



# Business Case Analysis of Lunar Thermal Mining

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# Previous BCAs of Lunar Mining Concepts Contain Multiple Assumptions and Draw Different Conclusions

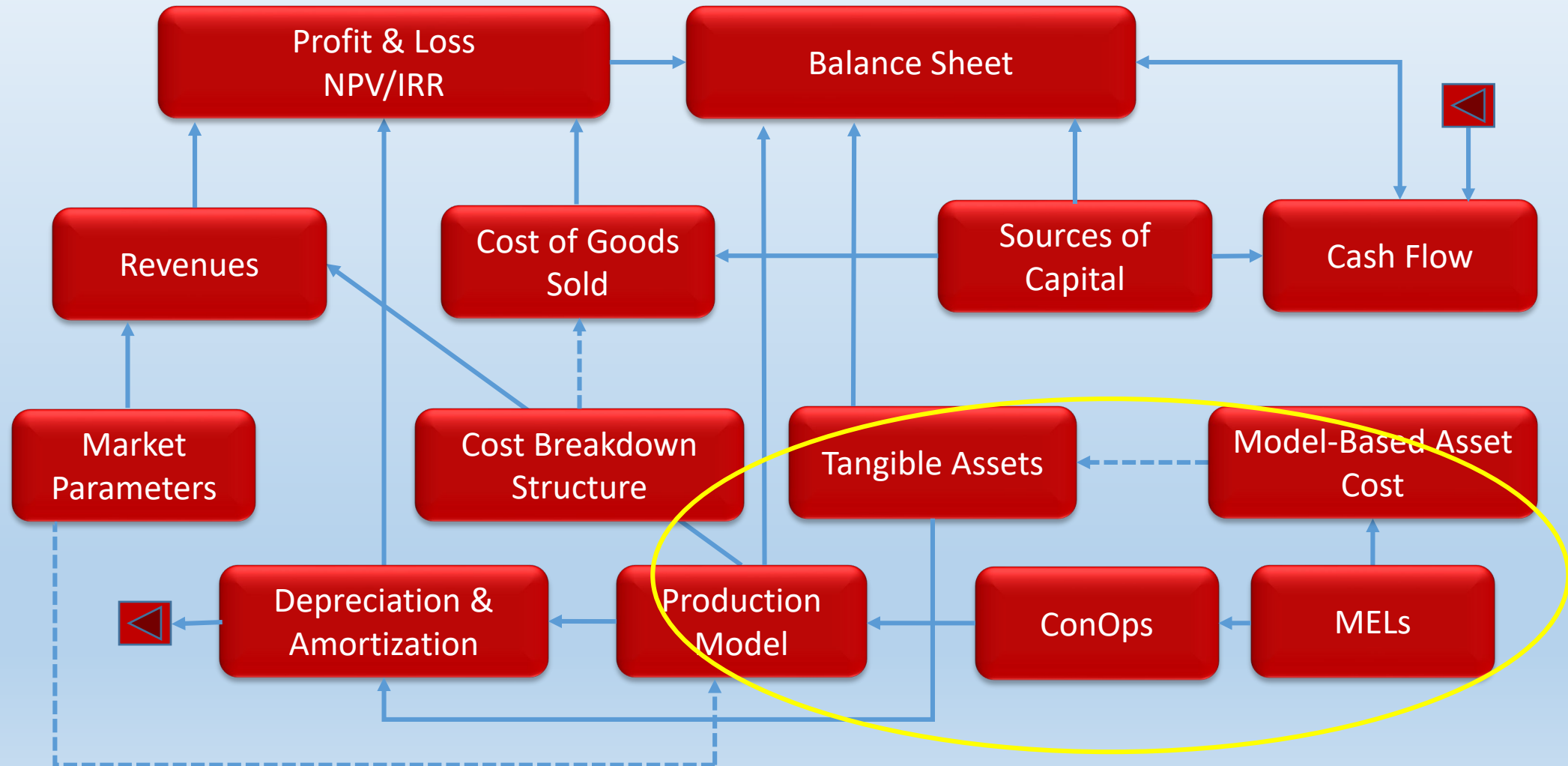
- Charania, A.C., DePasquale, D., “Economic Analysis of a Lunar ISRU Propellant Services Market,” IAC Paper 07-A5.1.03, 2007
  - Financial model computes sales price/kg such that  $NPV(0.217, 18) = 0$ ; uses \$80K/kg for equipment capital costs + \$90K/kg for lunar deployment (FY19); 20.94 mt mine (including nuclear power plant) produces 49.4 mt/year of propellant.
  - Three main delivery scenarios—lunar surface, LLO, GEO—with variations; sales prices are \$35.3K/kg, \$176.1K/kg, >\$9M/kg respectively.
- Kornuta, D., et al., “Commercial Lunar Propellant Architecture,” CSM/ULA, 2018.
  - Financial model computes NPV and IRR; uses \$100K/kg for equipment capital costs + \$35K/kg for lunar deployment; 30 mt mine producing 1640 mt/year of propellant.
  - Seven demand scenarios with two resulting in  $NPV < 0$  and five  $> 0$ ; LEO delivery market is worse case; price depends on delivery location.
- Jones, C., et al., “Cost Breakeven Analysis of Cis-lunar ISRU for Propellant,” AIAA-2019-1372, SciTech Forum 2019.
  - Uses kg/(kg/year) + \$/kg leveraged from CxP for surface mining systems; LSPC for commercial LVs, but RoM for SLS; none revealed.
  - To a cis-lunar aggregation point, “lunar ISRU propellant is 97% more expensive than Earth-based propellant.” \$40K versus \$78K per kg.
- Pelech, T., Roesler, G., Saydam, S., “Technical Evaluation of Off-Earth Ice Mining Scenarios Through an Opportunity Cost Approach,” *Acta Astronautica* 162 (2019) 388-404.
  - Avoids costs and NPV altogether; instead uses Propellant Payback Ratio (PPR); contains many useful mining equations.
  - Lunar *in situ* ice sublimation has a  $PPR < 1$  even after many years.
- Bennett, N., Dempster, A., “Geosynchronous Transit Orbits as a Market for Impulse Delivered by Lunar Sourced Propellant,” submitted to *Planetary and Space Science*, 2019.
  - Uses the same \$/kg factors as in Kornuta; calculates NPV and IRR; relies on propellant “burn-to-deliver ratio” calculated from the rocket equation.
  - GTO is a more viable market than LEO for impulse delivery; NPV and IRR are much higher (and  $> 0$ ) due to smaller scale of lunar operations.

# Purpose

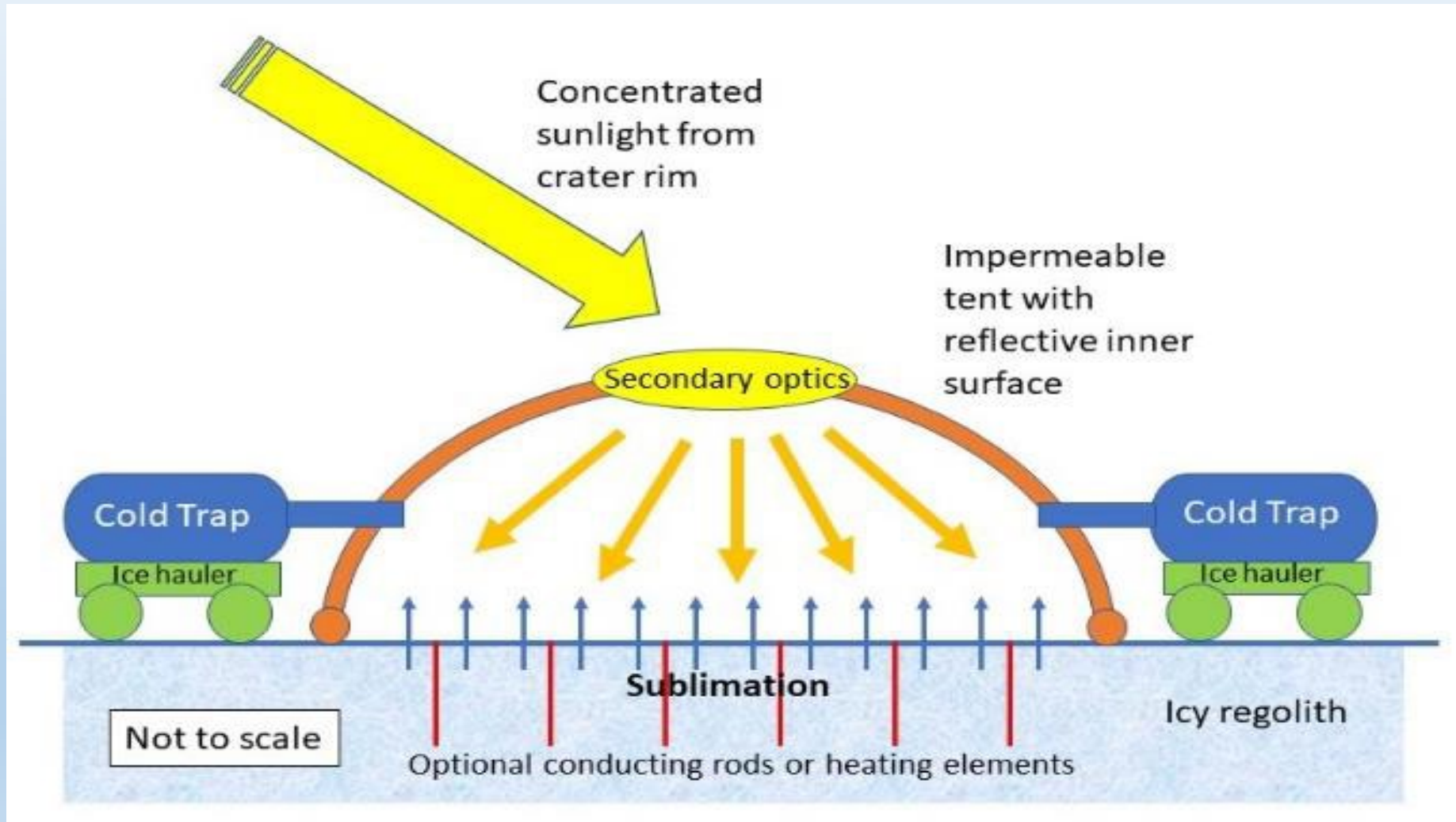
- Establish the case for the proposed ISRU technology against delivering propellant from Earth (or other alternative).
  - Establish at what level of demand, if any, does the business case close.
  - Determine if and where tipping points occur.
- Develop an engineering-based production rate model for the proposed ISRU technology that enables tradespace exploration.
  - Provide quantitative estimates for design parameters for cost models.
  - Determine which design parameters in the design vector have the greatest effect on production
  - Determine which feasible combinations of those design parameters make the most sense

**Note: Each technology requires a custom production rate model**

# Establishing the Business Case: Lean BCA Framework

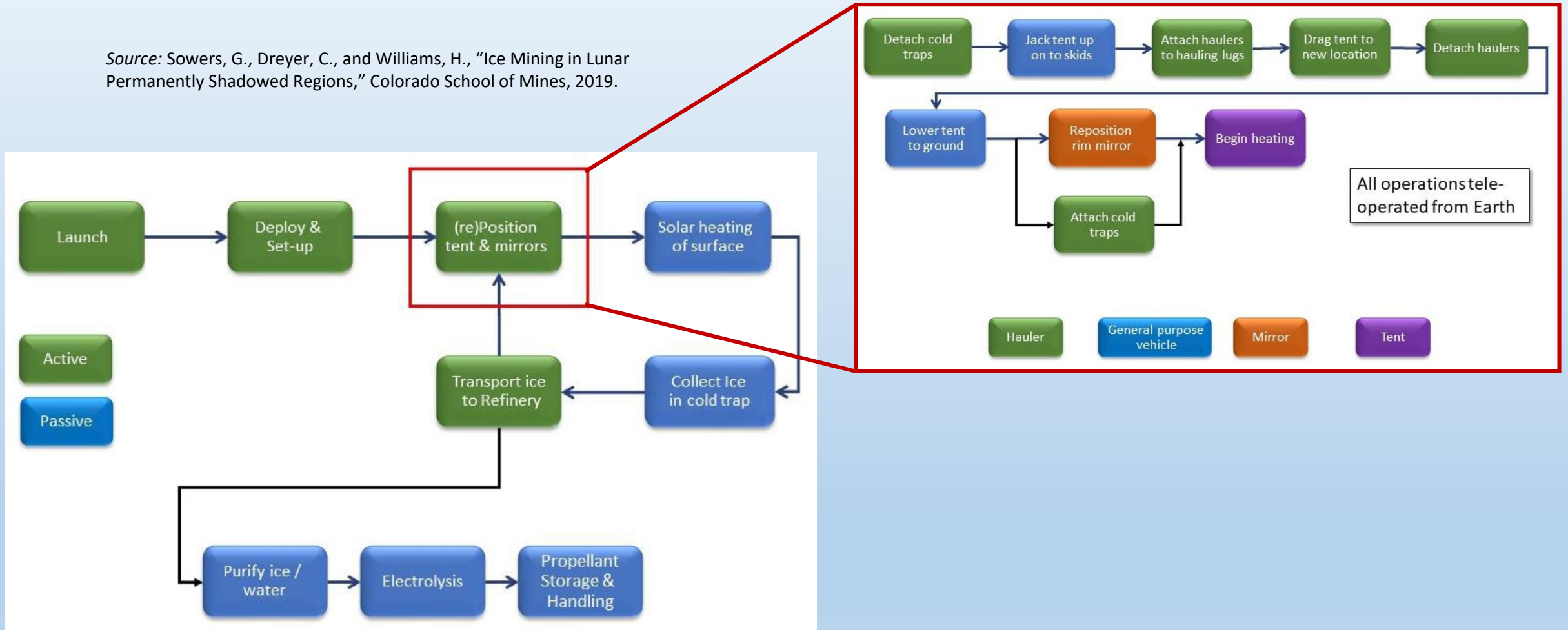


# Lunar Thermal Mining in Permanently Shadowed Craters

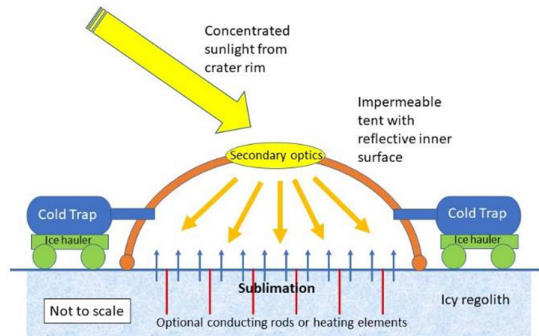
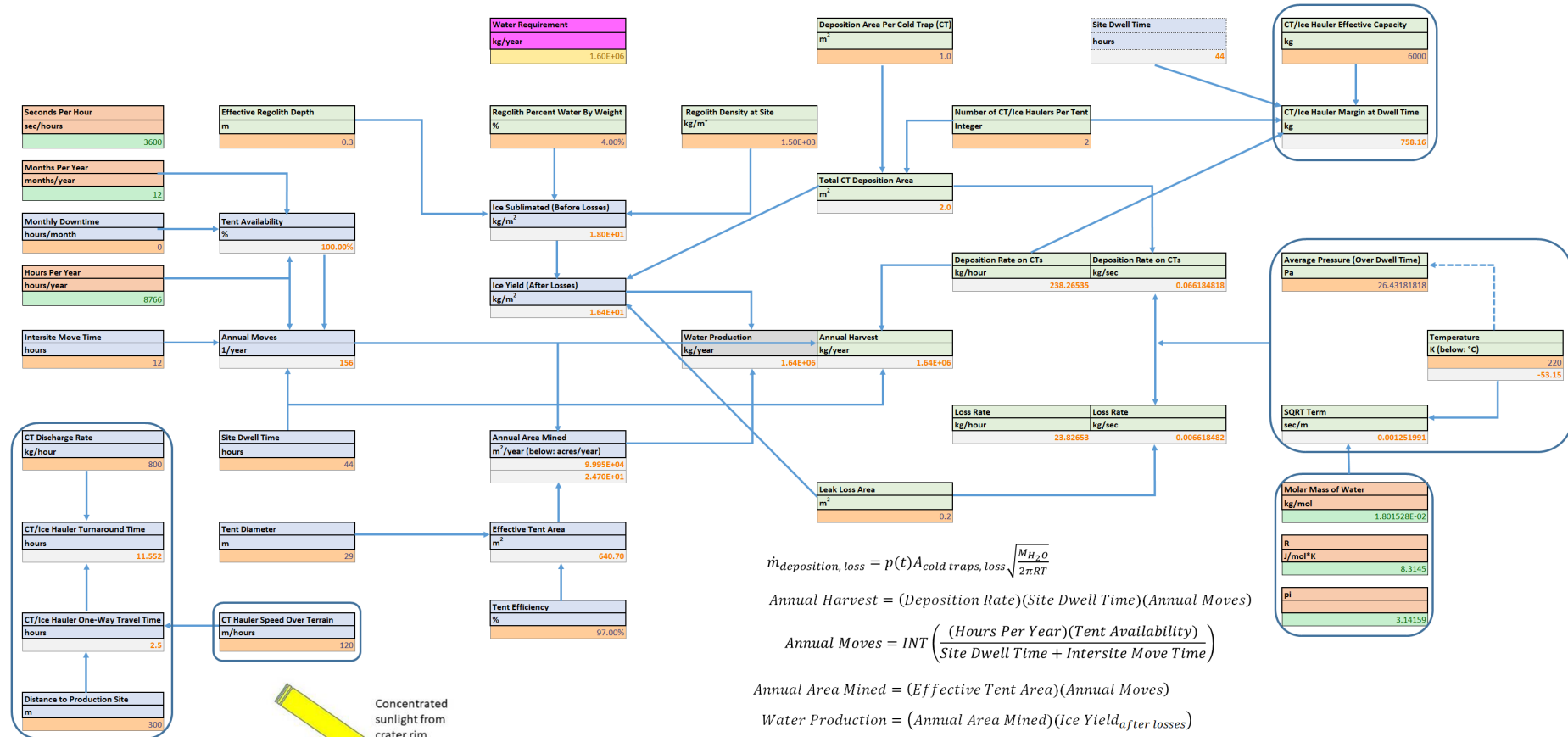


# Lunar Thermal Mining Concept of Operations

Source: Sowers, G., Dreyer, C., and Williams, H., "Ice Mining in Lunar Permanently Shadowed Regions," Colorado School of Mines, 2019.



# Lunar Thermal Mining Production Model: "Threads of Calculation"



$$\dot{m}_{\text{deposition, loss}} = p(t)A_{\text{cold traps, loss}}\sqrt{\frac{M_{H_2O}}{2\pi RT}}$$

$$\text{Annual Harvest} = (\text{Deposition Rate})(\text{Site Dwell Time})(\text{Annual Moves})$$

$$\text{Annual Moves} = \text{INT} \left( \frac{(\text{Hours Per Year})(\text{Tent Availability})}{\text{Site Dwell Time} + \text{Intersite Move Time}} \right)$$

$$\text{Annual Area Mined} = (\text{Effective Tent Area})(\text{Annual Moves})$$

$$\text{Water Production} = (\text{Annual Area Mined})(\text{Ice Yield}_{\text{after losses}})$$

$$\text{Tent Availability} = 1 - \left( \frac{(\text{Monthly Downtime})(\text{Months Per Year})}{\text{Hours Per Year}} \right)$$

$$\text{Ice Sublimated}_{\text{before losses}} = (\text{Regolith \% Water by Weight})(\text{Regolith Density})(\text{Effective Depth})$$

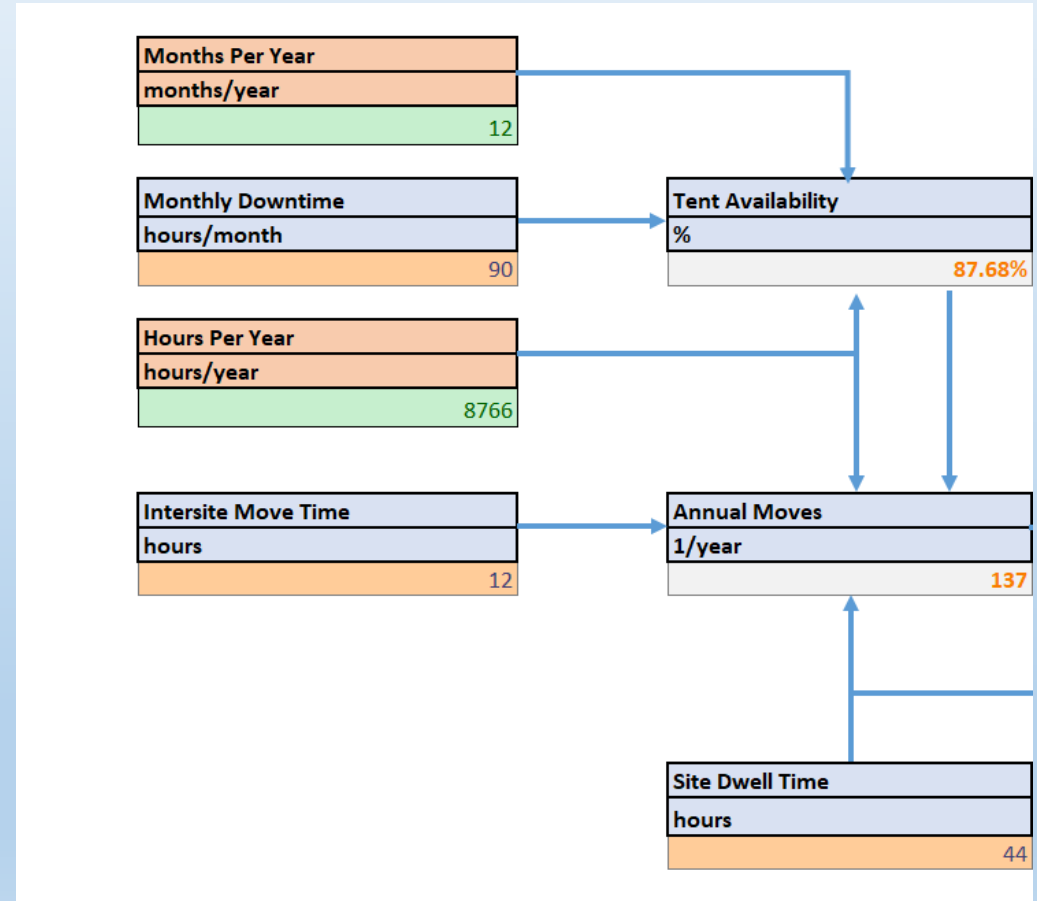
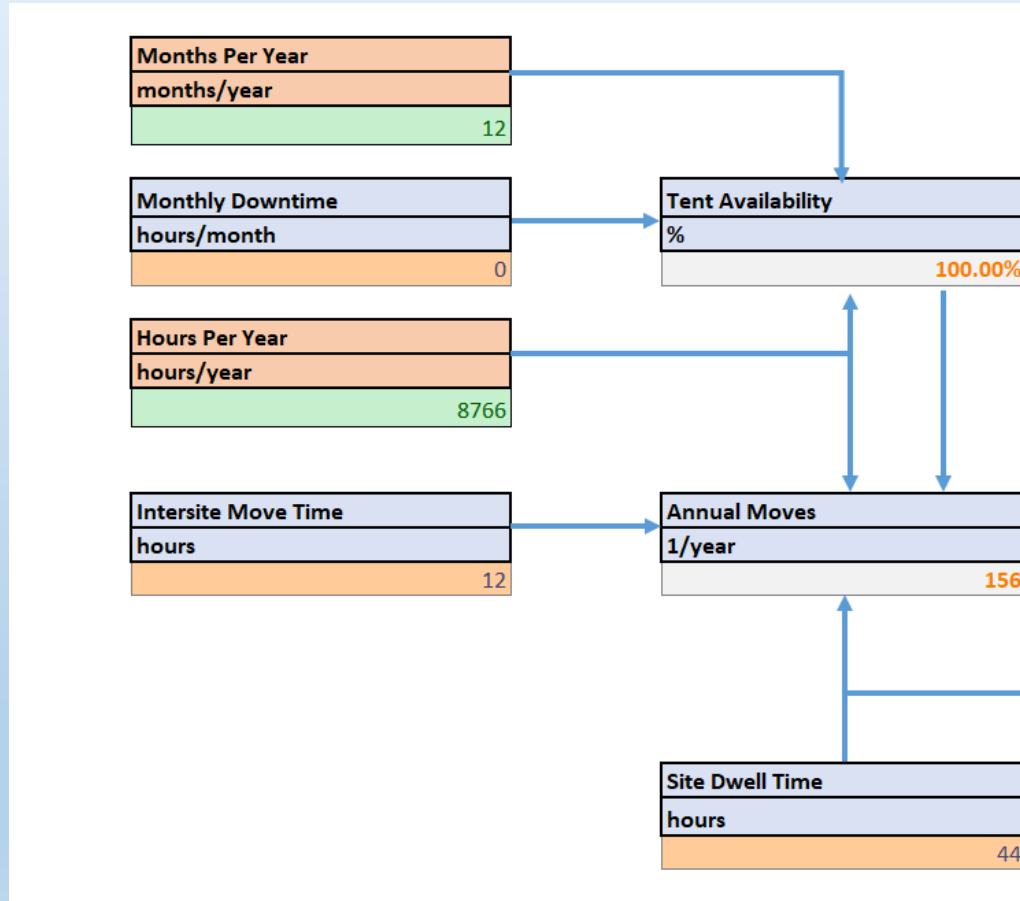
$$\text{Ice Yield}_{\text{after losses}} = \text{Ice Sublimated}_{\text{before losses}} \left( 1 - \frac{A_{\text{loss}}}{A_{\text{loss}} + A_{\text{cold trap}}} \right)$$

$$\text{Effective Tent Area} = \pi \left( \left( \frac{\text{Tent Diameter}}{2} \right)^2 (\text{Tent Efficiency}) \right)$$

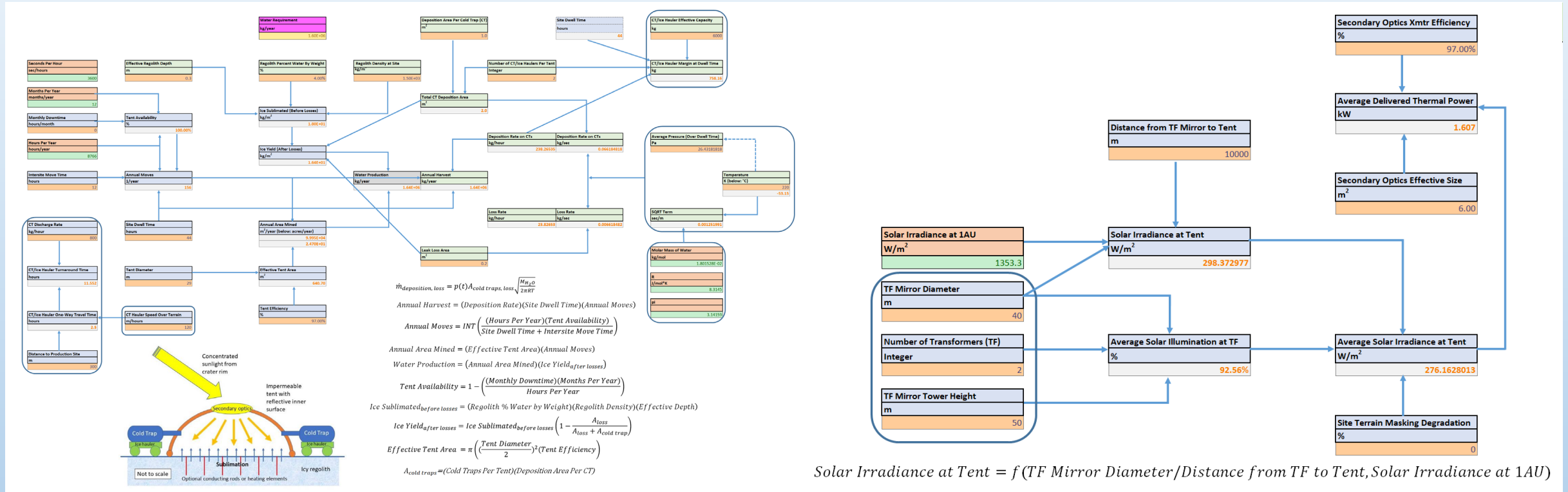
$$A_{\text{cold traps}} = (\text{Cold Traps Per Tent})(\text{Deposition Area Per CT})$$

Average Pressure (Over Dwell Time)	Pa	26.43181818
Temperature	K (below: °C)	220 -59.15
SQRT Term	sec/m	0.001251991
Molar Mass of Water	kg/mol	1.801528E-02
R	J/mol*K	8.3145
pi		3.14159

# “Threads of Calculation” from Tent Downtime to Annual Tent Moves and Annual Production



# Lunar Thermal Mining Production Model: "Threads of Calculation"

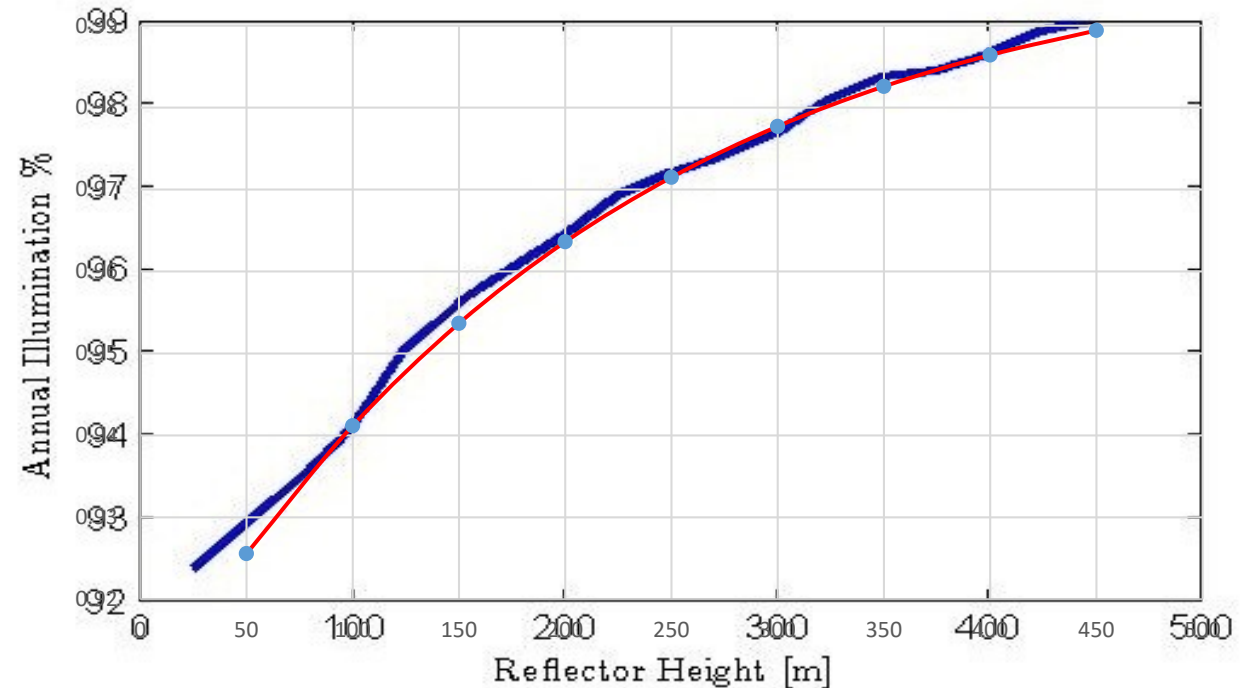
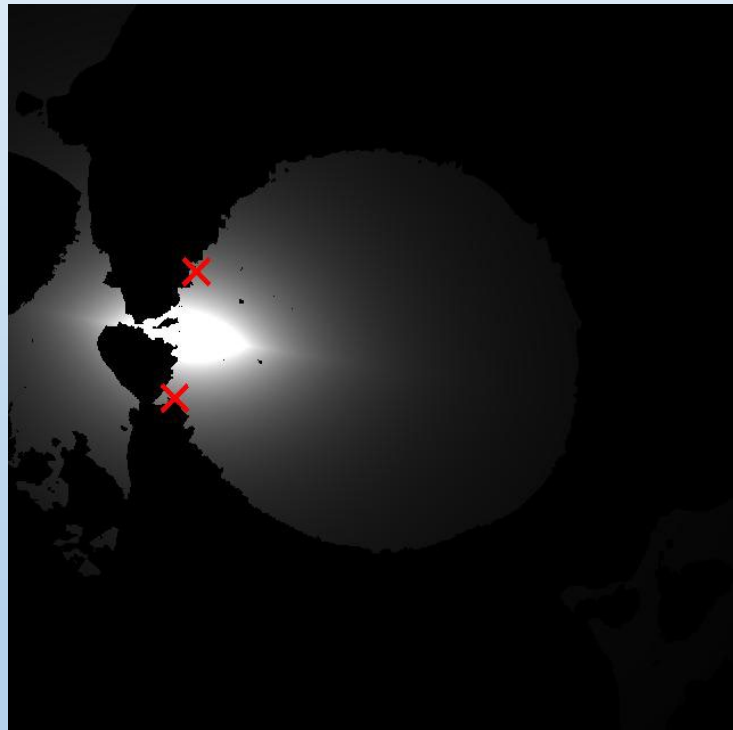


In total so far, the design vector has 22 input variables, excluding physical constants.

# Average Solar Illumination

Source: Henrickson, J., Stoica, A., "Reflector Placement for Providing Near-Continuous Solar Power to Robots in Shackleton Crater," IEEE Aerospace Conference, Big Sky, MT, 2017.

**Results for Two TransFormers Located at  
89.9029°S 145.2301°W and 89.6876°S 162.8645°W**



$$L = \exp(2.26844 + 0.00504H) / (1 + \exp(2.26844 + 0.00504H))$$

# Production Model Engineering Database (Partial)

Maintains configuration management for tradespace exploration input and output data.

Production Model

Mass estimates are critical to costing these surface systems.

MELs

Scenario ID	Equipment ID	Equipment Name	Parameter ID	Parameter Name	Parameter Units	Parameter Value
1	1	Thermal Tent Mobility/Setup Robotics	3	Monthly Downtime	hours	5
1	1	Thermal Tent Mobility/Setup Robotics	4	Design Life	years	10
1	1	Thermal Tent Mobility/Setup Robotics	12	Unit Dry Mass	kg	1000
1	2	Cold Trap/Ice Hauler	3	Monthly Downtime	hours	
1	2	Cold Trap/Ice Hauler	4	Design Life	years	10
1	2	Cold Trap/Ice Hauler	5	Effective Capacity	kg	6000
1	2	Cold Trap/Ice Hauler	6	Distance (Excavation Site-to-Plant)	m	300
1	2	Cold Trap/Ice Hauler	12	Unit Dry Mass	kg	1050
1	2	Cold Trap/Ice Hauler	18	Effective Speed Over Terrain	m/hour	180
1	3	Solar Reflectors (TransFormers)	2	Height	m	50
1	3	Solar Reflectors (TransFormers)	8	Diameter	m	40
1	3	Solar Reflectors (TransFormers)	9	Efficiency	%	96
1	4	ISRU Water Purification and H2-O2 Production	3	Monthly Downtime	hours	
1	4	ISRU Water Purification and H2-O2 Production	4	Design Life	years	10
1	4	ISRU Water Purification and H2-O2 Production	10	Nominal Production Rate	mt/year	
1	4	ISRU Water Purification and H2-O2 Production	12	Unit Dry Mass	kg	3000
1	5	Liquefaction Unit	3	Monthly Downtime	hours	
1	5	Liquefaction Unit	4	Design Life	years	8
1	5	Liquefaction Unit	10	Nominal Production Rate	mt/year	
1	5	Liquefaction Unit	12	Unit Dry Mass	kg	3000
1	6	Integrated Cryo-Propellant Hauler w/CFM	3	Monthly Downtime	hours	
1	6	Integrated Cryo-Propellant Hauler w/CFM	4	Design Life	years	10
1	6	Integrated Cryo-Propellant Hauler w/CFM	5	Effective Capacity	kg	
1	6	Integrated Cryo-Propellant Hauler w/CFM	7	Distance (Plant-to-Lander Site)	m	1000
1	6	Integrated Cryo-Propellant Hauler w/CFM	12	Unit Dry Mass	kg	1000
1	6	Integrated Cryo-Propellant Hauler w/CFM	18	Effective Speed Over Terrain	m/hour	180
1	7	Thermal Tent w/Secondary Optics	8	Diameter	m	29
1	7	Thermal Tent w/Secondary Optics	9	Efficiency	%	0.97
1	7	Thermal Tent w/Secondary Optics	11	Move and Set Up Time	hours	12
1	7	Thermal Tent w/Secondary Optics	12	Unit Dry Mass	kg	8000
1	8	Power Generation Station	3	Monthly Downtime	hours	
1	8	Power Generation Station	4	Design Life	years	15
1	8	Power Generation Station	12	Unit Dry Mass	kg	4000
1	8	Power Generation Station	16	Power	W	

# Lunar Thermal Mining In-Service Elements

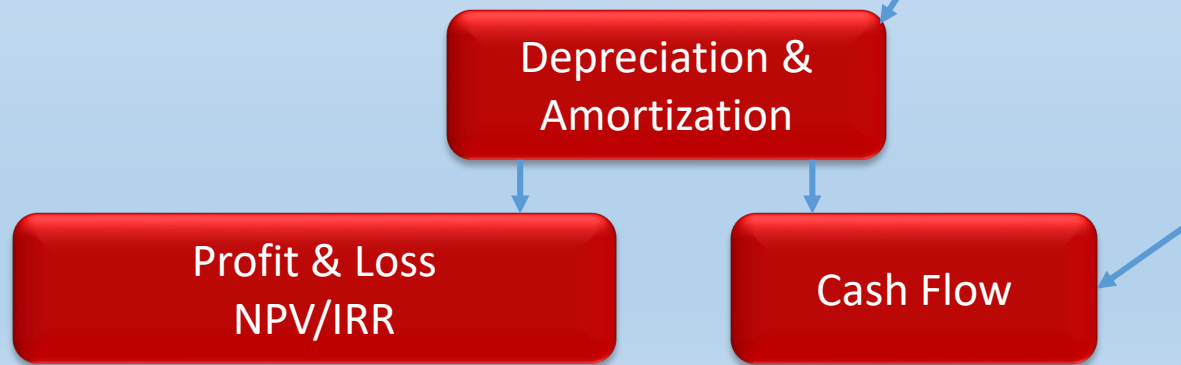
Production Model

Scenario ID	Equipment ID	Equipment Name	Equipment Operating Location	Required Operational Quantity	Required Spares Quantity
1	1	Thermal Tent Mobility/Setup Robotics	PSR	3	2
1	2	Cold Trap/Ice Hauler	PSR	2	1
1	3	Solar Reflectors (TransFormers)	Crater Rim	3	0
1	4	ISRU Water Purification and H2-O2 Production	PSR	2	0
1	5	Liquefaction Unit	PSR	1	0
1	6	Integrated Cryo-Propellant Hauler w/CFM	PSR	2	0
1	7	Thermal Tent w/Secondary Optics	PSR	1	0
1	8	Power Generation Station	PSR	1	0

Depreciation & Amortization

# Tangible Assets Attributes

- Contains development and TFU estimated cost, acquisition time, dry mass, volume, power, data rate, capacity, availability, design life (replacement time), cost margin to be applied.
- Calculates year-by-year costs.
- Development and TFU cost CT/Ice Hauler from *Quickcost v.6.0*, released March 2016
  - 1.05 mt dry mass
  - 50% new design



Lunar Thermal Mining Corporation  
**TANGIBLE ASSETS ATTRIBUTES** Note: Provide names for assets in Row 8. These names will be copied automatically throughout the workbook, as needed.

Do Not Overwrite ---->

Attribute	Asset #1	Asset #2	Asset #3	Asset #4	Asset #5	Asset #6	Asset #7	Asset #8	Asset #9	Asset #10
Name	Setup Robotics	CT/Ice Hauler	Solar Reflectors	IHOP	Liquefaction Unit	CryoProp Hauler	Thermal Tent	CryoProp Storage	Power Gen Stn	MCC
Description	Thermal Tent Mobility and Setup Robotics	Integrated Cold Trap and Mobility Robotics	Tower-Mounted Solar Reflectors to Redirect Solar Energy	Water Purification and H2 - O2 Production	Produces Cryogenic LH2 - LO2 Propellant	Cryo-Propellant Hauler Robotics with Integrated CFM	Captures Sublimated Ice Using Redirected Solar Energy	Stores Cryogenic LH2 - LO2 Propellants	Provides power to Haulers, IHOP, and Liquefaction Unit	Earth-based Monitoring of Autonomous Operations
Development Cost (in \$FY19M)	\$	370.8								30.0
Unit Production Cost (in \$FY19M)	\$	55.6								20.0
Cost Margin Applied (%)		50%								0%
Planned Replacement Time (years)	10	10	15	7	7	10	15	15	15	20
Depreciation Schedule	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated	Straight Line Accelerated
Depreciation Period (years)	10	10	10	7	7	10	15	15	15	15
Acquisition / Development Time (years)	3	4	5	1						
Acquisition / Production Time (years)	1	2	3	1		5	2	5		
Payment Schedule	50/50 One-Time	50/50 One-Time	50/50 One-Time	50/50 One-Time	50/50 One-Time	50/50 One-Time	50/50 One-Time	40/60 One-Time	40/60 One-Time	One-Time Quarterly
Dry Mass, Predicted (kg)	1000	1050.0	2500	3000		500	8000		4000	
New Design (%)		25%	50%	50%	25%	25%	75%	0%	0%	
Volume, Packaged for Launch (cu-m)										
Power, Avg (kW)										
Power, Peak (kW)										
Data Rate (Mb/sec)										
Effective Capacity (kg)		6000								
Output Rate (kg/hour)										
Availability (%)	87.7%									
Design Life (years)	10	10	15	7	7	10	15	15	15	20
Lease or Buy or Produce	Buy Lease Produce	Buy Lease Produce	Buy Lease Produce	Buy Lease Produce	Buy Lease Produce	Buy Lease Produce	Buy Lease Produce	Lease Produce	Lease Produce	Buy Lease Produce
Unit Lease Cost (in \$FY19M/year)	\$	\$	\$	\$	\$	\$	\$	\$	\$	(7.905)

**MODEL-BASED COST ESTIMATES**

	Asset #1	Asset #2	Asset #3	Asset #4	Asset #5
Development Cost (in \$FY19M)		\$ 247.2			
Theoretical First Unit Production Cost (in \$FY19M)					
Sustainment Cost (in \$FY19M)					

**INVESTMENT COST SPREADER**

	Asset #1	Asset #2	Asset #3	Asset #4	Asset #5	Asset #10
Development Cost 1st Year	\$ 29.66					
Development Cost 2nd Year	\$ 118.64					
Development Cost 3rd Year	\$ 152.01					
Development Cost 4th Year	\$ 70.44					
Development Cost 5th Year	\$ -					
Development Cost 6th Year	\$ -					
Development Cost 7th Year	\$ -					
Development Cost 8th Year	\$ -					
Development Cost 9th Year	\$ -					
Development Cost 10th Year	\$ -					
<b>Total Development Cost (Check)</b>	\$ -	\$ 370.75	\$ -	\$ -	\$ -	\$ -
Production Cost 1st Year	\$ 22.25					
Production Cost 2nd Year	\$ 33.37					
Production Cost 3rd Year	\$ -					
Production Cost 4th Year	\$ -					
Production Cost 5th Year	\$ -					
Production Cost 6th Year	\$ -					
Production Cost 7th Year	\$ -					
Production Cost 8th Year	\$ -					
Production Cost 9th Year	\$ -					
Production Cost 10th Year	\$ -					
<b>Total Production Cost (Check)</b>	\$ -	\$ 55.61	\$ -	\$ -	\$ -	\$ -

**Model-Based Asset Cost**

**MELs**

$$C = 1.1847 \exp(-0.26 + 0.585 \ln(M) + 2.6\text{Percent New Design} + 0.231\text{Location})$$



# Profit and Loss Calculations

Lunar Thermal Mining Corporation

## PROFIT & LOSS STATEMENT

Target

^

In Millions of US\$

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Sales Revenue	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Less: Cost of Goods Sold (COGS)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Less: Direct Overheads	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Gross Margin</b>	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Less: Indirect Overheads	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>EBITDA</b>	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Less: Depreciation and Amortization	\$ 1.333	\$ 1.333	\$ 11.445	\$ 20.545	\$ 28.634	\$ 25.601	\$ 22.567	\$ 19.534	\$ 16.500	\$ 13.467	\$ 10.434	\$ 7.400	\$ 14.478	\$ 21.556	\$ 28.634	\$ 24.267	\$ 21.234	\$ 18.201	\$ 15.167	\$ 12.134
<b>EBIT</b>	\$ (1.333)	\$ (1.333)	\$ (11.445)	\$ (20.545)	\$ (28.634)	\$ (25.601)	\$ (22.567)	\$ (19.534)	\$ (16.500)	\$ (13.467)	\$ (10.434)	\$ (7.400)	\$ (14.478)	\$ (21.556)	\$ (28.634)	\$ (24.267)	\$ (21.234)	\$ (18.201)	\$ (15.167)	\$ (12.134)
Plus: Interest Income	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Less: Interest Expense	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Net Profit Before Taxes</b>	\$ (1.333)	\$ (1.333)	\$ (11.445)	\$ (20.545)	\$ (28.634)	\$ (25.601)	\$ (22.567)	\$ (19.534)	\$ (16.500)	\$ (13.467)	\$ (10.434)	\$ (7.400)	\$ (14.478)	\$ (21.556)	\$ (28.634)	\$ (24.267)	\$ (21.234)	\$ (18.201)	\$ (15.167)	\$ (12.134)
Less: Income Tax Expense	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Net Profit After Taxes</b>	\$ (1.333)	\$ (1.333)	\$ (11.445)	\$ (20.545)	\$ (28.634)	\$ (25.601)	\$ (22.567)	\$ (19.534)	\$ (16.500)	\$ (13.467)	\$ (10.434)	\$ (7.400)	\$ (14.478)	\$ (21.556)	\$ (28.634)	\$ (24.267)	\$ (21.234)	\$ (18.201)	\$ (15.167)	\$ (12.134)
Less: Dividends Paid Out	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Retained Earnings</b>	\$ (1.333)	\$ (1.333)	\$ (11.445)	\$ (20.545)	\$ (28.634)	\$ (25.601)	\$ (22.567)	\$ (19.534)	\$ (16.500)	\$ (13.467)	\$ (10.434)	\$ (7.400)	\$ (14.478)	\$ (21.556)	\$ (28.634)	\$ (24.267)	\$ (21.234)	\$ (18.201)	\$ (15.167)	\$ (12.134)

## NET PRESENT VALUE TABLE

Discount Rate 12.5%

In Millions of US\$

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
<b>Net Profit After Taxes</b>	\$ (1.333)	\$ (1.333)	\$ (11.445)	\$ (20.545)	\$ (28.634)	\$ (25.601)	\$ (22.567)	\$ (19.534)	\$ (16.500)	\$ (13.467)	\$ (10.434)	\$ (7.400)	\$ (14.478)	\$ (21.556)	\$ (28.634)	\$ (24.267)	\$ (21.234)	\$ (18.201)	\$ (15.167)	\$ (12.134)
Plus: Depreciation and Amortization	\$ 1.333	\$ 1.333	\$ 11.445	\$ 20.545	\$ 28.634	\$ 25.601	\$ 22.567	\$ 19.534	\$ 16.500	\$ 13.467	\$ 10.434	\$ 7.400	\$ 14.478	\$ 21.556	\$ 28.634	\$ 24.267	\$ 21.234	\$ 18.201	\$ 15.167	\$ 12.134
Less: Capital Investment	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Net Cash From Operations (Cash Flow)</b>	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
<b>Investor Cash Flow</b>	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -

Net Present Value	\$0.00
Project Internal Rate of Return	#NUM!
Investor Internal Rate of Return	

# Results Recapitulation

- An engineering-based production rate model is essential to build a defensible BCA.
- Progress in creating a thermal mining production rate model as a function of the “assets” (elements) to be deployed and employed on the lunar surface.
  - Reliability and maintainability considerations (MTBF and MTTR) are important in estimating the overall production rate and the number of “stand-by” assets needed.
  - Other logistics considerations regarding robotic travel distances and speed over terrain could add waiting time, thereby decreasing the overall production tempo.
  - To be consistent, the CT/Ice Hauler dry mass needed to be ~15% — 30% larger than previously published.
  - Location (e.g., %water by weight) and element position geometry matter (e.g., solar thermal power delivered within tent depends strongly on the distance from the crater rim-sited solar reflectors and the tent, and on reflector diameter and height above terrain.)
- Estimating the costs of each element will be a continuing challenge.
  - Current cost models for spacecraft may not be appropriate for surface systems

# Moving Forward

- Relationship between the thermodynamic properties of regolith/lunar ice and the ice deposition rate (via tent pressure build-up) not yet established.
  - Not a clear relationship yet between solar thermal power delivered and tent pressure build-up as a function of percent water by weight and other tent physical parameters.
  - Thermal diffusivity of regolith at PSR conditions.\*
  - Sublimation, vapor transport, and deposition processes and rates.\*
  - Effects of ice grain size, porosity, and impurities.\*
- Need actual lunar demonstrations informed by laboratory simulations
- Need more detail in the ops concept in order to validate production rate model.
- Need to incorporate both market (e.g., demand) and physical uncertainty (e.g., water content in regolith).
- **Need a new approach to estimating and scaling costs for these kinds of lunar surface systems; \$ per kg is just not sufficient for high confidence.**

\*See References 3-8 in backup

# General Observations

- The good news—business economists, mining engineers, and space systems engineers are beginning to have the needed conversations.
- The bad news—real BCA models and calculations need to replace the generally “toy models” used in the past; cost engineers need to step up to this challenge.
  - No consensus on market demand.
  - No consensus on the capital expenditures needed for a lunar “mine.”
  - No consensus even on the cost of a propellant delivery service from Earth to various cis-lunar nodes, much less from the lunar surface.

# Backup

Business Case Analysis of Lunar Thermal Mining

# Establishing the Business Case: The Lean Framework Implemented

- Sheet Name: System MEL (1 Sheet Per System)  
Contains the mass of spacecraft and surface systems, and the ConOps for their employment.
- Sheet Name: Launch Vehicles and Costs  
Contains LV performance and costs.
- Sheet Name: Detailed In-Service Schedule  
Contains the number of assets placed in service quarterly. Also contains quarterly costs associated with launch services. Use of this detailed sheet is optional, if the user wants to provide placed-in-service on a year-by-year basis directly on the depreciation sheet.
- Sheet Name: Cost Breakdown Structure  
Sets the high-level cost structure used in the COGS sheet.
- Sheet Name: Schedule and Activity Cost  
Provides detailed accounting of all costs. Nominally, the quarterly costs entered on this sheet are aggregated to annual costs on the COGS sheet. Use of this detailed sheet is optional, if the user wants to provide costs on a year-by-year basis directly on the COGS sheet.
- Sheet Name: Cost of Goods Sold (COGS)  
Contains all costs against each cost breakdown structure element.
- Sheet Name: Tangible Assets  
Contains the list of all assets with asset characteristics such as development and production costs, development and production durations, replacement schedules, type of depreciation, buy-or-lease, etc. Also spreads development and production costs across multiple years according to asset characteristics specified by the user.
- Sheet Name: Depreciation  
Computes depreciation (and amortization) based on tangible asset characteristics and the number of each asset place in service each year. Depreciation (straight-line or accelerated) is computed using VBA code.
- Sheet Name: Thermal Mining Production Model  
Determines how many mining surface systems,  $k_1, k_2, \dots, k_n$ , are needed to satisfy annual customer demands.
- Sheet Name: Power and Illumination Model  
Determines how many power surface systems,  $k_{n+1}, k_{n+2}, \dots, k_{n+m}$ , are needed to satisfy annual customer demands.
- Sheet Name: Detailed Revenue Forecast  
Contains a detailed (by quarter) revenue (sales) forecast. Use of this detailed sheet is optional, if the user wants to provide revenues on a year-by-year basis directly on the sales sheet.
- Sheet Name: Sales  
Aggregates all sales/revenues, computed from quantity sold and sales price for each revenue stream. Allows price to change from year-to-year.
- Sheet Name: Cash Flow  
Computes cash flow and accounts for all sources of capital.
- Sheet Name: Balance Sheet  
Aggregates total assets and liabilities and computes total equity.
- Sheet Name: Profit and Loss  
Aggregates revenues and costs, depreciation and taxes to get net profit. Also computes NPV and IRR when feasible.

# References

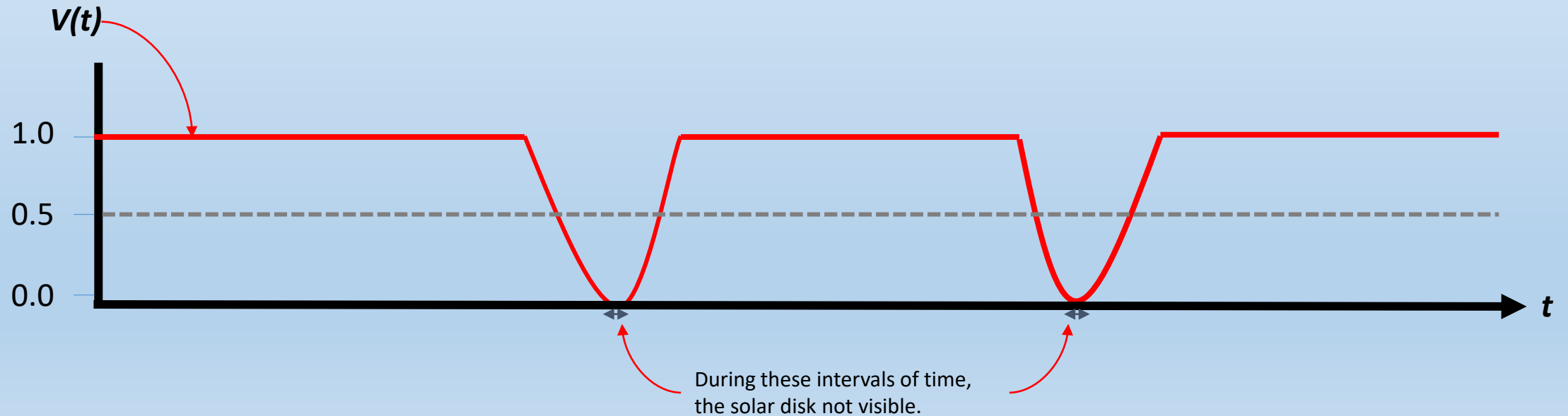
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# Definition: Average Solar Illumination

$$\overline{S}_\theta = \left( \frac{1}{T_2 - T_1} \right) \int_{t=T_1}^{t=T_2} V(t; \theta) dt \quad \text{where } V(t; \theta) = \begin{cases} V(t), & 1 \geq V(t) \geq \theta \\ 0, & \text{otherwise} \end{cases}$$

Note 1:  $V$  is the fraction of the solar disk that is visible at a specific location on the lunar surface.  $\theta$  is the fraction of the solar disk visibility above which the visibility is to be included in the average, so  $\overline{S}_\theta$  averages  $V(t)$  over the full time domain. Similarly,  $\overline{S}_1$  counts  $V(t)$  only when the full solar disk is visible.

Note 2: Usually, the average is taken over a calendar year or a longer multi-year period.



# Definition: Average Solar Visibility

$$\bar{V}_\theta = \left( \frac{1}{T_2 - T_1} \right) \int_{t=T_1}^{t=T_2} V(t; \theta) dt \quad \text{where } V(t; \theta) = \begin{cases} 1, & 1 \geq V(t) \geq \theta \\ 0, & \text{otherwise} \end{cases}$$

Note 1:  $V$  is the fraction of the solar disk that is visible at a specific location on the lunar surface.  $\theta$  is the fraction of the solar disk visibility above which the visibility is to be included in the average, so  $\bar{V}_\theta$  is the fraction of time any solar light is visible. Similarly,  $\bar{V}_1$  is the fraction of time the full solar disk is visible.

Note 2: Usually, the average is taken over a calendar year or a longer multi-year period.

Note 3: Average Solar Visibility  $\geq$  Average Solar Illumination.

