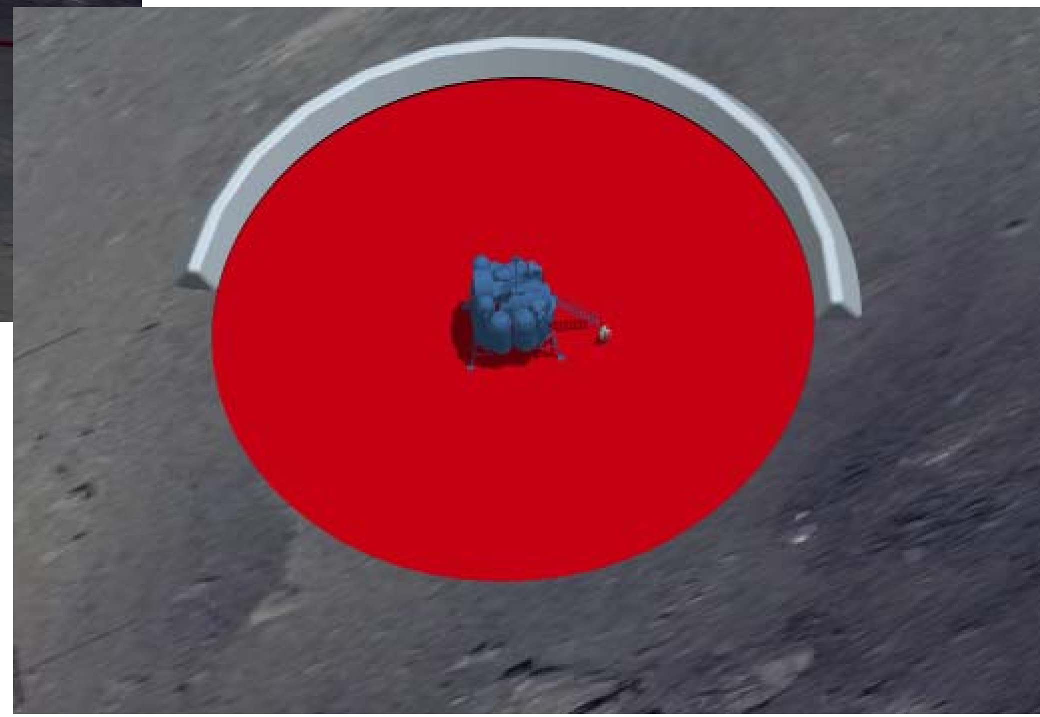
Aerial Views of Landing Pad

Landing Pad = 50 m Diameter



Margin of Error for Landing = 2 Vehicle Diameters each side (20 m)

Landing Pad Concept

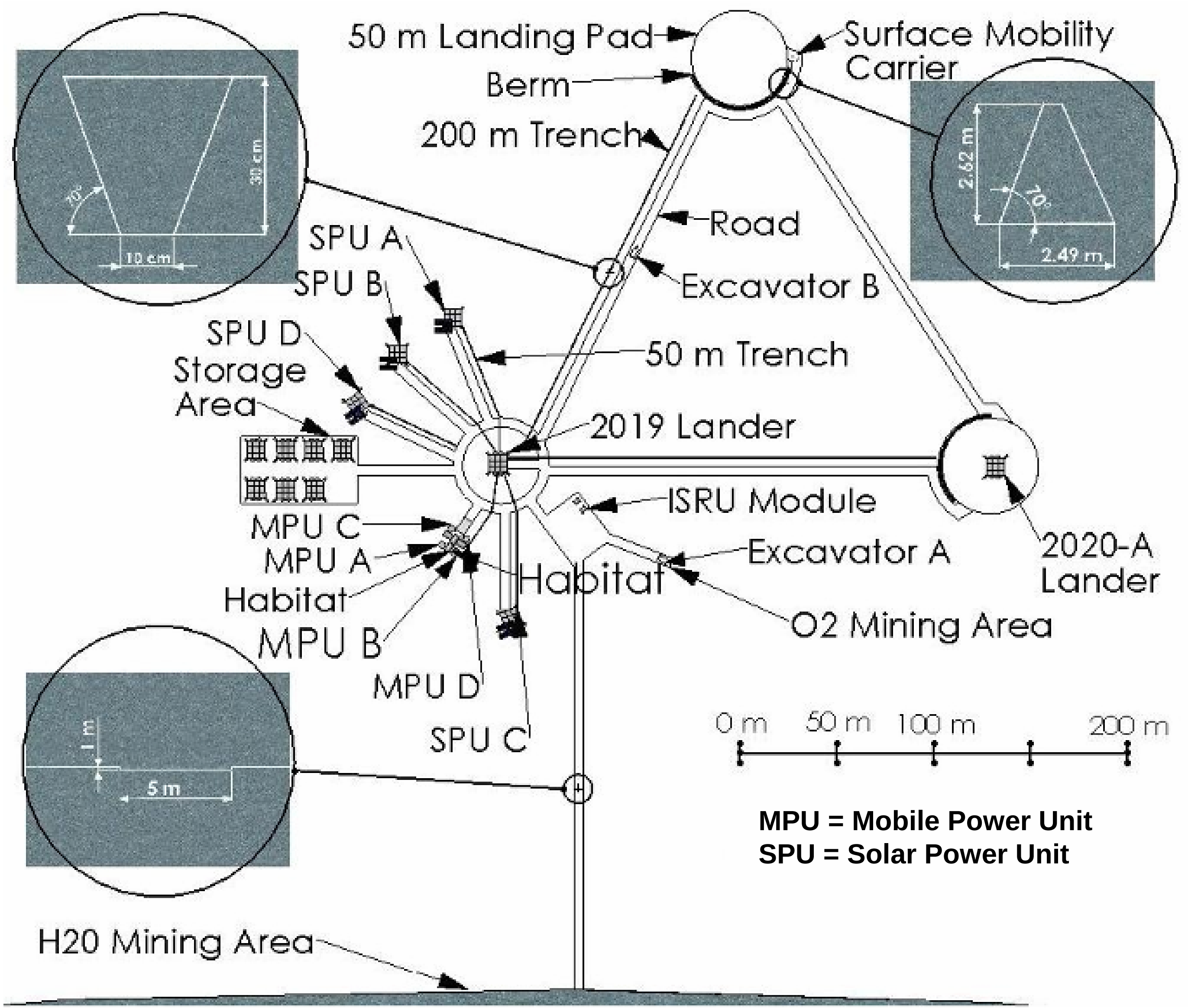
Based on current analysis from Plume Ejecta Team

- Landing pad and berms is largest outpost emplacement excavation requirement
  - 871 MT of regolith moved for every pad/berm prepared
- If landers are not moved, a new pad needs to be prepared *every 6 months*
  - Single pad can potentially be used for Option 4 - mobile landers

Landing Pad	Min.	Max.
•Pad Diameter:	50 m	100 m
•Depth of scraping:	0.2 m	0.2 m

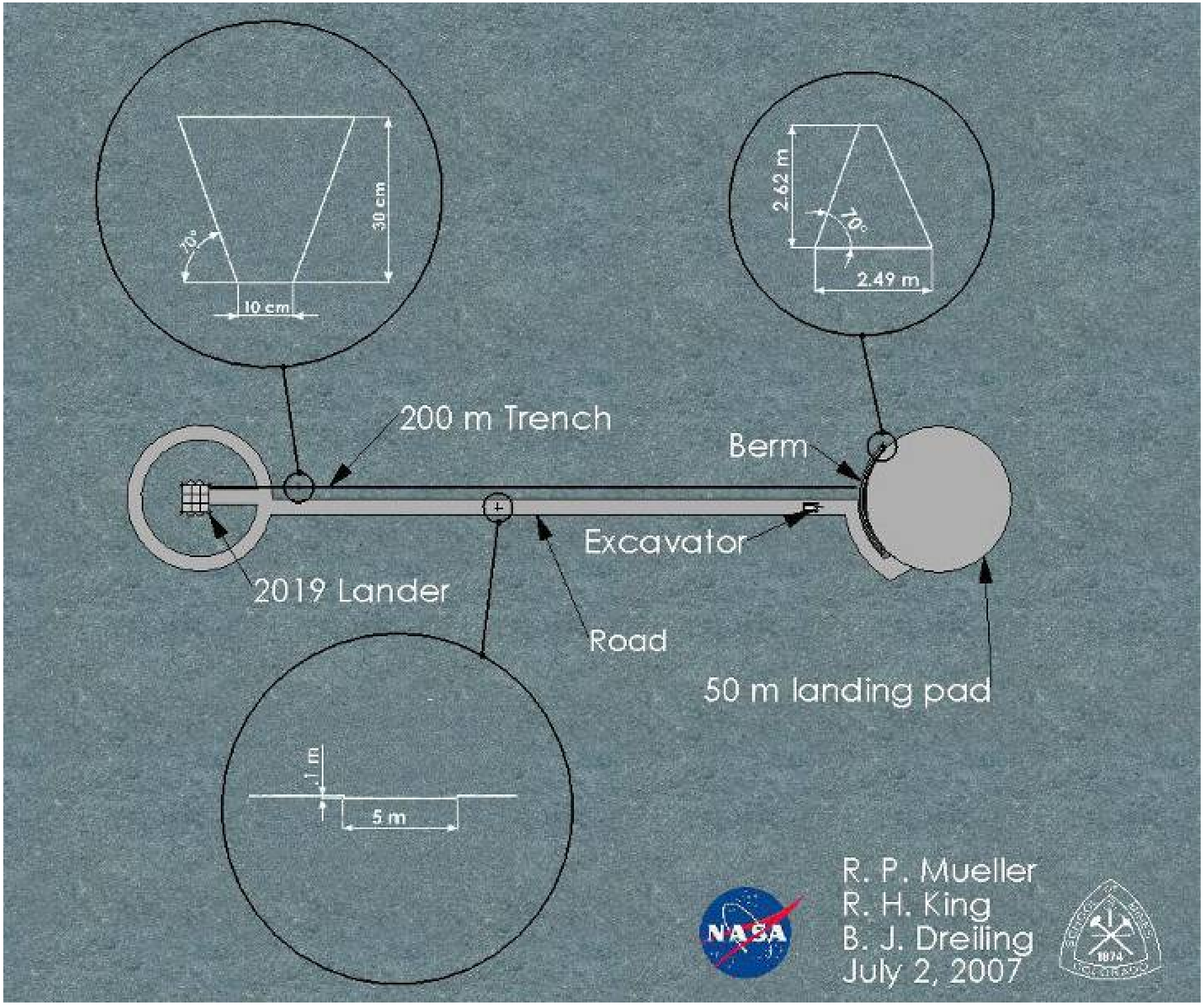
Berms	Min.	Max.
•Pad Diameter:	50 m	100 m
•Plume ejecta ang:	3°	3°
•Berm Height:	1.31 m	2.62 m
•Berm Height w/margin:	1.5 m	3 m
•Top Width	0.3 m	0.3 m
•Bottom Width:	1.39 m	2.49 m

Example 2023-B Mission Excavation Layout

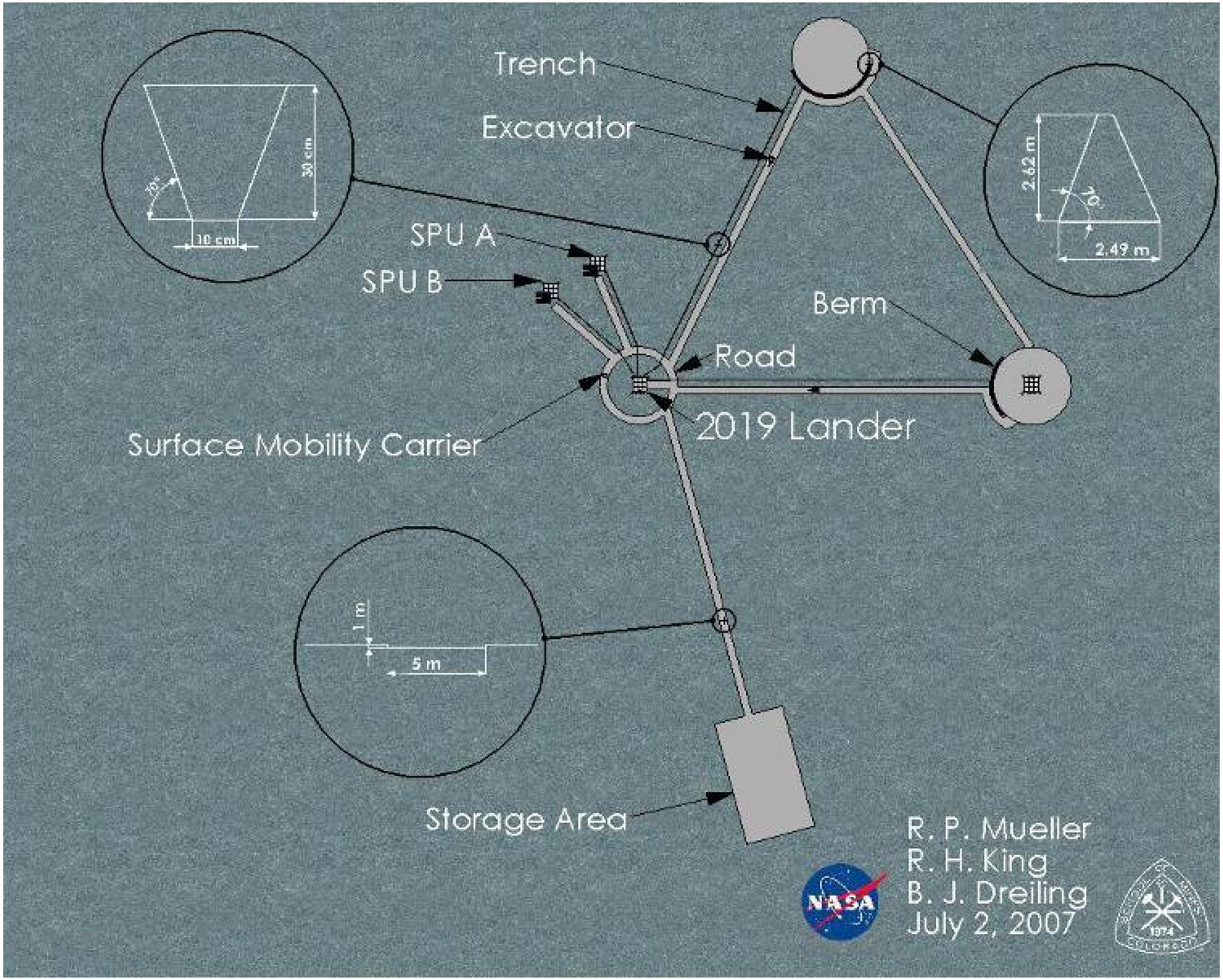


MPU = Mobile Power Unit
SPU = Solar Power Unit

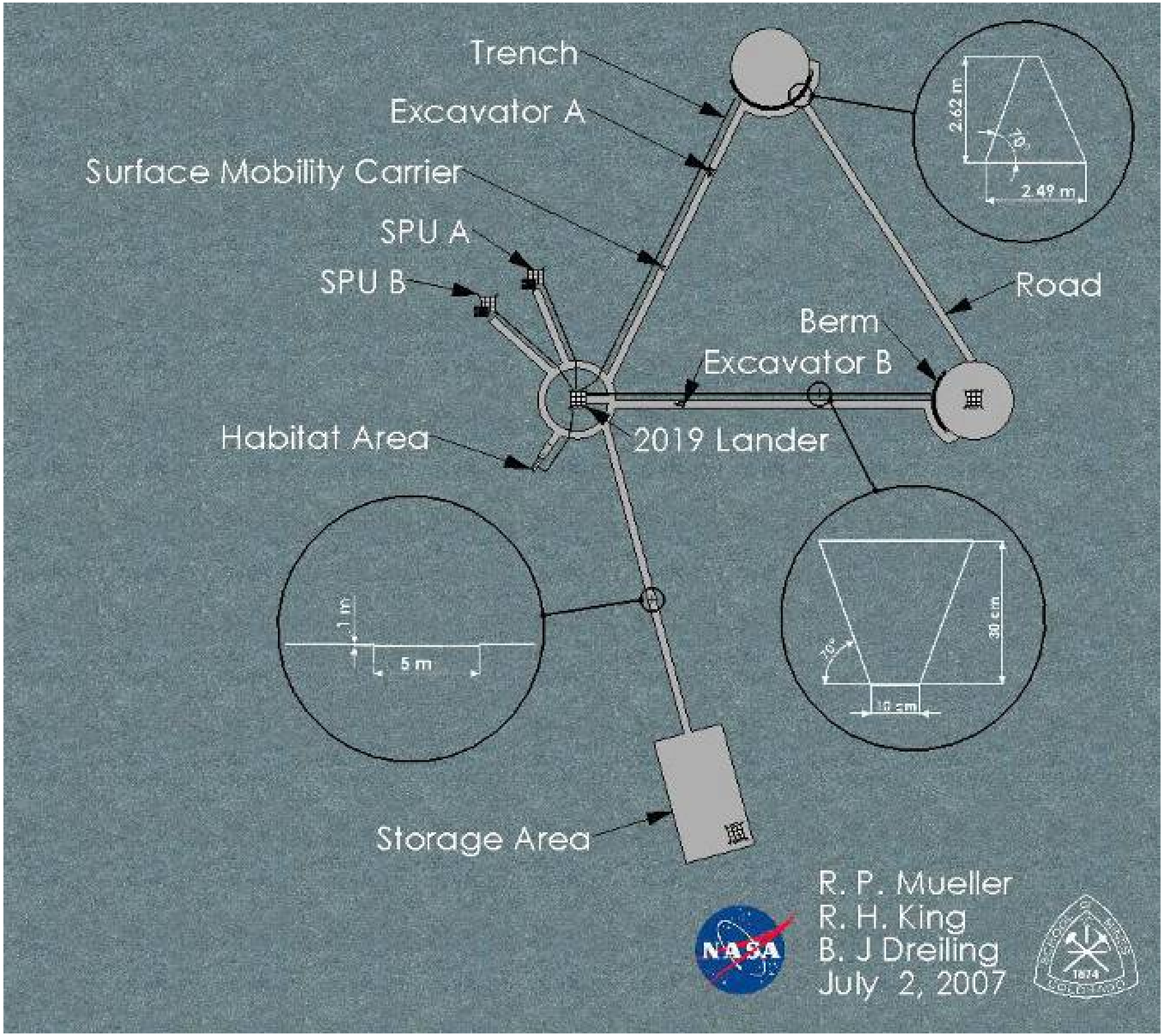
Example 2019 Mission Excavation Layout



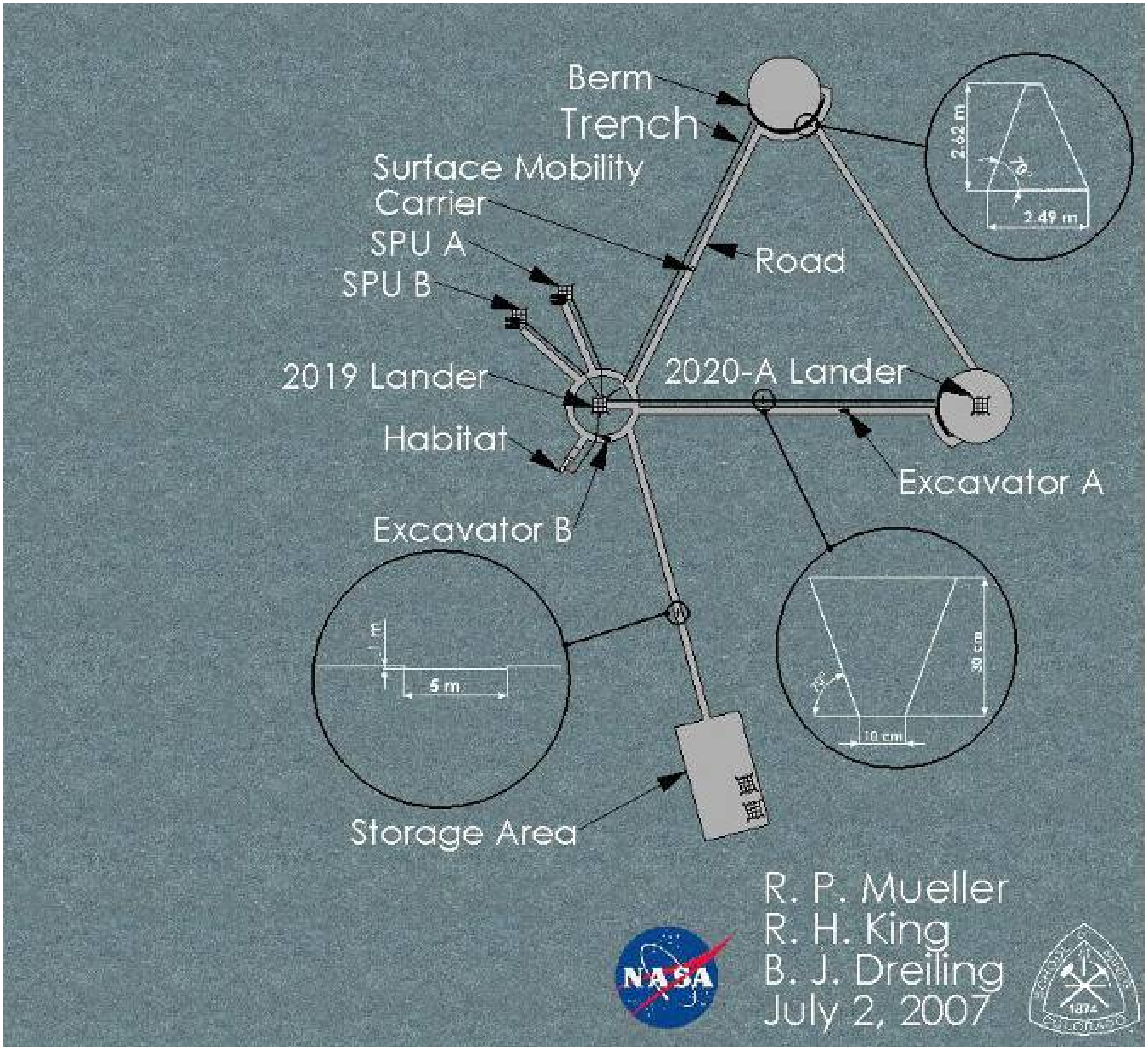
Example 2020A Mission Excavation Layout



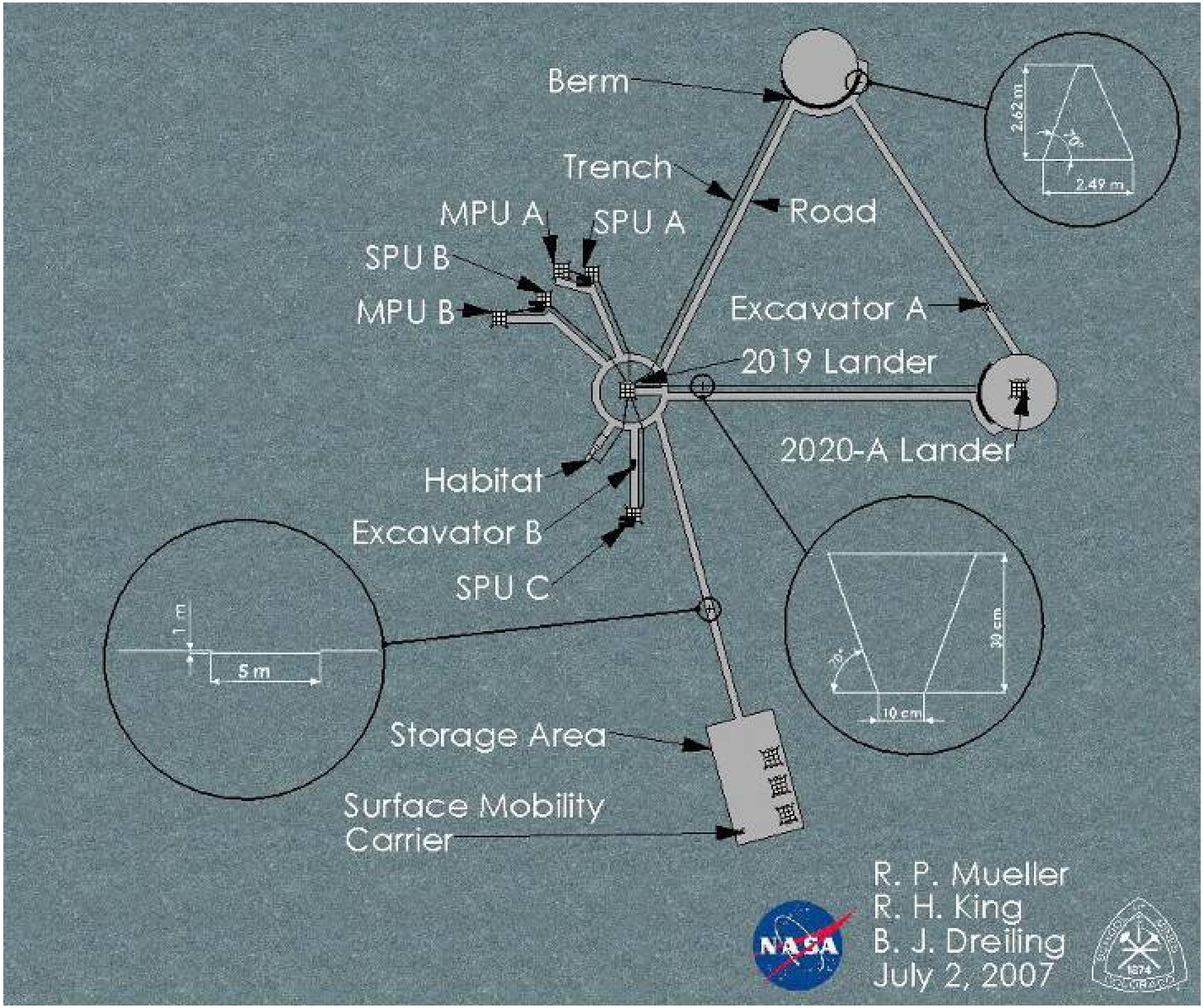
Example 2020B Mission Excavation Layout



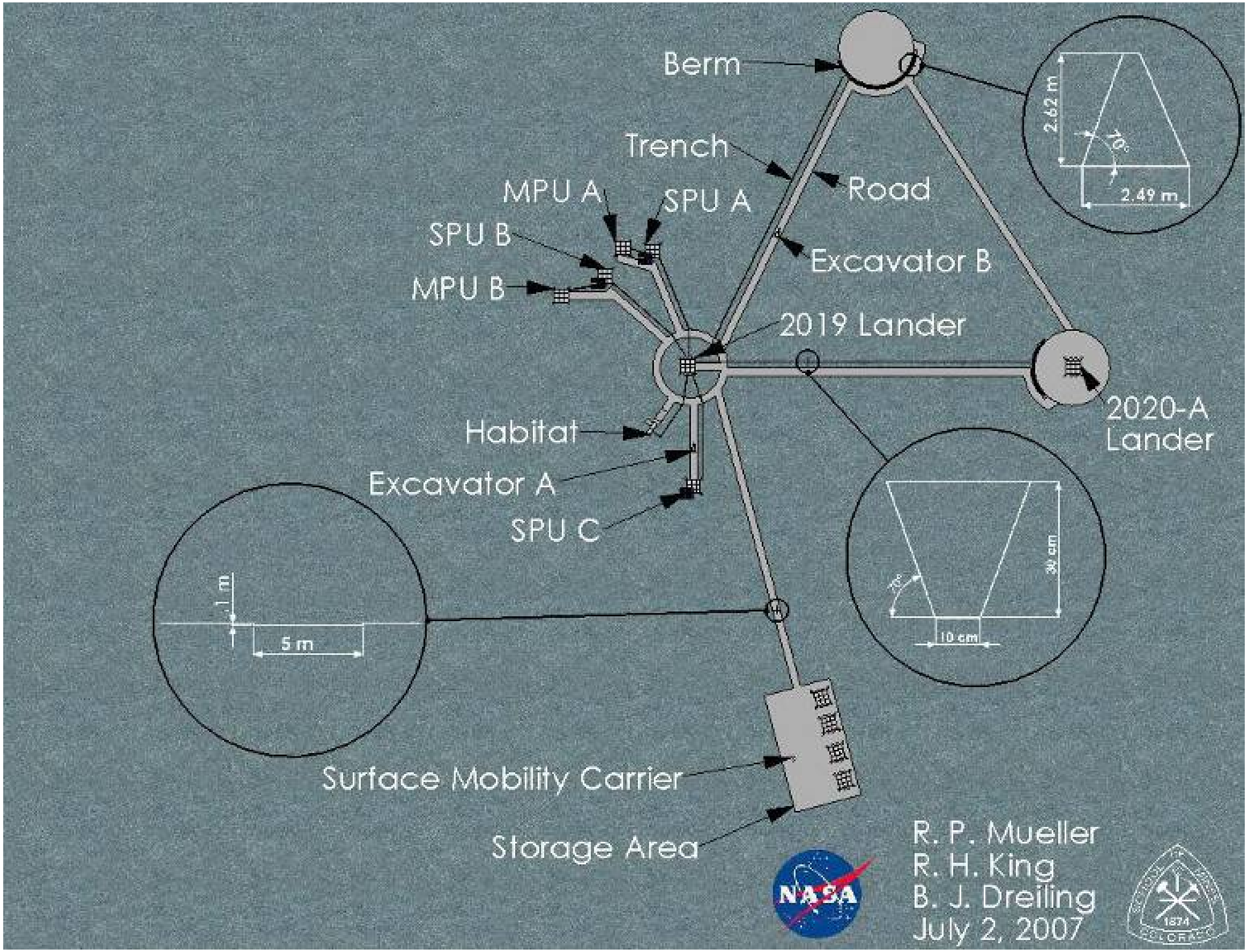
Example 2021A Mission Excavation Layout



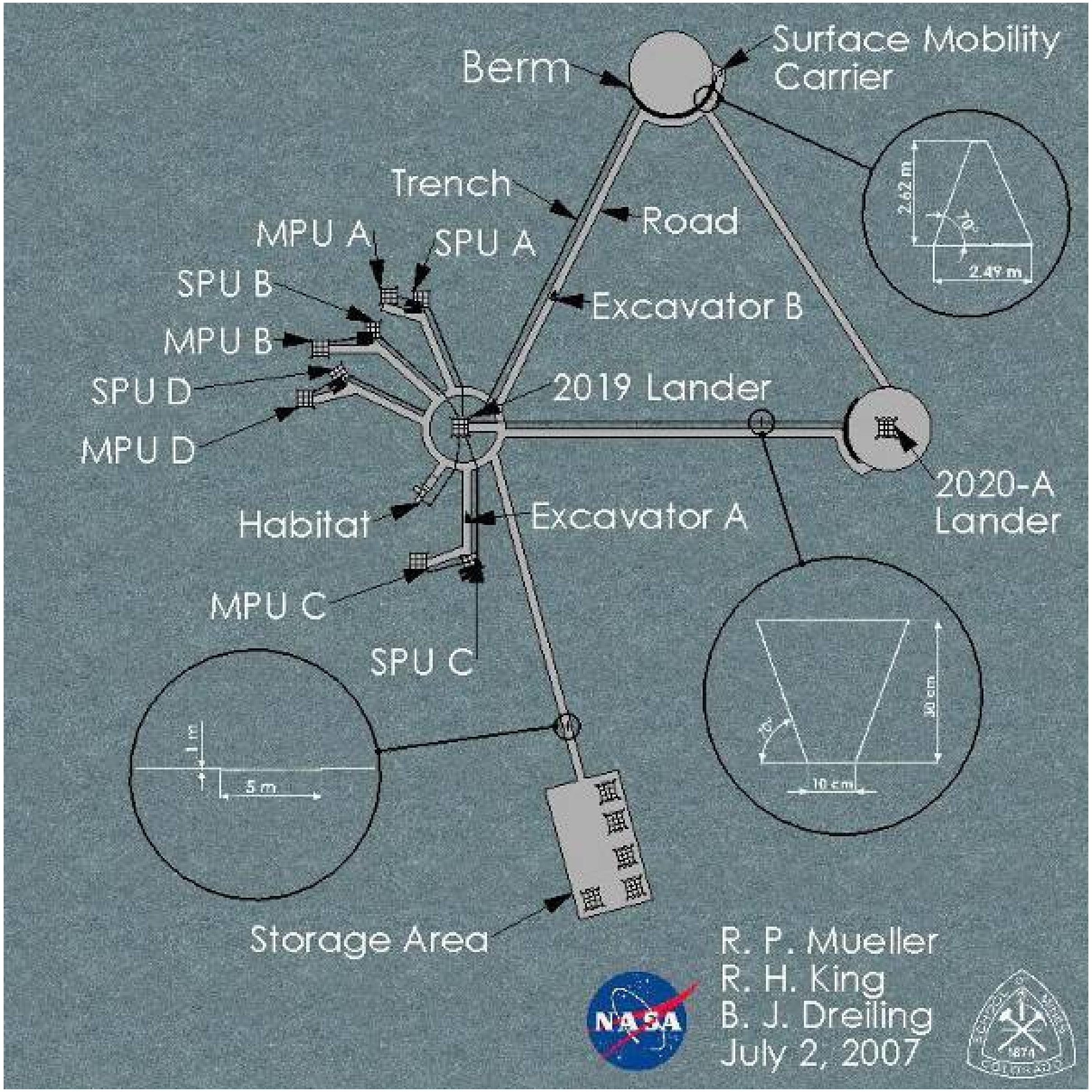
Example 2021B Mission Excavation Layout



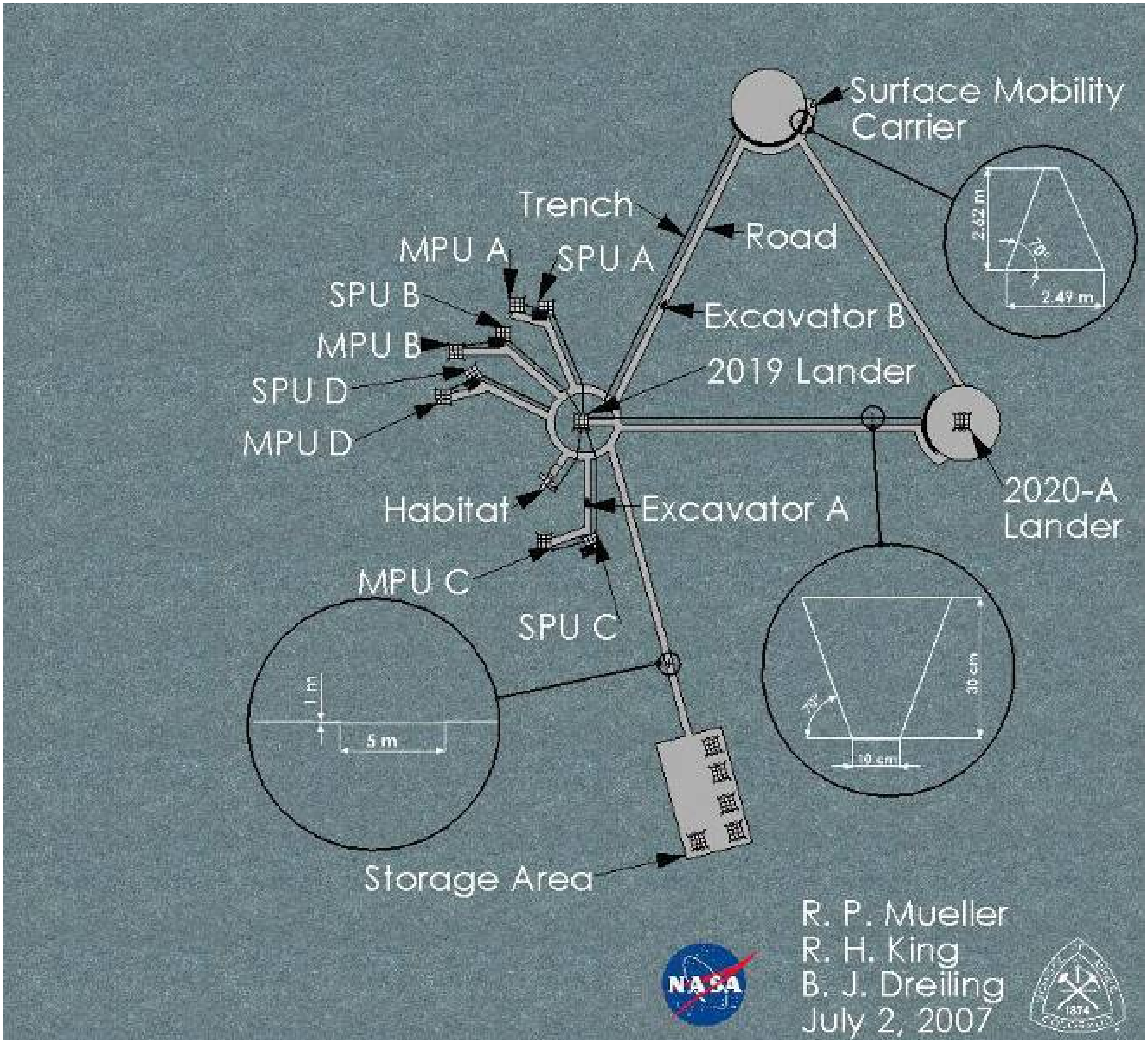
Example 2022A Mission Excavation Layout



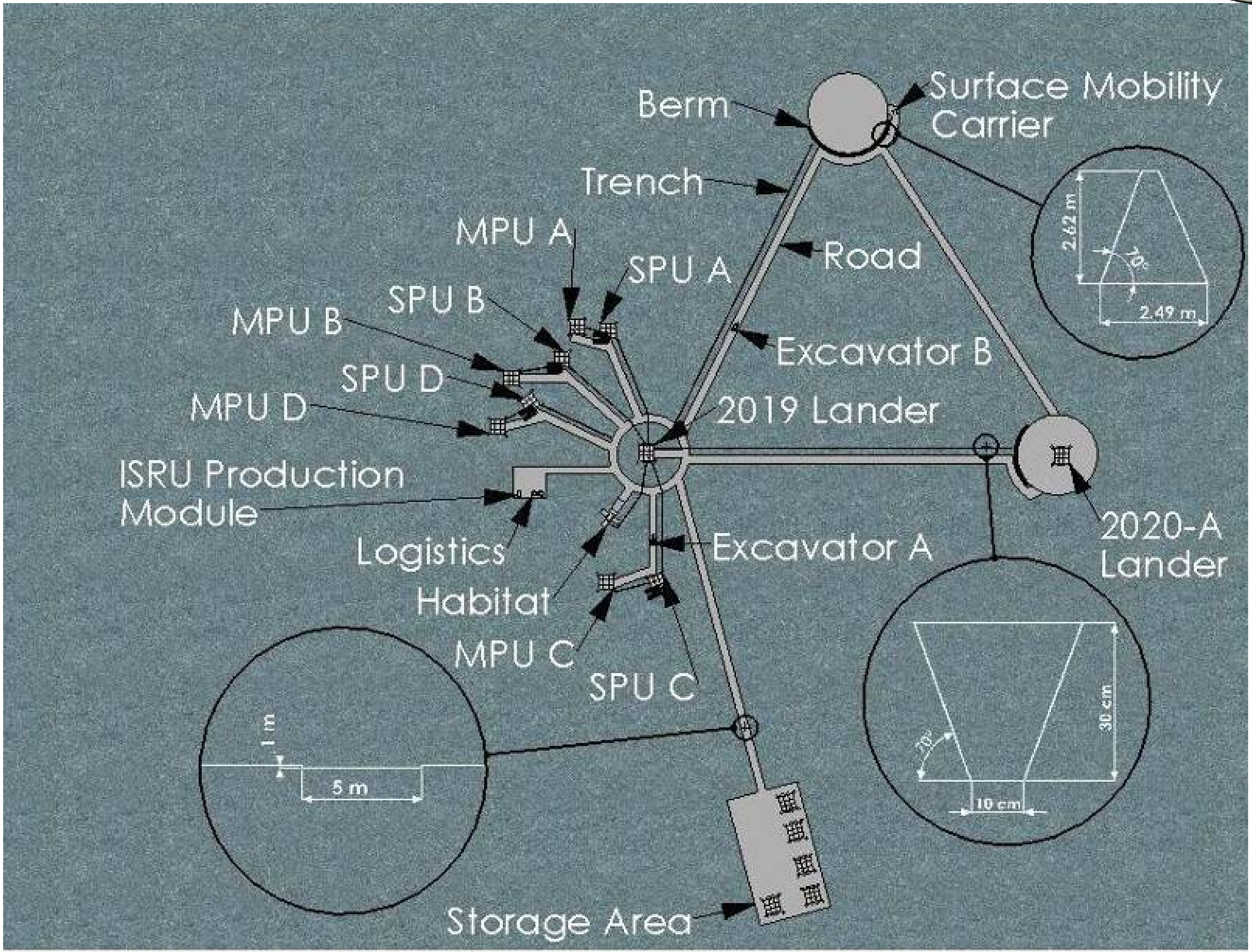
Example 2022B Mission Excavation Layout



Example 2023A Mission Excavation Layout



Example 2023B Mission Excavation Layout



Regolith Shielding Concept

Assumptions

- Depth of Trench 4 m
- Width of Trench 4 m
- Length of Trench 6 m
- Angle of Ramp 15°
- Number of Ramps 1
- Number of Habs 4 + node

RAMP 15 degrees
4W X 6 L
RAMP 15 degrees | 4W x 6L | 3X3 | 4W X 6L | RAMP 15 degrees
4W X 6 L
RAMP 15 degrees

Habitat Regolith Shielding - Requirements

- Requires 323 MT excavation of compacted regolith and 100 MT of backfill/covering per 6 months for 4 missions
- ~30% of total outpost emplacement requirements
  - Second highest requirement after landing pads

Ref: Smitherman, D.

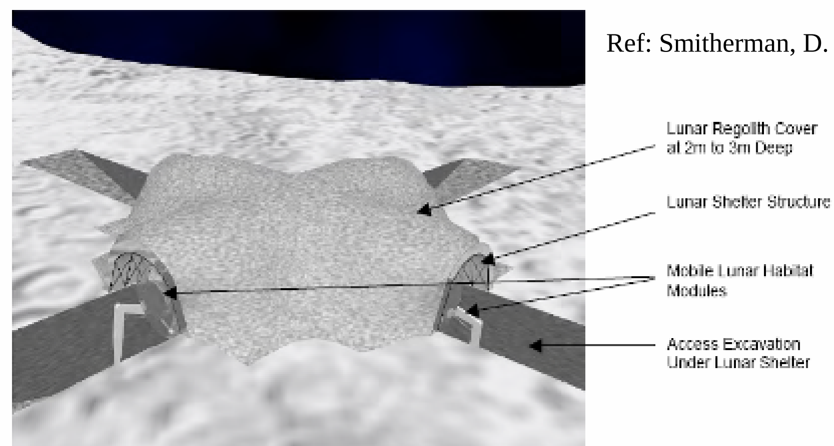


FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules.

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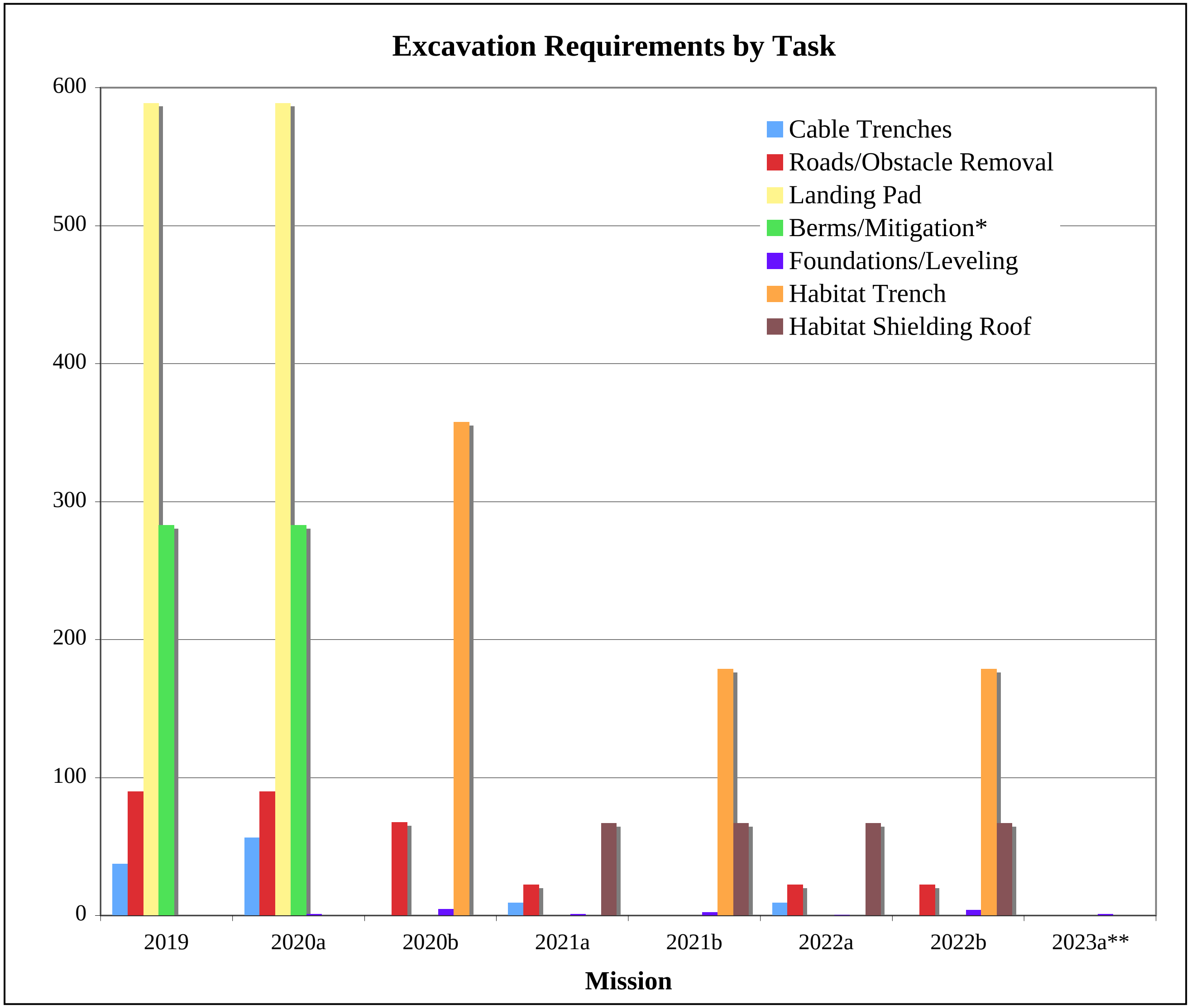
Excavation Requirements by Mission for the H2 Reduction O2/Hab Shield Alternative (Option 1)

	2019	2020a	2020b	2021a	2021b	2022a	2022b	2023a	2023b
Cable Trenches	37,644	56,465	0	9,411	0	9,411	0	0	0
Roads	150,000	150,000	112,500	37,500	0	37,500	37,500	0	0
Landing Pad	588,750	588,750	0	0	0	0	0	0	0
Berms	282,726	282,726	0	0	0	0	0	0	0
Foundations	0	1,200	4,500	1,200	2,250	600	4,200	1,350	0
Hab/Shield Trench	0	0	357,668	0	178,834	0	178,834	0	0
Hab/Shield Roof	0	0	0	66,880	66,880	66,880	66,880	0	0
O2 ISRU	0	0	0	0	0	0	0	250,000	250,000
Ice ISRU	0	0	0	0	0	0	0	50,000	50,000
Total Regolith (MT)	**1,059**	**1,079**	**475**	**115**	**248**	**114**	**287**	**251**	**250**
Total Ice Regolith (MT)	0	0	0	0	0	0	0	**50**	**50**

Note: All quantities are in Kg of Regolith at 1.5 g/cm^3 bulk density, unless noted in Metric Tonnes (MT)

Excavation by Task

- Time sequence of tasks based on LAT II Option 1 Concept of Operations



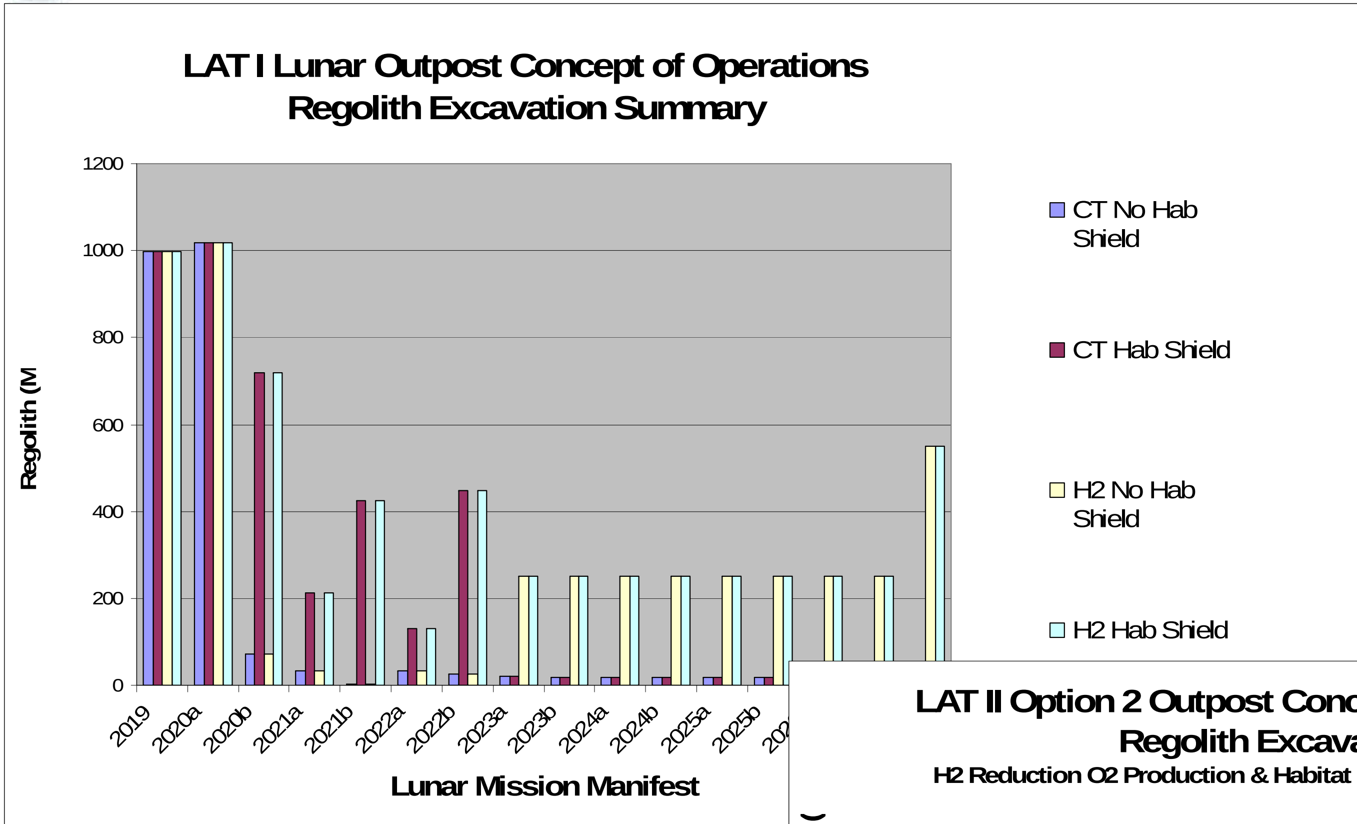
Summary of Option 1 Excavation Mass

Excavation Tasks Mass (Kg)	2019	2020a	2020b	2021a	2021b	2022a	2022b	2023a	2023b	Total	%
Cable Trenches	37,644	56,465	0	9,411	0	9,411	0	0	0	112,931	4
Roads/Obstacle Removal	90,000	90,000	67,500	22,500	0	22,500	22,500	0	0	315,000	10
Prepare Landing Pad	588,750	588,750	0	0	0	0	0	0	0	1,177,500	37
Prepare Berms/ Mitigation	282,726	282,726	0	0	0	0	0	0	0	565,452	18
Foundations / Leveling	0	1,200	4,500	1,200	2,250	600	4,200	1,350	0	15,300	0
Habitat Regolith Shielding Tren	0	0	357,668	0	178,834	0	178,834	0	0	715,337	23
Habitat Regolith Shielding Roof	0	0	0	66,880	66,880	66,880	66,880	0	0	267,521	8
										3,169,041	100
ISRU for O2 (H2)	0	0	0	0	0	0	0	250,000	250,000	500,000	83
H20 Mining	0	0	0	0	0	0	0	50,000	50,000	100,000	17
										600,000	100

Note: All quantities are in Kg at Bulk Density of 1.5 g/cm^3

SUMMARY	
Task	**%**
Trenching	4
Clearing and Compacting	48
Building Berms	18
Habitat Shielding	31
	100
Ice Mining	17
Regolith Mining	83
Construction	84
Mining	16

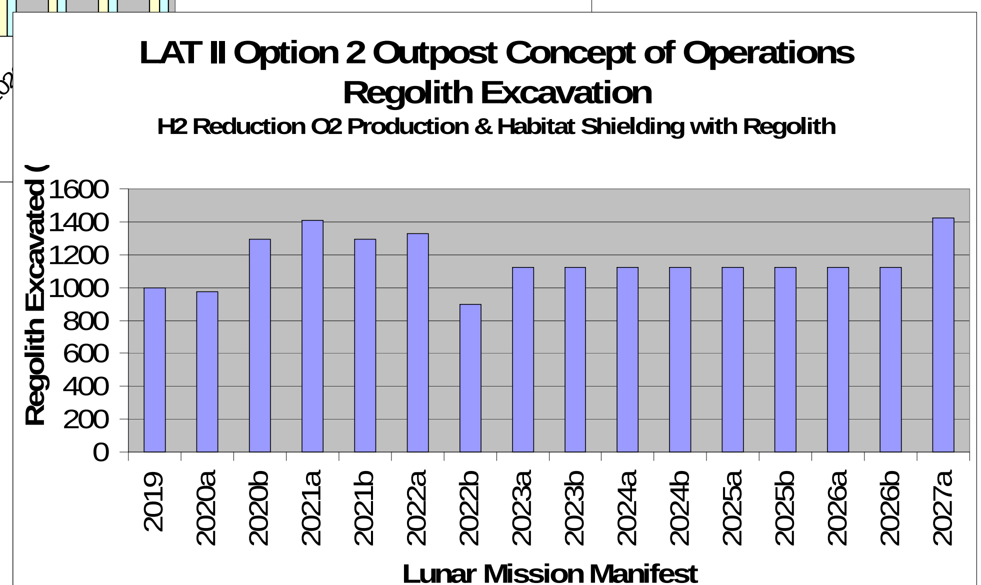
Option 1 vs Option 2



CT= CarboThermal

H2 = Hydrogen Reduction

In Option 2 a new landing pad must be built for each landing due to lack of mobility



Lunar Excavation Key Performance Parameters

Customer Requirements/ Needs	ETDP Technology	Key Performance Parameter	State of the Art	Threshold Value	Goal Value
Regolith Excavation & Material Transport	All excavator and hauler systems	Operation Duration, days	Lab, 10's to 100's minutes	180	1095
		Mean Time Between Repair, days of operation	No tests to failure yet	180	365
		Temperature range during daylight operations (°C to °C)	Lab env.	120 to -32	123 to -181
Regolith Excavation for Oxygen Production	Bucket wheels & scoopers	Excavation rate, kg/hr	150 (Lab env.)	35	53
		Maximum size of rock excavated, cm dia.	No tests to date	1	5
		Excavation depth, cm	8 to 10 uncompacted	8	30
Regolith Handling for Site Preparation & Surface Construction	Cutters, backhoes, & front-end loaders	Excavation rate, kg/hr	No Tests to date	150	300
		Maximum size of rock excavated, cm dia.	No tests to date	5	25
		Cleared Lunar surface area, m, diameter	No tests to date	10	50
		Excavation depth, cm	8 to 10 uncompacted	30	500
		Height of berm, cm	No tests to date	100	250

Lunar Regolith Resource Properties

Property	Units	Apollo	Variation w/ Depth	Shackleton	Source
D_{50}	mm	0.072			1, 2, 3
D_{95}	mm	1.37			1, 2, 3
D_R	%	0-85	75 @ 5cm 85 @ 10cm		1, 2, 3
ρ	g/cm^3	1.30	$\rho = 1.92 (z + 12.2) / (z + 18)$		1, 2, 3
c	kPa	0.1 - 1			3
ϕ	°	30-50			3
δ					
C_a					
T	K	250-255		100	
β_E	°	90	60 for 10 m excavation		3
β_C	°	90	50 for 10 m pile		3
β_D	°	60-70	40 for 10m pile		3
q_{ult}	kPa	3k to 11k			3
q_{all}	kPa	2			3

Z = depth in cm
D50 = Particle size where 50% passes this sieve opening size
D95 = Particle size where 95% passes this sieve opening size
G = Specific Gravity
ρ= bulk density
D_R = Relative density
T = soil temperature
Slope Angle, βE = Excavated Slope Angle (F.S. = 1.5),
βC= Compacted Pile Slope Angle
βD= Dumped Pile Slope Angle (Angle of Repose)
qult=Ultimate Static Bearing Capacity,
qall=Allowable Static Bearing Capacity (at 1 cm allowable settlement)

Shear strength is defined by Mohr's equation:
$\tau = \sigma \tan \phi + c$

Where τ = shear strength,
ϕ = internal friction angle,
σ= normal stress, and c = cohesion

The equation that defines sliding stress is:
$S = \sigma \tan \delta + Ca$
Where S = sliding stress, δ = the angle of sliding friction,
σ = normal stress, and Ca = adhesion

Regolith References

- 1. Carrier, W. D. (2003) “Particle Size Distribution of Lunar Soil”, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 129, No. 10, Oct, pp. 956-959.
- 2. Carrier, W. D., and Mitchell, J. K. (1989) “Geotechnical engineering on the Moon”, *De MelloVolume*, Editora Edgard Blücher Ltda., São Paulo, pp. 51-58.
- 3. Carrier, W. D., Olhoeft, G. R., and Mendell, W. (1991) “Physical Properties of the Lunar Surface”, *Lunar Sourcebook*, G. Heiken, D. Vaniman, and B. M. French, eds., Cambridge University Press, Cambridge, pp. 475-594.

Excavation Concept Evaluation Criteria

Primary Criteria		Secondary Criteria	Primary Weight		Secondary Weight
Capability			30		
		Trenching			5
		Clearing and Compacting			5
		Building Berms			5
		Habitat Shielding			5
		Ice Mining			5
		Regolith Mining			5
Mining Productivity			2.4		
		Ice Mining			0.4
		Regolith Mining			2
Construction Productivity			12.6		
		Trenching			0.5
		Clearing and Compacting			6
		Building Berms			2.3
		Habitat Shielding			3.9
Reliability			15		
		Number of Major Subassemblies			2.5
		Number of Motor/gear Assemblies			2.5
		Maturity of Technology			2.5
		Rock Plugging Points			2.5
		Control Complexity			2.5
		Polar Environment Capable			2.5
Dust Generation			10		
		Material Transfer Points			5
		Discharge Height			5
Power efficiency			10		
Maintainability			10		
		Number of Motor/gear Assemblies			3.4
		Number of Major Subassemblies			3.3
		Chains			3.3
Supportability			5		
Versatility			5		
Total			100		

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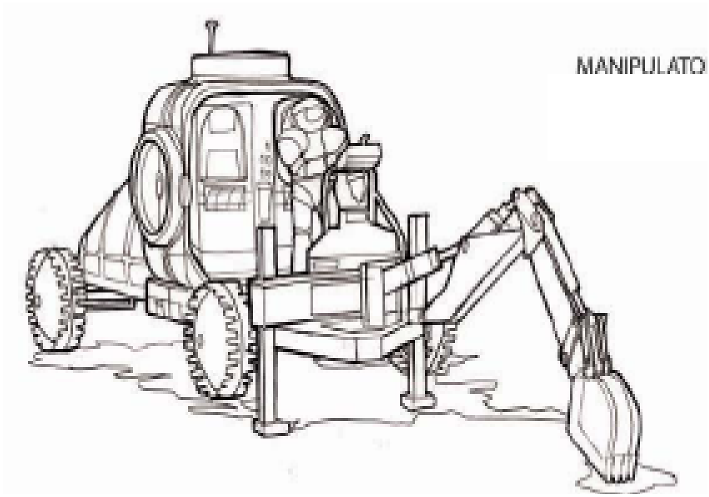
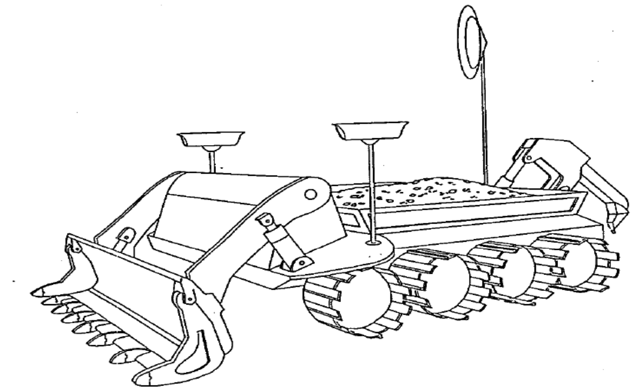
Conclusion: Excavation Concepts Evaluation





The Excavation Concept *<u>Requirements, KPP's & Evaluation Criteria</u>*, in conjunction with regolith properties, analysis and Lunar Environment considerations provide a method for evaluation of various alternative excavation system concepts for a Lunar Outpost