Business Case Analysis of Lunar Thermal Mining

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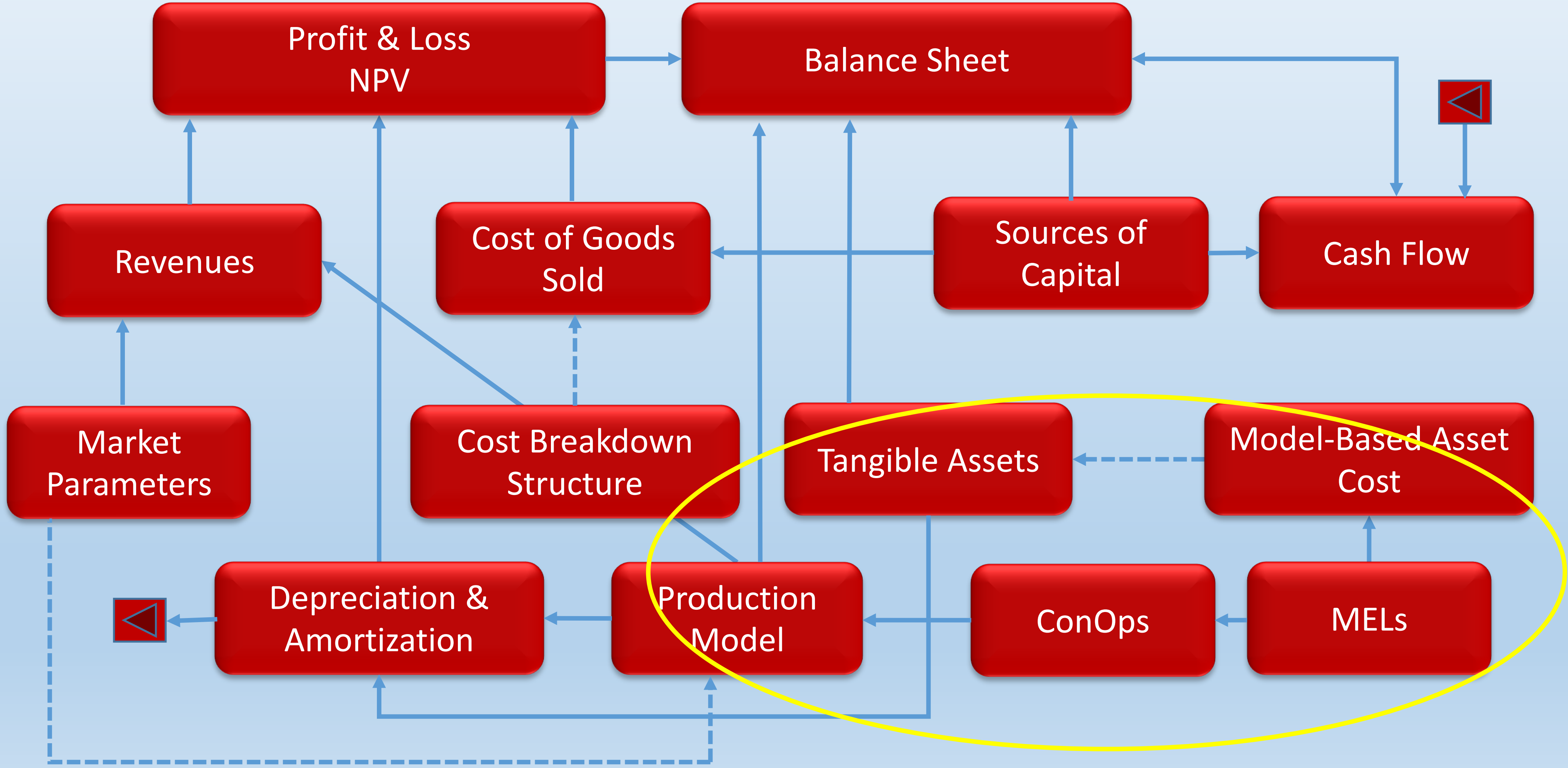
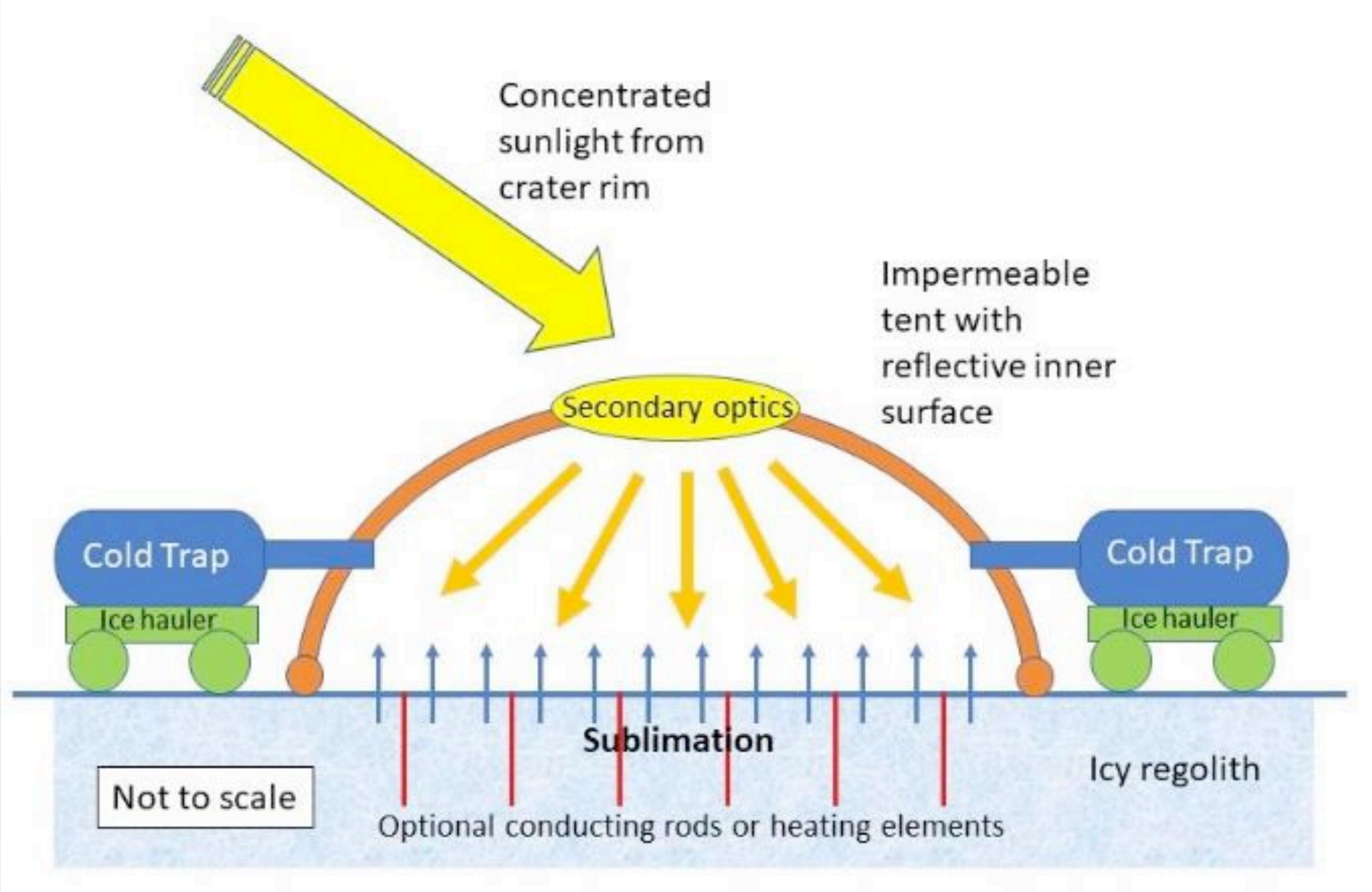
Purpose

- 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 (e.g., element mass).
  - 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?

Establishing the Business Case: Lean BCA Framework

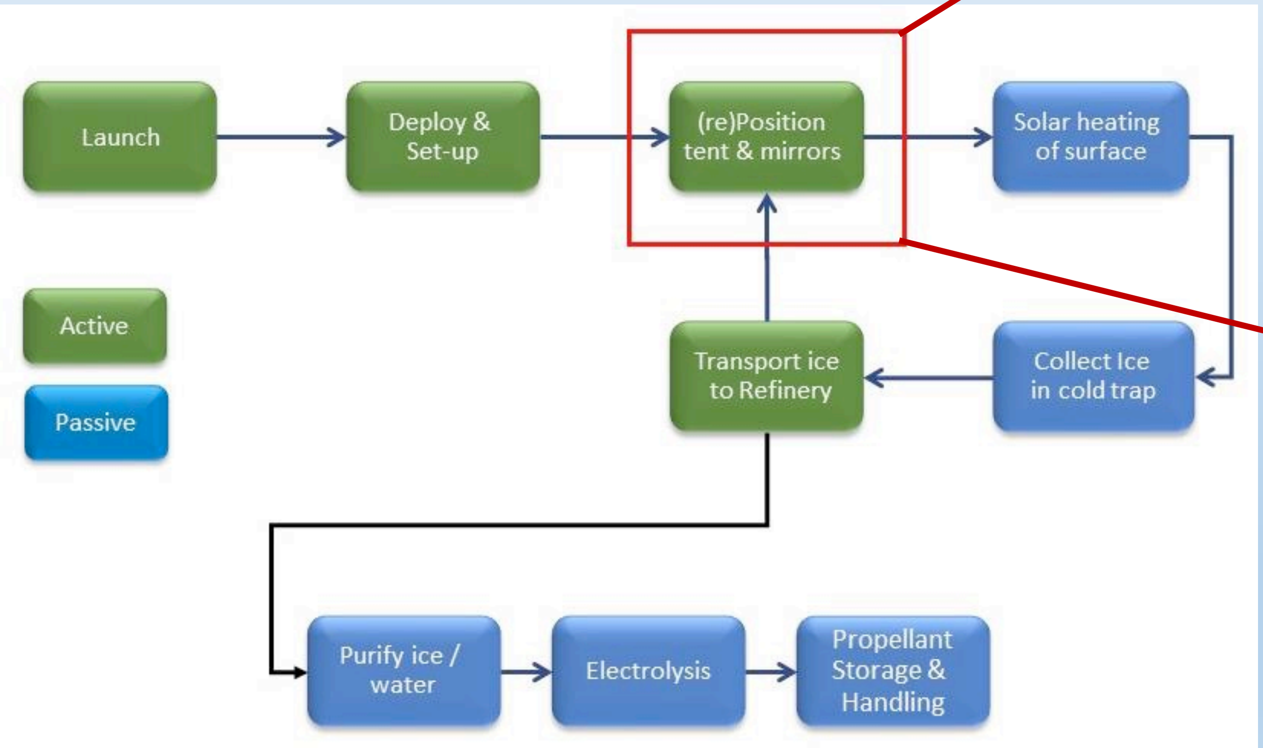


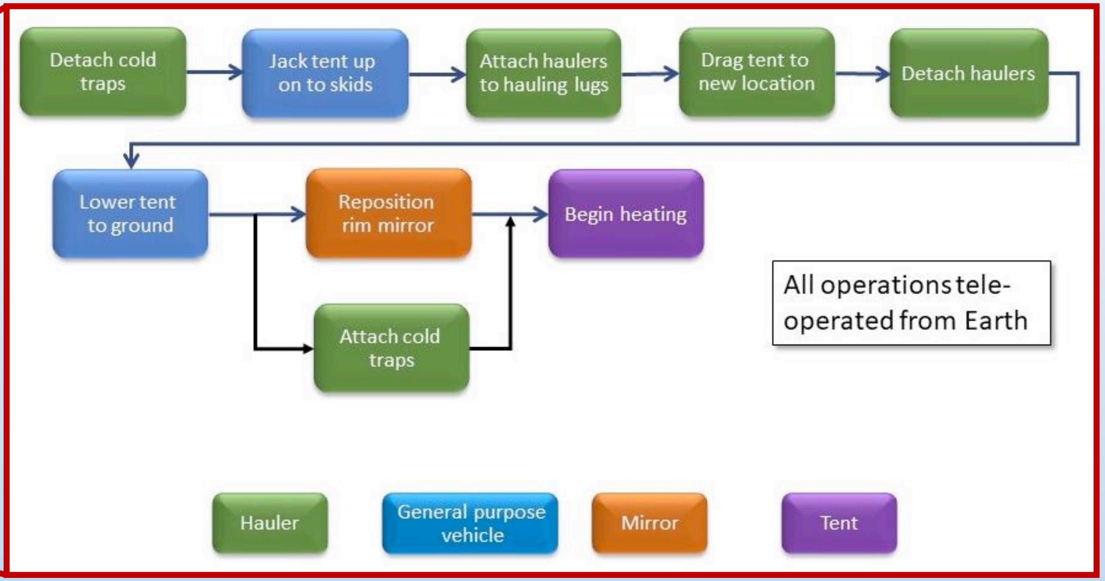
Lunar Thermal Mining Concept



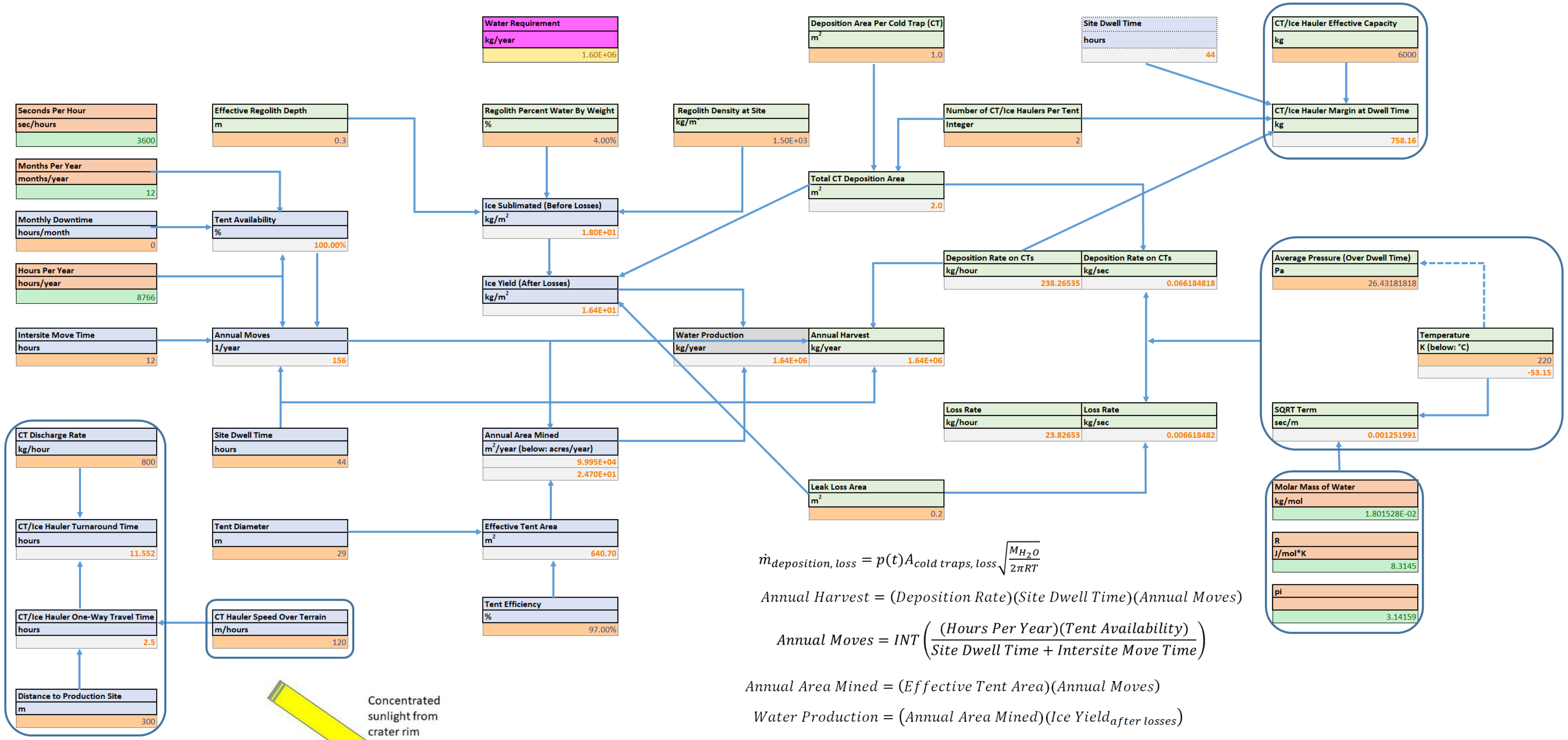
Lunar Thermal Mining Concept of Operations

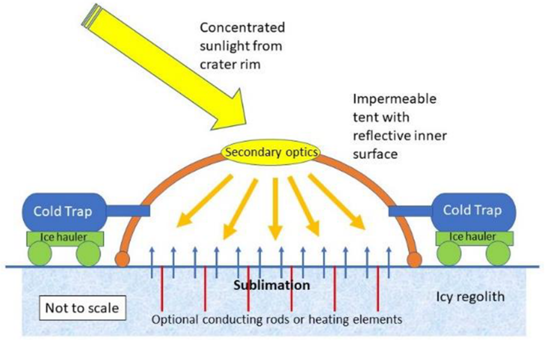
Source: Sowers, G., Dreyer, C., and Williams, H., “Ice Mining in Lunar Permanently Shadowed Regions,” Colorado School of Mines, 2019.





Lunar Thermal Mining Production Model: "Threads of Calculation"





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

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

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

$$Annual\ Area\ Mined = (Effective\ Tent\ Area)(Annual\ Moves)$$

$$Water\ Production = (Annual\ Area\ Mined)(Ice\ Yield_{after\ losses})$$

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

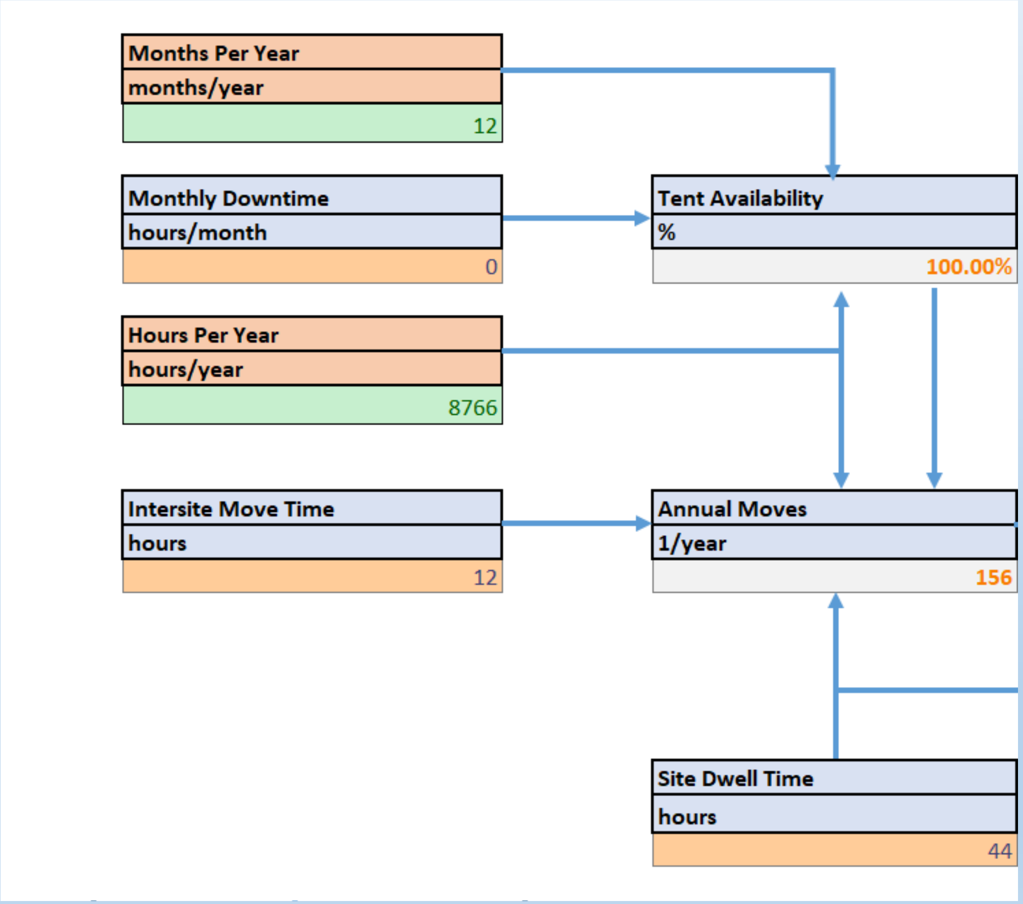
$$Ice\ Sublimated_{before\ losses} = (Regolith\ \%\ Water\ by\ Weight)(Regolith\ Density)(Effective\ Depth)$$

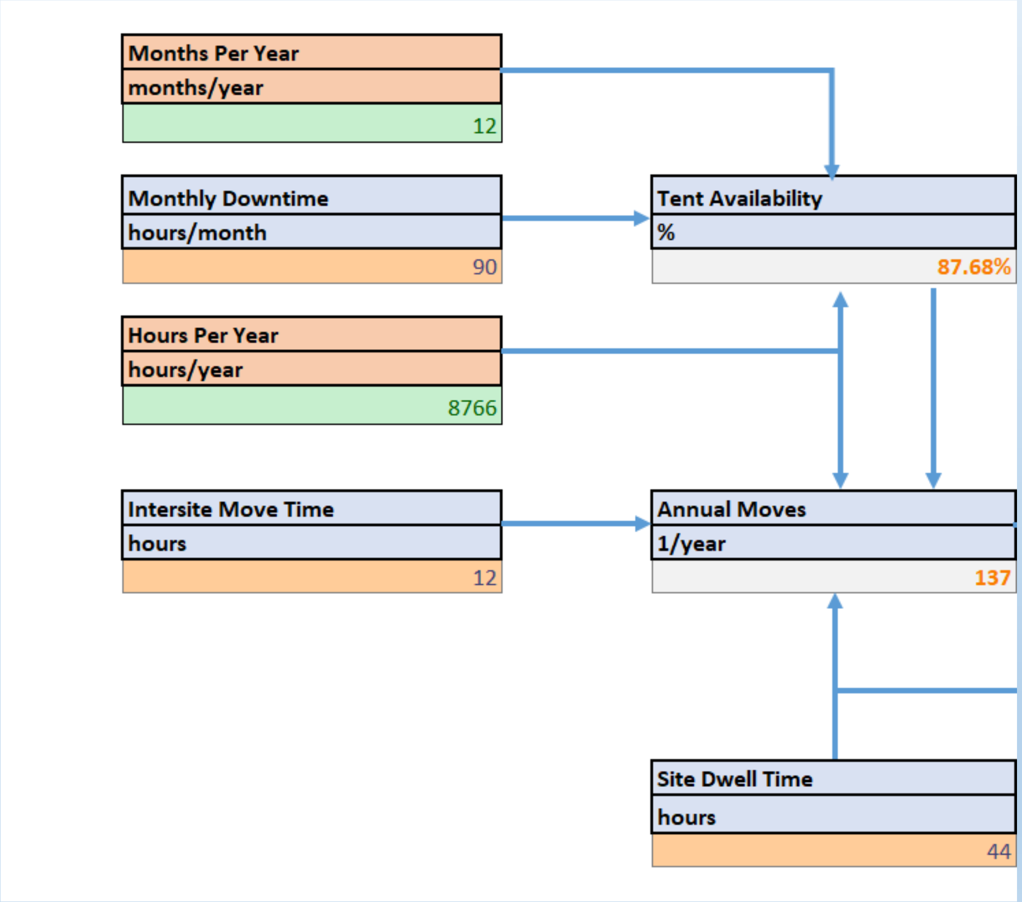
$$Ice\ Yield_{after\ losses} = Ice\ Sublimated_{before\ losses}\left(1 - \frac{A_{loss}}{A_{loss} + A_{cold\ trap}}\right)$$

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

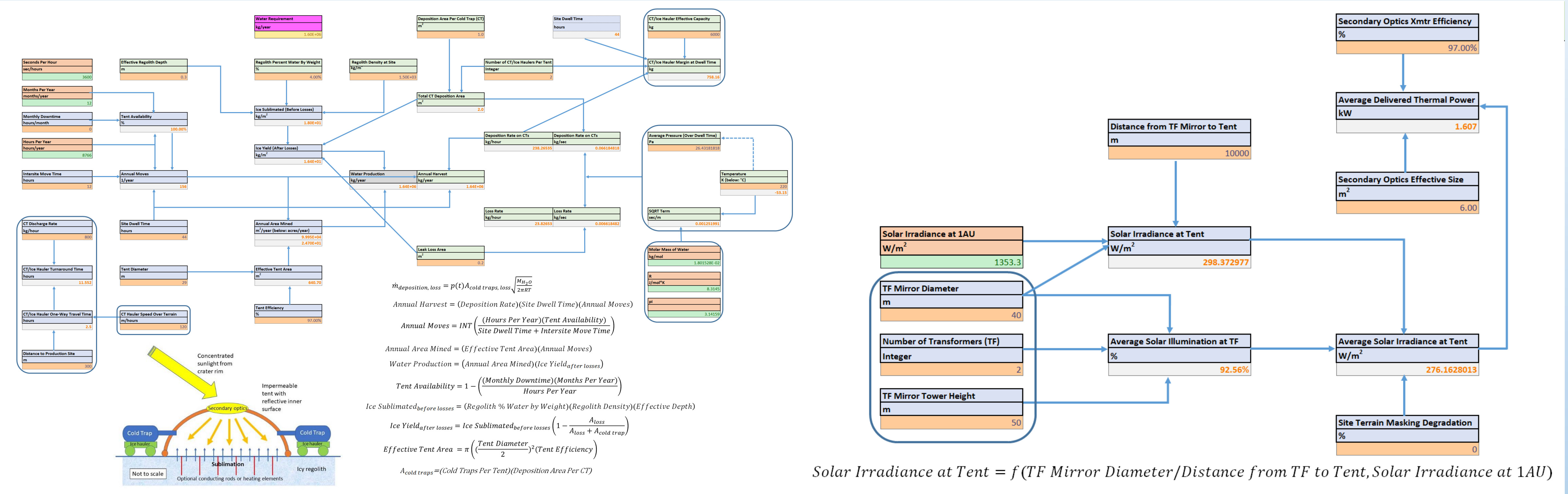
$$A_{cold\ traps} = (Cold\ Traps\ Per\ Tent)(Deposition\ Area\ Per\ CT)$$

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





Lunar Thermal Mining Production Model: “Threads of Calculation”

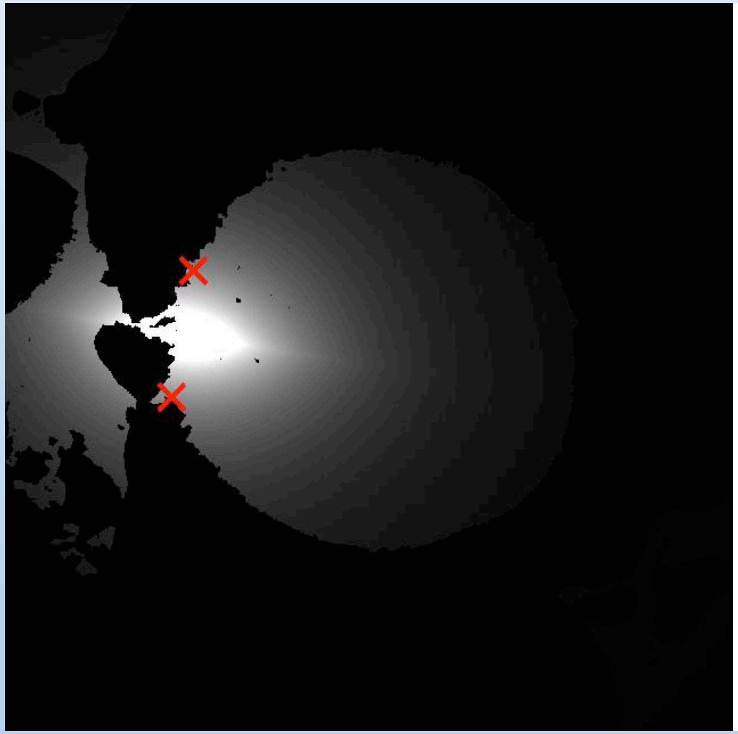


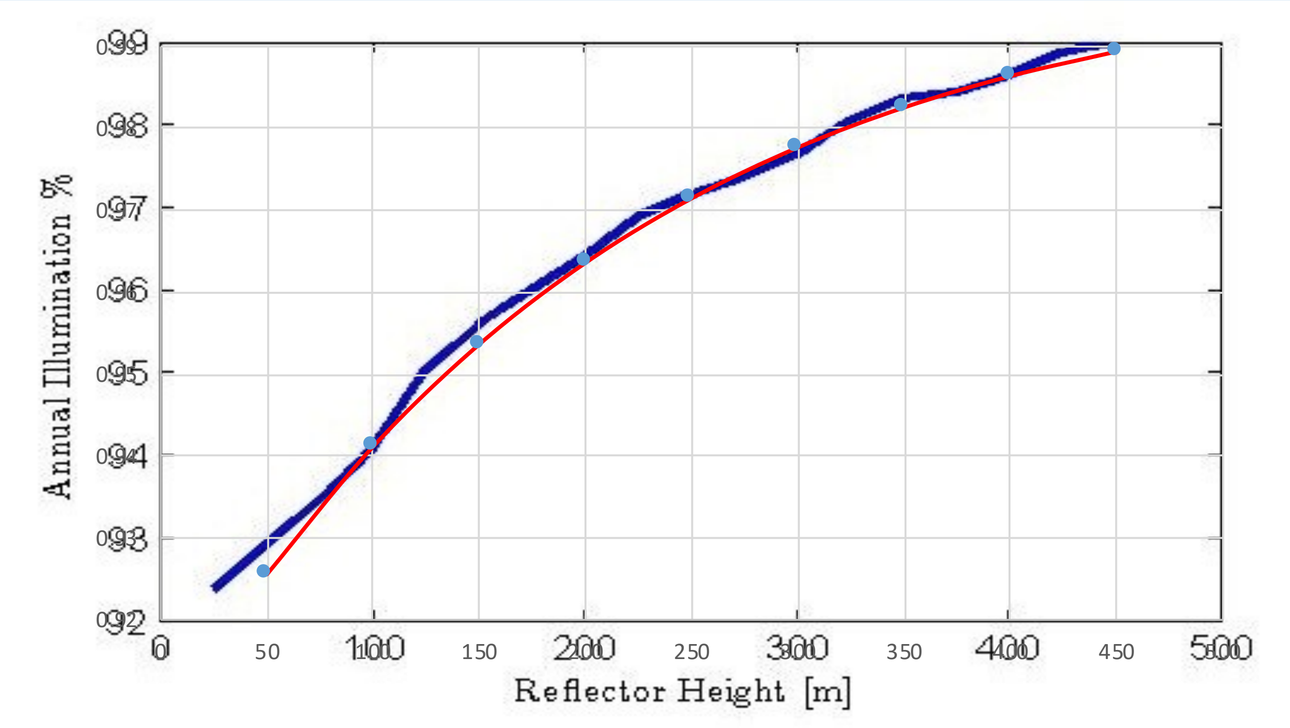
In total so far, the design vector has 22 input variables, excluding physical constants.

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



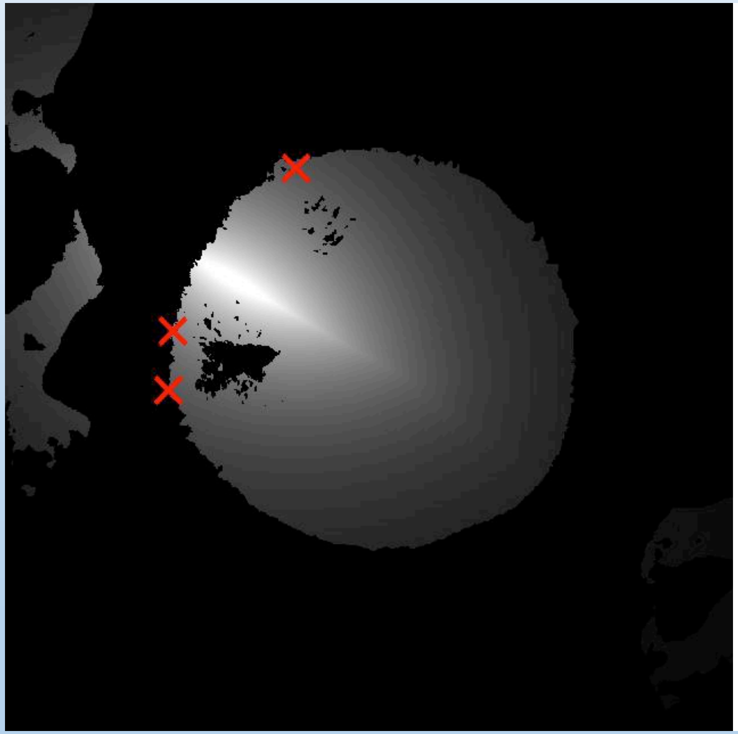


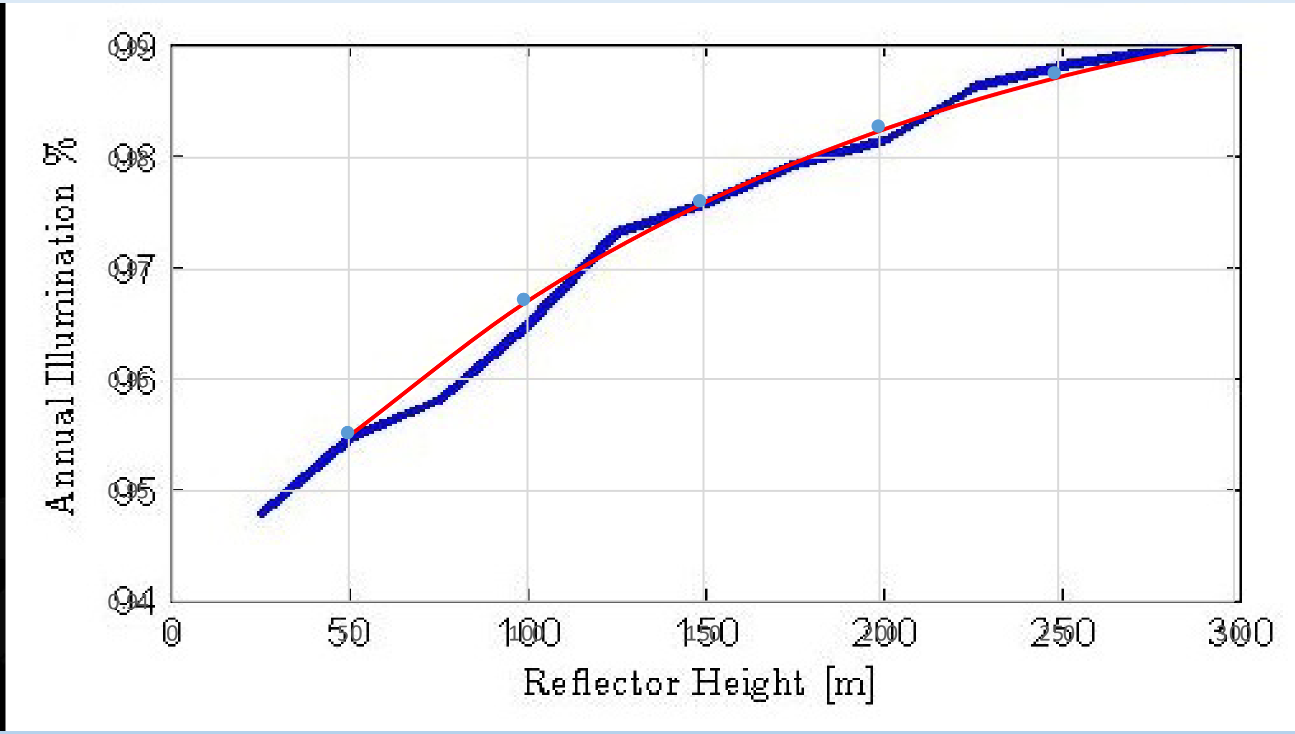
$$L = exp(2.26844 + 0.00504H)/(1 + exp(2.26844 + 0.00504H))$$

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 Three TransFormers Located at 89.8172°S 153.5004°W, 89.8262°S 52.8422°E, and 89.6876°S 162.8645°W





$$L = exp(2.729668 + 0.00648656H)/(1 + exp(2.729668 + 0.00648656H))$$

Production Model Engineering Database

Maintains configuration management for tradespace exploration input and output data

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

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

Do Not Overwrite ----> 1 2 3 4 5 6 7 8 9 10

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 Reflectors to Redirect Solar Energy	Integrated Water Purification and H2 - O2 Production	Produces Cyrogenic 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								
Unit Production Cost (in $FY19M)	$ 100.0	$ 55.6								
Cost Margin Applied (%)		50%								
Planned Replacement Time (years)	10	10								
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	4						
Acquisition / Development Time (years)	3	4	5	1						
Acquisition / Production Time (years)	1	2	3	1		5	2	5		
Payment Schedule	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time	40/60 / 50/50 / One-Time
Dry Mass, Predicted (kg)		1050.0								
New Design (%)		50%								
Volume, Packaged for Launch (cu-m)										
Power, Avg (kW)										
Power, Peak (kW)										
Data Rate (Mb/sec)										
Effective Capacity (kg)										
Output Rate (kg/hour)										
Availability (%)	90.0%									
Design Life (years)		10								
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	Buy / Lease / Produce	Buy / Lease / Produce	Buy / Lease / Produce
Unit Lease Cost (in $FY19M/year)	$ -			$ 10.000						

MODEL-BASED COST ESTIMATES

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

Model-Based Asset Cost

INVESTMENT COST SPREADER

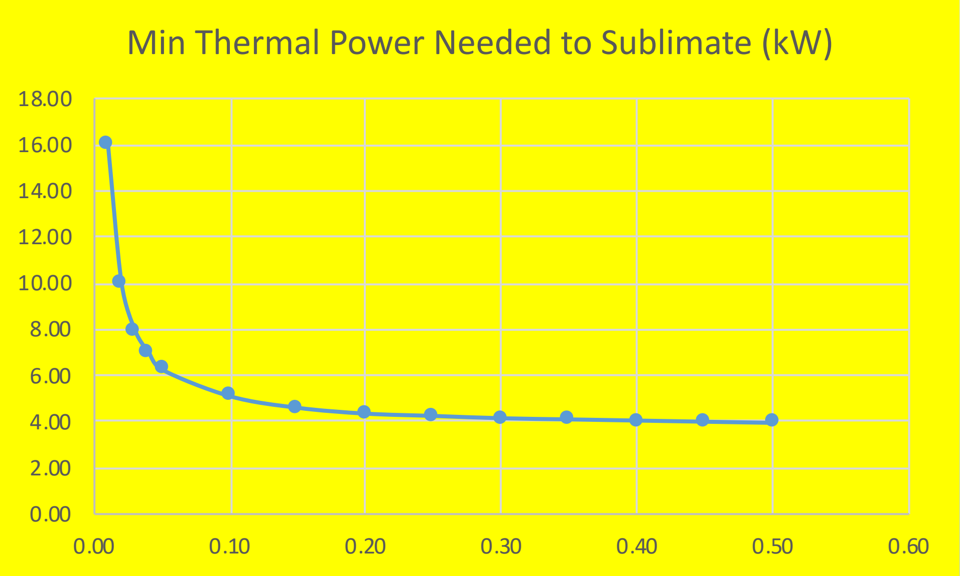
	Asset #1	Asset #2	Asset #3	Asset #4	Asset #5					Asset #10
Development Cost 1st Year		$ 37.08								
Development Cost 2nd Year		$ 148.30								
Development Cost 3rd Year		$ 148.30								
Development Cost 4th Year		$ 37.08								
Development Cost 5th Year		$ -								
Development Cost 6th Year		$ -								
Development Cost 7th Year		$ -								
Development Cost 8th Year		$ -								
Development Cost 9th Year		$ -								
Development Cost 10th Year		$ -								
Total Development Cost (Check)	$ -	$ 370.75	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Production Cost 1st Year	$ 100.00	$ 27.81								
Production Cost 2nd Year	$ -	$ 27.81								
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	$ -	$ -								
Total Production Cost (Check)	$ 100.00	$ 55.61	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -

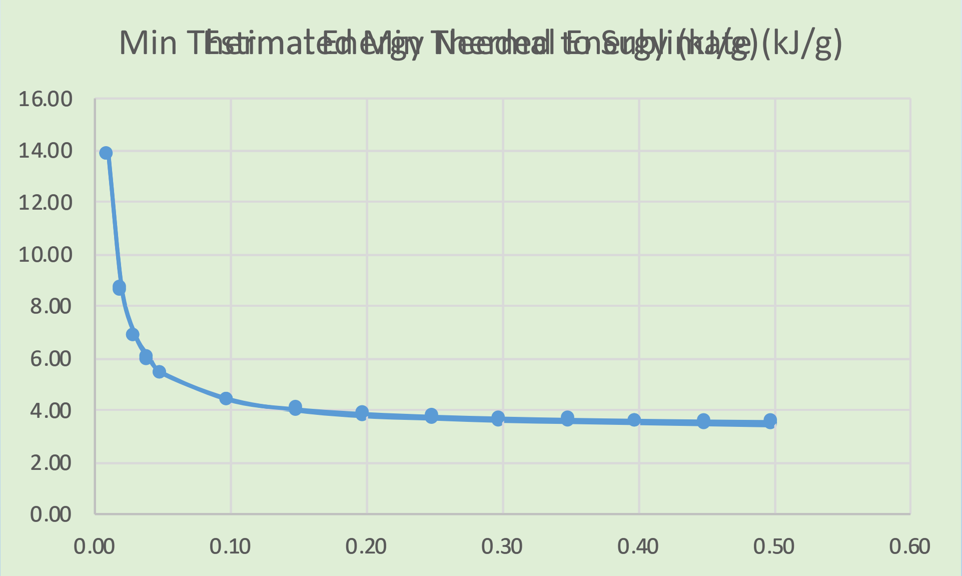
MELs

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

Thermal Power Needed to Sublimate 100 kg/day Versus Percent Water in Icy Regolith

Source: Stoica, A., et al., "TransFormers for Extreme Environments: Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures," NIAC Phase II Final Report, November 2017.





$$P = 3.312084 + 0.1056103 \coth w$$

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 uncertainty.

*See References 3-8, next slide

References

1. Kornuta, D., et al., “Commercial Lunar Propellant Architecture – A Collaborative Study of Lunar Propellant Production,” 2018. http://isruinfo.com/docs/Commercial%20Lunar%20Propellant%20Architecture.pdf
2. Sowers, G., Dreyer, C., and Williams, H., “Ice Mining in Lunar Permanently Shadowed Regions,” Colorado School of Mines, 2019.
3. Kossacki, K.J., Leliwa-Kopystynski, J., “Temperature dependence of the sublimation rate of water ice: influence of impurities,” Icarus 233 (2014) 101-105.
4. Hedge, U. et al., “Analysis of Water Extraction from Lunar Regolith,” NASA/TM-2012-217441, May 2012 (also available as AIAA-2012-0634).
5. Andreas, E.L., “New estimates for the sublimation rate for ice on the Moon,” Icarus 186 (2007) 24-30.
6. Piquette, M., Horanyi, M., and Stern, A., “Laboratory experiments to investigate sublimation rates of water ice in nighttime lunar regolith,” Icarus 293 (2017) 180-184.
7. Reiss, P., “A combined model of heat and mass transfer for the *in-situ* extraction of volatile water from lunar regolith,” Icarus 306 (2018) 1-15.
8. Frias, J., Shafirovich, E., and Van Woerkom, M., “Extraction of Volatiles from Lunar Regolith Using Solar Power,” J. Thermophysics and Heat Transfer, Vol.28, No. 2, April - June 2014.
9. Stoica, A., et al., “TransFormers for Extreme Environments,” NIAC Phase I Final Report, May 2014.
10. Stoica, A., et al., “TransFormers for Extreme Environments: Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures,” NIAC Phase II Final Report, November 2017.
11. Henrickson, J., Stoica, A., “Reflector Placement for Providing Near-Continuous Solar Power to Robots in Shackleton Crater,” IEEE Aerospace Conference, Big Sky, MT, 2017.
12. Mazarico, E., et al., “Illumination conditions of the lunar polar regions using LOLA topography,” Icarus 211 (2011) 1066-1081.
13. Bryant, S., “Lunar Pole Illumination and Communications Statistics Computed from GSSR Elevation Data,” AIAA-2010-1913, SpaceOps Conference 2010, Huntsville, AL.

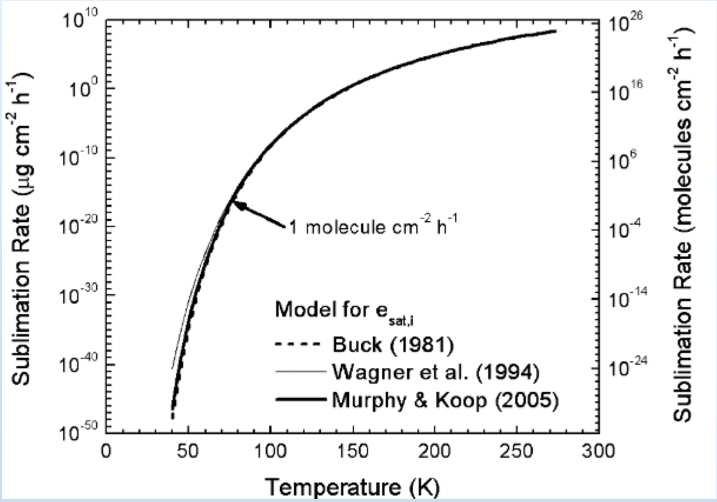
Backup

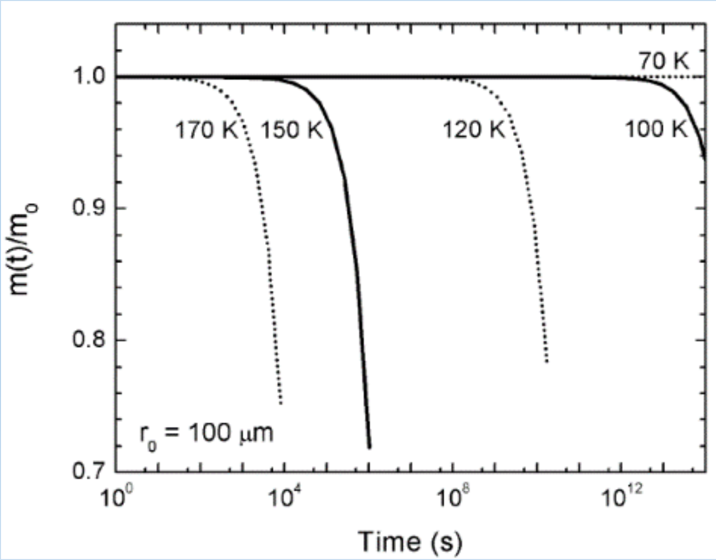
Business Case Analysis of Lunar Thermal Mining

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, . . . 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}, . . . 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.

Lunar Thermal Mining: Sublimation Rates (Ref. [5]*)





Temperature	**Density of Pure Ice(T)***	**S_0t/Density of Pure Ice (T)**
K	**kg/m^3**	**m**
170	929.4312888	1.68E-08
r_c*	**Surface Tension***	**Time**
m	**J/m^2**	**sec**
2.98948E-09	0.109	1.50E+01
r_0*	**Mass Fraction [Eq. (15)]***	**r_c - r_0**
m		**m**
1.00E-06	0.950290198	-9.97E-07
	From Andreas Eq. 15	
Saturation Vapor Pressure(T)**	**Saturation Vapor Pressure(T)***	
Pa	**Pa**	
0.000720296	0.000730967	
0.000705933	From Andreas Eq.4	
First is from Andreas Eq. 2		
Second number is alternative eq.	**Max Sublimation Rate, S_0***	
	kg/m^2-sec	
	1.04108E-06	
acki (2014)	No return flux	
Max Mass Loss Over Dwell Time*	**Max Sublimation Rate***	
kg/m^2	**kg/m^2-hour**	
0.164907786	0.003747904	

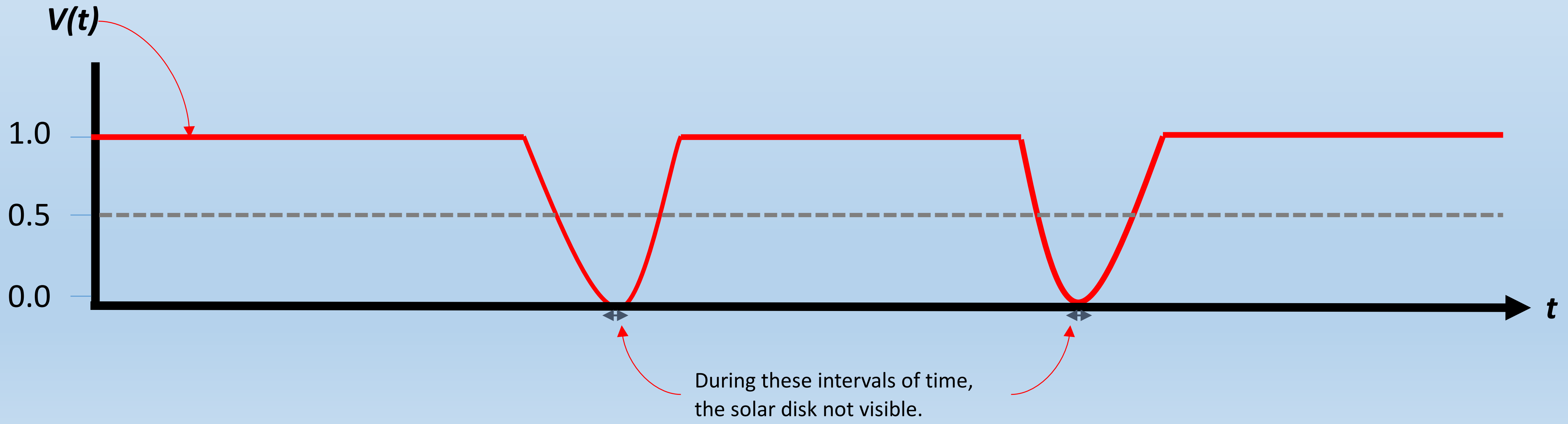
*Andreas, E.L., “New estimates for the sublimation rate for ice on the Moon,” Icarus 186 (2007) 24-30.

Definition: Average Solar Illumination

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

Note 1: *V* is the fraction of the solar disk that is visible at a specific location on the lunar surface. *Θ* is the fraction of the solar disk visibility above which the visibility is to be included in the average, so $\overline{S_0}$ 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

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

Note 1: V is the fraction of the solar disk that is visible at a specific location on the lunar surface. Θ is the fraction of the solar disk visibility above which the visibility is to be included in the average, so $\overline{V_0}$ is the fraction of time any solar light is visible. Similarly, $\overline{V_1}$ 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 ≥ Average Solar Illumination.