



NIAC Phase I Final Report

Lunar South Pole Oxygen Pipeline (LSPOP)

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Team Members

Lunar Resources, Inc. (LUNAR), a space industrial company focused on developing technologies for the in-situ utilization of space resources, is leading the Lunar South Pole Oxygen Pipeline, LSPOP, study effort. LUNAR is currently funded by NASA and the National Science Foundation to develop oxygen and metal extraction from lunar regolith using its Molten Regolith Electrolysis, MRE, technologies. In addition, NASA has also funded LUNAR to develop technology to capture, purify, and store oxygen, OxPS, from a MRE reactor operating on the Moon. LUNAR has also been funded to develop metal additive manufacturing, coating, and welding techniques applicable to the lunar environment by the Department of Defense and NASA. For this study LUNAR has teamed with Wood, PLC a leading global midstream oil and gas pipeline engineering firm to support LSPOP design, construction, and implementation of the study. Wood PLC has also been ranked #1 on Engineering News Record's Top Pipeline Companies in 2019 and 2020. They have designed and managed more than 50 large-scale pipeline projects totaling more than 600,000 km of pipelines and engineered marine terminals and pipelines which have created new gas gateways across continents. In addition, Matt Laborde, a subject matter expert in gaseous pipeline supports the modeling aspects of the study as the consultant. He has worked on projects such as ANR Pipeline, Port Neches Link, and Keystone pipelines and numerous pressurization facilities.

Introduction to *LSPOP*

The sustainability of the Artemis program and its goal of developing a permanent human presence on the Moon is dependent on the ability to utilize in-situ resources to reduce the cost and risk of lunar operations. NASA and the US government have invested significant funding in developing the ability to extract oxygen from lunar regolith and water from lunar ice. The oxygen will be used for: 1) human habitats, crewed rovers, fuel cells, other life support systems with a constant supply of high purity oxygen for human consumption; and 2) an oxidizer for launch vehicles departing the Moon. These oxygen extraction technologies are planned to be demonstrated at large scale on the Moon prior to the Artemis III human landing and provide direct support to Artemis astronauts shortly thereafter.

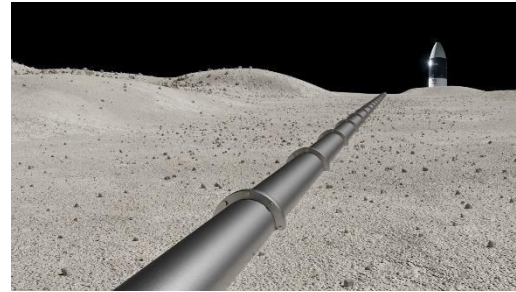


Figure 1: Rendering of LSPOP from the Phase I proposal

No explicit approach has been identified by the Artemis Program for the transport of oxygen from the extraction site to potential use sites. Concepts for in-situ extracted oxygen transport usually consist of bottling the oxygen in compressed gas tanks or to liquefy and store it in dewars. Either approach requires trucking tanks or dewars to various facilities for use. The process of moving this oxygen on rovers is more energy intensive than the extraction process and would be the most expensive aspect in obtaining in-situ oxygen for use on the Moon considering the long distances a resource extraction area may be from a human habitat or liquification plant (1 – 10 km). A more effective method of oxygen transport is by pipeline.

The Lunar South Pole Oxygen Pipeline (LSPOP – Figure 1) Phase I NIAC, is to analyze the feasibility of constructing a pipeline at the Moon's South Pole for transporting gaseous oxygen from point of generation to point of use. A lunar pipeline has never been pursued and will revolutionize lunar surface operations for the Artemis program and reduce cost and risk. Our starting concept is for a 5 km pipeline to transport oxygen gas from an oxygen production source, for example from our molten regolith electrolysis (MRE, currently at TRL 5, see references^{[1],[2],[3],[4],[5],[6]} for technical discussions of the MRE process) extraction site, or any other source, to an oxygen storage/liquification plant near a lunar base. The pipeline is designed to: 1) be constructed robotically from regolith-derived metals with minimal material transferred from Earth, 2) be repairable robotically, 3) have an oxygen flow rate of ~2 kg/hour, which is commensurate with the NASA initial projected need of 10,000 kg/year, 4) operate with minimal power over the lifetime of the pipeline, with a goal of high operational reliability and the ability to survive in the lunar environment for > 10 years. We compare this concept to a pipeline concept with pipe produced on Earth and then transported to and assembled on the Moon. Both approaches will use earth-based compressors, valves, and fittings which are integrated into the pipeline on the Moon.

In this highly successful nine-month Phase I NIAC project the lunar south pole oxygen pipeline evolved significantly in appearance and detail during the study. Feasibility was clearly demonstrated, and the concept was shown to be a high value/low risk option for NASA to consider for the Artemis Program. To do this we conducted a general design and comparison study of a 5 km lunar pipeline, defined a general pipeline design for the Moon utilizing

extracted materials for pipe segments, identified pipeline support systems that must be produced on Earth, quantitatively compared the LSPOP in-situ system vs. all Earth transported system. We demonstrated feasible pipeline paths, studied pipeline risks and health and safety issues. Pipeline capacity and length expansion sensitivity analysis demonstrated expandability. A high-level financial model of the shows reasonable pipeline costs.

1.0 General Design and Comparison Study (Task 1)

1.1 General Pipeline Design Preliminary Hydraulic Analysis

1.1.1 Pipeline Basis of Design

A first pass, conceptual hydraulic analysis was developed for the Lunar South Pole Oxygen Pipeline (LSPOP), a 5 km pipeline to transport oxygen gas from an oxygen production source to an oxygen storage/liquification plant near a lunar base. The baseline design for LSPOP is to use in-situ manufactured aluminum pipe segments that are passivated and welded or fitted together to span the 5 km distance and deliver at least 2 kg/hr. oxygen to the pipeline terminal.

The hydraulic model includes:

- One reciprocating/positive displacement compressor.
- The pipeline itself.

For the purpose of this hydraulic analysis, the following assumptions/approximations were made for the base case:

- A 20% margin was added to the length of the pipeline (5 km) to account for deviations, obstacles, horizontal or vertical slopes. The hydraulic model length of the pipeline is 6 km.
- Pipe material was assumed to be Aluminum 6063, UNS designation 96063 rated for temperature between -269°C and 204°C. This widely used pipe/tubing material is similar in mechanical and thermal properties to the pure Aluminum that potentially will be produced on the Moon. Furthermore, the major alloying elements of 6063 are magnesium and silicon, which are expected to be produced from regolith from the envisioned extraction process. Thus, producing 6063 in situ is expected to be feasible.
- Inlet pressure at the beginning of the pipeline (discharge pressure of the compressor) was kept at a minimum of 50 psi (345 kpa) to minimize the compression requirements.
- Suction pressure of the compressor was assumed to be 15 psig (103 kpa).
- For simplicity of the model, no piping components (valves, sensors, etc.) were included in the preliminary analysis. The impact of adding these components is minor compared with the pipeline itself.
- Lunar soil (regolith) was assumed to have a ground thermal conductivity of 0.02 W/ (m*°C). This is consistent with empirical measurements.
- Pipe was considered below ground, with a buried depth of between 20-40 cm.
- The Lunar soil temperature for these calculations was assumed to be -100°C.
- Nominal pipe size was set at 3/4 in (19 mm) for the base case.
- Pipe wall thickness was assumed to be 0.12 in (3 mm), a value consistent with the internal pressure requirement, but also carrying a sufficient allowance to withstand external loads.
- The pipe absolute roughness was indicated to be around 0.04 in (1 mm).

- No insulation was added to the pipe.
- No elevation profile of the pipeline was considered at this stage. The impact of the elevation profile is assumed to be insignificant with the assumption that the transported oxygen is going to be always in gas phase along the pipeline.
- Pure oxygen was modelled with no expected impurities. The phase envelope of the oxygen is illustrated below, in Figure 1.1 – Oxygen Phase Envelope

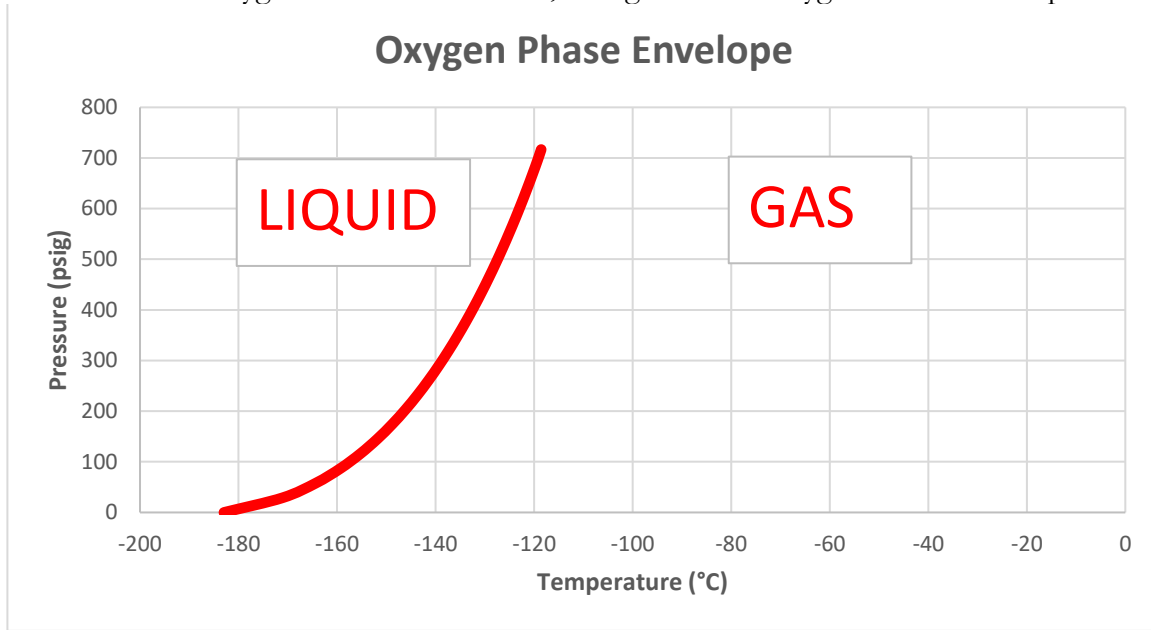


Figure 1.1 – Oxygen Phase Envelope

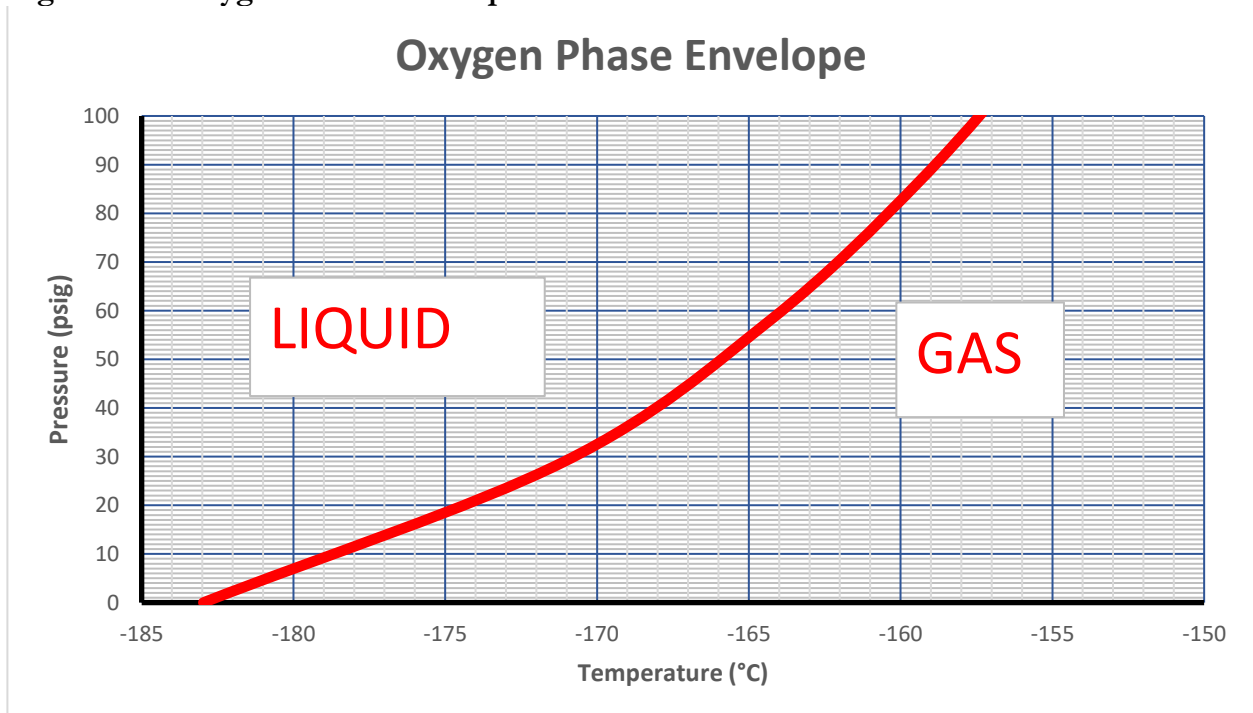


Figure 1.2 – Oxygen Phase Envelope - Extracted from Figure 1.1.

- From the phase envelope, expanded in Figure 1.2, it is evident that in the expected range of simulation pressures (0-50 psig or 0-3.4 barg) the oxygen temperature must be maintained higher than -165°C in order to preserve gas phase.

1.1.2 Software information

The pipeline system was modelled using ProMax by Bryan Research & Engineering, a steady state multi-phase simulator which presents several characteristics appropriate for this project:

- Inclusion of a powerful GIS Tool allowing the creation of pipeline network systems directly from geographic information system (GIS) data and manipulation of the data under its current layout.
- Comprehensive Equation of State (EOS) collection. GERG 2008 Equation of State was utilized in the simulation.
- Powerful and robust density correlation.
- Mass and volumetric flow rate modelling with compositional analysis.
- Pipe Heat Transfer embedded module with multiple ground types available for buried pipe with default thermal conductivities provided, but updateable.

Version 5.0 (2019) was utilized for this project phase.

1.1.3 Results and discussion

1.1.4 Pipeline Pressure Profile

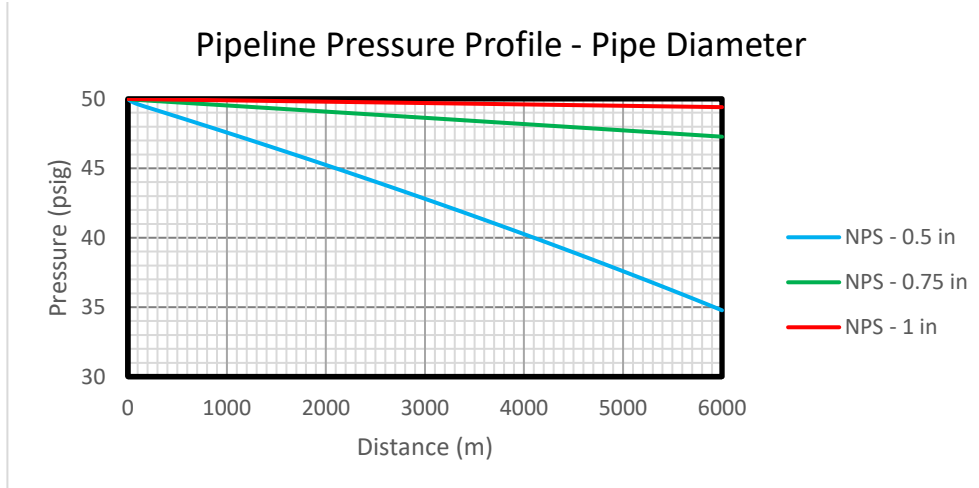


Figure 1.3 – Pipeline Pressure profile – Pipe diameter variation

Figure 1.3 gives the pipeline pressure drop with distance. The figure shows that the $\frac{3}{4}$ in normal pipe size, NPS, pipeline is a viable option for the given flow rate of 2 kg/hr.

The 1" NPS pipeline creates only 0.6 psi pressure drop, which represents 0.1 psi/km – extremely low number; this is considered oversized, but has potential for future expansion of system capacity, if needed.

The 0.5" NPS pipeline creates 15.2 psi pressure drop, which represents 2.6 psi/km – relatively high number, this is considered undersized.

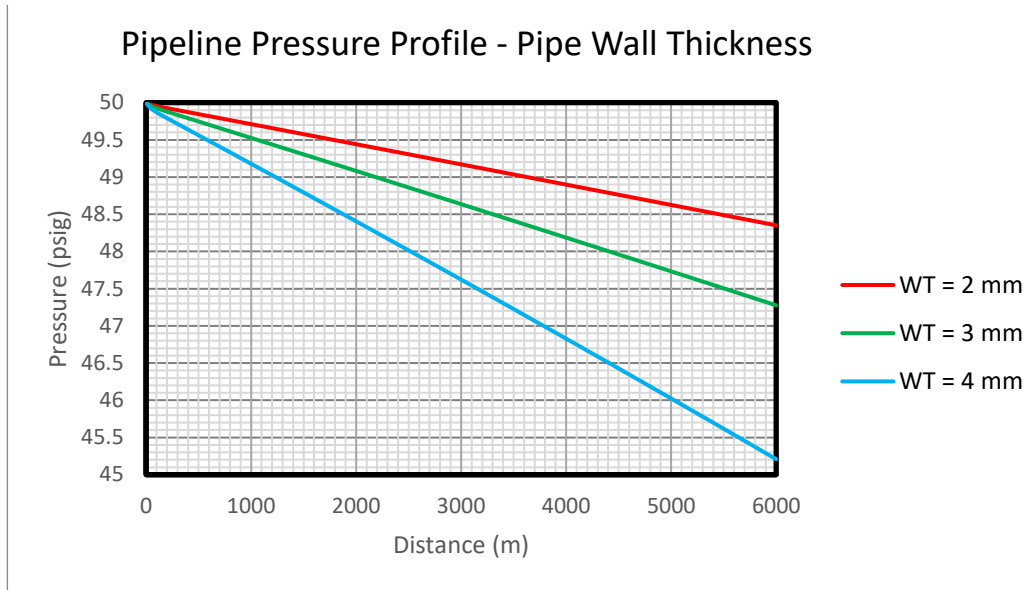


Figure 1.4 – Pipeline Pressure Profile – Pipe wall thickness variation

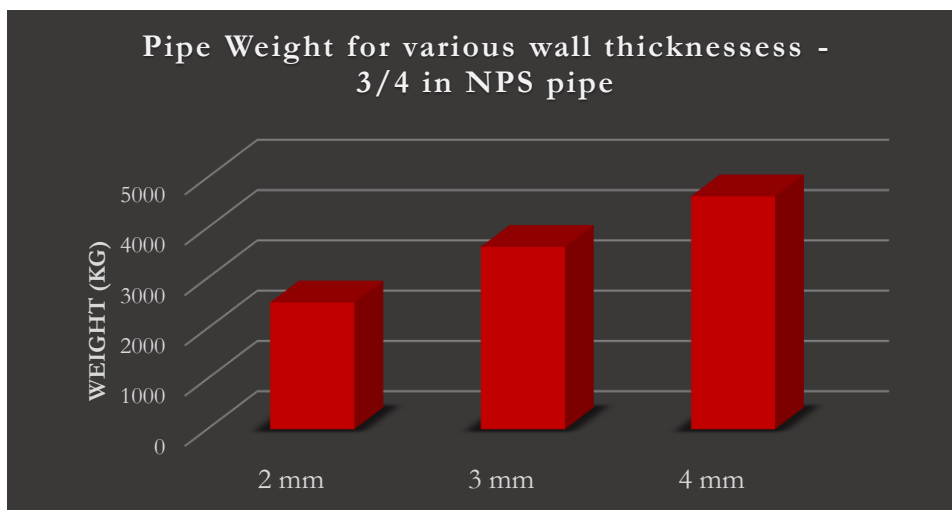


Figure 1.5 – Pipe Weight for various wall thicknesses – 3/4 in NPS pipe

Figure 1.4 show the impact of wall thickness on the pipeline pressure profile for the 3/4 in outside diameter pipe. Figure 1.5 illustrates the weight comparison of the entire pipe for various wall thicknesses. The pipeline weight impacts the trade of in-situ vs. Earth transported pipe segments and determines the production rate of in-situ aluminum required for the pipeline.

A pipe of 3 mm wall thickness is considered optimal; sufficiently strong for external loads and reasonable mass (~3,600 kg for the entire pipeline).

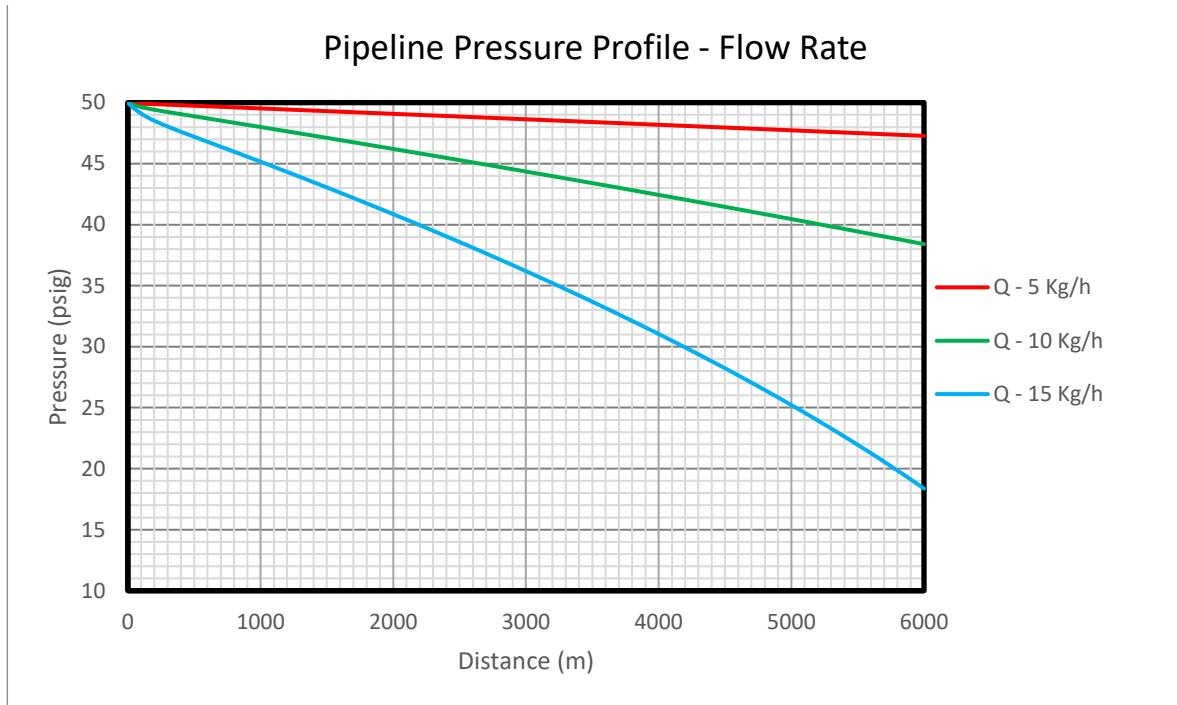


Figure 1.6 – Pipeline Pressure Profile – Future expansion

Figure 1.6 – “Pipeline Pressure Profile – Future expansion” demonstrates that there is significant capacity for future expansion. Flow rates of up to 3 times greater than the base case of 2 Kg/h can be accommodated with acceptable pressure drop over 6 km.

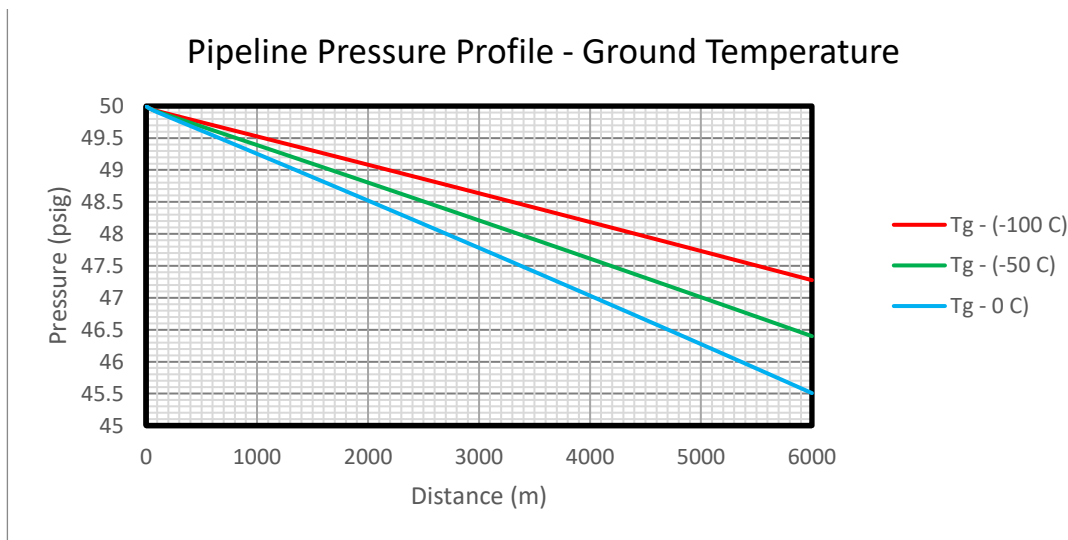


Figure 1.7 – Pipeline Pressure Profile – Ground Temperature Variation

Figure 1.7 – Pipeline Pressure Profile – Ground Temperature Variation shows relatively minor impact of ground temperature for the pipeline pressure profile. The colder the temperature of ground is, the better the pipeline friction loss is assuming the oxygen remains gaseous.

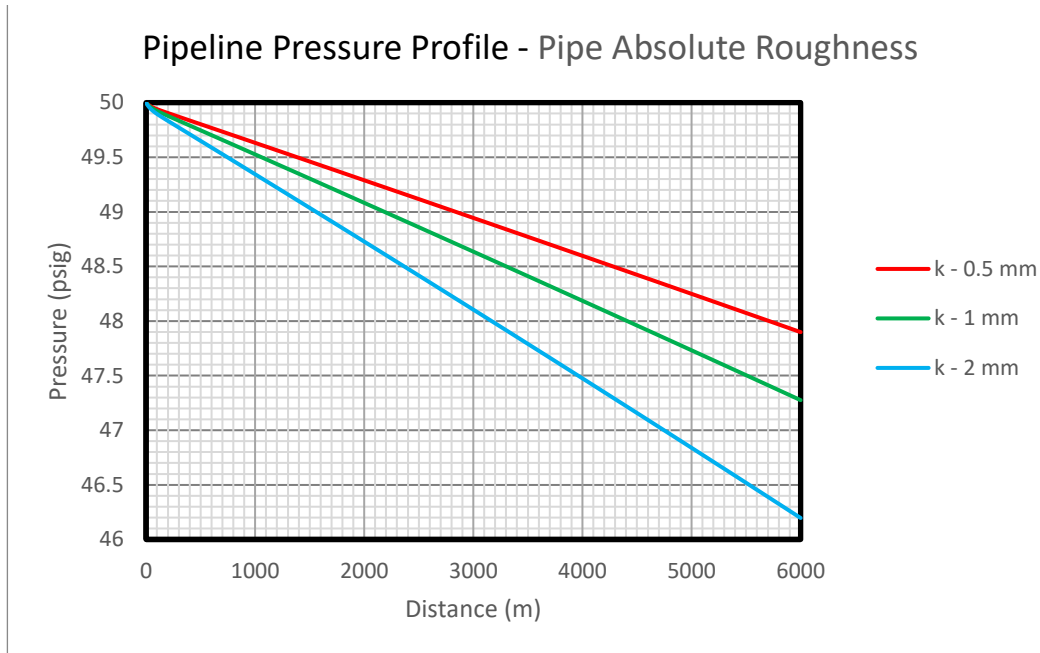


Figure 1.8 – Pipeline Pressure Profile – Pipe Absolute Roughness

Figure 1.8 – Pipeline Pressure Profile – Pipe Absolute Roughness illustrates the increase in pipeline pressure drop as a function of pipe absolute roughness increase.

1.1.5 Pipeline Temperature Profile

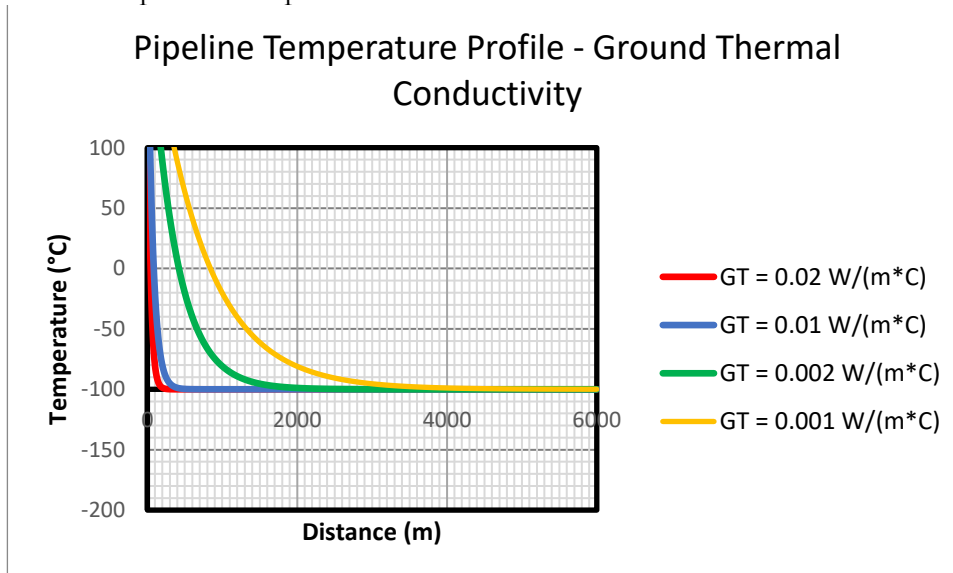


Figure 1.9 – Pipeline Temperature profile – Ground Thermal Conductivity

Figure 1.9 – Pipeline Temperature profile – Ground Thermal Conductivity shows the impact of ground thermal conductivity over the temperature profile of pipeline. The initial temperature of the inlet oxygen is -100 °C. The oxygen gas is heated by the inlet compressor. The oxygen leaves the compressor and cools back towards ground temperature with distance according to the thermal conductivity of the regolith as shown in Figure 1.9. The compressor heating is dissipated

in all cases to ambient before the pipeline traverse is complete. Analysis of actual ambient conditions may show the need for auxiliary heating along the pipeline path.

1.1.6 Conclusions and Next Steps:

- More analysis is needed on pipe/tubing material, the base model was built with Aluminum as pipe material.
- Insulation/Heating will not drastically alter the pressure profiles. More analyses are needed for the next phase of the project.
- Oxygen purity is going to be researched and embedded in the model at the next revision.
- Sensitivity study to be finalized at later stages (optimum compression discharge pressure vs vessels size, underground vs. above ground layout, different pipe materials, etc.).
- A more comprehensive thermal model considering diurnal/periodical temperature variations will be utilized later when available Lunar data are analyzed.
- Different insulation methods are going to be investigated quantifying their impact on thermal properties, but also on the system weight.
- A rigorous as possible elevation profile will be embedded in the updated model.
- Piping components and other equipment will be included in the future model.

1.2 General Pipeline Design Using Extracted Resources

1.2.1 Materials Production

In situ production of pipe sections using extracted resources was analyzed for the general pipeline design comparison study. The extraction of materials from lunar regolith has been developed under separate projects funded by NASA and NSF [1-5, 7] and is being matured under a current Phase III effort in vacuum at a relevant scale [6]. In this Phase I NIAC study, we assume that the extraction technology is developed and in place on the Moon producing oxygen and metals for NASA and other customers. The system as developed by Lunar Resources consists of a reactor system, MRE, in which oxygen is produced and fed into an oxygen purification system, OxPS, [6] which exits oxygen at required purity for human consumption and propellant oxidizer as rendered in Figure 3.1.

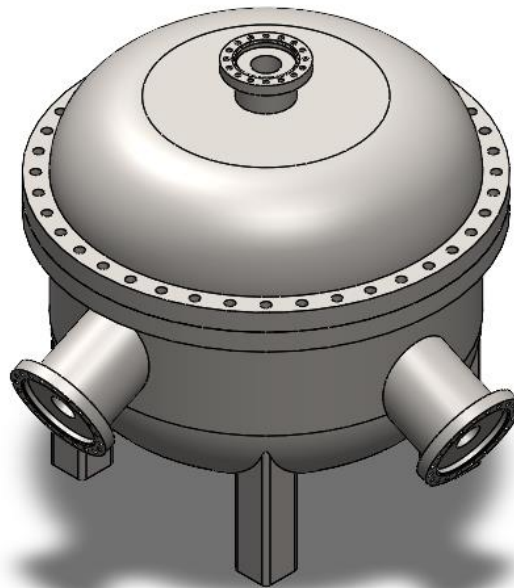


Figure 1.2.1 Render of Molten Regolith Reactor Chamber.

For the General Pipeline Design, we assume that the reactors are scaled to produce 10 MT / yr. of oxygen per Artemis baseline requirements. The composition of the lunar south pole regolith has only been measured by remote sensing. There have been sample returns from Apollo 11, 12, 14, 15, 16, 17, and Luna 16, 20, 24, as well as the recent lunar far side missions. We assumed that the lunar south pole regolith is similar in composition to the lower latitude highlands regolith. We have chosen Apollo 16a as an initial baseline for our study. Lunar Resources has developed a proprietary analysis tool which uses electrochemistry analysis and existing data as inputs and yields the anticipated reactor outputs, power requirements, and scale data as outputs. Using the oxide composition of the Apollo 16a sample taken from the Descartes Highlands, each MRE producing 10 MT of oxygen can also produce 2 MT Fe, 5.6

MT Si, 0.06 MT Cr, 0.17 MT Mn, 1 MT Mg, and 2 MT Al. However, polar mineralogy data is expected as early as 2024. These values will be updated for future phases of the project.

1.2.2 Materials Selection

The available in-situ materials were examined to determine viable candidates for pipe segment construction. Pipe segment construction utilizing Fe-Si, Al, or Al-Mg-Si were selected as the primary candidates. Melted regolith pipe segments may also be possible but would present additional obstacles since there is little precedent for gas pipelines on Earth with similar materials. Fe-Si can be brittle depending on the Fe to Si ratio, but suitable mechanical properties might be obtained with control of the Si content. Fe alloys will oxidize in the presence of oxygen gas which will necessitate passivation of the internal surfaces of the pipe. Aluminum in the presence of 50 psi gaseous oxygen should give more than 70nm of native Al_2O_3 on the pipe interior. This is more than enough for passivation against oxidation degradation of the pipe. Aluminum alloys are used for oxygen transport on Earth for small systems but for larger pipelines copper alloys are favored because they have much less propensity to burn in atmosphere. On the Moon copper is scarce, and the burning problem is mitigated by the vacuum environment. If an accident like a micrometeoroid strike were to ignite the aluminum pipe the damage can be limited by pressure sensors and valves. Pipeline repair could then be done using a version of the in-situ construction processes at hand. Thus, our baseline material for the General Pipeline Design is aluminum. Further study of the mechanical properties' requirements due to pressure and stresses on the lunar surface may lead to an aluminum alloy. An example is the 6xxx series alloy which could be made in situ with Al, Mg, and Si. For example, 6063 Aluminum which is utilized for pipe [8] is about 99% Al, 0.6% Mg and 0.4% Si. Thus, the baseline material selected for the General Pipeline Design using in-situ materials is aluminum or an alloy. Baseline mechanical properties will include pure aluminum and 6063 aluminum alloy.

1.2.3 In-Situ Pipe Segment Manufacture

Methods of manufacturing pipe segments in situ that were examined include casting, extrusion, and 3D printing. Molten aluminum from the reactor could be fed through a tundish, cooled to casting temperature by radiation, and poured into a vertical steel mold with a core insert to form the pipes. This is a feasible option but would require specialized robotics and various molds that could deal with the various curves and contours of the pipeline path. Extrusion is a common process for forming hollow aluminum castings. The aluminum would be forced through a die and then cut into pipe segments. Adapting this process to operate on the Moon space radiators for cooling may be feasible but will entail a significant design effort. Additive manufacturing or 3D printing of aluminum pipe could be a viable option. The advantages include low weight, flexibility, and implementation into the early robot rovers and arms for Artemis. Additive manufacturing could enable production of numerous pipe segment curvatures with a single tool. Lunar Resources is developing 3D printing technology, PE3D, optimized for printing in space and on the lunar surface [9, 10]. The PE3D utilizes a proprietary pulsed energy method that when optimized can greatly reduce the mass and power requirements relative to other methods. Figure 1.2.2 shows the weight and power consumption advantages of an optimized PE3D versus SOA laser and ebeam systems.

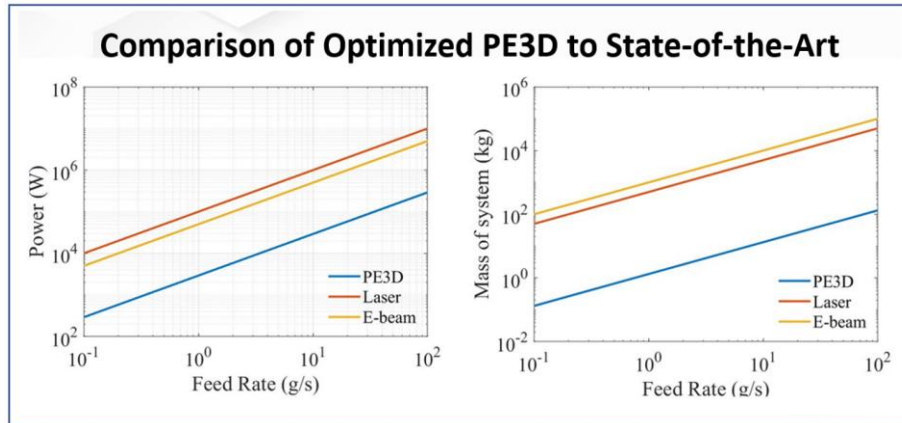


Figure 1.2.2 Analytical Comparison of PE3D with SOA Laser and Ebeam [9].

PE3D has undergone integration into robotic arms systems relevant to those being developed for Artemis rovers and is being tested for vacuum operations, Figure 1.2.3.

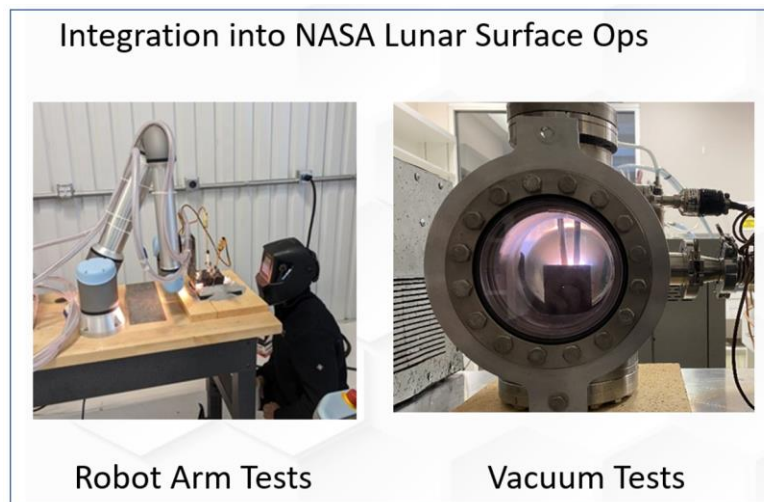


Figure 1.2.3 Relevant Arm Integration of PE3D (left) and Vacuum Test (right)

Current system specifications are flight weight of 11 kg and power requirement of 5 kW, aluminum printing rate of 2 kg/hr. The printing rate for 25 mm dia. 23 mm ID pipe is estimated to be 4.5 m of pipe per hour. The PE3D can use powder or wire feed material. Lunar Resources has developed a proprietary process to make wire from the refined aluminum on the Moon. The process is expected to produce up to 16 kg/hr of aluminum wire made from aluminum on the Moon. Thus, from the above considerations our baseline process for the formation and joining of the in-situ pipe segments is additive manufacturing using the PE3D with in-situ produced aluminum wire. However, we will continue to study other pipe segment in-situ manufacturing methods. One potential solution is shear assisted processing and extrusion (ShAPE) [11]. We are working with a leading manufacturer of shear assisted extrusion hardware to determine if it is feasible to adapt the process to our lunar manufacturing requirements. Thus, in-situ pipe manufacturing is clearly feasible with at least two methods of production.

1.3 Quantitative Comparison Earth Based vs. In-Situ Pipe

The LSPOP pipeline will require a number of components beyond just the pipe segments in order to be operational. Whereas we propose the pipeline segments can be produced in-situ from lunar material, the remaining components because of the complexity of their manufacturing are assumed to be produced on earth and transported to the Moon for construction and operation of the pipeline. **Table 1.3.1** shows a comparison between the mass of each component for manufacturing all components on Earth vs. the alternative of manufacturing the pipe segments in-situ on the lunar surface.

Earth vs. Lunar in-situ Materials		
Component	Earth Manufactured Weight (kgs)	Lunar In-Situ Weight (kgs)
Mainline Pipe Material	2,500	75
O2 Compressor skid	50	50
SS Accumulation Vessels (X2)	300	300
valves and actuators (~30)	45	45
flow meters (X2)	5	5
interconnecting piping	100	0
IE&C components	50	50
Misc. structural	50	25
Total	3,100	550
Alternative 1/2" HT/I tubing	3,000	75

Table 1.3.1 - Earth vs. Lunar In-Situ Material Weight Comparison for 6 km Pipeline

1.3.1 Mainline Pipe Material- The baseline study assumes $\frac{3}{4}$ " nominal outside diameter Aluminum pipe with a wall thickness of 3mm for both scenarios. The Earth weight assumes the total weight of 6,000 meters of industrial grade, seamless, passivated Aluminum pipe cut into uniform straight segments with beveled edges ready for joining on the lunar surface. An average weight of Aluminum alloys commonly used for pipe material (2024, 3003, 5052, and 6063) were used to approximate the total weight of the material at 0.414 kg/ m. Alternative materials such as the below $\frac{1}{2}$ " heat traced and insulated tubing or Carbon Fiber tubing may provide other advantages in the construction and operation of the pipeline but need to be studied further for compatibility. The lunar weight assumes only the weight of the PE3D printing device that is needed to turn raw aluminum mined from the lunar regolith into pipe segments of similar specifications to above for the pipeline.

1.3.2 Oxygen Compressor Skid- The total weight a single (sparing philosophy to be developed later) oxygen compressor to be used to pressurize the oxygen to 50 psig (3.4 barg) including, electrical motor, base plate, enclosure, and safety relief devices is conservatively estimated to be 50 kg. This assumes the use of stainless-steel materials produced on Earth, and a reduction in weight can be realized with the use of materials such as titanium or carbon fiber and will be further

researched in future studies. Due to the criticality of the equipment, complexity of manufacturing and precise engineering, the compressor skid(s) are assumed to come from Earth.

1.3.3 Accumulation Vessels- A total of two (2) accumulation vessels are assumed to be required for the successful operation of the LSPOP pipeline, each with a capacity equal to at least 1 Earth days' worth of Oxygen production. One vessel installed at the origination and termination points of the pipeline will allow operational flexibility for the extractive electrolysis operations and allow for proper treatment of the O₂ after transportation. The weight of the vessels is based upon standard earthly fabrication using 316L stainless steel, but alternative materials may offer a significant reduction in weight and are subject to further study. Use of the PE3D printing device may enable fabrication of Aluminum vessels on the lunar surface but will require further study for pressure rating and capacity limitations.

1.3.4 Valves and Actuators- An estimated total of 20 isolation valves, 4 check valves, and 6 Pressure Safety Valves (PSVs) are required for safe operation of the pipeline. All isolation valves will require electric actuators for remote operation, while check valves will be swing or wafer self-actuating, and PSVs pilot operated. All valves must be manufactured on Earth and transported to the lunar surface for installation.

1.3.5 Flow Meters- A total of two flow meters are required to be installed at the origination and termination of the pipeline to monitor for mass balance and leaks in the system. These engineered pieces of equipment add minimal weight to the operation and must be transported from Earth.

1.3.6 Interconnecting Piping- Much like the mainline pipe, the material of construction for all interconnecting piping is assumed to be either industrial grade aluminum from Earth or printed from aluminum extracted from lunar regolith and additional studies are needed for alternative in-situ materials. Since the weight of the PE3D device is already accounted for in the mainline pipe, no additional weight is needed for the interconnecting pipe. The interconnecting piping accounts for all adjoining pipe that connects equipment at the facilities, as well as segmental fittings that can be cut to match exact angles for Points of Inflection (PIs), sags, and overbends in the pipeline route. This length of pipe is estimated to account for <5% of the total weight of the pipe and will be optimized in detailed engineering in a Phase II study.

1.3.7 Instrumentation, Electrical, and Control Components- A multitude of equipment is needed to power equipment, monitor fluid and ambient conditions, and control operations. Items such as pressure and temperature transmitters, electrical breakers, and PLCs must all be manufactured on Earth and are estimated to not exceed 50 kg.

1.3.8 Miscellaneous Structural Components- Structures such as insulated enclosures, pipe supports, and anchor bolts will be required to protect the pipeline equipment and reduce the chance of failure. Some equipment may be able to be printed with In-situ material from the lunar surface, so an estimated reduction in weight of 50% is applied vs. all earth-bound material.

The quantitative comparison of the LSPOP in-situ system vs. all earth-transported pipeline is scheduled to continue through the remainder of the project and this the model will continue to be refined. However, this initial analysis indicates a substantial earth launch mass advantage resulting from in-situ pipe segment manufacturing. This advantage will grow as the length of the required pipeline increases above 5 km to accommodate Artemis and commercial requirements.

1.4 Comparison with Alternative Oxygen Transport Concepts

The current Artemis Program architecture documents and published NASA Roadmaps do not identify an explicit approach for the transport of oxygen from the extraction site to potential use sites. In addition to the pipeline concept developed here, there are two basic approaches to this transport problem: 1) filling gas cylinders at the oxygen extraction site and then transporting them to the use site in a crewed (or robotic) vehicle or 2) building a railroad-like track system (this could be physical rails or a levitation system such as the NIAC funded FLOAT concept^[12]) from the extraction site to the Base Camp. Much like terrestrial commodity transportation, pipelines offer significant advantages to vehicle or rail transport systems in terms of safety, efficiency, and cost. These terrestrial benefits should translate directly to lunar applications for the transport of oxygen. Early in the study we performed a top-level system level comparison of these approaches.

Table 1.4.1 presents the results from our analysis of the energy cost of transporting 10 MT oxygen 5km. Utilizing LSPOP can result in a >99% decrease in energy compared to transporting oxygen via rovers! In addition to the energy cost savings, LSPOP does not tie up valuable astronaut time, it operates autonomously and has considerably less risk. Setting up the pipeline will add cost relative to a gas cylinder system, but the implementation is straight forward with decades of terrestrial knowledge to inform our processes and procedures.

Table 1.4.1: Energy cost of transporting 10 MT of Oxygen 5 km			
Rover Oxygen Transport Assumptions		Pipeline Oxygen Transport Assumptions	
Oxygen mass/49 L tank	8.8 kg	Oxygen temperature	100 C
Tanks per trip	8	Oxygen Density @ 100 C	1.031 kg/m ³
Rover energy per km	450 kWh/km	Oxygen flow rate	0.083 m ³ /min
Round trip distance	10 km	Motor power	120 V@15 amp
Energy per round trip	4500 kWh	Compressor discharge pressure	100 PSIG
Trips required	~142	Energy to move 1 kg of O ₂	0.36 kWh
Total Energy Required	~640,000 kWh	Total Energy Required	~ 3,600 kWh

A rail system is much harder to evaluate due to a lack of detailed studies of lunar rail systems in the literature. However, relative to an LSPOP-like pipeline, the rail system has a number of additional issues. Since the system sits on the lunar surface it must endure the extreme temperature cycling environment, the upper lunar regolith has a very low density so an analysis would need to be performed to determine how deep the rail path would need to be to support the transport, if it is a wheeled system, the impact of lunar dust on the wheels need to be analyzed.

Our LSPOP concept eliminates most of these issues. Oxygen flows autonomously, without using astronaut time, from the extraction site to the use site, in a buried pipeline that greatly mitigates the effect of the lunar environment. As discussed in this report risks are low, particularly to humans, the pipeline is expandable, reliable, and long lived. LSPOP offers the most cost effective, lowest risk, longest lived option to transport oxygen to and around the Artemis Base Camp.

2.0 Engineering Analysis (Task 2)

2.1 Analysis on Feasible Lunar Paths

Our initial analysis of possible LSPOP paths focused upon the Malapert Massif region. This site was chosen for two reasons: 1) it is one of the possible Artemis III landing sites (Figure 2.1), and 2) it has a high quality, high resolution LRO map (LROC NAC 1-m Malapert Massif Mosaic – Figure 2.2). Analyses of potential pipeline paths in the region around the crater Malapert A, where the IM-1 mission plans to land, were also explored and compared to the Malapert Massif path results. We focused more upon the Malapert Massif area because it appears characteristic of a greater number of

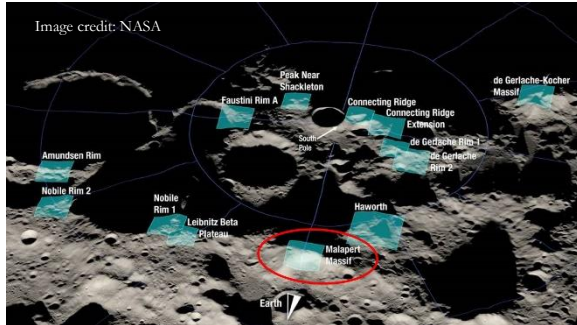


Figure 2.1 A rendering of 13 candidate

the Artemis III landing sites and likely locations for the Artemis Base Camp. The combined analyses (Malapert Massif and Malapert A) should be applicable to any location in the south polar region of the Moon.

The first phase of the analysis was to identify locations that met the general Artemis landing site requirements, particularly the requirement for slopes to be $\leq 15^\circ$. For the Malapert Massif region this confined us to the top of the massif, or the flatter “foothills” regions (Figure 2.2).

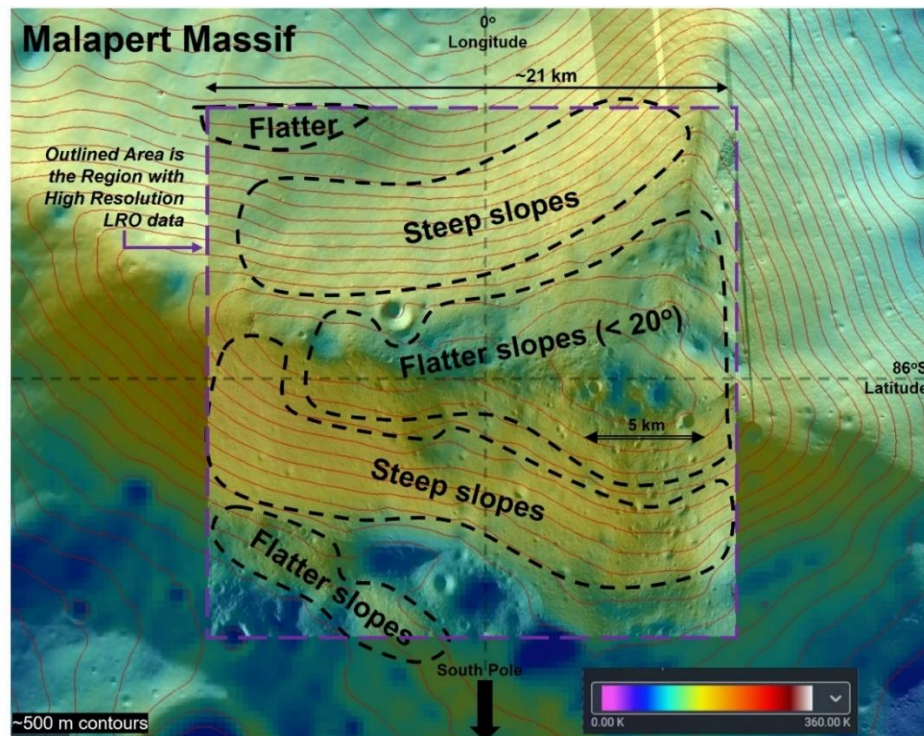


Figure 2.2 LRO map of Malapert Massif. The purple dashed box indicates the region covered by the LRO 1-m resolution data. Colors indicate average temperatures with the color key located in the lower right of the figure. The areas enclosed by the black dashed curves are labeled according to their average slopes. The regions labeled “Steep slopes” exceed Artemis slope requirements and are too steep to build LSPOP. Also indicated is a span of 5 km, the

Within the flatter regions of the mountain, multiple potential paths were developed with different starting/ending positions and different lengths. Mapping the path was the equivalent of navigating a maze. Because of the many obstacles on the lunar surface (craters/rocks/ridges, localized steep slopes), it is not possible for the pipeline to be built in a straight line; turns in the pipeline will be required to avoid major obstacles regardless of where it is built. While the obstacles are randomly distributed, they can, and regularly do, cluster together. This means that, like navigating a maze, one must do a rough mapping of the entire path before beginning a more detailed analysis, so as to avoid dead ends or major detours. It also means that the path details are very dependent upon start and stop points. Malapert A had no significant slope issues, but otherwise had the same issues as Malapert Massif. We performed a series of manual Monte Carlo-like path analyses in the Malapert Massif and Malapert A regions to determine general characteristics for the pipeline path. Requirements imposed on the pipeline were that the pipeline region must have broad area average slopes less than 15°, lower crater densities, and a straight-line span (start point to end point) of at least 5 km. This latter requirement meant that the length of the pipeline will be more than 5 km due to turns to avoid localized obstacles along the path. Four key statistical results were derived from these analyses:

1. Large turns in the pipeline ($> 20^\circ$) will occur every 250 to 500 meters, but it is also possible to have straight-line distances of around 1 km. This frequency and size of turns should not be an implementation issue.
2. Small turn ($< 20^\circ$) circumstances are much less understood. They will be more common, and some will be accommodated by the inherent flexibility of the pipe material and bonding joints. However, these small turns are also very dependent upon the capabilities of the rover laying the pipeline and the details of the bonding process. Therefore, the number and system impact of small turns is indeterminate at this stage of the study and must await further definition of the pipeline material and manufacturing process, the bonding process for pipe segments, and the capabilities of the rover laying the pipeline. A true evaluation of the small turn circumstances and impact higher resolution imagery, particularly with respect to slopes, will be required as well as a better characterization of the upper layers of the regolith in the area on Malapert Massif and general south polar area. This topic will be revisited as the project continues.
3. Performing some level of surface preparation such as smoothing or moving bigger rocks will reduce the number of turns in the pipeline, particularly smaller angle turns ($< 10^\circ$), and shorten its length. A greater degree of surface processing – “plowing” the path by filling in small craters and moving bigger rocks – will have a major positive impact upon the pipeline path, simplifying and reducing risk for the laying of the pipeline.
4. These required turns will increase the pipeline’s actual length relative to the 5 km straight line distance by 10% to 30% (0.5 to 1.5 km). This increase in length can be reduced with surface preparation.

The only major difference between the Malapert Massif path analyses and the Malapert A analyses was that there were more options for paths at Malapert A and it was easier to find paths with longer straight segments because of its relatively flat terrain. Brief analyses of other Artemis III landing sites suggest that our Malapert Massif analyses will be characteristic of the ridges and crater rims of landing sites selected by the Artemis Program.

No insurmountable issues were found for establishing a reasonable surface path for LSPOP in the lunar south pole region. Therefore, finding a path for LSPOP, given a specific start and stop point in any Artemis Program designated site, should be very feasible.

2.1.1 Example Paths

In this section we present and discuss four example paths for the LSPOP. All the paths reside in the upper regions of Malapert Massif (the right-hand side of the central “Flutter Slopes” region in Figure 2.2). This region was chosen for our path mapping because of the high-resolution imagery available from the LROC NAC 1-m Malapert Massif Mosaic. The four paths meet all the preliminary requirements for the pipeline: slopes $\leq 15^\circ$, minimal large craters and other surface obstacles, and a better than average (i.e., warmer) thermal environment. Comparison of these four paths did not reveal any major differences in characteristics, so we believe that these four paths are representative of pipeline paths in any of the Artemis III landing sites. Figure 2.3 shows the four paths (labeled A, B, C, and D) as blue irregular lines. Path A is a highly curved path that was chosen to investigate major

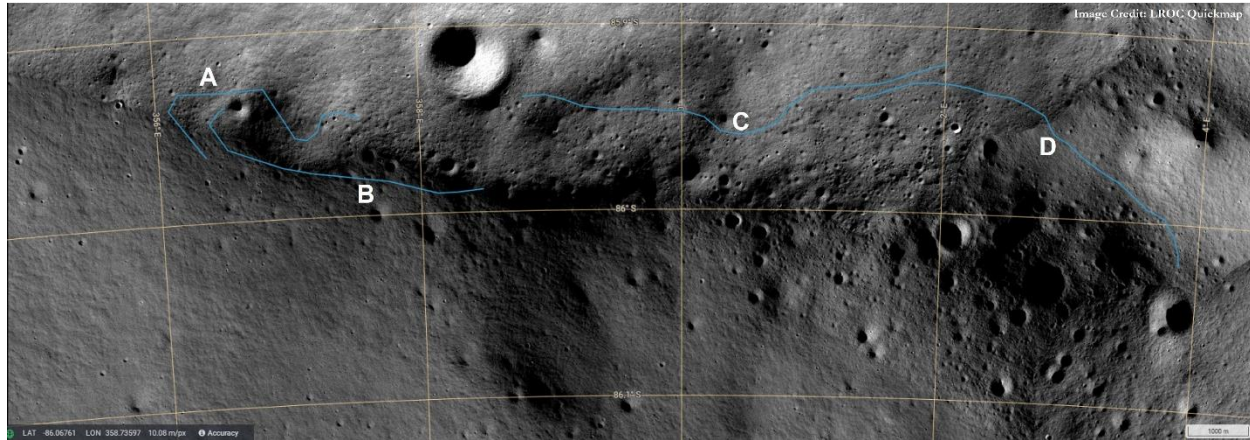


Figure 2.3 Upper region of the Malapert Massif showing four representative paths for the LSPOP.

obstacle avoidance issues. Path B is along a narrower ridge line to determine our ability to lay pipeline in more surface constrained areas. Paths C and D were in a more favorable surface environment to provide data on what the LSPOP would look like if it were located in more optimal locations. The lunar terrain in this latter region would easily allow paths C and D to be connected as a single long pipeline. In addition, path B could be connected to the beginning of Path C along a smooth and manageable downhill slope ($\sim 7^\circ$), creating a long (~ 20 km) pipeline that would span a linear distance of ~ 16 km. Figures 2.4, 2.5, and 2.6 present expanded views of the four paths. Table 2.1 presents three sets of key path parameters for the four paths and the two combined paths as follows:

1. The first two columns give the path length of the sinuous pipeline and the straight-line distance between the start and stop points. These values show that the identified paths can meet the study requirement of at least a 5 km pipeline.
2. The middle three columns give the average slope along the pipeline (100 m resolution), the height range for the path, and the maximum variation in height for the pipeline, providing an assessment of the flatness of the path. This is a key parameter because one of the major programmatic constraints on travel within the Malapert Massif region is maintaining a slope of less than 15° .
3. The last section of the table gives the temperature environment along the pipeline. Understanding the temperature environment is critical for keeping the oxygen gaseous and for determining the heating needs for the pipeline. The temperatures are obtained from Williams

et al (2019) ^[13] and have a resolution of 240 m/pixel, so they cannot account for small terrain the induced variations (e.g., shadowing). The first two columns of this section present the full range of temperature along the path, while the last two columns give the average variation in temperature along the length of the pipeline at any given time. The temperature variation along the pipeline shows minimal change with the seasons.

Table 2.1 - LSPOP Path Parameters

Path	Pipeline Path Length (km)		LOLA Average Slope	Terrain Height Range	Maximum Height Variation Across Pipeline	Broad Area Average Temperatures (C) (From DIVINER)			
	Pipeline	Linear Start Point to End Point	Degrees (100 m resolution)	meters wrt Geode	meters	Seasonal		Range Across Pipeline	
						Max (Summer)	Min (Winter)	Summer	Winter
A	5.0	2.6	12.1	4860-4940	80	-21	-209	65	12
B	5.1	4.5	10.5	4915-4940	25	-28	-211	65	15
C	7.6	7.0	10.4	4720-4940	220	-15	-204	25	10
D	6.7	6.0	10.0	4940-5060	120	-27	-211	30	10
C+D	12.7	11.0	11.4	4720-5060	340	-15	-211	35	10
B+C+D	19.5	15.8	11.0	4720-5060	340	-15	-211	90	25

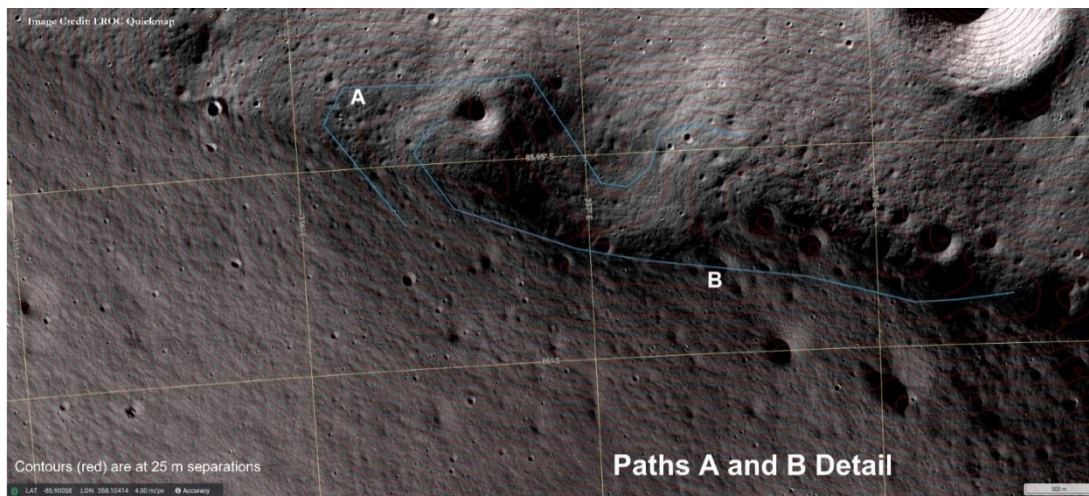


Figure 2.4 Expanded view of Paths A and B.

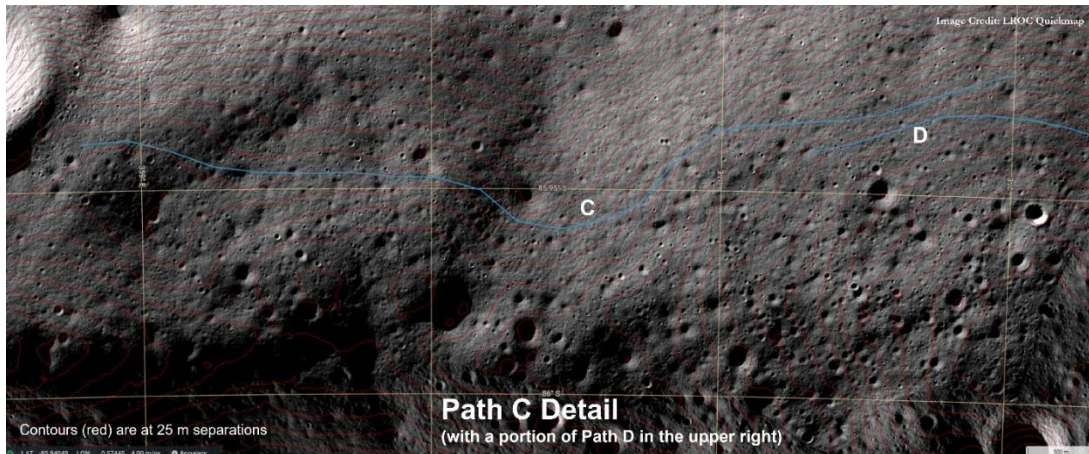


Figure 2.5 Expanded view of Path C.

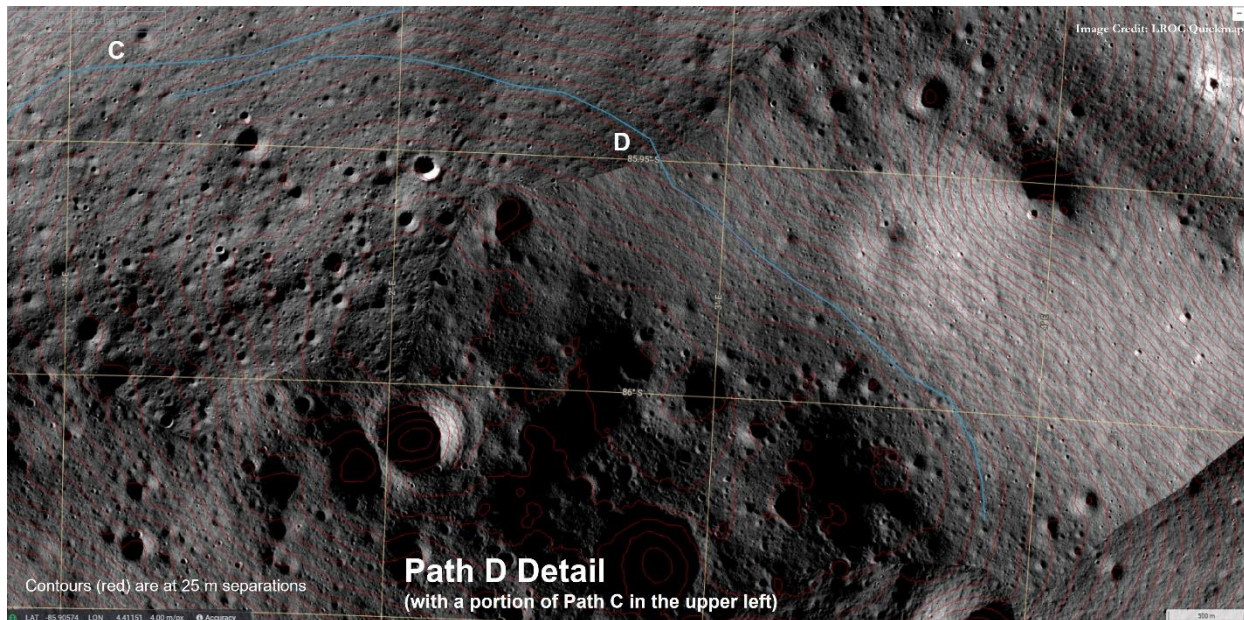


Figure 2.6 Expanded view of Path D.

2.1.2 Pipeline Path Study Conclusions

Finding suitable paths for the LSPOP in the south polar regions has been shown to be highly feasible, even for the mountain tops and ridgelines favored for the Artemis landing sites and eventual Artemis Base Camp. Developing specific details for an “ideal” pipeline path is not possible because these details are very dependent upon the specific starting point and stopping point for the pipeline. However, generalized pipeline path characteristics are obtainable, and these show a relatively narrow spread in their major attributes. The most constraining parameter for finding a suitable pipeline path was maintaining the Artemis requirement operating in areas where the mean slope was less than 15° . Not surprisingly, the mountain tops, crater walls, and ridges where there are higher amounts of sunlight also have steeper average slopes. Our analyses show that while this slope limit reduces the usable terrain, there is still more than sufficient suitable territory for the pipeline to be built. It is important to note that this slope constraint is not pipeline unique, it will apply to any method for the transport of oxygen. Our analyses also indicate that some level of surface preparation (minor smoothing, rock removal, filling in small depressions, etc.) as well as a careful mapping of the pipeline path prior to deployment will greatly speed and simplify the building of the pipeline and reduce overall risk for deployment, normal operations, and repair and servicing.

The analysis of ~200 independent pipeline paths in multiple polar areas, has shown, statistically, that achieving the LSPOP requirement of a 5 km length for the pipeline will not be difficult; examples were given that achieve a ~16 km straight-line distance from the start point to the end point of the pipeline. The pipeline itself will not be straight, but will have, on average, large ($> 20^\circ$) turns every $\frac{1}{4}$ to $\frac{1}{2}$ km. This turn rate is not expected to be a manufacturing or deployment issue. Smaller angle turns should also not be an issue, but quantitative results were not obtainable because of the low resolution of the slope data (0.1 km/pixel). Going around large obstructive features such as a large crater or outcropping presents no difficulty and navigating an undulating terrain with slopes $< 15^\circ$ are not an issue.

Overall conclusion: finding a suitable path for a pipeline that meets Artemis Program requirements is very feasible.

2.2 Lunar Polar Temperature Environment

A baseline of the Lunar south pole temperature data was developed using remote infrared and microwave sensing from Feng and Siegler^[14] supplemented by additional data and theoretical models from other papers studying non-polar locations. Fen and Siegler looked at 4 sites in detail. Location 1 is a sloping ridge not that different from our Malapert Massif site (Fig. 2.2). Location 2 is a crater bottom that is 20-30° cooler than Location 1 and our Malapert site. Location 3 and 4 are both permanently shadowed craters and are much colder. There is also an extensive set of direct measurement data from the Chang'E landing site (-45.4°, 177.6°)^[15]. We found that these multiple analyses are consistent within the level we need for the LSPOP Phase I analysis. These studies show that the top 20-40 cm of regolith have significant density gradients and show a lot of daily and seasonal temperature variations; however, at depths below 40 cm the regolith has shallow density gradients and do not show daily or seasonal temperature variations. The temperatures are essentially constant year-round near the average surface temperature for the location.

2.2.1 Surface Heating

While it is true that direct solar illumination is $\sim 1340 \text{ W/m}^2$, the amount absorbed by regolith (and the pipeline) is a lot less. This is due to the low incidence angle of sunlight at the poles. For example, Location 2^[15] (a crater bottom) is $\sim 4\%$ of the full solar flux. In general, the absorbed flux at any site is very dependent on the angle of solar illumination. It also should be noted that the thermal gradient with depth can be positive or negative. The permanently shadowed regions warm with depth due to heat transfer from the non-shadowed regions, while non-shadowed regions cool with depth.

2.3 Analysis of Temperature vs. Depth in the Lunar Polar Regions

When the temperature and density gradients for a couple of polar regions and the Chang'E-4 site were analyzed we found that the temperature gradients are all very similar in shape and show daily and seasonal variations down to 20-50 cm, then no daily or seasonal variation below that depth, but at a temperature that is dependent upon the location. For the LSPOP Phase I analyses, we adopted the $\pm 80^\circ$ temperature profile which is the closest in surface temperature and solar illumination to the Malapert Massif site. We used the Location 2 profile as our minimum temperature case which is a good example of the coldest place Artemis would build a base camp.

For both the $\pm 80^\circ$ and Location 2 temperature profiles the temperature below 0.5 m is slightly warmer than the average surface temperature. For example, the LSPOP Malapert Massif location (Fig. 2.2) has a temperature range of 65 to 250 K ($\Delta 185^\circ\text{K}$) and average temperature of 145 °K. This is warmer than the $\pm 80^\circ$ location and much warmer than Location 2.

2.3.1 Relevance of Temperature vs. Depth Analysis to LSPOP

The Artemis Basecamp is planned to be set up in a more illuminated (i.e., warmer) area, so the pipeline ≥ 40 cm below will give us a more uniform temperature with daily or seasonal variations. This will keep the oxygen in the pipeline warm enough to be gaseous year-round (Figure 2.2.1) and remove the requirement to heat the pipeline.

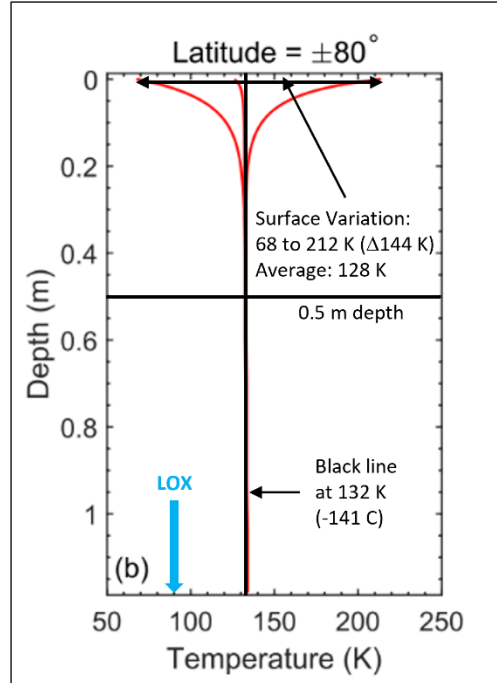


Figure 2.2.1 Temperature versus depth at $\pm 80^\circ$ latitude. The blue arrow indicates the temperature where oxygen liquefies. Figure was adapted from Figure 2 in reference [14].

Burying the pipeline will also ease some threats to the pipeline electronics from thermal cycling, micrometeoroid, and radiation events. However, a buried pipe may complicate other aspects of the pipeline, including deployment, pumping, monitoring, and repair. A detailed trade study to determine if burying the pipeline will be a net system level benefit will be done as part of a Phase II study.

2.4 LSPOP Construction Methodology

The LSPOP Pipeline will be constructed remotely on the Moon's surface with the use of advanced lunar rovers, robotics, and 3D printing, but it will follow similar pipeline construction methodology as on Earth. The entirety of the pipeline is expected to be constructed via open trenching with backfill and no drilling, boring, or direct pipe methods will be utilized. To achieve this, the entire pipeline route will first be trenched using a dedicated trenching tool or an attachment to the lunar rover, and the excavated regolith (spoils) piled away from the trench prior to laying any pipe in the ditch. This will allow for a clean and efficient working area as well as identify any underground obstructions in the path and allow ample time for rerouting and design changes.

Earthen pipelines typically use excavators to dig the trenches to a sufficient depth and safe slope angle to allow for pipeline installation. However, a traditional bucket hoe alone will not be an efficient method of trenching the route, so alternative methods such as a rotary trencher or plow can be fixed to a rover to speed along the process. The sharp, uneroded edges of the regolith material may be destructive to rotating equipment and decrease its functional lifespan, therefore requiring additional spare equipment to be brought to the Moon. The designed depth of cover for the LSPOP line will be 20- 50 cm below the surface, and it is anticipated that the regolith at this depth will be

loose and unconsolidated which would be suitable for the plow technique to be used. The plow can be fixed with a deflecting plate and angled such that the loose regolith spoils accumulate only on one side of the trench. It may take multiple passes with the plow to clear any loose material from the trench, but this is still anticipated to be the most efficient method. Any small rocks or obstructions to the path that would inhibit the plow from creating a clean trench can be removed with the robotic arm on the rover, whereas any large objects will need to be routed around. Pipeline markers or indicators can be placed along the route during excavation to delineate any locations requiring instrumentation or fittings during the installation process.

To lay the pipe into the trench, the LSPOP team plans on mirroring construction methodology of offshore pipelines on earth and continuously join and lower pipe segments into the trench along the route. The lunar rover will be configured with a cargo bay on one side to haul multiple pipe segments, a robotic arm on the other to maneuver the segments, a pipe track and clamping mechanism to position and secure the segments for bonding, the PE3D pipe bonding tool, and guiding arms off the back of the rover to safely lower the pipe into the trench (see rendering in Figure 2.4.1). The rover will straddle the excavated trench and load pipe segments from the cargo bay to the pipe track to position them at the appropriate angle for joining. Once the segments are secured in the proper position with pipe clamps, PE3D machine will complete a weld between a pipe segment on the track and the segments trailing off the back of the rover into the trench. The guiding arm(s) on the back of the rover will help support the joined pipe as it is lowered into the trench as well as secure the pipeline for the joining of additional segments. Once the segments are joined, the rover will progress down the excavated route and load the next segment for joining, repeating this process for the entirety of the route.

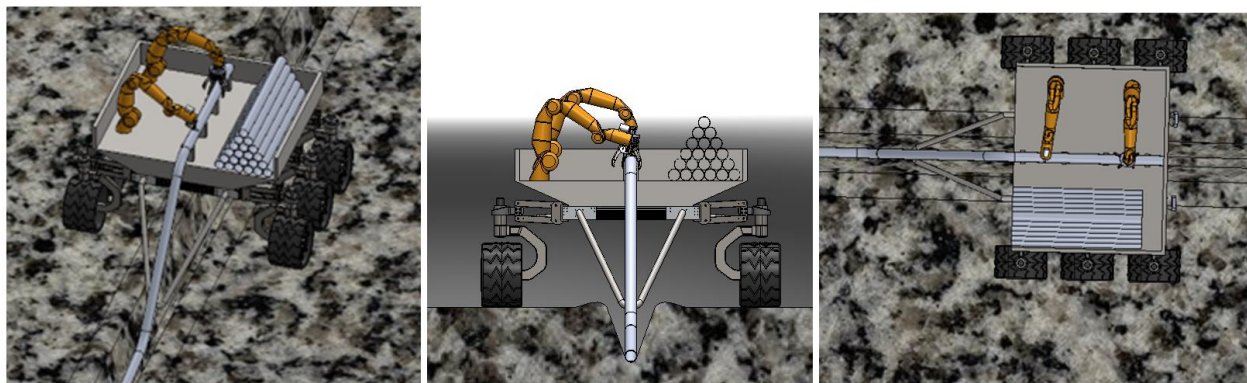


Figure- 2.4.1 Renderings of Rover Laying Pipe: Isometric (left), Front (center), Top (right).

If any heat tracing or instrumentation is to be added to the pipeline, it will need to be done while the trench is open to avoid spot digging around the pipe and potentially damaging it. Instrumentation can be prefabricated to pipe segments on earth and transported to the moon to be loaded on the rover and installed at pre-determined interval locations. After the pipe has been laid in the trench and joined, the pipeline can be backfilled to protect the installed segments. Bedding the pipe with sand and compaction of the backfill material around the pipeline will not be required due to the lunar environment and operational nature of the line. A grading blade can be fixed to the rover to push the spoils back over the pipe and back fill the pipeline below, taking care not to run over the line and risk damaging the pipe with overburden pressure. Above grade markers should be installed

along the pipeline route to identify the pipeline below to more easily locate any anomaly digs as well as prevent accidental travel across the line. A schematic of the process is given in Figure 2.4.2.

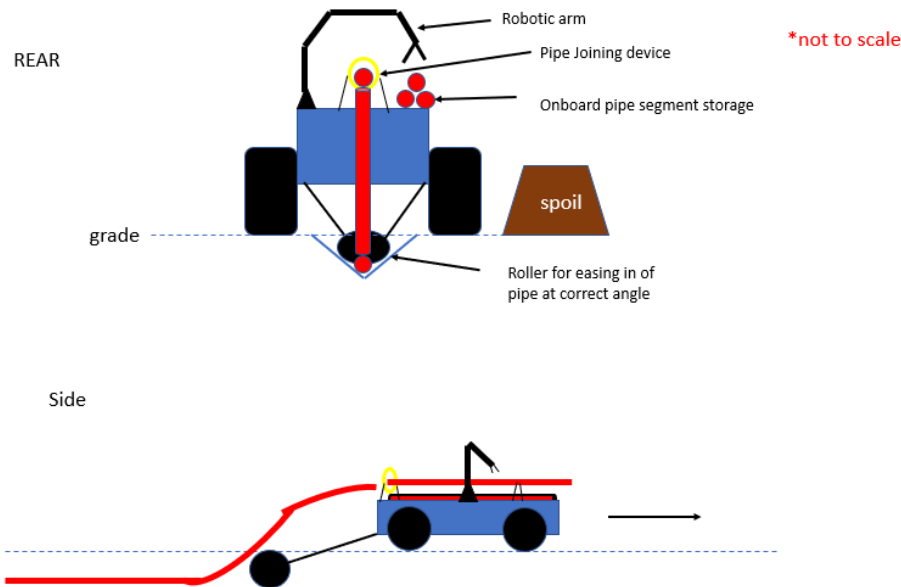


Figure- 2.4.2 Schematic of Rover attachments and Construction process.

Testing the integrity of the welds on the pipeline and the hydraulic stability of the entire pipeline system are items to be determined in Phase 2 of the LSPOP study.

2.5 Pipe Sections Welding and Pressure Test

As described in the previous section on Construction Methodology, our baseline plan is to weld the in-situ produced pipe sections together as the pipeline is deployed by the construction rover. The baseline welding apparatus is the PE3D which is optimized for operations in the lunar environment. Due to the time and budget constraints of the Phase I effort we planned to demonstrate a weld of earth produced aluminum pipe using the laboratory version of the PE3D apparatus and to test the result under pressure.

2.5.1 PE3D Aluminum Pipe Butt Welding Feasibility Demonstration

One inch outside diameter, 1/4" wall thickness pipes of aluminum 6061 alloy were cut, and their ends machined for welding. The PE3D head was held stationary, and the pipe was rotated to complete the welding. For the lunar welding operation, we are developing a rotation head which will be suitable for operation on the pipe deploying rover system. This will be developed and tested in the follow-on project. Final settings that produced fusion joints were done with 15 A of average PE3D current, with the best results using a thin wall flange extended land joint with 1/16" wall thickness. 4043 aluminum filler was added to yield a 1/4" increase from the initial pipe outside diameter. The joints were tapered by 60 degrees to allow fusion of the joints by minimizing the thermal conduction loss from the initial melt pool for fusion of pipes. Welding joints were done in an argon-controlled

atmosphere with less than 100 ppm of oxygen in the chamber using 1/8" tungsten electrodes. During lunar pipeline deployment the welding will be done in ambient vacuum conditions. The absence of oxygen is expected to yield superior weld performance in relation to laboratory tests in Argon.

2.5.2 Results of PE3D Pipe Section Welding Feasibility Demonstration

The parameters of the PE3D were adjusted to control the weld pool, and to minimize oxidation at the weld joint. With that accomplished the feasibility of PE3D aluminum pipe weld joints were demonstrated. Figure 2.5.1 shows an example of a pipe joined using the PE3D and pressure tested to 20 psig. Plans for Phase II include optimizing the joining process and testing to about 3 times operational pressure or 150 psi.



Figure 2.5.1: The final flanged pipe design used for PE3D pipe section fusion joints (top left). Welded pipe segments integrated with pressure gage (bottom left), pressure test to 20 psig (right). The pipe material is aluminum 6061 with a 1-inch outside diameter.

3.0 System Architecture Implementation and Performance (Task 3)

3.1 Laying the Pipeline

A simplified, top-level architecture of LSPOP is shown in Figure 3.1, followed by a description of the three principal components: Oxygen Ingest and Compressor Station, Pipeline, and Receipt Station.

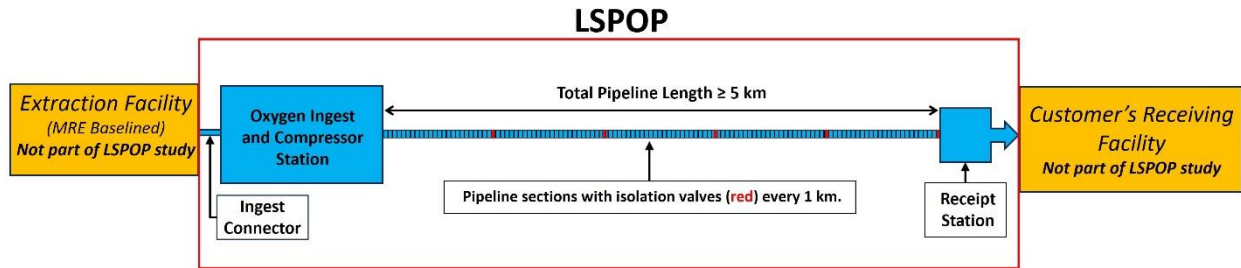


Figure 3.1 Top-level LSPOP Architecture

3.1.1 Oxygen Ingest and Compressor Station

The purpose of the Ingest Station and Compressor Station is to take in the hot oxygen from extraction facility and store the oxygen, prepare it for transmission through the pipeline, and, utilizing a compressor, send it to the Receipt Station 5+ km distant. All the components in this facility are Earth-built and will be transported as an integrated unit, with some component modularity to facilitate replacement/maintenance. Contents will include compressor and electric motor skid packages with all supporting electronics, suction drum with pressure control relief valves, internal piping and monitoring systems, temperature monitors/transmitters, a flow meter with a matching system at compressor discharge for matching of receipt volumes, and general station infrastructure (communication and command and control hardware, hardware processors to run everything, heaters, miscellaneous sensors, etc.).

The compressor system will be redundant with at least 2 independent compressor systems and automatic switchover systems. Additional compressor systems will be in storage in proximity to the site for additional redundancy to ensure a long life with uninterrupted operation for the pipeline.

3.1.2 The Pipeline

The pipeline is what carries the oxygen to the Receipt Station for delivery to the customer. It consists of the bonded pipe segments, spanning a straight-line distance of 5 km (from our path analysis we estimate it will take ~6 km of pipe segments to account for the expected bends in the pipeline (see Section 2.1). The pipeline will be buried 20-40 cm below the lunar surface to maintain thermal stability. A TBD number of pressure/temperature sensors and communication relays will be located along the pipeline.

3.1.3 Receipt Station

The purpose of the Receipt Station is to ingest the oxygen from the pipeline and transfer it to the customer supplied storage facility. Any additional processing of the oxygen is expected to be done by the customer. As with the Ingest station, all the components in this facility are Earth-built and will be transported as an integrated unit, with component modularity for ease of

replacement/maintenance. The contents will include: pressure control hardware and relief valves (all redundant), custody transfer flow meters (all redundant), pressure and temperature transmitters, standard exit fittings to connect to customer receipt facility and station infrastructure: processors to run everything (PLC programmable logistics controller), heaters, miscellaneous sensors, etc., communication and command and control hardware, including a point-to-point surface link and an Earth/Moon link, all redundant. The assumption is that the data flow will be small and can be located at the Receipt Station end of the pipeline because of the greater infrastructure at the customer site.

One of the key issues for the pipeline is the need to keep the oxygen in a gaseous phase in the cold lunar south pole environment. Fortunately, the regolith is an excellent insulator and burying the pipeline more than 20 cm below the lunar surface will maintain the pipeline temperature above the liquefaction point of oxygen without additional heaters^[14, 15] and Section 2.3. The density of the polar regolith at these depths is low^[15] and should not present any trenching issues. NASA's RASSOR and other excavation systems in development appear more than capable of meeting the excavation needs of LSPOP.

LSPOP will use a rover system to lay the pipeline. This rover system is expected to be autonomous or semi-autonomous but could also be crewed. The preferred scenario is that the rover used by LSPOP would be leased from existing rovers at the Artemis Basecamp. However, if the use schedule would make this type of leasing impossible, a dedicated LSPOP vehicle could be used. Similarly, the trench digging vehicle was assumed to be leased from an existing Artemis pool, rather than a dedicated LSPOP vehicle. For the Phase I study we baselined Lockheed's Lunar Mobility Vehicle (LMV)^[16]. This vehicle is in development by Lockheed for application in the south polar region in support of the *Artemis* Program. The current design appears to meet or exceed nearly all LSPOP requirements. The expectation is that the LMV (or another rover) would be operated with the supervised autonomy system that is part of the current LMV design. While the LMV seems to meet LSPOP requirements, a more detailed analysis of all likely rovers will be performed in Phase II.

In the first lunar day(s) of operation, while the pipe segments are being built, the LMV will perform a survey the final path (determined earlier from orbital imagery) to ensure it meets requirements and mark the path for future use. The trenching system will then trench the pipeline path. LMV will again survey the path to ensure that no issues were generated by the trenching. Once sufficient pipe segments have been manufactured, the bonding hardware will be attached to the LMV, the LMV robotic arm will pick up pipe segments from the manufacturing site, place them in their payload bay, and transport them to the start point of the pipeline. Individual pipe segments will be picked up from the payload bay and placed into the bonding hardware by the LMV robotic arm, and the segments will be bonded together as the rover proceeds producing a continuous pipeline and deposited into the waiting trench as outlined in Section 2.4. The LMV will continue laying pipe segments until it uses all the segments in the payload bay, it will then return to the manufacturing site, load more pipe segments, return to the end of the pipeline, and continue adding pipe segments to create the pipeline. Portions of the pipeline that involve curved pipe segments will be handled in a similar manor as the straight segments.

Overall conclusion: while details of how the pipeline will be built is a task for Phase II, no major issues were identified in Phase I and the pipe laying requirements are achievable and clearly very feasible.

3.2 Implementation Timeline

In this section we present a very preliminary timeline for LSPOP from initial landing to full operations. For this discussion our “work” time unit is 1 lunar daytime interval (14 Earth days = 336 hours sunrise to sunset) minus 12 hours after sunrise and minus 12 hours prior to sunset, and no work being done during lunar night. This equates to a total of 312 working hours per lunar orbit. For the manufacturing and bonding functions and for the LMV activities a 25% overhead was added to all times to account for unknown unknowns and other unexpected issues that are likely to arise in building LSPOP. It is quite possible that the pipeline would be built at a location with more hours of daylight, in that case the timeline would be shortened. LSPOP support equipment that would need to be transported from Earth are the Oxygen Ingest and Compressor Station (multiples for redundancy/risk mitigation), the receipt Station (multiples for redundancy/risk mitigation), the pipe manufacturing hardware, a small power system, surface and Earth-Moon communication systems, and various sensors. None of the LSPOP support hardware is large or heavy, so delivering all the components needed to implement LSPOP should be possible in a single launch/landing.

3.2.1 LSPOP High-Level timeline.

- Lunar Day 1
 - Land hardware.
 - Perform system checkout of all components.
- Lunar Day 2
 - Deploy pipe manufacturing system to manufacturing site.
 - Deploy and set up PE3D hardware and support equipment.
 - Set up manufacturing power system and run all necessary tests to declare system operational.
 - The remaining equipment, the Ingest and Receipt stations, including redundant units, spare components, etc., are moved to long term storage to protect it from the environment. One compressor station will not be put into storage but rather used for extensive testing of the pipeline as it is being built.
 - Start pipe manufacturing system after final checkout and inspect/validate initial pipe segments before going into production mode.
 - Deploy LMV. This LMV could be drawn from existing units drawn from the nearby Artemis base or landed with LSPOP hardware.
 - Perform survey of the potential path(s) that were identified from orbital imagery or prior investigation and send back information needed to make a final path selection.
 - Perform any surface modification (smoothing, removing rocks, etc.) needed for the path.
- Lunar Day 3
 - Continue pipe segment manufacturing.
 - If needed, LMV will finish surveying pipeline paths or preparing surface.
 - Request a trenching system (either part of the LSPOP Project or “rented” unit) from Artemis Basecamp to dig trench for the pipeline along the agreed to path.
 - Have LMV reinspect the pipeline path to validate that there are no issues.
- Lunar Day 4

- Continue pipe segment manufacturing.
- Start deploying pipeline. A sufficient pipe segment backlog should now exist and LMV's other LSPOP duties are complete.
 - Load LMV with pipe segments and travel to pipeline beginning and start laying pipe.
 - After ~ 1km of pipeline has been built, stop laying new pipe segments and perform system tests on the 1 km length of the pipeline using the Compressor Station designated for that testing and oxygen from an oxygen cylinder(s) transported to the moon for that purpose. If pipeline testing validates that all the requirements are being met, continue with the laying of the pipe segments. If issues are discovered, stop manufacturing and pipe laying, evaluate the issues and devise a recovery/mitigation plan.
- Lunar Day 5 to 8
 - Continue pipe segment manufacturing.
 - Continue deploying pipeline.
 - At sundown every day, LMV stays in place or returns to another location.
- Lunar Day 9-28 (pipe segment manufacturing should be complete at the end of Lunar Day 8)
 - Continue deploying pipeline.
 - At sundown every day, LMV stays in place or returns to another location.
 - Perform additional pipeline validation testing, as done on Lunar Day 4, as needed.
- Day 29 (Pipeline deployment has now been completed)
 - Using LMV and/or astronauts
 - Deploy Ingest/Compressor station.
 - Deploy Receipt Station.
 - Deploy pipeline sensors and communication nodes.
 - Connect everything to power.
 - Set up system communication links and test system.
 - Perform final system checkout/validation/etc. and prepare for lunar night.
 - If all checks out, cover the pipeline with regolith. If the system checkout identifies problems, perform repairs.
- Lunar Day 30
 - If needed continue repairs and/or perform additional checkout.
 - Connect to oxygen source.
 - Purge pipeline and perform operational testing.
 - If the pipeline checks out, declare it operational. If the system checkout identifies problems, perform repairs, retest the system until all requirements are met and the pipeline can be declared operational.
- Lunar Day 31 (2.5 years from landing)
 - Connect the Receipt Station to the customer facility and begin the operational phase of LSPOP.
- Lunar Day >32
 - The pipeline is now fully functional and delivering oxygen to the customer(s) per their requests.
 - In parallel, the pipeline will be end-to-end monitored using the multitude of sensors associated with the pipeline.
 - Should leaks, compressor or other hardware failures, or any other issues arise, the location will be identified, and repairs implemented. Details of this process will be outlined in Phase II.

4.0 System Architecture: Safety, Risks, Evolution, and Costs (Task 4)

4.1 Safety and Risk Management

Initial Assessment of LSPOP Safety and Risks

The purpose of developing the LSPOP pipeline for transportation of oxygen on the Lunar surface is to provide the safest, most efficient mode of transportation of gaseous oxygen from production sites to Artemis and commercial customers points of distribution. Despite some public perception, terrestrial pipelines are significantly safer at transporting fluids on a ton per mile basis and account for roughly 70% of liquid and 98% of gaseous transportation. Gas transportation via pipeline allows for safe and effective transmission and distribution of gaseous fluids from source to end use around the world and there is a long-standing history of refined best practices, specifications, and regulations that can be leveraged for lunar deployment of a gaseous pipeline.

4.1.1 Risk Register:

For this phase of the LSPOP project, a preliminary risk register was developed for comparison against terrestrial pipeline projects. A sample list of risks from a typical pipeline project was evaluated for the likeliness of the event to occur as well as the severity of the impact that event could have to project, timeline, cost, safety, or feasibility. This pipeline risk register and further risk studies for the origination and receipt facilities supporting LSPOP will be revisited in future study phases as well. An arbitrary value of 1-5 was chosen for both likeliness (1 being least likely and 5 almost certainly happening) and impact (1 being very small impact and 5 a catastrophic impact) and compared against the terrestrial pipeline projects. This is an initial version of the full Risk Register that is a baseline for the Phase I feasibility study. A full project risk register will be developed as the Project continues and will require that these rankings have specific values or attributes attached to them, and those values and attributes require collaboration from multiple parties and information that is will be developed at later phases of the project. From these values and designations, a risk matrix can be developed alongside a risk strategy to determine the overall risk of an event accounting for likeliness, severity, and mitigation measures in place. As the design and development of the LSPOP project progresses, additional tasks may be identified as having potential risk and will need to be evaluated. It is important to continually update the risk register throughout the project lifecycle and evaluate each task for potential impacts. The LSPOP project will also adhere to any risk evaluation criteria set by NASA and other governing agencies, and the Artemis Accords, throughout the development of the project, and receive full approval before moving into execution and operation. The risk register was reviewed by personnel with experience in terrestrial pipeline projects for feasibility, but the rankings assigned to each task are up for interpretation and should be peer reviewed by subject matter experts in future phases of the project.

Table 4.1.1- Preliminary LSPOP Pipeline Risk Register: Public Relations and Government Affairs

Category	Item	Impact	Risk	Terrestrial Likelihood (1-5)	Terrestrial Impact (1-5)	Lunar Likelihood (1-5)	Lunar Impact (1-5)	Comments and Mitigations
Public Relations	Business Impacts	Cost, Schedule	Business interruption costs associated with construction timing or location	2	3	3	4	Timing & coordination with other lunar operations is uncertain and requires significant additional studies and approvals before proceeding. Opportunities to de risk as projects develop.
Public Relations	Infrastructure or Transportation Impacts	Cost, Schedule	Impacts on infrastructure or interruption of transportation associated with construction timing or location	2	3	3	4	Transportation to the moon is major risk and undefined at current stage of project.
Government Affairs	Legal and Regulatory Requirements	Cost, Schedule, Sanctions	Failure to identify or understand all relevant environmental and social legal and regulatory requirements that may impact the project.	1	2	2	3	unclear what if any regulations for lunar development at this phase of the project.
Government Affairs	Permits	Cost, Schedule	Failure to obtain permits or significantly delayed permit process.	2	3	2	3	unclear what if any regulations for lunar development at this phase of the project. Unsure of global government perception of lunar development and potential opposition.

Table 4.4.2- Preliminary LSPOP Pipeline Risk Register: Environmental and Right of Way

Category	Item	Impact	Risk	Terrestrial Likelihood (1-5)	Terrestrial Impact (1-5)	Lunar Likelihood (1-5)	Lunar Impact (1-5)	Comments and Mitigations
Environmental		Cost	Release of product into the environment.	1	3	2	1	O2 release not hazardous to lunar environment, but may be regulated
Environmental		Cost	Pollution/Contamination exposure	1	2	1	1	O2 release not hazardous to lunar environment, but may be regulated
Environmental	Water Resources	Cost, Safety, Public Relations	Interruption or Contamination of Surface/Ground/Transboundary Water Ingress	1	2	N/A	N/A	no water on lunar surface and no contaminants in LSPOP process
Environmental	Protected/Sensitive Areas and Wildlife	Cost, Schedule	Reroutes required to avoid protected/sensitive environmental areas or wildlife.	2	3	N/A	N/A	no environmentally sensitive areas currently defined on lunar surface
Environmental	Protected/Sensitive Areas	Cost, Schedule	Discovery of archaeological artifacts during construction.	2	3	N/A	N/A	no archeological artifacts anticipated on lunar surface
Environmental	Construction Method	Cost	Excessive mitigation costs/negotiations.	2	2	1	1	lunar restoration and remediation not expected but identified as small potential risk.
Environmental	HDD Frac outs	Cost, Schedule, PR	Hydraulic fracture releasing drilling fluid into sensitive habitat, which could jeopardize cost, schedule and reputation.	2	2	N/A	N/A	No drilling installation or hydraulic fluid used.
Environmental	H-test water sourcing and returning	Cost, Schedule, PR	Public likely will perceive risk associated with hydrostatic test water discharge after testing.	2	2	N/A	N/A	no hydrostatic testing or discharge for LSPOP
ROW	Accessibility	Cost; Schedule	Contact work stoppages due to unresolved acquisition of property from individual property owners	2	2	N/A	N/A	no individual land owners on the moon. All approvals will be at federal level
ROW	Accessibility	Cost; Schedule	Contact work stoppages due to unresolved acquisition of property from tribal property owners	2	2	N/A	N/A	no tribal land owners on the moon. All approvals will be at federal level
ROW	Accessibility	Cost; Schedule	Contact work stoppages due to unresolved acquisition of permits (non-environmental permits)	1	3	1	3	Identify and obtain all permits prior to proceeding, undefined at this stage
ROW	Permit Acquisition for Route through Protected/Sensitive Areas	Cost, Schedule	Inability to get permit to cross through protected/sensitive areas	2	3	1	3	no sensitive areas identified at this stage. If not identified early, may cause significant delays.
ROW	Title and Ownership	Cost; Schedule	Ownership gaps and other title (lease) deficiencies; physical location of legal land lessee	2	2	N/A	N/A	no land owners on lunar surface
ROW	Labor	Cost, Schedule, Quality	Lack of available experienced local contractors and utilizing inexperienced ROW agents that require training	1	2	2	2	No experience with acquiring permissions to develop on lunar surface. May be extensive process
ROW	Procedure	Cost; Schedule	Inability to start title work, file and easement preparation, and other ROW work on schedule	2	2	N/A	N/A	no title or ownership information on the moon
ROW	Expenditures and Easements	Cost; Schedule	Lack of defined authorization parameters for ROW agents	2	2	N/A	N/A	no ROW agents being utilized
ROW	Legal	Schedule	Slow responses and processing by legal local and country agencies	2	2	N/A	N/A	no local agency involvement, federal only
ROW	Easement Cost	Cost; Schedule	Offering insufficient payments for right-of-way; payments do not meet criteria for "Good Faith" offers and negotiations	2	2	N/A	N/A	no payments for ROW acquisition
ROW	Acquisition	Schedule	Inability to reach a settlement for ROW acquisition.	2	2	N/A	N/A	no payments for ROW acquisition
ROW	Public Relations	Cost; Schedule	Negative landowner and tenant response to pipeline because of previous experience with pipeline or utility companies.	2	3	N/A	N/A	no local landowners
ROW	Accessibility	Cost; Schedule	Road access to ROW is limited, must use ROW to transport material, crews and equipment.	2	2	4	2	no roads or defined transportation routes on lunar surface. Will be difficult to maneuver.
ROW	Settlement	Cost; Schedule	Damages to 3rd Party property	2	3	2	4	Working in close proximity to other Artemis operation introduces risk at interface points
ROW	Acquisition	Cost; Schedule	Difficulty obtaining sub-leases with private parties	2	3	1	3	requires close coordination with other parties involved in Lunar operations. Interruptions to work due to disagreements will be costly
ROW	Densely populated areas	Cost, Schedule	Difficulty with establishing ownership and/or acquiring ROW through densely populated areas.	3	2	N/A	N/A	no population on the lunar surface

Table 4.2.3- Preliminary LSPOP Pipeline Risk Register: Engineering Design, Materials, and Execution

Category	Item	Impact	Risk	Terrestrial Likelihood (1-5)	Terrestrial Impact (1-5)	Lunar Likelihood (1-5)	Lunar Impact (1-5)	Comments and Mitigations
Engineering & Design	Design	Cost, Schedule	Design errors, late engineering deliverables, changing requirements and known unknowns (i.e. assumptions)	2	3	4	3	a lunar pipeline has never been designed so there are no historical references for best practices. Extensive review will be required and may lead to delays in approved design and multiple revisions.
Engineering & Design	Standards	Cost, Schedule	Inability to align standards utilized by Owner	2	3	2	4	inability to design and construct a pipeline that meets the standards of the end user is a risk to the project feasibility. Those standards have not yet been identified
Engineering & Design	Design	Cost, Schedule	Unforeseen eng/design work required to support permits	2	2	2	2	unknown permitting requirements may result in additional engineering deliverables to satisfy all entities.
Engineering & Design	Manpower	Cost, Schedule	Adequate, qualified and client-familiar engineering resources (people)	1	2	3	3	leveraging well respected and experienced terrestrial pipeline design firms for engineering but no lunar experience
Engineering & Design	Storage	Cost	Inadequate storage capacity at the receipt facility to handle an extended pipeline shutdown; pipeline rupture, station outage, etc.	1	2	N/A	N/A	storage at receipt facility outside of LSPOP scope beyond small buffer.
Engineering & Design	Emergency (Major)	Cost, Safety, Schedule	Product solidifying/ liquifying in pipeline due to an extended pipeline shutdown period (e.g., due to major pipeline rupture, major equipment failure/damage, delayed repairs, operation errors, etc.)	1	2	1	3	consistent data shows temperatures at pipeline depth do not reach liquefaction point of O ₂ . would require extreme event.
Engineering & Design	Flood Protection	Cost, Safety, Public Relations	Inadequate negative buoyancy design.	1	3	N/A	N/A	no need for buoyancy control on lunar surface
Engineering & Design	Pipeline Corrosion/Cathodic Protection	Cost, Safety, Schedule	Inadequate or improper corrosion/cathodic protection design.	1	3	N/A	N/A	no need for cathodic protection on lunar surface
Engineering & Design	Fault Crossings and Seismic Activity	Cost, Safety	Pipeline or station designs not adequate to withstand anticipated seismic activity.	1	3	N/A	N/A	no anticipated seismic activity
Engineering & Design	Landslides, Steep Incline/Declines	Cost, Safety, Schedule	Landslide exposes or damages pipeline.	2	3	1	3	landslides caused by impacts to lunar surface could uncover portions of the pipeline.
Engineering & Design	Pipeline Design in Densely Populated Areas	Cost, Safety	Pipeline not adequately designed for ensuring public safety in densely populated areas.	1	3	2	3	Artemis base to be considered densely populated. Failure of pipeline near inhabited spaces on lunar surface could have serious consequences.
Materials and Equipment	Procurement	Cost, Schedule	Sourcing of adequately designed equipment	2	2	3	2	lunar equipment will be subject to harsh environments and needs to be specifically designed and manufactured to operate in those conditions
Materials and Equipment	Procurement	Cost, Schedule	Material purchases relating to potential re-routes	2	2	2	1	high chance of reroutes, but pipe manufactured in situ to provide spare capacity at will
Materials and Equipment	Procurement	Cost, Schedule	Determine the need to maximize in country provided materials and services	3	2	N/A	N/A	material manufactured on site
Materials and Equipment	Logistics	Schedule	Road restrictions due to weather impedes transport of materials and equipment (heavy loads)	2	2	N/A	N/A	no weather delays for equipment deliveries
Materials and Equipment	Procurement	Schedule	Timeliness of Vendor responses.	1	2	1	2	vendor management will need to be closely coordinated
Materials and Equipment	Procurement	Cost; Schedule	Unavailability or late delivery of materials or equipment. Need for expediting.	2	2	1	4	scheduling all non in situ materials will need to be closely coordinated or cause significant delays
Materials and Equipment	QA/QC	Cost; Schedule	Defective materials or equipment from manufacturer/vendor.	2	3	2	4	equipment testing on earth for lunar environments prior to shipping
Materials and Equipment	Logistics	Cost; Schedule	Damaged materials or equipment during transit	1	3	3	4	space transit provides significant risk
Materials and Equipment	Procurement	Cost; Schedule	Material or equipment order not placed when required to meet schedule.	2	2	2	3	material coordination must be closely monitored to not delay expensive lunar operations.
Project Execution	Schedule	Schedule, Cost	Timely approval for engineering, procurement and contract award.	2	2	2	2	coordination with all engineering, supply, and contract parties in a timely manner is key to meeting schedule and minimizing costly delays
Project Execution	Scope	Schedule, Cost, Relationships	Change, misalignment, and revision of project objectives and deliverables in order to meet the agreed Design Basis.	2	3	3	3	clear design basis and battery limit for the project will help focus scope. Due to complexity of design, review, and approval process, changes to the design basis can cause significant delays
Project Execution	Schedule	Cost, Errors, Problems	Inadequate project schedule, release of work, and project funding	2	3	2	3	timely approvals and funding will prevent delays and complications
Project Execution	Organization	Cost, Errors, Problems	Roles, responsibilities, and expectations not clearly defined or executed	1	2	1	2	identification of key stakeholders, approvals, and scope of supply are crucial to advancing project design.

Table 2.4.4- Preliminary LSPOP Pipeline Risk Register: Personnel, Project Survey, and Construction

Category	Item	Impact	Risk	Terrestrial Likelihood (1-5)	Terrestrial Impact (1-5)	Lunar Likelihood (1-5)	Lunar Impact (1-5)	Comments and Mitigations
Project Personnel	Job Performance	Unacceptable Work, Safety, and Loss	Unacceptable personnel and/or individual job performance resulting in an accident or environmental impact	1	3	1	3	fewer personnel involved in construction or operation of plant but higher risk due to lunar environment
Project Personnel	Contracting Strategy	Cost, Schedule	Mobilization, transition, coordination of independent teams	1	2	2	3	deployment of construction team and handover from design with proper oversight will be key
Civil Survey	Access Roads	Schedule	Timely consent to design, bid, award access roads construction	1	2	N/A	N/A	no access roads on lunar surface
Civil Survey	Accessibility	Cost, Schedule	Lack of access to properties.	2	2	N/A	N/A	free access to all lunar territory
Civil Survey	Crew Productivity	Schedule	Availability of modern survey equipment and probability of equipment failure.	1	2	2	2	relying on multiple agencies and governments for updated data for project
Civil Survey	Labor	Cost, Schedule	Inability to find adequate/qualified personnel	1	2	2	3	no labor force available with lunar development and execution experience. Will be learning on the job
Civil Survey	Right of Way Access Safety/ Security	Safety, Security, Cost, Schedule	Security/Safety risk with encountering unfriendly population or animals	2	2	N/A	N/A	no risk of external security threats from personnel
Construction	Welding Procedures	Cost, Schedule	Welding procedures may be very restrictive and require considerable testing.	2	2	4	2	PE3D is leading welding technology and will be thoroughly tested
Construction	Unforeseen	Cost, Schedule	Encounter sub-surface rock formations during pipeline installation	2	2	4	2	sub surface terrain along LSPOP pipeline route is impossible to accurately survey and will likely require reroutes. No blasting or clearing possible in lunar environment.
Construction	Unforeseen	Cost, Schedule	Difficulty maintaining proper drainage	2	2	N/A	N/A	no drainage required on lunar surface due to absence of liquid water
Construction	Pipeline Contractor Performance	Cost, Schedule	Poor performance/productivity due to an extreme circumstance	1	4	2	4	progress on LSPOP construction will be slower than terrestrial pipeline construction and conducted in a harsher environment.
Construction	Document Control	Cost, Schedule	Utilization of current and approved engineering specifications and drawings	1	3	1	3	full approval of reviewed drawings and design package before starting construction
Construction	Labor	Cost	Cost of labor compared to estimate basis.	2	3	1	3	use of third party equipment rates to be negotiated up front. Conservative schedule to avoid cost overrun.
Construction	Labor	Cost, Schedule	Other ongoing competing work interfering with productivity	2	2	1	3	interference from other Artemis activities unlikely, requires significant coordination.
Construction	Weather Related	Schedule	Excessive inclement weather, such as rain and wet conditions, and floods restricts construction progress	2	3	N/A	N/A	no weather conditions on lunar surface
Construction	Road / Bridge Limitations	Cost, Schedule	Integrity of roads and bridges inadequate for transport of heavy haul	2	3	1	1	no roads on lunar surface but potential for challenging terrain along route
Construction	Access Roads	Cost, Schedule	Inadequate access roads	2	3	4	1	no roads on lunar surface but potential for challenging terrain along route
Construction	Construction Start	Cost, Schedule	Government restrictions on start of construction.	2	3	2	3	uncertainty of government oversight and restrictions on lunar infrastructure development at this stage of the project.
Construction	Permit	Schedule	Local permitting issues not related to area of Federal	1	2	N/A	N/A	only federal oversight, no local regulations
Construction	Rule Compliance	Cost, Schedule	Construction non-compliance with environmental rules and guidelines to the point of requiring action (sanctions) of the regulatory authority.	1	3	1	3	uncertainty of environmental oversight and requirements, minimal anticipated.
Construction	Corporate Relations	Schedule	Resistance or lack of cooperation from parallel entity	2	2	1	3	close coordination with all third parties involved in lunar infrastructure development
Construction	Owner Construction Management	Cost, Schedule	Inadequate or unqualified field construction management and inspection resources	2	3	3	3	No experienced personnel for lunar infrastructure available. Will utilize best terrestrial talent available and peer reviewed industry practices
Construction	Hydro Test Water	Cost, Schedule	Availability of quantity of water required for hydro testing; facility piping, tankage and pipeline hydro testing	2	2	N/A	N/A	no hydro testing of equipment on lunar surface. Any terrestrial equipment testing will not require excessive water.
Construction	Material Equipment	Cost, Schedule	Defective materials or equipment from manufacturer/vendor.	2	4	1	4	extensive terrestrial testing of all equipment in simulated lunar environments prior to installation.
Construction	Incidents	Cost, Schedule	Construction incident/disruption occurrences.	2	4	2	3	unforeseen complications during construction may cause significant delays to operation
Construction	Addition damage/repair to pipe and coating from rough travel	Cost, Schedule	Damaged or defective pipe or coating	3	2	3	1	no coating on LSPOP pipe. Pipe manufactured on site to minimize travel. If manufactured pipe has defects, additional material can easily be made available to replace.
Construction	Traffic control and safety	Safety, Cost, Schedule	Injury and property damage	2	4	1	4	minimal personnel involved in construction of LSPOP compared to terrestrial pipeline. Some terrestrial manufacturing will require strict safety oversight.
Construction	Lateral slopes	Cost, Schedule	Erosion and ROW instability	2	2	N/A	N/A	no erosion forces on lunar surface.
Construction	Seismic faults	Cost, Schedule	Encounter sub-surface conditions different than expected	2	3	3	3	impossible to know sub surface challenges along entire LSPOP route. May require reroutes or design changes.
Construction	Unforeseen	Cost, Schedule	Rock blasting more difficult than expected.	2	2	N/A	N/A	no blasting of rock will be used in LSPOP construction.
Construction	Meta-stable slopes	Cost, Schedule	Operational risk with slope movement inducing stress on pipe	2	3	1	3	LSPOP will be constructed on sloped terrain, but reduced gravity means there is less force being enacted on the pipe.

Table 2.4.5- Preliminary LSPOP Pipeline Risk Register: Personnel, Civil Survey, and Commissioning

Category	Item	Impact	Risk	Terrestrial Likelihood (1-5)	Terrestrial Impact (1-5)	Lunar Likelihood (1-5)	Lunar Impact (1-5)	Comments and Mitigations
Project Personnel	Job Performance	Unacceptable Work, Safety, and Loss	Unacceptable personnel and/or individual job performance resulting in an accident or environmental impact	1	3	1	3	fewer personnel involved in construction or operation of plant but higher risk due to lunar environment
Project Personnel	Contracting Strategy	Cost, Schedule	Mobilization, transition, coordination of independent teams	1	2	2	3	deployment of construction team and handover from design with proper oversight will be key
Civil Survey	Access Roads	Schedule	Timely consent to design, bid, award access roads construction	1	2	N/A	N/A	no access roads on lunar surface
Civil Survey	Accessibility	Cost, Schedule	Lack of access to properties.	2	2	N/A	N/A	free access to all lunar territory
Civil Survey	Crew Productivity	Schedule	Availability of modern survey equipment and probability of equipment failure.	1	2	2	2	relying on multiple agencies and governments for updated data for project
Civil Survey	Labor	Cost, Schedule	Inability to find adequate/qualified personnel	1	2	2	3	no labor force available with lunar development and execution experience. Will be learning on the job
Civil Survey	Right of Way Access Safety/ Security	Safety, Security, Cost, Schedule	Security/Safety risk with encountering unfriendly population or animals	2	2	N/A	N/A	no risk of external security threats from personnel
Commissioning	Labor	Cost, Schedule	Adequate and qualified personnel available to commission/operate the system.	1	2	3	2	best available terrestrial pipeline resources used to plan, coordinate, and execute the commissioning of the system.
Commissioning	3rd Party Customers	Cost, Schedule	3rd Party connections being ready per schedule	2	2	2	2	Communication and continued meetings with 3rd Party activities.
Commissioning	Equipment or Material Theft	Cost, Schedule	Security not adequate to prevent theft of materials/equipment during construction or commissioning.	2	2	N/A	N/A	no risk of material theft of lunar surface

4.1.2 Health and safety Risk evaluation:

Although pipelines are the safest and most efficient mode of fluid transportation, the construction and operation of a pipeline in any environment can still pose a variety of health and safety risks to the personnel building and operating the system as well as bystanders and the general public. There are a variety of potential hazards that can be identified throughout the lifecycle of a pipeline and many of them can be mitigated sufficiently with proper training and attention to procedures. Human error is always present in any scenario. Automation and tele operation will remove personnel from harm's way and further mitigate the risk to human health. Although it is impossible to identify all the potential risks to human health with a lunar pipeline, historical experience in terrestrial pipeline construction and operation activities can highlight areas of concern, and these activities can be studied for mitigation. For this study, the most common risks to health and safety associated with terrestrial pipeline construction and operation are evaluated for their potential risk in a lunar environment.

The construction of terrestrial pipelines, like any heavy construction activity, can pose a risk to the personnel located near the job site. Large equipment, heavy machinery, work at heights, excavations and other potentially hazardous items are unavoidable to complete the task, but workers with the proper training, safety equipment, and procedures can navigate the job without injury. The terrestrial pipeline construction activities that pose the most risk to human safety is excavation, welding, moving vehicles, and pressure testing. These activities have been evaluated for the LSPOP project to identify areas of concern that need to be addressed further:

- Excavation will be performed remotely with the lunar rover and no personnel will be lowered in or near the open top of the excavation site. Excavation depths for LSPOP installation during automated construction will be less than the protection protocols required

for human maintenance and construction including engineered protection equipment like trench boxes, shoring, or confined space rescue.

- Welding of the LSPOP pipeline will be performed remotely by the PE3D equipment attached to the lunar rover. No personnel will be performing the welding/ joining of the pipe joints or other pipeline equipment. Joints will not be stressed under tension with pipe clamps for tie in welds due to continuous lay methodology, eliminating risk of springing loose and injuring nearby personnel.
- Moving vehicles and heavy machinery will be present during the construction of the LSPOP pipeline, but they will be mostly operated remotely and not near personnel. Any human activities near LSPOP construction will need to be coordinated and evaluated for site and task specific risks.
- Pressure testing of the LSPOP line will be performed remotely, with an exclusion radius established around all pressurized equipment. Due to the operating conditions of the LSPOP system, the pipeline will be tested at much lower pressures than most terrestrial pipelines and will pose less potential for injury in the event of a failure.

Operational risks associated with pipelines are largely due to failures resulting from equipment failure, poor design, or impacts to the pipeline from human or natural forces. The terrestrial pipeline risk scenarios that pose the most risk to health and safety that have been evaluated for LSPOP are overpressure scenarios, leaks, or ruptures, fouling of gas or harmful additions to the line, and loss of communications.

- Overpressure scenarios on the LSPOP system will be less impactful due to the low operating pressure on the line, but will be mitigated by redundant Pressure transmitters, control, and relief valves, and Emergency Shut Down (ESD) logic to control compressor output.
- Leaks on the LSPOP system will pose a negligible threat to personnel due to the product being nontoxic and the vacuum environment preventing combustion. Leaks and ruptures will be monitored throughout the pipeline with flow meters and intermediate pressure transmitters and isolation valves. In the event of a leak or rupture, oxygen will immediately be dispersed into space due to the vacuum environment of the Moon. The loss of pressure on the pipeline will be detected by the intermediate pressure transmitters, and isolation valves will close to limit the loss of oxygen and secure the system.
- Fouling of the oxygen gas could be possible regardless of transportation methodology in a lunar environment. The LSPOP system will be outfitted with filters and monitored by gas chromatographs and can be vented prior to reaching receipt destination where harm can be done. The system can be purged to remove impurities.
- Loss of communication can lead to a number of potential failures and uncontrollable outcomes throughout the system. To mitigate this risk, LSPOP will utilize redundant and diverse path communication systems (radio and fiber). In the event that communications are still lost, control logic can ESD the pipeline system to prevent potential unwanted outcomes.

4.2 Evolution and Expandability of the Pipeline System

4.2.1 Pipeline Basis of Design

A second revision, conceptual hydraulic analysis is developed here for the Lunar South Pole Oxygen Pipeline (LSPOP), a 5 km pipeline to transport oxygen gas from an oxygen production source to an oxygen storage/liquification plant near a lunar base. LSPOP is going to be composed of in-situ manufactured aluminum pipe segments that are passivated and welded or fitted together to span the 5 km distance.

The hydraulic model includes:

- One reciprocating/positive displacement compressor.
- The pipeline itself.

For the purpose of this hydraulic analysis second pass input variables were fine-tuned compared with the first revision and the following assumptions/approximations were made:

- A 20% margin is added to the length of the pipeline (5 km) to account for deviations, obstacles, horizontal or vertical slopes. The hydraulic model length of the pipeline is 6 km.
- Pipe material is assumed to be Aluminum 6063, UNS designation 96063 rated for temperature between -269°C and 204°C. This widely used pipe/tubing material is similar in mechanical and thermal properties to the pure Aluminum that potentially will be produced on the Moon.
- The suction pressure of the compressor is assumed to be 15 psig.
- Lunar soil (regolith) is assumed to have a bulk thermal conductivity of 0.04 W/(m*°C).
- Pipe is considered below ground, with a buried depth of 20-30 cm.
- Pipe Outside Diameter (OD) is set at 25 mm.
- Pipe wall thickness is assumed to be 3 mm, a value consistent with the internal pressure requirement, but also carrying a sufficient allowance to withstand external loads.
- The pipe absolute roughness is indicated to be around 1 mm.
- No insulation is added to the pipe.
- No elevation profile of the pipeline is considered at this stage. The impact of the elevation profile is assumed to be insignificant with the assumption that the transported oxygen is going to be always in gas phase along the pipeline.
- Pure oxygen is modelled with no expected impurities. The phase envelope of the oxygen is illustrated below, in Figure 4.2.1 gives the oxygen phase envelope as a

function of temperature at from 0 to 170 psig. Figure 4.2.2 extracts the data in the range of most interest from 0 to 100 psig for the baseline pipeline design. Figure 4.2.3 gives the phase envelope for consideration of a higher pressure expansion from baseline - 100 to 200 psig.

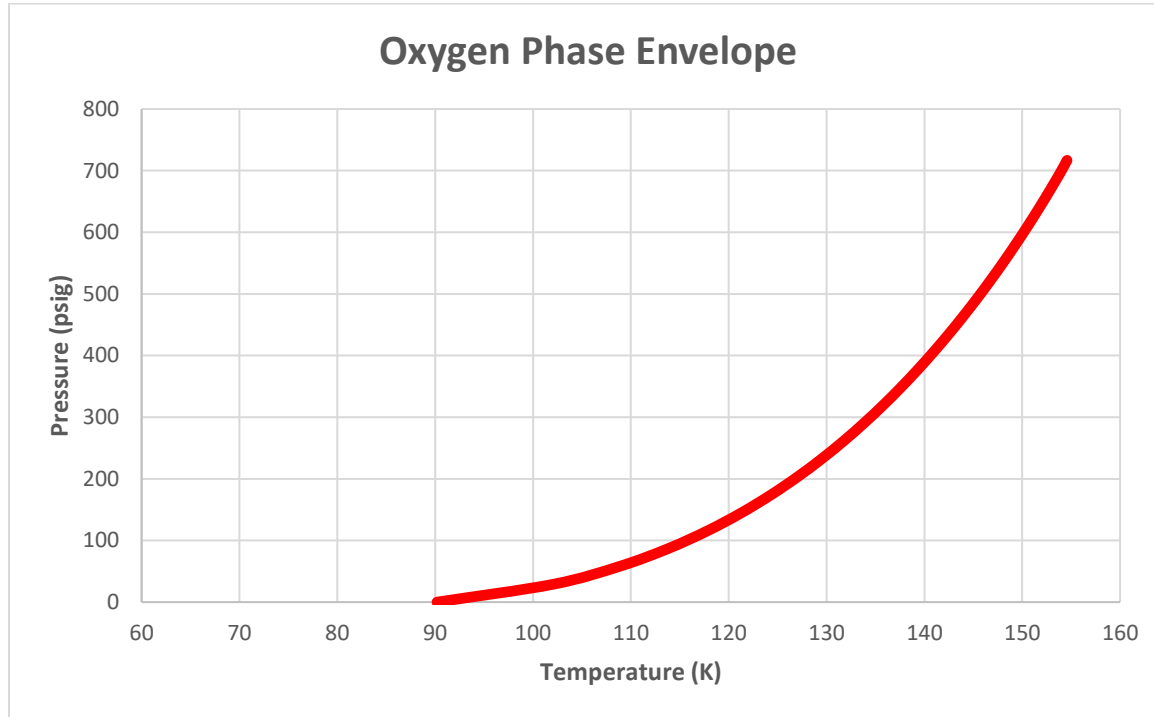


Figure 4.2.1 – Oxygen Phase Envelope

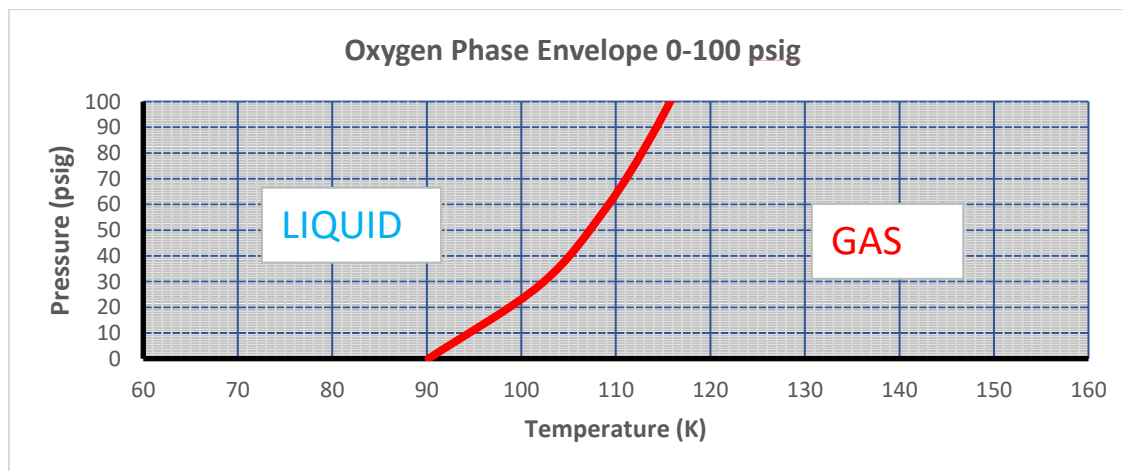


Figure 4.2.2 – Oxygen Phase Envelope – Extract 0-100 psig

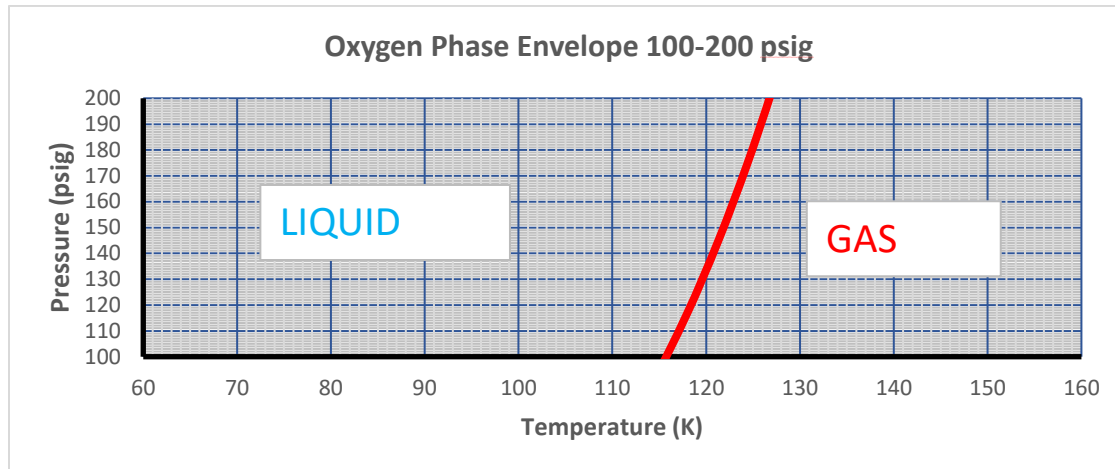


Figure 4.2.3 – Oxygen Phase Envelope – Extract 100-200 psig

From the phase envelope, several observations are evident:

At atmospheric pressure (0 psig), liquefaction temperature of O_2 (T_L) is 90 K (-183 °C)

At 50 psig (3.45 barg), $T_L = 107$ K (-166 °C)

At 100 psig (6.89 barg), $T_L = 116$ K (-158 °C)

At 200 psig (13.79 barg), $T_L = 127$ K (-146 °C)

Lunar soil temperature is assumed to be 128 K (-145.2 °C). In Section 2.3 “Analysis of the Temperature Versus Depth in Lunar Polar Regions” data are presented showing that the subsurface temperature year-round is a constant value of about 132 K below 0.25 m soil depth. Thus, setting the temperature in the hydraulic model at 128K maintains a margin over the liquefaction temperature of oxygen of 4 K. Therefore, no additional heating is required either at the inlet or anywhere else along the pipeline, oxygen remains in gas phase for all the pipeline normal operating conditions. See **Figure 2.2.1** “Temperature versus depth at 80° south latitude.”

The baseline Pipeline Inlet pressure is set at 50 psig (3.45 barg), a value that maintains a large safety margin over the liquefaction temperature and minimizes the pipeline compressor horsepower requirements.

The goal of this revision of the analysis is to demonstrate what is the maximum flow capacity considering as main variables extended length of the pipeline (beyond the 5 km +20% considered in the base case) and higher volumes of oxygen (greater flow rates than the baseline case of 5 kg/h).

4.2.2 Software information

The pipeline system is modelled using ProMax by Bryan Research & Engineering, a steady state multi-phase simulator which presents several characteristics appropriate for this project:

- Comprehensive Equation of State (EOS) collection. GERG 2008 Equation of State is utilized in the simulation.
- Powerful and robust density correlation.
- Mass and volumetric flow rate modelling with compositional analysis.

- Pipe Heat Transfer embedded module with multiple ground types available for buried pipe with default thermal conductivities provided, but updateable.

4.2.3 Maximum capacity of the base model

The maximum capacity of the 6 km pipeline system in the base case scenario is 12.4 kg/h. See **Figure 4.2.4 – Pipeline Pressure Profile - Flow variation for 50 psig inlet**.

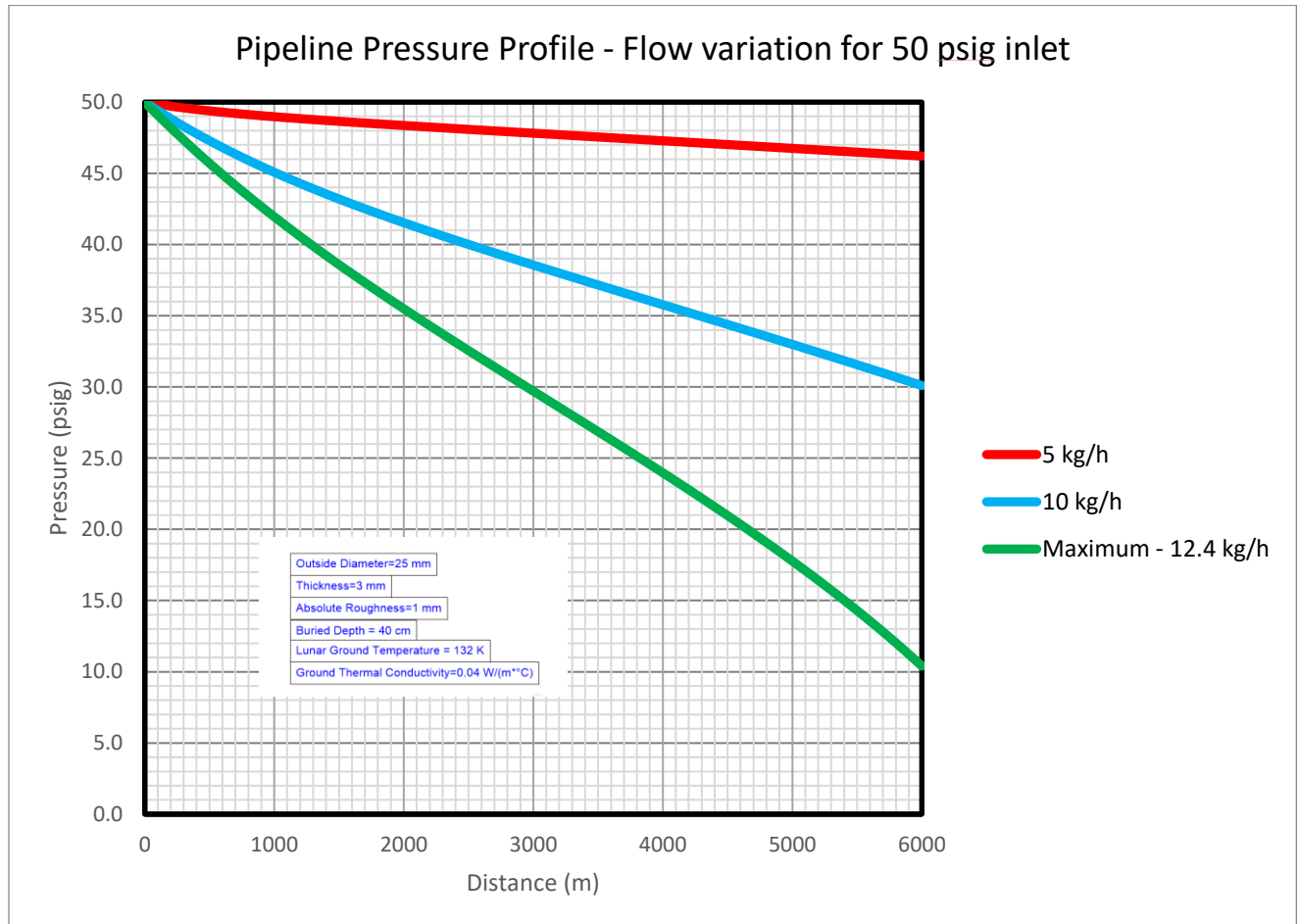


Figure 4.2.4 – Pipeline Pressure Profile - Flow variation for 50 psig inlet

No pressure boosting is required along the pipeline. No extra hardware is required with the exception of an additional compressor unit.

If the pipeline inlet pressure is increased to 100 psig (6.89 barg), the maximum capacity of the pipeline becomes 21.4 kg/h.

No pressure boosting is required along the pipeline. No extra hardware is required with the exception of additional compressor units.

See **Figure 4.2.5 – Pipeline Pressure Profile - Flow variation for 100 psig inlet**.

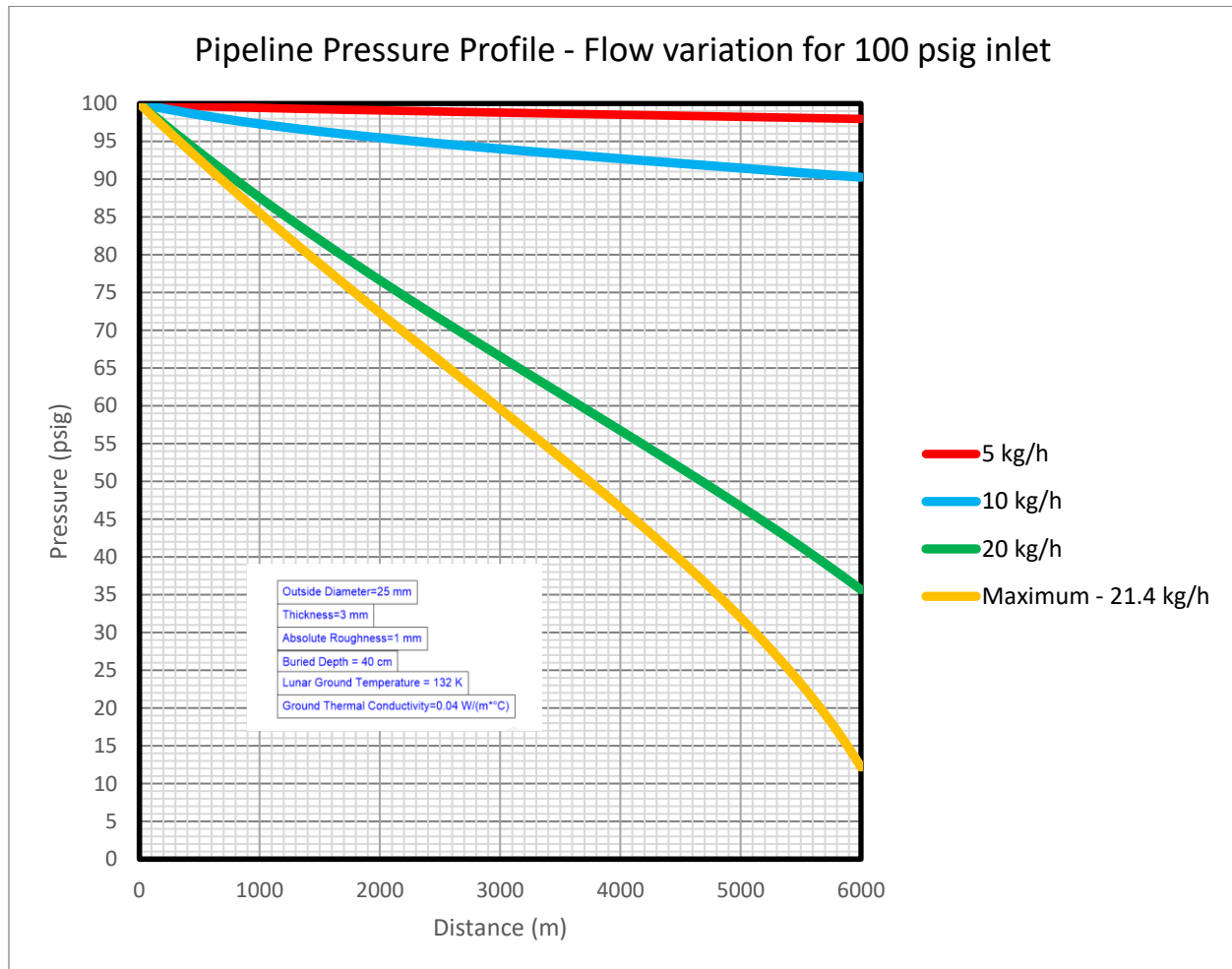


Figure 4.2.5 – Pipeline Pressure Profile - Flow variation for 100 psig inlet

4.2.4 Pipeline length extension beyond the base case (5 km)

The base case flow rate of 5 kg/h can be transported without pressure boosting for more than 30 km of extended pipeline length. See **Figure 4.2.6 – Pipeline Pressure Profile – Extended Pipeline Lengths**

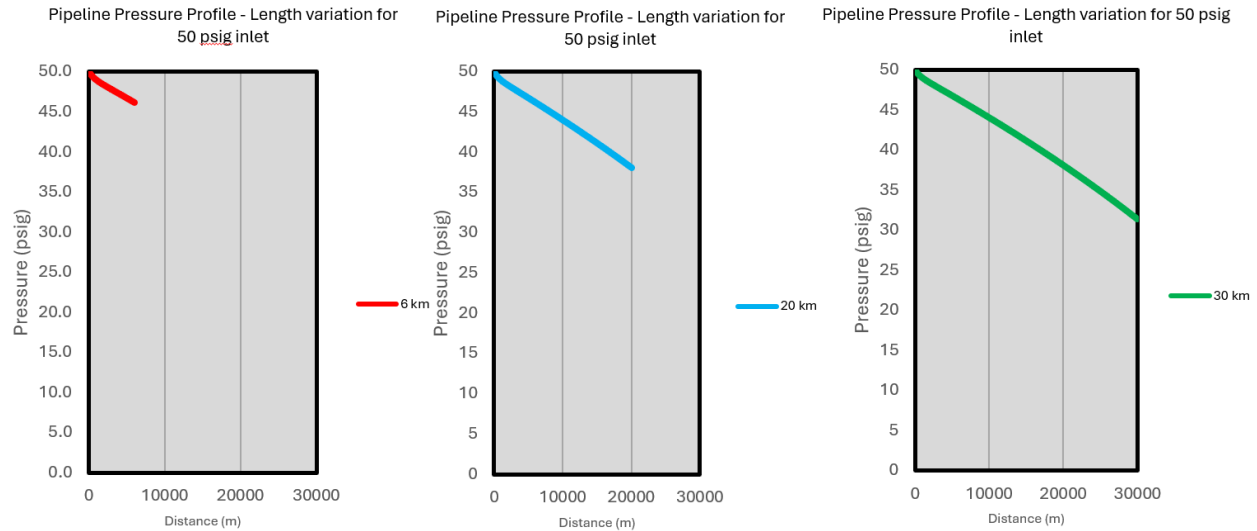


Figure 4.2.6 Pipeline Pressure Profile Extended Pipeline Lengths: 6 km (left), 20 km (center), 30 km (right)

4.2.5 Pipeline length extension and capacity expansion beyond the base case (5 km and 5 kg/h)

Pipeline maximum capacities were calculated for extended pipeline lengths (20 and 30 km, respectively) modelling additional pipe outside diameters (35 mm and 45 mm). See **Figure 4.2.7 – Pipeline Capacities for various pipe outside diameters (OD) – 20 km route** and **Figure 4.2.8 – Pipeline Capacities for various pipe outside diameters (OD) – 30 km route**.

Pipeline capacity exponentially increases with OD increase:

For the 20 km route:

- OD = 25 mm, Maximum Capacity = 7.9 kg/h
- OD = 35 mm, Maximum Capacity = 23.5 kg/h
- OD = 45 mm, Maximum Capacity = 49.3 kg/h

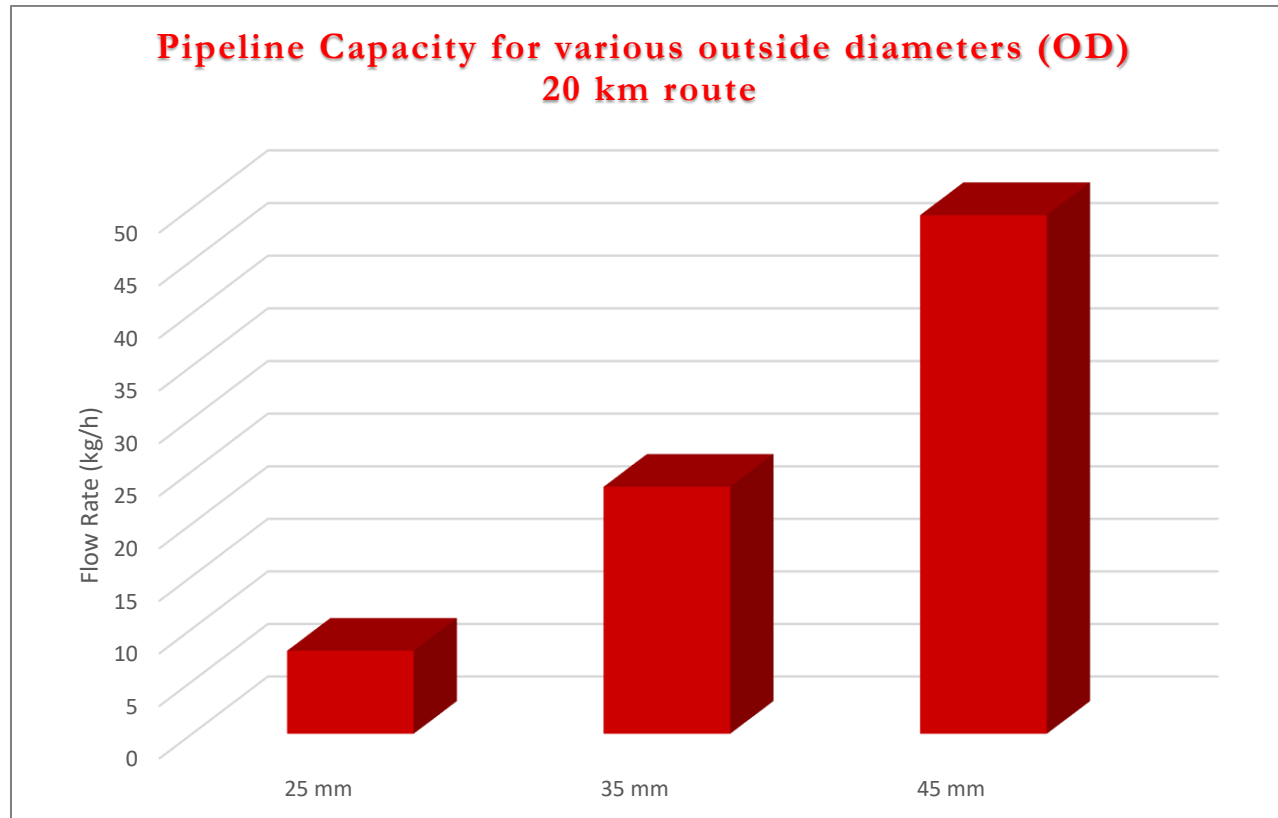


Figure 4.2.7 – Pipeline Capacities for various pipe outside diameters (OD) – 20 km route

For the 30 km route:

- OD = 25 mm, Maximum Capacity = 6.5 kg/h
- OD = 35 mm, Maximum Capacity = 20.1 kg/h
- OD = 45 mm, Maximum Capacity = 42.9 kg/h

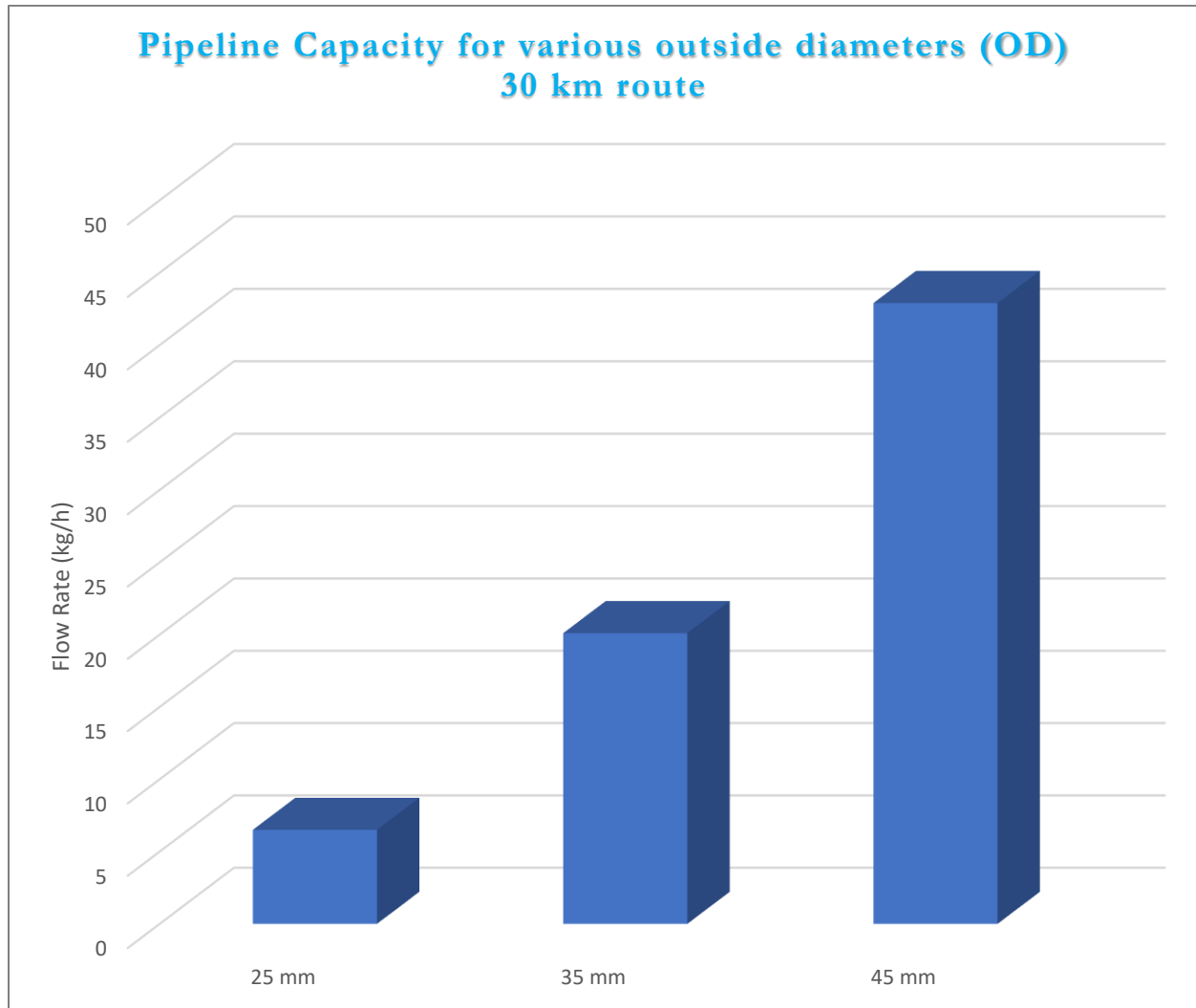


Figure 4.2.8 – Pipeline Capacities for various pipe outside diameters (OD) – 30 km route

4.2.6 Compression requirements

- Base case (6 km, 50 psig inlet, 5kg/h flow rate) requires 384 W of power.
- Compressor horsepower is directly proportional to flow rate.
- Inlet pressure increase to 100 psig requires 598 W of power for base case.
- No boosting compression was modeled in this revision.

Pipe weight for various diameters

Pipe average weight per unit length varies between 562 kg/km and 1073 kg/km for Pipe OD between 25 mm and 45 mm. See **Figure 4.2.9 – Pipe Weight for various outside diameters (OD)**

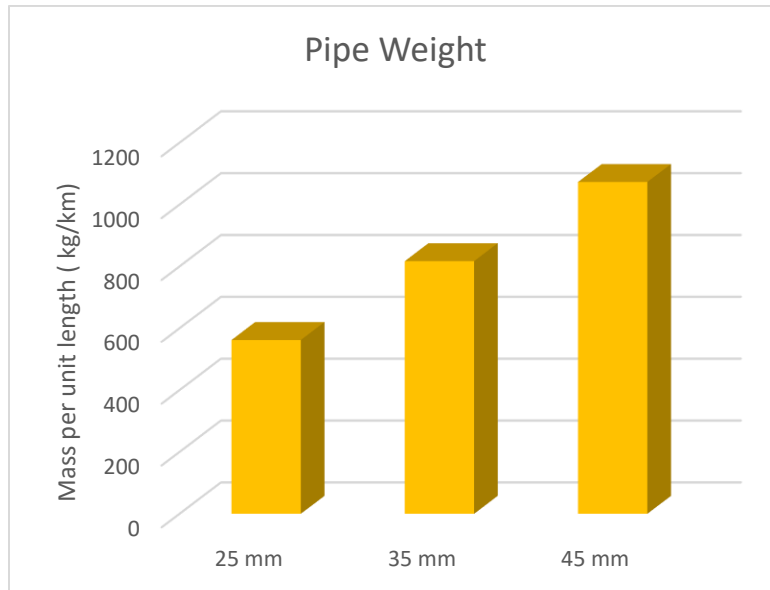


Figure 4.2.9 – Pipe Weight for various outside diameters (OD)

4.2.7 Evolution and Expandability Conclusions and Phase II recommendations:

- More research is needed on pipe/tubing material, the base model was built with Aluminum as pipe material.
- Oxygen purity is going to be researched and embedded in the model at the next revision.
- Sensitivity study to be finalized at later stages (optimum compression discharge pressure vs vessels size, different pipe materials, etc.).
- A more comprehensive thermal model considering diurnal/periodical temperature variations will be developed later when more Lunar data will become available.
- A rigorous elevation profile will be embedded in the updated model.
- Piping components and other equipment will be included in the future model.
- Pressure boosting options along the pipeline will be analyzed during the next phase of the design.

4.3 High Level Costs Model

A high-level cost concludes the Phase I System Architecture feasibility study (Task 4). The purpose of the model is to provide a high-level estimate of the LSPOP system costs and includes a comparison of the costs of a system with lunar manufacturing of the pipe segments with that of a system with the pipe segments made and transported from Earth. This model is expected to be updated and increase in fidelity in subsequent phases of the LSPOP project.

The general assumptions of the model are given in Table 4.3.1. It is assumed that 6 km of pipeline will be required from the Oxygen Ingest Facility at the point of oxygen production to reach a customer Terminal Connector 5 km distance away. The launch cost from Earth to any point on the lunar surface is assumed to be \$800k. The cost of rover transport and operations is assumed to be \$150k per km. Electrical power available on the Moon is assumed to cost \$150 per kWh. It is assumed that the regolith excavation required to bury the pipeline will cost \$150 per kg. It is assumed that the robot arms and trenching excavator can be leased and the 6 km pipeline will require 10,000- and 200-hours lease time respectively.

Table 4.3.1 General Assumptions

Category	Unit	Amount
Total length of pipeline	km	6
Launch Cost	kg	\$ 800,000
Rover transport	km	\$ 150,000
Electrical Power	kWh	\$ 150
Excavation of regolith	kg	\$ 150
Robot Arm Lease	hours	10,000
Robotic Excavator Lease	hours	200

4.3.1 Lunar Manufactured Pipe Segments:

The following section describes the cost estimation for building the LSPOP with the pipe sections manufactured on the Moon with aluminum extracted by a Molten Regolith Electrolysis (MRE) system. The construction assumptions are given in Table 4.3.2. The LSPOP baseline system pipe has an outside diameter of 25 mm and a thickness of 3 mm. This requires about 800 kg of aluminum per km. The efficiency of the MRE extraction system process is assumed to provide 1 kg of aluminum per 10 kg of regolith. It is assumed that the rover will need to move 3 km for every km of pipeline constructed. The pipe production method is assumed to be PE3D additive manufacturing with a pipe production rate of 3 kg per hour.

Table 4.3.2 Construction Assumptions for Lunar Constructed Pipe Segments

Category	Unit	Amount	Total for 6 km
Aluminum Required	kg/km	800	4800
Regolith per kg Aluminum	kg	10	48000
Regolith per Excavation Scoop	kg	1	48000
Rover Transport per km of pipe	km	3	18
PE3D additive manufacturing	kg/hr.	3	1600

The equipment costs for building a lunar gas pipeline are not well defined since there is no prior experience with such an engineering project. Space flight hardware can cost many times more than similar components built for operations on Earth. A factor of 30 times over Earth components is common for routine flight hardware. For development of lunar hardware without prior art is much higher. For this analysis we assume that the lunar hardware is 500 times more expensive than similar components used on Earth. It should be noted that with time and experience building lunar infrastructure the cost of this hardware should be much less estimated here. Using this basis of estimation the assumed Equipment Costs are given in Table 4.3.4.

Table 4.3.4 Equipment Cost for Lunar Constructed Pipe Segments

System	Equipment Cost	# for 6 km	Total Cost
PE3D	\$ 2,000,000	3	\$ 6,000,000
Robot Arms	\$ 2,000,000	6	\$ 12,000,000
MRE System	\$ 10,000,000	2	\$ 20,000,000
Trenching System	\$ 2,500,000	2	\$ 5,000,000
Pipe Guide System	\$ 500,000	2	\$ 1,000,000
Support Hardware	\$ 2,500,000	1	\$ 2,500,000
Sensors	\$ 44,000,000	1	\$ 44,000,000
Oxygen Ingest Facility	\$ 5,250,000	1	\$ 5,250,000
Terminal Connector	\$ 4,400,000	2	\$ 8,800,000
Logistic Controllers	\$ 10,000,000	2	\$ 20,000,000

Transportation from Earth to the Moon can be the most expensive component of building lunar infrastructure, thus the mass of components transported is an important factor in system costs. Table 4.3.6 gives the assumed equipment masses for the LSPOP system components. These masses are taken from spaceflight prototypes and similar components used on Earth. In the actual LSPOP these masses may be reduced by lunar specific designs.

Table 4.3.5 Equipment Mass for Lunar Constructed Pipe Segments

System	Launch Mass (kg)	Units per 6 km	Earth Launch Mass Total (kg)
PE3D	70	3	210
Robot Arms	100	6	600
MRE System	1200	2	2400
Trenching System	20	2	40
Pipe Guide System	10	2	20
Support Hardware	80	1	80
Sensors	200	1	200
Oxygen Ingest Facility	175	1	175
Terminal Connector	150	2	300
Logistic Controllers	50	2	100

It is assumed that electrical power will be available on the lunar surface at the price of \$150 per kWh. Table 4.3.6 gives the assumed power requirements for the LSPOP system components.

Table 4.3.6 Power for Lunar Constructed Pipe Segments

System	Description	kWh per unit	Total for 6 km	Total kWh
PE3D	kWh / kg Aluminum	10	4800	48,000

Robot Arms	kWh / kg Pipeline	1.4	6	8.4
MRE System	kWh / kg Aluminum	11.9	4800	57,120
Trenching System	kWh / km of trench	1.4	6	8.4
Pipe Guide System	kWh / km of trench	0.5	6	3
Support Hardware	kWh all support systems	1	6	6
Sensors	kWh / km Pipeline	1	6	6
Oxygen Ingest Facility	kWh for Ingest Facility	2	1	2
Terminal Connector	kWh for Terminal	1	2	2
Logistic Controllers	kWh per km	0.5	6	3

4.3.2 All Earth Manufactured System

This section gives the values for the All Earth Manufactured System. Most of the values are same as the previous section except that the pipe is manufactured on Earth and transported to the lunar surface. There are many options for Earth manufactured pipe. These will be examined in detail in subsequent Phases of the LSPOP project. For this top-level cost model Earth produced high quality 6061 T6511 aluminum tubing is used to estimate costs. For consistency of the cost comparison, the bonding method is the same as for the lunar pipe segment manufacture scenario - PE3D welding of pipe segments. In the Earth manufacturing case, (as shown in Table 4.3.7 Construction Assumptions) we assume that the pipe is transported in rolls 100 meters in length. This gives the Earth pipe the advantage of less welds and less time welding.

Table 4.3.7 Construction Assumptions for Earth Constructed Pipe Segments

Category	Unit	Amount	Total for 6 km
Pipe Segments per km	Pipe Segments	10	60
Rover Transport per km of pipe	km	3	18
PE3D welds pre pipe segment	Number of Welds	5	30
Hours per weld	Hours	5	12

The Equipment Costs (Table 4.3.8) are the same for the Earth Constructed Pipe with the exception that no MRE is required for the Earth Constructed Pipe scenario, but the Pipe must be purchased on Earth.

Table 4.3.8 Equipment Cost for Earth Constructed Pipe Segments

System	Equipment Cost	# for 6 km	Total Cost
PE3D (welding)	\$ 2,000,000	3	\$ 6,000,000
Robot Arms	\$ 2,000,000	6	\$ 12,000,000
Trenching System	\$ 2,500,000	2	\$ 5,000,000
Pipe Guide System	\$ 500,000	2	\$ 1,000,000
Support Hardware	\$ 2,500,000	1	\$ 2,500,000
Sensors	\$ 44,000,000	1	\$ 44,000,000
Oxygen Ingest Facility	\$ 5,250,000	1	\$ 5,250,000
Terminal Connector	\$ 4,400,000	2	\$ 8,800,000
Logistic Controllers	\$ 10,000,000	2	\$ 20,000,000
Earth Constructed Pipe	\$ 136,934,000	1	\$ 136,934,000

The Equipment Mass for the Earth Constructed Pipe scenario is the same as for the Lunar Constructed Pipe except that the MRE mass is not required but the earth constructed pipe mass must be transported from Earth to the Moon (Table 4.3.9).

Table 4.3.9 Equipment Mass for Earth Constructed Pipe Segments

System	Launch Mass (kg)	Units per 6 km	Earth Launch Mass Total (kg)
PE3D	70	3	210
Robot Arms	100	6	600
Trenching System	20	2	40
Pipe Guide System	10	2	20
Support Hardware	80	1	80
Sensors	200	1	200
Oxygen Ingest Facility	175	1	175
Terminal Connector	150	2	300
Logistic Controllers	50	2	100
Earth Constructed Pipe	4440	1	4440

The power requirements for the Earth constructed pipe scenario are less than that for the Lunar constructed pipe section scenario since the lunar extraction of aluminum from regolith is no required (Table 4.3.10).

Table 4.3.10 Power for Earth Constructed Pipe Segments

System	Description	kWh per unit	Total for 6 km	Total kWh
PE3D	kWh / kg Aluminum	10	4800	48,000
Robot Arms	kWh / kg Pipeline	1.4	6	6160
Trenching System	kWh / km of trench	1.4	6	8.4
Pipe Guide System	kWh / km of trench	0.5	6	3
Support Hardware	kWh all support systems	1	6	6
Sensors	kWh / km Pipeline	0.5	6	3
Oxygen Ingest Facility	kWh for Ingest Facility	2	1	2
Terminal Connector	kWh for Terminal	1	2	2
Logistic Controllers	kWh per km	0.5	6	3

4.3.3 Cost Comparison between Lunar and Earth Manufactured Pipe Systems

Table 4.3.11 summarizes the cost data for the lunar and Earth pipe segment manufacturing scenarios discussed above in this section. It should be noted that the transportation costs from Earth to the Moon dominate the costs of the Lunar South Pole Oxygen Pipeline construction. Even with the higher construction power and equipment costs for the lunar pipe segment construction case, the savings in Earth to Moon transportation costs by lunar pipe segment construction bring the LSPOP costs for a 5km pipeline down from \$4.9B to \$3.5B or a cost savings of 33%.

Table 4.3.11 Cost Summary and Total Cost Comparison

System Costed	Lunar Manufactured Pipe	Earth Manufactured Pipe
Equipment Cost	\$ 124,550,000	\$ 241,484,000
Launch Cost	\$ 3,300,000,000	\$ 4,932,000,000
Electrical Power Cost	\$ 15,773,820	\$ 7,588,110
Robotic arm lease	\$ 16,000,000	\$ 16,000,000
Trenching system	\$ 4,800,000	\$ 4,800,000
Robotic rover lease	\$ 2,700,000	\$ 2,700,000
TOTAL COSTS	\$ 3,463,823,820	\$ 5,204,572,110

5.0 Summary and Conclusion

During the LSPOP NIAC Phase I, we have developed a General Design and a comparison study of an in-situ system, where the pipe segments are manufactured on the Moon using materials extracted from lunar regolith, and compared a system where all the pipeline components are transported from Earth.

To determine the feasibility of LSPOP we performed a hydraulic analysis which helped determine a baseline design. The baseline design is 19 mm OD, 3 mm thick aluminum pipe, 6 km total length (5 km + 20%) buried in 20 cm of lunar soil assumed to be -100°C. The pipeline has an oxygen flow rate of 2 kg/hr. which can transport 10 MT of oxygen per year. The in-situ pipeline segments are constructed from Al, Mg, Si extracted from lunar regolith to form a 6063 alloy. The material is refined from the lunar regolith using the MRE refiners. Baseline in-situ pipe segment manufacture would utilize PE3D additive manufacturing. Each unit is estimated to produce 4.5 m of pipe per hour.

To determine the feasibility of finding a 5 km pipeline path in the lunar south polar region we focused on the Malapert Massif region, because it is one of the possible Artemis III landing sites and has high-quality, high-resolution mapping data available. We identified locations that met the general Artemis landing site requirements and mapped 6 feasible paths that were 5 km in length. The overall conclusion from the path study is that finding suitable paths for a 5 km pipeline that meets Artemis Program requirements is very feasible.

To test the feasibility of maintaining gaseous oxygen we studied the surface and subsurface temperature data from remote sensing and landers. We found although the surface temperature at $\pm 80^\circ$ Latitude the surface temperature can fluctuate from 68 to 212 K, however at 30 cm below the surface the temperature is a constant 132 K. Since for the pipeline operating pressure of 50 psi, oxygen liquifies at about 108 K, a pipeline buried at that depth could flow gaseous oxygen day and night year-round without needing auxiliary heating.

A LSPOP construction methodology was developed demonstrating the feasibility of remote construction of the pipeline using a trenching system, rover, PE3D printer and welder. A laboratory demonstration of PE3D welding a 6063-aluminum pipe in argon was completed and tested to 20 psig.

A feasible system architecture was developed for the baseline LSPOP that utilized specifications of the Lockheed Martin Lunar Mobility Vehicle. The overall conclusion is that while the details of how the pipeline will be built is a task for Phase II, no major issues were identified in phase I and the pipe laying requirements are achievable and clearly very feasible.

An implementation timeline was developed that would have the pipeline built connecting the receipt station to the customer facility in 2.5 years after which operations would proceed.

Safety and risk management were evaluated. A Risk Register was developed similar to those used in the Earth pipeline industry. Health and safety risks were evaluated focusing on the most common risks in terrestrial pipeline construction and operation and evaluating their potential risk in a lunar environment. The conclusion was that minimization of these risks to industrial standards is feasible.

The pipeline design was evaluated for evolution and expandability over the baseline. Calculations show that maintaining the pressure at 50 psi but increasing the throughput of oxygen 2.4 times to 12.4 kg/h is feasible by increasing the flow rate above baseline. Increasing the pipeline pressure to 100 psi could increase the pipeline throughput to 21.4 kg/h. Maintaining the baseline pressure and flowrate it is feasible to extend the pipeline length from 5 to 30 km without needing an intermediate

pumping station. These sensitivity calculations show that it is feasible to expand the pipeline over the baseline with minimal additional costs.

A high-level cost model was developed for building LSPOP using pipe segments built on Earth and shipped to the lunar surface compared to building LSPOP using pipe segments constructed on the Moon using aluminum extracted from the lunar regolith. The model showed that even with the higher construction power and equipment costs for the lunar pipe segment construction case, the savings in Earth to Moon transportation costs by lunar pipe segment construction bring the LSPOP costs for a 5km pipeline down from \$4.9B to \$3.5B or a cost savings of 33%.

In conclusion, the Lunar South Pole Oxygen Pipeline Phase I study demonstrates that building a pipeline utilizing pipe segments constructed on the Moon from aluminum extracted from lunar regolith for transportation of oxygen in the lunar polar regions is safe, efficient, cost effective and feasible.

6.0 References

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